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Associated with Hydrogen and High Hydrogen Content Fuels

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Abstract

As simulation capability improves exponentially with increasingly more cost effective CPUs and hardware, it can be used “routinely” for engineering applications. Many commercial products are available and they are marketed as increasingly powerful and easy to use. The question remains as to the overall accuracy of results obtained. To support the validation of the CFD, a hierarchical experiment was established in which the type of fuel injection (radial, axial) as well as level of swirl (non-swirling, swirling) could be systematically varied. The effort was limited to time efficient approaches (i.e., generally RANS approaches) although limited assessment of time resolved methods (i.e., unsteady RANS and LES) were considered. Careful measurements of the flowfield velocity and fuel concentration were made using both intrusive and non-intrusive methods. This database was then used as the basis for the assessment of the CFD approach.

The numerical studies were carried out with a statistically based matrix. As a result, the effect of turbulence model, fuel type, axial plane, turbulent Schmidt number, and injection type could be studied using analysis of variance. The results for the non-swirling cases could be analyzed as planned, and demonstrate that turbulence model selection, turbulence Schmidt number, and the type of injection will strongly influence the agreement with measured values. Interestingly, the type of fuel used (either hydrogen or methane) has no influence on the accuracy of the simulations. For axial injection, the selection of proper turbulence Schmidt number is important, whereas for radial injection, the results are relatively insensitive to this parameter.

In general, it was found that the nature of the flowfield influences the performance of the predictions. This result implies that it is difficult to establish a priori the “best” simulation approach to use. However, the insights from the relative orientation of the jet and flow do offer some guidance for which approach to take. Overall, the results underscore the importance of model “anchoring” (i.e., “tuning” the model to provide “reasonable” agreement with a well characterized geometry/flow).

Finally, the results obtained have been carefully compiled into a standalone database following a standard format that is contained in an Appendix. This database is thus available for use by others for CFD modeling evaluations.

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Executive Summary

As simulation capability improves exponentially with increasingly more cost effective CPUs and hardware, it can be used “routinely” for engineering applications. Many commercial products are available in the market and they are marketed as increasingly powerful and easy to

use. This is a direct result of increasing capability in computing hardware that allows sophisticated graphics and user interfaces that provide a convenient means to carry out simulations on a routine and increasingly time efficient basis. In essence, CFD has become as ubiquitous as a calculator or CAD package in terms of availability and convenience. As a result, it can be and is used for a myriad of design purposes. Of interest to the present project is the use of CFD for design of premixers as might be utilized in low emissions gas turbine combustion systems. The constraint on the CFD strategies considered herein is that they must be time efficient enough to screen designs. As a result, the project focus is on common Reynolds averaged numerical simulation (RANS) models found in the majority of commercial CFD products. In addition, limited evaluation of higher resolution strategies including Unsteady RANS and large eddy simulation (LES) was also carried out. The computational platform used is an 8 node cluster which would be a reasonable computational resource available for this purpose. To this end, it is noted that 3D simulations of a typical premixer configuration required 1-2 days for typical two-equation RANS (e.g., $k-\epsilon$), 1-2 weeks for Reynolds stress models, and 2-3 months for LES. Of principle interest is the ability of the computational approach to predict the mixing characteristics of gaseous fuels of interest. In the present work, methane, hydrogen, and mixtures of both are considered. These two fuels have significantly varying thermo physical properties and therefore reflect an interesting range of conditions with which to gauge the effectiveness of the CFD approaches evaluated.

To support the validation of the CFD, a hierarchical experiment was established in which the type of fuel injection (radial, axial) as well as level of swirl (non-swirling, swirling) could be systematically varied in addition to fuel composition. Figure ES-1 illustrates the test hardware used. Careful measurements of the flowfield velocity and fuel concentration were made using both intrusive and non-intrusive methods. The resulting database was then used as the basis for the assessment of the CFD approach.

Figure ES-1. Test Hardware Schematic.

A statistically design matrix was developed for the evaluation of the CFD strategies. Turbulence models, and turbulent Schmidt number values were studied for each of the experimental conditions. Care was given to grid generation and refinement for each case in order to ensure a stable, well converged solution was reached that that was independent of the grid used. The results from the various simulations were compared with the measured values and this comparison was used as the basis for evaluation of the CFD strategy. Table ES-1 summarizes the approaches examined.

Table ES-1: Summary of Numerical Approaches Evaluated.

Turbulence Model	Injection type	Swirl	Fuel	Sc_t
$k - \varepsilon$	Radial, Axial	No	Hydrogen, Methane	0.2-0.7
RSM	Radial, Axial	No	Hydrogen	0.2-0.7
LES	Radial	No	Methane	0.7
URANS	Radial	No	Methane	0.7
$k - \varepsilon$	Axial, Radial	Yes	Hydrogen, Methane	0.7
RSM	Axial, Radial	Yes	Hydrogen, Methane	0.7

The numerical studies were carried out with a statistically based matrix. As a result, the effect of turbulence model, fuel type, axial plane, turbulent Schmidt number, and injection type

could be studied using analysis of variance. Figure ES-2 summarizes the subset of the numerical runs that were isolated for the analysis of variance (ANOVA).

Study Type	Factorial	Runs	96				
Design Type	Full Factorial	Blocks	No Blocks				
Center Points	0						
Design Model	2FI	Build Time (ms)	1.2921				
Factor	Name	Type	Subtype	Low Actual	High Actual		
A	Turb Model	Categoric	Nominal	K-E	RSM	Levels:	2
B	Fuel	Categoric	Nominal	Methane	Hydrogen	Levels:	2
C	Plane	Categoric	Nominal	0.3125	1.875	Levels:	3
D	T-Sch	Categoric	Nominal	0.2	0.7	Levels:	4
E	Injection Type	Categoric	Nominal	Axial	Radial	Levels:	2

Figure ES-2: Summary of the Statistical Design used for Analysis of Variance.

Before summarizing the results of the ANOVA, some results are shown to get a feel for the variation observed between the predicated and measured results. In the present work, the averaged magnitude of the difference between the measured and predicted air/fuel ratio for all points over the plane is used. To provide better comparison between the two fuels, the values are normalized by the overall fuel/air ratio based on mean fuel air ratio measured in each plane. As a result, the values shown are essentially the average % difference between the measured and predicted values. Of course, the use of percent variation can be problematic; especially in regions with low absolute values. Regardless, this is the approach adopted to make the assessment.

The results for the non-swirling cases are summarized in Figures ES-3 and ES-4. The shorter bars indicate better overall agreement between the predicted and measured results. The results show some interesting trends. For example, as shown in Figure ES-3, URANS and LES do not provide significantly superior results to the RANS models for the radial injection of methane. Also, it is noted that different values of turbulent Schmidt number and the type of turbulence model affects the agreement. Further, some sensitivity to the type of fuel, either hydrogen or methane can be observed. Figure ES-3 shows results for the radial injection and Figure ES-4 shows results for axial injection. Hence comparing between these two figures illustrates that the type of fuel injection (either normal to [i.e., radial injection] or in line with [i.e., axial injection] plays a role in how accurate the simulations are.

Figure ES-3. Summary of Normalized Averaged Fuel/air Differences Between Experiment and Numerical cases at 3 planes for Radial Injection into a Non-Swirling Flow.

a) Methane

b) Hydrogen

Figure ES-4. Summary of normalized averaged fuel/air differences between experiment and numerical cases at 3 planes for axial injection into a non-swirling flow.

To provide a more quantitative assessment of the quality of the simulations, analysis of variance is carried out for the study. In this analysis, five factors are studied as summarized in Figure ES-2. The associated ANOVA is shown in Table ES-2. Consistent with ANOVA principles, the factors with highest F values are the most important factors in determining the relative agreement with the measured values. In this case, the turbulence model, the turbulent Schmidt number, and the Injection type. In addition, interactions are shown between the axial plane and injection type as well as turbulent Schmidt number and injection type. These interactions are due to the fact that the impact of one factor depends on the level of the other. For example, in

the case of the injection type and turbulent Schmidt number, it is noted that for radial injection, the value of turbulent Schmidt number doesn't matter very much. However, for axial injection, value of the turbulent Schmidt number is very important for getting good agreement.

Table ES-2: Analysis of Variance for Non-Swirling Cases

	Sum of		Mean	F	p-value
Source	Squares	df	Square	Value	Prob > F
Model	3.664	25	0.147	11.438	< 0.0001
A-Turb Model	0.504	1	0.504	39.322	< 0.0001
B-Fuel	0.088	1	0.088	6.896	0.0106
C-Plane	0.053	2	0.027	2.075	0.1332
D-T-Sch	1.162	3	0.387	30.224	< 0.0001
E-Injection Type	0.520	1	0.520	40.566	< 0.0001
CD	0.237	6	0.040	3.085	0.0097
CE	0.475	2	0.237	18.524	< 0.0001
DE	0.467	3	0.156	12.136	< 0.0001
CDE	0.159	6	0.026	2.065	0.0684
Residual	0.897	70	0.013		
Cor Total	4.561	95			

The major conclusions of this study are as follows:

In terms of overall observations and insights from the experiments:

- The Pitot-Static probe shows good agreement with more advanced techniques (i.e., Particle Image Velocimetry) even for cases with no fuel injection.
- The use of Laser Raman scattering for measurement of fuel concentration proved challenging in the absence of beam stretching. The available short pulse duration laser systems tried yielded ignition of the hydrogen without attaining sufficient Raman signal.
- The downstream mixing of fuel is determined primarily by the flow field, and has little to no dependence on the fuel section. With use of a constant fuel jet to air momentum

flux ratio, hydrogen behaved no differently than methane for all of the cases investigated.

- The result that the mixing behavior was insensitive to fuel type reaffirms that momentum flux ratio (J) is an important parameter for the determination of the spatial fuel distribution. This is evidenced by the ability of existing 1-D correlations in the literature to successfully predict the jet penetration in the near field for the non-swirling cases.
- Measurements of the velocity field with and without the fuel injected suggests that, for the conditions studied, the fuel selection has little effect on the velocity field downstream of the injection point. There is a limited effect near the jet itself.
- Flow swirl improved the symmetry of the flow, and quickly “smeared” any pattern due to distinct individual fuel jets in the case of radial injection.
- For the axial injection cases flow swirl works to decrease the jet area and generated a stronger and sharper peak, effectively making the jet less mixed and more centrally located.
- For radial injection cases flow swirl moved the fuel peaks inward, and reduced the effects of jet.

In terms of observations based on the comparison of the predicted fuel distributions with those measured:

- For the present geometry, use of quarter symmetry to represent the full domain is not appropriate. This is evidenced by the strong periodicity of the results which are not found when the full geometry is considered.
- Improper treatment of the coefficient of discharge for the fuel injection holes has a significant effect on the numerical predictions:
- Local refinement of grid near the centerline can contribute to numerical benefits in both axial and radial geometries:
- For the radial jet configuration, time averaged numerical results using RSM turbulence models are similar to those using LES and URANS, yet with significantly less computational time.
- For radial fuel injection into non-swirling flows, the CFD predictions are sensitive to the turbulence model used, but not to the value of Sc_t .
- For axial fuel injection into non-swirling flows, the CFD predictions are very sensitive to Sc_t values, but are not sensitive to the turbulence model used.

- For non-swirling flows, the RSM turbulent model provides more reliable numerical prediction of mixing properties of fuel and air compared to the $k - \varepsilon$ turbulence model in both axial and radial injection configurations.
- For swirling flows, it was very difficult to get the RSM turbulence model to converge to second order. As a result, the study could only assess the performance of the k- ε model (in this case the RNG variant of the k- ε model was expected to provide superior performance for swirling flows).
- The agreement between the RNG k- ε turbulence model with measured values was poor for the swirling cases.
- In general, it was found that the nature of the flowfield influences the performance of the predictions. This result implies that it is difficult to establish apriori the “best” simulation approach to use. However, the insights from the relative orientation of the jet and flow do offer some guidance for which approach to take.
- Overall, the results underscore the importance of model “anchoring” (i.e., “tuning” the model to provide “reasonable” agreement with a well characterized geometry/flow).

1 Introduction

1.1 Overview

The increasing focus on global issues such as pollution emissions and fuel security has led to a number of changes in the way energy is viewed. The perpetual use of fossil fuels is no longer seen as viable, both due to the climate issue as well as the scarcity of fossil fuels themselves. To overcome these issues new forms of clean energy and their corresponding technologies need to be developed and investigated.

Hydrogen has many advantages which align well with these interests and desired changes. The use of hydrogen for combustion has no emissions of CO, CO₂, or hydrocarbon species, with the only pollutant of concern being the generation of NO_x. Hydrogen has also unique properties such as a wide flammability limit which allows lean combustion. This lean combustion can aid in reducing combustion temperature, which in turn will reduce NO_x emissions. The chemical bonds within hydrogen also contain a large amount of energy, making it a useful energy carrier.

The use of hydrogen fuel is not without challenges which counter its emission advantages. As a fuel hydrogen must first be produced from another form of energy. If this is a hydrocarbon source, or uses energy from fossil fuels, a net emission of CO₂ is still present. Hydrogen also has the disadvantage of occurring naturally in a gaseous form, with a low density. This makes the storage and transport of large quantities of energy a challenge. Additionally hydrogen has a propensity for both flashback and auto-ignition, both of which make the use of hydrogen in low emissions applications a difficult design process.

To fully utilize hydrogen to its fullest potential an understanding of the mixing process of hydrogen and air is essential. While research in this area does exist, information in this area is still limited, and room exists for additional study.

For gas turbine combustion and premixing techniques such as jet in crossflow, co-flowing jets, and swirl are all common and accepted techniques for the mixing of fuels and air. An investigation of hydrogen under these mixing strategies, and its comparison to a similar and well understood hydrocarbon fuel such as methane, provides a valuable level of insight into the hydrogen mixing process. This information is critical for the future design of efficient, clean, and reliable engines operating on hydrogen fuel.

The direct combustion of hydrogen in the gas turbine combustor results in various challenges, especially resultant high flame temperature which can result in a high NO_x emission in the exhaust. To achieve low NO_x emission to meet the regulations, a lean premixed combustion strategy can be used. Lean mixtures of hydrogen and air reduces the temperature in the combustor and thereby reduces the NO_x emission. However, lean combustion techniques can lead to pressure oscillations, flashback, and autoignition. Among other issues, the proper design of the fuel/air premixer is crucial in order to address these challenges.

Premixer research requires both analytical and experimental studies to characterize and understand processes associated with the mixing of fuel and air. Since theoretical approaches are not generally able to provide accurate information over a broad range of various configurations, computational fluid dynamics (CFD) modeling can be utilized as a design tool for the assessment of relevant parameters of the investigated system (Broadwell and Breidenthal, 1984). The use of CFD as a design tool for fairly complex geometries has been made possible in recent years as a result of enhanced computer power. In the current study, Reynolds-Averaged Navier-Stokes (RANS) computations are used for the investigation of the velocity and combustion field properties, such as temperature and concentration field within gas turbine combustors (e.g., Stopford, 2002). With respect to some unsteady behaviors of flow field in a variety of the configurations, a number of unsteady computational approaches such as Large Eddy Simulation (LES) and Unsteady Reynolds-Averaged Navier-Stokes (URANS) are applied as well as typical steady RANS computational strategies. Efforts can be found which evaluate how these different types of modeling approaches compare with results for various types of flows (e.g., Bradshaw, 1997; Leschziner, 2000; Bourgeois, et al., 2011). In the present work, focus is given to the types of flows found in premixing ducts/swirler assemblies as might be used in lean premixed gas turbines.

Simulations are carried out for both methane and hydrogen content fuels. Methane is used as a point of departure for the study of hydrogen containing fuels. It should be mentioned that this study is accomplished for two configurations including axial injection of fuel to the main stream of the air, and radial injection of fuel into the main stream.

To evaluate the CFD predictions, experimental tests are conducted for both methane and hydrogen with appropriate strategy for each one of them.

1.2 Goals

The main goal of this work is to establish the general capabilities of various time-efficient Computational Fluid Dynamics (CFD) approaches to provide reliable predictions of flow field properties of next generation lean combustion premixers of fuel and air.

The second goal is to identify the most effective numerical approaches for the design of lean combustion premixer technologies.

2 Background

In this section, a review of lean premixed combustion is provided to help understanding the significance of this research, the benefits and challenges associated with utilizing hydrogen as a fuel, and the concept of CFD modeling of turbulent mixing. In addition, important features of turbulent mixing flows are explained and various numerical methods are discussed. For instance, governing equations of RANS simulations are presented to garner insight into the crucial parameters involved in the turbulent modeling of the flow field.

2.1 Hydrogen as a Fuel

As it was briefly described in the introduction chapter, hydrogen as a carbon free fuel is projected to be widely used in the future power generation activities (National Research Council, 2004). As a result, using gaseous hydrogen as a fuel is of growing interest to the power industry (Chiesa, et al., 2005). Considering hydrogen as an upcoming fuel, some special features of hydrogen should be carefully taken into consideration. For instance, the laminar flame speed of hydrogen is two orders of magnitude higher than methane at stoichiometric condition (on the order of meter per second) (Koroll, et al., 1993). Moreover, the stoichiometric adiabatic flame temperature is well above the “trigger” temperature (~ 1900 K) for the production of thermal NO_x . Thus, premixed lean combustion is the strategy that is emerging for hydrogen is evolving (Todd and Battista, 2000).

Due to the fact that hydrogen can react with air very easily, the premixing of hydrogen and air is challenging. Therefore, special considerations must be given to designing premixers to make sure the desirable level of mixing is provided in the absence of autoignition and flashback. A proper premixer design results in combustion stability and pollution emission mitigation. Consequently, a systematic evaluation and prediction of mixing properties of hydrogen into air is required.

The application of using hydrogen as a main fuel or adding hydrogen to the major fuel is growing in the powering of gas turbine engines. Clearly, the mixing properties of hydrogen are important. The current project addresses hydrogen mixing with the air in gas turbine engine applications.

2.2 Lean Premixed Combustion

Due to the fact that air quality regulations are becoming more restrictive, advanced combustion techniques have been developed to fulfill the low emission and high efficiency design goals. As an example, for stationary gas turbines, lean combustion techniques have been considered to reduce NO_x emission [e.g., Lefebvre and Ballal, 2010]. Increasing combustion efficiency of gas turbines has resulted in reduced emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO).

The major source of NO_x in gas turbine combustion is thermal NO_x which starts to form in appreciable quantities at temperatures above 1850K (e.g., Turns, 2000). Figure 1 presents the variation of temperature and NO_x emission versus fuel equivalence ratio. It is obvious that, in the lean region, the UHC, CO, NO_x and soot emissions are lower than emissions at the stoichiometric ratio. Thus, the main target of the lean premixed approach is to minimize the NO_x emission in the lean region. However, the main challenges are to stabilize the combustion reaction and mitigate the onset of both autoignition and flashback. The premixer design must reflect and appropriately address these challenges.

Figure 1 is shown for a typical hydrocarbon as the fuel. Utilizing “carbon-free” hydrogen as a fuel itself will remove the emission of CO, UHC, and soot. Thus, NO_x emission is the principal challenge of emission mitigation for hydrogen combustion. Providing a well mixed mixture at the entrance of the combustion chamber by means of proper design of the premixer is highly desirable to avoid local hydrogen rich spots in the combustion chamber which cause high local temperature and high NO_x emission (e.g., Lyons, 1982).

Figure 1-Emission versus fuel equivalence ratio (Samuelsen, 1975).

2.3 Turbulent Flow

Turbulent mixing of fuel and air plays a significant role in gas turbine combustion with respect to pollutant formation, emissions and chemical reactions (e.g., Wegner, et al., 2004). For modern low-emission gas turbines, the level of mixing between fuel and oxidant prior to combustion is a crucial design parameter. As a result, the design of a premixer must account for the turbulent flowfield into which the fuel/air mixture is injected. For instance, lean well mixed low NO_x combustion is an essential feature of modern power generating gas turbines. Single digit NO_x emissions, in some case even below 3ppm, are now achievable without catalytic after-treatment, but only with considerable optimization of the fuel/air mixing (e.g., King, et al., 2009; Burattini, et al., 2004). To achieve sufficient mixing, discrete jets are often used in both premixers as well as in the combustor where they are arranged around the circumference of combustion chambers to enhance combustion performance in the primary zone and also to dilute the exiting hot combustion product (e.g., Adreopoulous and Rodi, 1984). As a result, the jet in crossflow is an important class of mixing strategies for gas turbines. Moreover, axial injection along swirl generation module is used to make a stable combustion in the recirculation zones.

In general, turbulent mixing is experienced in numerous processes in the power generation applications. Turbulent mixing which includes the diffusion processes of all of

scalars, such as temperature and species concentration, occur in the turbulent flow (e.g., Jischa and Rieke, 1979). Complications involved in the mixing turbulent have been subjects of thousands of research activities in the world since 1960 (e.g., Reynolds, 1974; He, et al., 1999). Besides studies leading to understanding of the flow field velocity and pressure features, mixing properties have been investigated based on early Prandtl and Schmidt number approach (Reynolds, 1974). However, in highly turbulent cases, it is theoretically challenging to provide any information about velocity and pressure flow field in practical premixers. Therefore, empirical and numerical CFD predictions can be required to provide a robust evaluation of turbulent mixing properties (Dunham, et al., 2009).

Overall, the accuracy of modeling of turbulent flow itself can lead to accurate turbulent mixing model. Turbulent flows that are common in the industrial applications need to be well understood in order to make accurate predictions. Almost always jet injection applications include high turbulent flow. For instance, Figure 2 presents the planar illustration of a turbulent jet in two different Reynolds numbers. The instantaneous injection of a round jet into quiescent ambient air was captured in Figure 2 by means of laser diagnostics apparatus.

Figure 2-planar images of concentration in a turbulent jet (a) $Re = 5,000$ (b) $Re = 20,000$ [Dimotakis, 2000].

The flow field is highly chaotic at high Reynolds numbers, and contains a variety of different length scales. The chaotic characteristics of turbulent flow for velocity field are demonstrated in Figure 3.

Figure 3—the time history of the axial component of velocity $U_1(t)$ on the center line of a turbulent jet [(Warhaft, 2000)].

It is observed that the axial velocity of a jet in turbulent flow varies significantly. Although the fluctuations seem very random and chaotic, the time-averaged velocity follows some certain rules. That's why for turbulent flows, which is mostly considered at Reynolds numbers higher than 4000, a number of time-averaged numerical models have been suggested to properly resolve the flow field properties. This concept is explained more in the CFD section.

2.4 Computational Fluid Dynamics (CFD)

In general, fuel injection in the form of jets into main stream in the gas turbine premixer, in either axial or radial injection, is an example of a free turbulent shear flow which inherently contains turbulent flow complications (e.g., Keffer and Baines, 1963).

Because of the great practical importance of mixing, several methods such as numerical, analytical and experimental analyses have been used to study and predict this phenomenon. Since turbulent flow, especially the case of radial injection into cross flow, entails complex

phenomena, analytical approaches are generally not able to provide accurate information in broad range of configurations (Broadwell and Breidenthal, 1984). As a result, computational fluid dynamics modeling can be utilized as a design tool for the assessment of relevant parameters of the investigated system. The use of CFD as a design tool for fairly complex geometries has been made possible in recent years as a result of enhanced computational power.

In the case of turbulent mixing, CFD can overcome the difficulties described in the previous section. For instance, time-averaged CDF modeling such as RANS simulations can provide steady state result of mixing. On the other hand, transient and dynamic properties of the flow field can be evaluated by means of using the unsteady CFD.

Due to the fact that governing equations of turbulent mixing flow fields are partial differential equations (PDE) Navier-Stokes equations, finding exact solutions for those equations requires solving highly non-linear equations. In the case of gas turbine premixer, regarding complex configurations, high level of turbulent, and resultant non-linear governing equations, exact theoretical solution for the flow field properties is almost impossible to find. Thus, imposing some simplifications and assumptions, numerical method can model the governing equations and provide information about flow field properties. The accuracy of the provided results depends on the numerical methodology. In a lot of engineering practical applications, CFD can provide fruitful information.

In current design practice, Reynolds-Averaged Navier-Stokes (RANS) computations are the most often used CFD tools for investigation of the velocity and mixing properties in gas turbine combustors and premixers. This is a result of the relative tradeoff between computation time (relatively short for RANS) and accuracy (hard to assess a priori). However, in premixer designs, especially for hydrogen, it would be helpful to identify the CFD approaches accuracy in general. In the context of RANS modeling various models exist to close the set of equations. The major classifications of modeling approaches for the turbulent stresses are (e.g., Bardina, et al., 1997):

- Eddy Viscosity model
- Reynolds Stress Model (RSM)
- Algebraic Stress Model

The $k - \varepsilon$ turbulence model is classified as an eddy viscosity model, with two partial-differential equations for compressible and incompressible fluids. The Realizable $k - \varepsilon$ model is

reportedly the most reliable $k - \varepsilon$ turbulence model for the jet in cross flow problem (Xiao and Tang, 2006). In addition to the $k - \varepsilon$ turbulence model, the RSM model is examined here as a “more accurate” RANS turbulence model.

Due to potential unsteady behavior of the flow field, especially for radial injection into cross flow configurations, two unsteady turbulence model strategies have been implemented as well. During the last decade, many experimental as well as numerical studies have observed the three-dimensional and unsteady vortical structures which provide a very efficient mechanism for the mixing process between the jet and the cross-flow. The jet in cross flow consists of four known vortical structures shown in Figure 4: 1) horseshoe vortices 2) jet shear layer 3) wake structures, and 4) counter-rotating vortex pairs (Fric and Roshko, 1994).

Figure 4-the known vortical structures of the jet in the cross flow (adapted from Smith and Mungal, 1998; Fric and Roshko, 1994).

Due to increased recognition of the role of dynamic phenomena in the jet in cross flow, unsteady simulations using CFD (e.g., Large Eddy Simulation, Unsteady RANS, direct numerical simulation) have been considered necessary to capture the key features of the mixing (e.g., Ivanova, et al., 2009).

The large eddy simulation (LES) approach, by filtering the governing equations, utilizes modeling for eddies smaller than the so-called sub-grid scales (SGS) while it explicitly resolves all of the larger scales. Although LES has shown promising results in various applications, it is computationally expensive. Thus, unsteady RANS (URANS) is often considered as an alternative unsteady strategy to predict the dynamic scalar fields. Both approaches are considered in this work.

Like radial injection cases, unsteady behaviors have been observed for the axial single jet into the main flow (Caruyer, et al., 2010). However, due to the fact that primary results of steady cases suggested reliable predictions, unsteady numerical cases for the axial injection mode have been avoided.

A reliable CFD simulation requires care in formatting and implementing the approach. The numerical grid must resemble the actual configuration. After that, accurate boundary conditions must be imposed. Then, high quality mesh generation is necessary for the geometry to enable solving the governing equations by means of a CFD solver such as Fluent®. Accurate computations of turbulent flows require careful mesh generation. While high accuracy is desired, because turbulent fluctuations play a significant role in the transport of all parameters, it is critical to ascertain that the turbulent quantities are suitably resolved. Due to the strong interaction of the boundary conditions with main turbulent flow, numerical results for turbulent flows, especially those for mass transport, are more prone to grid quality dependency than those for laminar flows. Thus, it is vital that grid independency studies are carried out.

After completion of pre-processing of numerical results, appropriate turbulent model must be selected to solve the governing equations. As mentioned earlier, various steady and unsteady models are available with various cons and pros. For instance, LES model still uses numerical estimations, but they are used in scales that are presumably small enough that the overall solution is more accurate than RANS models.. However, using LES necessitates spending much more time for solving the flow field governing equations. RANS models though, by spending less time can provide predictions of the flow field properties with supposedly less accuracy.

In addition to sensitivity to turbulent models, sensitivity to different Sc_t number is observed (e.g., He, et al., 1999; Yueng, et al., 2002). The implementation of RANS modeling to solve turbulent flows with mass transfer generally estimates the turbulent scalar flux by

presuming the gradient diffusion hypothesis, which requires the definition of the turbulent Schmidt number Sc_t .

$$Sc_t = \frac{\nu_t}{D_t} \quad \text{Eq. 1}$$

Conceptually, Sc_t is similar to the Schmidt number, Sc , which is a dimensionless number approximating the ratio of molecular kinematic viscosity to molecular mass diffusivity. Because Sc can vary widely in different applications from order 10^{-3} in liquid metals to orders approaching unity in gaseous flames to thousands and higher in organic mixtures and biological fluids, an understanding of its influence in numerical solutions is important (Yeung, et al., 2002). The value of Sc also depends on the gases being mixed. For example, for methane and air, Sc is 0.9, whereas for hydrogen and air, Sc is 0.2. In turbulent flows, however, the role of Sc in mixing is reduced and Sc_t generally dominates the predicted mixing behavior. The appropriate value of Sc_t is defined based upon either empirical or analytical relations in specific flow configurations. In general, the proposed range of Sc_t in jet into main flow applications is 0.2 to 0.7; however ranges from 0.2 to 1.3 have been used in some cases (e.g., Tominaga and Stathopoulos, 2007). The range of Sc_t used in the present work is 0.2 to 0.7 for RANS cases for both axial and radial injection modes to capture the best Sc_t number for each configuration and each fuel.

After investigating the appropriate turbulent models and also coefficients, it is necessary to process the obtained data in a process called post-processing. The major purpose of post-processing is to visualize the data including velocity, pressure, and concentration fields. Plots, figures and animations are produced in this step.

2.4.1 Governing Equations

To garner more insight into major features of mixing turbulent modeling of flow fields, it is helpful to take a look on the governing equations associated with them. In this section, the governing equations of $k - \varepsilon$ turbulent model are presented to illustrate special roles of important parameters involved in these equations. For an incompressible steady flow with constant viscosity, the Reynolds averaged governing equations for mass, momentum, species concentration, turbulent kinetic energy and its dissipation rate for the $k - \varepsilon$ model can be

written in the general following format (e.g., Launder and Spalding, 1990; Dudokovic and Pjanovic, 1999):

$$\frac{\partial}{\partial x_i}(\rho U_i \Psi) = \frac{\partial}{\partial x_i} \left(D_\Psi \frac{\partial \Psi}{\partial x_i} \right) + S_\Psi \quad \text{Eq. 2}$$

The equations are specified in detail in Table 1. It should be noted that Ψ is an arbitrary variable which can be replaced with an appropriate variable according to Table 1 and D_Ψ is the diffusion term.

Table 1 Detailed governing equations

Ψ	D_Ψ	S_Ψ
1	0	0
$U_j, j=1,2,3$	μ_t	$-\partial P / \partial x_j + \partial \{ \mu_t (\partial U_i / \partial x_j) \} / \partial x_i$
S	μ_t / Sc_t	0
k	μ_t / σ_k	$G - \rho \varepsilon$
ε	$\mu_t / \sigma_\varepsilon$	$(\varepsilon / k)(c_1 G - c_2 \rho \varepsilon)$

μ_t , which is the turbulent viscosity defined as:

$$\mu_t = C_\mu \rho k^2 / \varepsilon \quad \text{Eq. 3}$$

Where $C_\mu=0.09$, $c_1=1.44$, $c_2=1.92$, $\sigma_k=1.0$ and $\sigma_\varepsilon=1.3$. S represents the species concentration and Sc_t is the turbulent Schmidt number.

Regarding the equation, if the Ψ is replaced by S , the species concentration equation is obtained. In this equation, it is apparent that Sc_t can play a role in the mixing equation. For instance, increasing Sc_t , which can be related to an increase in turbulent dynamic viscosity or a decrease in turbulent diffusivity, offers that mixing is mostly due to the turbulent fluctuation. To interpret that, it should be noted that there is a direct correlation between Reynolds number and Sc_t (e.g., Dudukovic and Pjanovic, 1999). On the contrary, a decrease in the Sc_t , which inherently correlated to lower Reynolds number, means mixing is mostly due to turbulent diffusion.

2.5 Summary

To improve the air quality and meet more restrictive air quality regulations, alternative fuels to replace the traditional fossil fuels are being widely considered. Among alternative fuels, hydrogen presents a number of promising features as a future fuel source. As a result, combustion of hydrogen in the stationary gas turbine has been investigated in the recent decades. Hydrogen has some unique features, such as very high laminar flame speed, high diffusivity, low density and high flame temperature. The most important advantages of considering hydrogen as a fuel is that combustion of hydrogen is free of CO, UHC and soot. On the contrary, due to the high flame temperature, NO_x emission is a major challenge of hydrogen combustion. Consequently, lean premixed combustion is the strategy adopted to mitigate NO_x emission. To accomplish a combustion process that is stable, free of undesirable pressure fluctuations, autoignition, and flashback, a thorough understanding of the mixing properties of hydrogen in the gas turbine premixer is needed. To model turbulent mixing in the premixer, the knowledge of properties of turbulent flow is necessary. Turbulent flows contain random and chaotic flow field properties. Also, they are governed by non-linear equations. With respect to the fact the equations are not amenable to an analytical solution for the governing equations, a numerical simulation is required to resolve the flow field properties. CFD by means of making some simplifications and models can obtain predictions about momentum and mixing flow field. The accuracy of results of CFD depends on the turbulent model used and also some other parameters. For instance, sensitivity to coefficients such as Sc_t is observed. Thus, to find a reliable CFD approach, a thorough evaluation of all of the required steps should be maintained. The first goal of this study is to evaluate different numerical strategies for delineating the turbulent flow in a premixer. The second goal of this effort is to find a reliable design tool that can obtain detailed predictions about mixing properties of hydrogen in a model premixer.

From the literature, a single RANS model which is reliable and time-efficient for premixer design purposes in the lean combustion technique is not available. It is reported in some papers that the RSM model provides better prediction. However, it is reported that $k - \varepsilon$ has a better ability of prediction of flow field properties in other group of papers. Hence, it is desired to investigate for this type of applications, which RANS model provides better numerical results. Therefore, both RSM and $k - \varepsilon$ models are the subjects of this study to facilitate obtaining some useful design recommendations about this piece of missing information in the literature.

Moreover, it is not clear that how different Sc_t numbers contribute to various numerical predictions for typical premixer configuration in lean combustion applications. It has been tried in this work to come up with single value of Sc_t number with the most appropriate prediction in each case, through studies in axial and radial configurations for both methane and hydrogen.

Furthermore, the detailed challenges of lean combustion of hydrogen are missing in the literature. In order to have a better understanding of hydrogen combustion, mixing properties of hydrogen are addressed.

3 Methodologies

3.1 Experimental

The experiment was conducted at the University of California, Irvine Combustion laboratory (UCICL) using an atmospheric pressure test stand. This section describes the facility capabilities that were employed, the test stand hardware used, and the measurement techniques employed.

3.1.1 Experimental System parameters

The parameters of the test stand and supporting systems are first described. This includes the test stand as well as the air and fuel delivery systems which were employed.

3.1.1.1 Test Stand

The test stand employed consisted of a modular frame mounted within a 3-axis traverse system. The frame allows various test hardware to be installed within the traverse system, which in turn allows precision movement in experimental studies.

The 3-axis traverse system consists of a series of 3 worm gears, where each axis has a linear encoder (Mitutoyo, AT2-N500) tied to a digital readout (Mitutoyo, PM33L). This system allows the entirety of the test hardware to be moved in all three axes with a resolution of 0.0127 mm. Air and fuel are supplied to the test stand using flex lines to facilitate this movement. This system is shown in Figure 5, where the readout is visible in the upper right corner, x and y traverses are visible at the bottom center, and the z traverse is visible within the aluminum frame.

Figure 5: Experimental test stand

The traverse system is located between two optical benches. These benches are used for the installation of test and measurement equipment, and are designed to minimize vibrations. The main idea of this setup being that rather than move diagnostic equipment such as a laser and its optics, or a measurement probe, to move the test stand. This is especially beneficial for the situation of laser diagnostics, where the movement of the optics can be time consuming and delicate.

The test stand is also installed below a fume hood. This fume hood is tied to a blower and air handling system which removes and dilutes all exhaust from the test stand to ensure proper ventilation. To further ensure safe operation a set of hydrocarbon and CO₂ sensors are installed within the testing area to monitor the air quality.

3.1.1.2 Air Circuit

Air is supplied to the test stand through a central air compressed air system at the UCICL. This system consists of three air compressors (Ingersoll Rand, N100A/C and 2 HPE300) which supply air at a line pressure of 827.4 kPa. Additionally the air is passed through a series of filters and de-humidifiers, to supply clean, dry air at flow rates up to 5.66 SCMM.

For this study air flow rates were metered through the use of critical flow orifices. This included both a 1.524 and 4.572 mm flow orifice (Flow Systems Inc, critical flow orifices), which

allowed control over a wide range and allowed a split of the air flow if required. These orifices were calibrated using laminar flow elements (Meriam Laminar Flow Elements models: 50MW20-1 and 50MW20-2) and a coriolis meters (Micro Motion, CMF010). Pressure was monitored through the use of pressure transducers (NoShok Inc, 623-300-1-1-2-6 and Omega Engineering PX305-200GI) and digital readouts (two Athena, NXT16CCF060). These sonic flow orifices and their accompanying pressure transducers are shown in Figure 6.

Figure 6: Air circuit critical orifices (silver disks), and pressure transducers

3.1.1.3 Nitrogen Circuit

For some of the cases the air flow was replaced with nitrogen as it is non reactive with fuels. The nitrogen was supplied by an on-site liquid nitrogen storage tank installed in the rear of the facility. This tank was capable of supplying a continuous supply of nitrogen at up to 1.31 SCMM.

To facilitate the operation on nitrogen a series of three way valves were installed which allowed the nitrogen to be passed through the same critical flow orifices used for the air circuit. Calibration, similarly, was done using the laminar flow elements.

3.1.1.4 Fuel Circuit

The fuel circuit consists of the fuel supplies, flow rate meters and accompanying control system, and a fuel mixing plenum. As mentioned the primary fuels of interest for the study were hydrogen and methane.

Methane fuel was supplied through natural gas which is supplied to UCICL through the utility companies. The incoming methane is passed through a compressor to boost its supply pressure up to 758 kPa.

Hydrogen was supplied through the use of pressured gas cylinders. Commonly hydrogen comes in a set of six cylinders referred to as a six pack. A six pack contains roughly 42.5 SCM of hydrogen at over 98% purity.

For both fuels the supplied gas was then metered and controlled using Brooks Instruments equipment. This consisted of a mass flow controller (Brooks Instruments, 5851i) for each fuel stream, as well as the master control unit (Brooks Instruments, Model 0154). This master unit was used to manually set and monitor the flow rates, which the flow controllers then provided. For methane a factory calibrated flow meter was used while for hydrogen a second methane meter was recalibrated. Calibration was performed through the use of a laminar flow element (Meriam Laminar Flow Element, Model 50MJ10-13F) and coriolis flow meter (Micro Motion, CMF010). This controller was setup to operate on a percentage of the full flow rate, which was then manually calibrated using a laminar flow element. Additionally another mass flow controller was tied to this system to monitor flows of nitrogen if required. The master control unit is shown in Figure 7, with the individual mass flow controllers shown in Figure 8.

Figure 7: Fuel circuit master controller unit

Figure 8: Fuel circuit mass flow controllers (front), and fuel mixing plenum tank

After the fuel passes through the mass flow control systems it entered into a mixing plenum. This is simply a volume in the delivery system which is intended to mitigate any flow oscillations and allow mixing if multiple fuels are used. For this study the plenum had inputs for methane, hydrogen, nitrogen, and air to allow any combination of those supply gases. This plenum then fed the mixed gas to the test stand for injection. This plenum tank is shown in the background of Figure 8.

3.1.2 Test Hardware

The test hardware employed is designed to function as a model premixer, and is designed to be modular in nature. A hexagonal interface is used to ensure proper alignment of the various plates, with one plate having a hexagonal recess and the other the accompanying hexagonal protrusion. For this study a simple plate with the initially hexagonal interface is installed within the modular frame, with the test hardware being built up from this.

The initial component is the air plenum module, where air enters from four radial spokes. A sintered bronze ring is installed within the air plenum to minimize any flow swirl imparted by this radial entrance of the air. This air plenum, the air entrance spokes, as well as the hexagonal recession are shown in Figure 9. The additional test hardware is built up on top of this air plenum.

Figure 9: Air plenum module (left) and sintered ring (right)

The additional hardware components include a flow conditioning module, quarl, quartz liner, and finally an exhaust section. Fuel enters separately through the centerbody, which includes a threaded injection cap. The completed test hardware and basic flow diagram is shown in Figure 10.

Figure 10: Premixer section view with important components and flows labeled

For this hardware the inside diameter of the main section is 63.5 mm, with the centerbody having an outside diameter of 25.4 mm. The top of the centerbody is located 25.4 mm below the top of the quarl module. Axial fuel injection occurs at the top of the centerbody, while radial injection occurs 25.4 mm upstream of the end of the centerbody. The inside

diameter of the quartz liner is 81.28 mm, and this section is 161.54 mm until the liner is open to exhaust. Additional details of the geometry are shown in Figure 11, and detailed technical drawings of the various components can be found in the appendix.

Figure 11: Test hardware cross section with dimensions. Note all units are in mm

To ensure an air tight fit between components the quartz module, the final metal component of the premixer, has a lip for a metal plate. This metal plate is then bolted to the metal frame which the air plenum rests. These bolts are then tightened which compresses the various hardware components together, ensuring no leaks. The completed test hardware is shown in Figure 12, with the compression system bolts visible.

Figure 12: Modular premixer installed within test stand¹

3.1.2.1 Air Lines and Conditioning

Air flow quality was important for this study and a large effort was placed to make the flow as close to ideal as possible. This was seen as both a benefit to the experimental studies to minimize the effects of flow discrepancy, but also to facilitate improved comparison to CFD numerical simulations. As a result effort was directed to ensure symmetric flow, and in the case of non-swirling flow, ensure all residual flow swirl were removed. Flow symmetry was addressed through modifications of the air delivery lines while the improvement of the flow quality (swirl) was addressed through an additional flow straightening plate, which is discussed later.

Flow symmetry was initially checked through the use of a Pitot-static probe (velocity measurement) and found to be lacking. It was found that the air entering the air plenum was not evenly distributed among the four inlets. To address this discrepancy the air lines were remade, ensuring an even length of line to all of the inlets, and also working to have similar bends/turns for each line. The flow field was then rechecked through the use of the Pitot-static probe to verify a symmetric air flow field.

3.1.2.2 Injector Modules

Fuel injection is carried out through injection from the centerbody. To facilitate the modular design of this study a centerbody with a threaded cap module was designed. The main centerbody would provide the interface to the fuel delivery circuit while the cap would determine the injection type and numbers.

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The centerbody is nominally 25.4 mm in diameter, and 450 mm in length. The centerbody enters at the bottom of the test hardware, and is held in place through the use of a compression fitting with a Teflon ferule. This compression fitting allows both the height as well as the orientation (rotation) of the centerbody to be changed readily. Additional details of the centerbody specifications are shown in Appendix A.

The caps were also designed with the interest of CFD simulations in mind. As a result instead of having a rounded tip, which has been a typical design for this modular test stand, a square tip was used. This is due to the fact that rounded edges can cause complications in CFD methods during the meshing processes due to the rounded geometry. A comparison of a standard cap to the new square design is shown in Figure 13.

Figure 13: Centerbody cap edge comparison

Two main caps were designed. One providing axial injection through a single injection point located on the top of the cap. The second cap was designed for radial injection outward from the centerbody. This cap included eight injection points evenly spaced along the circumference of the cap. For each cap the injection hole sizing was selected to be 1.194 mm, based on previous designs. The centerbody and caps were fabricated by Ideal Engineering Inc. (Santa Ana, Ca), and the finished product can be seen in Figure 14. The technical drawings which these parts were fabricated from are including the appendix, with the caps shown in Appendix A-2 and Appendix A-3.

Figure 14: Axial injector cap (left), threaded centerbody (center), and radial injector cap (right)

3.1.2.3 Centerbody Alignment

It was also determined through the testing that the centerbody alignment with just the compression fitting at the bottom was not sufficient. The tip of the centerbody had a tendency to deviate, and this was especially a problem for the axial injection cases.

This problem was corrected through a series of band style clamps wrapped around the centerbody and tied to the modular test frame. A set of four clamps were used to allow adjustment in any direction. By tightening and loosening these bands the centerbody alignment could be corrected to a proper orientation.

3.1.2.4 Flow Conditioning Modules

The flow conditioning module sits on top of the air plenum and is the blue component in Figure 10. This module allows the installation of a flow conditioning plate, which for this study included either a flow straightener, or a swirler plate. The flow straightener was found to be a required component to ensure sufficient flow quality as the sinter ring was not capable of completely removing all flow swirl.

The flow straightener was constructed from two aluminum rings, with a section of aluminum honeycomb between them. These components were fabricated by MachineTek LLC. (Carlsbad, CA) and then assembled on site. The outermost aluminum ring sat in the flow conditioning module, while the inner ring slid over the centerbody. The inner ring was intended to protect the inner edge of the honeycomb, while being thin enough to minimize its impact on the flow. The honeycomb section consisted of hexagonal cells of 3.175 mm width. Each component had a depth of 18.97 mm. These components were initially press fit together, and

metallic glue was then used to ensure the components remained together and stationary. The finished product is seen in Figure 15.

Figure 15: Flow straightener plate

A swirler plate was also used when swirling flows were intended as part of the test case. For this study a 45° swirler plate was used, which was on site from previous work. This plate consists of a series of angled vanes which impart an angular momentum on the flow as it passes through the plate. This plate consisted of eight vanes with a total depth of 18.97 mm. This plate can be seen in Figure 16.

Figure 16: Swirler plate hardware

3.1.3 Measurement Techniques

The goal of the study is to provide mixing information for the mixing of hydrogen through various injection strategies. This mixing is evaluated through measurements of spatial

fuel concentration, with the evolution of mixing evaluated by taking measurements at varying distances downstream of injection. Additionally velocity measurements are of interest to provide additional insight into the flow fields of the test cases. For these measurements both simple probe based methods as well as more advanced laser diagnostic techniques were employed.

3.1.3.1 Extractive Probe

For measurements of fuel concentration an extractive probe technique was employed. This method used a 3.175 mm stainless steel probe inserted into the flow field. This probe was connected to a vacuum pump to allow a small sample of the flow to be extracted from the flow field to be analyzed. A number of various techniques were employed in the analysis of the samples and each is outlined below. For these methods spatial resolution was obtained by holding the probe fixed with the test hardware being moved in relation to it. The setup of the extractive probe used in non-swirling and swirling flows is shown in Figure 17.

Figure 17: Extractive probe experimental setup for non-swirling (left) and swirling (right) flows

3.1.3.1.1 Gas Chromatograph

The most prominently used method for this study was the use of a gas chromatograph (GC). Gas chromatography is a technique which measures the individual species of a volume of gas through the separation of the gas species and the use of a thermal conduction detector element.

Gas separation is performed within the GC through the use of an internal column. This column has an internal packing which interacts with the incoming fluid sample. Every species has a different affinity for the packing material, and as a result each elutes at a different time (Guiochon, 1990). The time this takes is known as the retention time. To facilitate the movement of the sample species a neutral carrier gas is used.

Each individual species is measured after separation through the use of a wheatstone bridge thermal conductivity detector, where the thermal conduction of each gas produces a measureable signal by changing the resistance due to temperature variations (Guiochon, 1990). The strength of the signal is directly related to the type and volume of the gas which passes over the detector element. To account for the influence of the carrier gas the separated sample with its carrier gas flows over one leg of the wheatstone bridge while a pure carrier gas stream passes over the reference leg of the bridge.

For this study an Agilent M200 Micro GC was used with a carrier gas of pure helium. The species of interest in their order of effluence include hydrogen, oxygen, nitrogen, and methane. An important aspect of the use of the GC is the calibration and spanning process. This GC can be seen in Figure 18, and for reference with its supporting components in Figure 19.

Figure 18: Gas chromatograph unit front panel, with sample inlet

Figure 19: Gas chromatograph unit with accompanying computer and carrier gas cylinders

In this study a multipoint calibration was used, with between three and seven points for each species. In this calibration strategy a number of gas species of known concentration are analyzed in the GC to create a correlation between the integrated detector signal and the volume of a species. The GC then assumes a linear relation between these points. Methane, oxygen, and nitrogen displayed a highly linear relation over their whole range, but hydrogen typically had a non-linear behavior, especially at low concentrations. This ability to use a multipoint calibration, despite the extra calibration complexity, was deemed critical for accuracy over the wide range of volume concentrations present within a measurement plane. As a result the GC was used for the vast majority of concentration measurements used with the extractive probe.

Calibration gases consisted initially of a number of span bottles, gas cylinders, of known concentrations. Due to the wide ranges needed, the fuel circuit was eventually used to produce mixtures of known concentrations for calibration. The air circuit was also fed into the fuel plenum during the calibration process for more variability on mixture composition. These mixtures were verified against the span bottles as a confirmation of the fuel circuit accuracy in mixture generation and the general calibration accuracy.

During a study the GC was used to analyze a sample at a number of various spatial locations. Typically two measurements were taken at each point and averaged, though if a large change was seen additional measurements were taken. A single measurement typically took on the order of ~50 seconds for hydrogen, and ~55 seconds when methane was present. This extra time was due to the longer retention time for methane.

3.1.3.1.2 Flame Ionization Detector

The flame ionization detector (FID) was a measurement strategy for methane fuel concentration. This detector functions by passing the sample through a small hydrogen jet flame which ionizes hydrocarbons. This ionization process produces a measurement signal which is directly related to the concentration of carbon atoms in the flow (McWilliam et al., 1958 and McWilliam 1983). As the fuel of interest in this study is methane (CH_4) containing only a single carbon atom, the FID reading is directly the volume concentration of fuel present in the sample volume.

In this study a Horiba FIA-236-1 FID was used. This system output a voltage signal directly proportional to the volume concentration of methane fuel present in the sample. This system relies on a linearly output, and as a result the calibration process is simply a two point calibration between a zero point (nitrogen) and a known span gas. Measurement values were obtained by averaging the voltage signal of the FID over one minute as the signal does fluctuate. If the signal was still changing after a minute additional time was used, and then a second number taken to verify accuracy. The FID itself is shown in Figure 20, with the voltage readouts being redirected to the terminals in the top right, and the sample inlet located at the top left.

Figure 20: Flame ionization detector front panel

As the detector functions on a measurement of carbon atoms, this detector is only viable for hydrocarbon fuels, and cannot provide information on hydrogen volume concentration. This detector also essentially destroys its sample during the measurement process due to the use of the hydrogen flame, and must be the last detector used if sensors are used in tandem.

3.1.3.1.3 Hydrogen Analyzer

The third measurement tool used with the extractive probe was a hydrogen analyzer. Like its name suggest it measures hydrogen volume concentration. This system operates similarly to the GC in that it uses a wheatstone bridge thermal conductivity detector to measure hydrogen concentration. The major difference though is that this system does not attempt to separate out individual species. This approach is viable for hydrogen as its thermal conductivity is approximately seven times that of oxygen and nitrogen.

For this study a Horiba TCA 300 hydrogen analyzer was used. This analyzer also uses a zero and span calibration technique like that of the FID, with a linear relationship between the two points. Also like the FID this analyzer outputs this signal as a voltage signal, which was averaged over one minute to minimize the effects of signal noise. If the signal was still changing after a minute additional time was used, and then a second number taken to verify accuracy. The hydrogen analyzer unit is shown in , the sample inlet as well as signal outputs are located on the rear of the unit.

Figure 21: Hydrogen analyzer unit, front panel

This technique has a number of issues, and as a result was used sparingly. Firstly it can only handle measurements of hydrogen in nitrogen accurately. Methane has a thermal

conductivity which is also greater than air, though not to the same extent as hydrogen, and as a result can skew the accuracy. This limited the ability to use this analyzer in tandem with the FID for fuel mixtures. The other large limitation is that the hydrogen analyzer cannot accept flammable mixture as it can damage the sensor. This meant that when this instrument was used the air was replaced with nitrogen as it is non reactive.

3.1.3.2 Pitot-Static Probe

Velocity measurements were also taken through the use of a Pitot-Static probe (United Sensor, PCC-24-KL) and a differential pressure gauge (Mid-West Instrument #60001). These probes measure both static and stagnation pressure simultaneously through a series of measurement ports. The tip contains one port which when aligned with the flow measures the stagnation pressure, while on the outside sleeve a series of smaller ports measure the static pressure as the air passes the probe. A schematic of a probe is shown in Figure 22, with the probe used shown in Figure 23.

Figure 22: Pitot-Static probe schematic

Figure 23: Pitot-Static probe

Through the use of Bernoulli's equation, equation 4, the dynamic pressure can be solved by the difference of these two measured pressures as shown in equation 5. This then allows for the axial velocity to be solved directly as shown in equation 6.

$$P_{stagnation} = P_{static} + 0.5 \rho U_{axial}^2 \quad \text{Eq. 4}$$

$$\text{Dynamic Pressure} = 0.5 \rho U_{axial}^2 = P_{stagnation} - P_{static} \quad \text{Eq. 5}$$

$$U_{Axial} = \sqrt{2(P_{stagnation} - P_{static})/\rho} \quad \text{Eq. 6}$$

This final equation though points out the limitation of the process. The density must be a known quantity. This is simple for a homogenous flow, such as pure air, but limits this technique for situations where fuel has been injected into the flow. As a result of this limitation this technique was used to measure air velocity and verify flow symmetry prior to fuel injection.

3.1.3.3 Laser Methods

Fuel location and concentration through the use of a laser diagnostic technique was also investigated. For this study, both laser Raman Scattering and planar laser induced fluorescence (PLIF) were considered.

3.1.3.3.1 Laser Raman Scattering

It was originally planned to use Laser Raman Scattering to measure the fuel gas species at a point. Figure 24 illustrates the setup used. This approach was desirable as it would allow simultaneous measurement of different fuel species at a point. This would allow profiles of the fuel as a function of species to be determined.

Figure 24: Laser Raman Setup.

A fair amount of effort was put into developing this methodology to compliment extractive probe measurements because the Raman method was non-intrusive. However, several challenges prevented a successful application. First, the high flammability of hydrogen

yielded ignition with the laser probe volume. This was due in part to the short laser pulse, resulting in high energy levels at the sample volume for a given laser power. The high power levels were desired to generate strong signals. To overcome this, “pulse stretching” can be used to extend the duration of the pulse from nanosec to microsec, allowing a strong signal but not breakdown (e.g., Kojima and Nguyen, 2002). Implementing such a strategy was beyond the scope of the original planned approach. Secondly, the use of the confined flow caused high noise levels from the reflections off windows and the liners. Finally, as early comparative results from methane and hydrogen became available, it was apparent that little difference in concentration profiles were observed, suggesting the need to consider dependency of fuel type on mixing behavior was not as important as originally thought. Further, the results suggested that a more straightforward method to non-intrusively measure the fuel mixing (e.g., acetone PLIF) might make more sense to apply.

3.1.3.3.2 Planar Laser Induced Fluorescence

This technique relies on the fluorescence property of a seeder species, in this case acetone. When excited by ultraviolet (UV) energy acetone releases the extra energy in the form of fluoresced light. This light can be imaged to obtain information on fuel location and concentration. An ultraviolet source is important for this technique, and a laser is typically used due to its high energy density. For this study a Continuum Surelite III-10 Nd:YAG system operating in the 4th harmonic (266nm) was used. This laser system is a water cooled, pulsed operation laser, with a maximum power output of 100 mJ at 266nm. This laser initially generates energy in the near infrared band at 1064 nm, but is reduced to 532 nm through a second harmonic generator, and finally 266 nm (UV) with a fourth harmonic generator. A series of dichroic mirrors are used to ensure residual 1064 and 532 nm light is removed from the beam.

This beam is then manipulated through a series of optics to generate a thin sheet of focused laser energy. This allows an entire plane to be imaged at once rather than a single point. This included a cylindrical plano-convex lens (Thor Labs, 500 mm focal length, #LA4579), which focused the beam downward, and a plano-concave rectangular lens (CVI Melles Griot, -125mm focal length, #RCC-40.0-25.4-63.6-UV), which spread it along a single direction into a sheet. These lenses working in tandem create a thin beam sheet, which in this sheet was horizontally orientated to be normal to the axial flow direction. Stray light was also cleaned up through the use of multiple adjustable apertures (Melles Griot) along the beam path.

As the sheet induces a fluorescing reaction in the flow it must then be imaged. This was done using an intensified charge coupled device (ICCD) camera. The ICCD camera was mounted above the test stand with the lens oriented straight down to be normal to the measurement plane. This orientation prevented image aberrations that are present when the camera is placed at an angle relative to the measurement plane. An Andor Istar ICCD was employed in this study. This camera has 16 bit resolution with a 1024 by 1024 pixel resolution chip, and a controllable exposure time. This exposure time was adjusted such that the camera only was imaging while the acetone was fluorescing to minimize noise. Additionally this camera is fitted with an intensifier unit which can amplify light intensity and also reduces signal noise. A non UV transmitting camera lens (Pentax, 35-70 mm focal length zoom lens, F-mount) was used to avoid contamination of the image by scattered UV light. Additionally a glass plate was mounted below the camera to ensure no acetone condensed on the lens. The camera, it's mounting relative to the test stand, and this plate is shown in Figure 25.

Figure 25: PLIF experimental setup

The final aspect to this experimental setup is that of the timing unit. Due to the pulsed nature of the laser the fluorescence of the acetone is not continuous. The camera also has a limited length of time in which the ICCD array is being exposed to light. These two occurrences must be synchronized to properly obtain images. This was done by using a trigger signal which is output by the laser prior to lasing, which combined with a delay generator, was capable of

properly timing the imaging process. The delay generator used was a Princeton Instruments Inc Programmable Pulse Generator (PG-200). This device functions by receiving an input signal and then outputting a signal at a controllable time later. The length of the delay was altered to ensure that the camera always detected the fluorescence occurrence. The overall experimental setup for the PLIF imaging is shown in Figure 26.

Figure 26: PLIF experimental setup diagram (side view)

3.1.3.3.2.1 Acetone Seeder Unit

To facilitate fluorescence, acetone was seeded into the fuel injection. Acetone normally is a liquid at room temperature, but has a low vapor pressure. By heating the acetone a significant molar fraction can exist in the gas phase. By injecting liquid acetone into the heated fuel stream, this liquid would evaporate and be carried along by the fuel and be injected into the premixer.

The first component of the acetone seeder is the acetone pressurized tank. This tank stores a reservoir of acetone, which is under the effect of a nitrogen blanket. This pocket of pressurized nitrogen above the acetone is a driving force to pump acetone as needed. The acetone flow rate was controlled through the use of a rotameter (Aalborg Teflon flowmeter with Brooks Instruments rotameter tube size R-2-15-A). As the rotameter valve was opened the acetone would flow due to the nitrogen pressure, and pass through a small perforated pipe as it was injected into a heated tank.

The heated tank is where the carrier gas, in this case fuel, and the acetone are mixed. The tank is heated to ensure all the acetone can exist in the gas phase. Prior to reaching this

tank the fuel is also heated as it is passed through a series of coils wrapped in heating elements. Fuel flow rate is controlled through the use of the fuel circuit, which is routed through the seeder unit.

The new mixture of acetone and fuel then travels through a heated flex line to be injected through the centerbody. The centerbody that is exposed below the premixer was also wrapped in band heaters to maintain the increased temperature. This constant heat is critical as if the temperature cools some to all of the acetone will condense out. The temperature of the heated flex line, the inlet fuel coil, and the heated tank were maintained through the use of two PID controllers (Omega Engineering, Inc, CN77R322-A2), with set points nominally at 95 °C for the tank and fuel coil, and 75 °C for the heated line. This resulted in an injection at roughly 50 °C. This temperature was above the minimum of 40 °C which was required to keep all of the acetone in the vapor phase.

To avoid condensation of acetone within the centerbody during start up the system was initially preheated with air until it reached the approximate flow temperature. This was intended to avoid acetone coming in contact with the cool metal walls. The bulk fluid was then changed to the fuel, in this case methane, and finally the acetone was added. The flow schematic of the acetone seeder unit is shown in Figure 29, with the unit itself shown in Figure 27 and Figure 28.

Figure 27: Acetone seeder unit front panel. Critical components include: PID controllers (top left); acetone rotameter (center); and fuel and nitrogen inlets (bottom right)

Figure 28: Acetone seeder unit components, top view. Critical components include: Acetone storage tank (top right); preheating coil (top left); and heated mixing tank (center, left)

Figure 29: Acetone seeding process diagram

3.1.3.3.2.2 Image Processing

The PLIF imaging technique obtains an image of light intensity over a spatial area. In these images the light intensity at each pixel corresponds to an acetone concentration, but must be adjusted to account for the laser intensity. As mentioned the light is directly related to the laser intensity, and the images must be normalized to a standard laser power.

This normalization process was carried out in the LaVision DaVis software as well as through the use of standard spreadsheet tools. Initially a number of images (ten) were taken of the laser sheet at the front, center, and back of the flow field. All of these images were taken of the laser shining on a paper surface 45° to the camera lens. At each location the images were then averaged, the background noise subtracted, and the values exported into a spreadsheet.

Using the spreadsheet tools, the maximum value in each row was found (the laser is oriented vertically in the images), and then averaged with two pixels from each side horizontally. Once this was done for the front, center, and back image a linear interpolation was used to fill in the space between the images and generate a laser intensity image. This image was then normalized by its maximum value to generate a relative laser intensity image, which was imported back into the DaVis software.

This new image was then passed through a 9x9 linear filter to remove graininess present in the vertical direction. An inverse image was then made by taking 1 over each individual pixel count. This image could then be multiplied against a standard image to correct for the laser intensity distribution in both the horizontal and vertical direction.

For each test configuration four post processing steps were taken. Initially the instantaneous images were averaged together to provide a time averaged acetone concentration image. Secondly the background noise was then subtracted from the image. This image was then multiplied by the inverse laser intensity image to correct for the laser strength, and finally a mask was applied to the image. This mask removed all data outside of the flow field as it is unneeded.

Finally the images were scaled accordingly. This step was based upon calibration images taken of known mixtures of acetone. These calibration images were taken through the same post processing as the test cases. These calibration images, once adjusted, provide a tie between pixel count and acetone concentration.

Examples of the various images of the image processing are shown below in Figure 30. This image shows the various stages of the image processing technique, and all are from the same test case.

Figure 30: Example images for PLIF processing, showing an instantaneous image (left), averaged image (center), and averaged image which has been corrected for laser intensity (right)

3.1.3.4 Particle Image Velocimetry

Velocity measurements with fuel injection were also investigated through the use of a laser diagnostic technique known as particle image velocimetry (PIV). This technique relies upon visible light reflection off of a seeded species, which in this case was olive oil. Small scale particles are inserted into the flow and then illuminated with a visible laser sheet. This visible sheet scatters when it hits a particle, illuminating each, which in turn is imaged to reveal and track its location. By taking a pair of images the velocity can then be determined for the flow field within the laser sheet. The separation of these images is typically on the order of microseconds, and requires special attention and hardware.

3.1.3.4.1 PIV Setup

A laser system is required for PIV operation as a source of a thin concentrated visible light sheet. Due to the small time separation required between the laser sheets a laser pair is typically used for PIV measurements. In this study a Surelite III PIV system was employed. This consists of two Surelite III-10 Nd:YAG laser systems optimized for PIV measurements. As a result both systems operate in the second harmonic (532nm, 380 mJ), and their beams are aligned in such a way as that they exit the laser co-linearly. This is critical so that the laser sheet does not move between pulses.

As for the PLIF method a series of optics are used to generate a laser sheet. The major difference for the PIV operation is that now a vertical sheet is preferred to allow the PIV measurements to determine the velocity in the axial direction. Again this laser sheet was generated through the use of a plano-convex cylinder lens (Thor Labs, 500 mm focal length, #LA4579) to focus the beam down, while a plano-concave rectangular lens (CVI Melles Griot, -

125mm focal length, #RCC-40.0-25.4-63.6-UV) was used to spread the beam thin in a single direction, thus generating a sheet. Due to the reliance on visible light extra concern was placed on scattered light, and multiple apertures (Melles Griot) and physical barriers were used to reduce this.

A CCD camera is then employed to image the scattered light from the laser sheets. The small time separation again requires specialized equipment, in this case what is known as a frame straddling camera. These cameras specialize in taking a pair of images rapidly, though typically will have a delay between image pairs as the images are moved to a computer for storage. For this study a LaVision Imager Intense CCD camera and Pentax F-mount zoom lens (35-70 mm focal length) were used. This lens was also fitted with a polarization filter (Hoya, Special Effect Filter-PL) which was used to minimize stray and scattered light intensity. The camera was mounted such that it was normal to the laser sheet. This ensures the highest level of accuracy in the PIV correlations as a non normal image can produce a loss of information in a single camera setup.

Timing for the PIV system is critical. This involves timing the generation of both laser sheets to have a known time separation, as well as timing the CCD camera to capture the light scattered by a single laser pulse on separate frames. For this a programmable timing unit (PTU, LaVision external programmable timing unit) was employed which functioned as the main control unit for the various pieces of equipment. This unit is capable of generating a number of output signals with a high degree of accuracy on their timing. In the PIV setup the PTU operated the lasers by sending a pair of signals to each. The first activated the flash lamps to prepare the laser, while the second fired the laser. Also the camera was controlled through a series of arming and fire signals which ensured the camera used its initial frame with the first laser pulse, while the second frame was the following pulse.

The overall schematic for the PIV imaging is shown in a top view in Figure 31, with a side view of the laser sheet and camera imaging shown in Figure 32.

Figure 31: Schematic of PIV setup (Top View)

Figure 32: Schematic of PIV optics and imaging (Side View)

3.1.3.4.2 PIV Flow Seeding

Critical to the operation of PIV imaging is the seeding of the flow. For this study olive oil is used. Oil droplets are ideal due to their spherical shape as well as their translucency, which allows good light scatter throughout the laser sheet.

A small oil seeder unit was built for this study. This system consisted of a reservoir of oil in which a metal tube was inserted. At the end of the tube a number of small holes were drilled. Air was then injected through this tube into the oil where it then was bubbled out. A port in the top of the sealed vessel then allowed the bubbled air, which was now carrying oil droplets, to then be injected into the air flow of the test hardware. A schematic of this unit is shown in Figure 33, along with the unit itself.

Figure 33: Olive oil seeder unit. Schematic (left) and actual unit (right)

Modification to the testing hardware was required to facilitate the seeding of the air flow. The sintered filter ring would not allow any oil droplets to pass through it, so seeding the air prior to enter the test hardware was not viable. A pair of ports were installed on the air plenum just inside the sintered ring in which the seeded air was injected. The ports were placed on opposite sides of the plenum to maximize the seeding effectiveness. It was shown that these ports either aligned with the laser sheet or normal to it, provided sufficient seed density for the PIV operation.

3.1.3.4.3 PIV Image Processing and Data

The PIV measurement process obtains a set of images of particle locations within the flow. Knowing how the particles move between the frames gives a displacement, while the time between frames allows for a velocity. The movement and displacement of the particles is carried out through a process known as cross correlation.

This image processing was carried out through the use of the LaVision DaVis software. In the cross correlation technique a multi-pass approach was taken. Initially each image is broken down into a number of 64 by 64 pixel interrogation windows, and pattern recognition is used to track the displacement of the particles from one image to another. A second pass is then taken using a smaller 32 by 32 pixel interrogation window, following the same idea, but using the displacement of the first pass to allow the software to find the proper particles in each image. Finally a third pass using another 32 by 32 window is used to further refine the accuracy of deriver velocity vectors. This processing technique provides an image of the instantaneous

velocity field. An example of an image obtained from the seeded flow, as well as the processed instantaneous velocity field is shown in Figure 34.

Figure 34: Example images of particle imaging (left) and instantaneous velocity field (right)

To obtain the time averaged velocity field a number of images is used, and their vectors averaged together. This process was done using the same software and a large number of instantaneous velocity field images to determine the time averaged velocity field. An example of the time averaged result is shown in Figure 35, this is the time averaged result built from images such as those shown above in Figure 34.

Figure 35: Time averaged velocity field example image

The final image processing technique used was image stitching. To obtain the velocity field for the whole region of interest, three measurement locations were used. The only component that changed in these measurements was their height above the test hardware. Image stitching was used to generate information on the whole flow field (top of quarl to exhaust) in a single image, rather than three separate images.

3.1.4 Experimental Conditions

To investigate the mixing performance of hydrogen as a fuel and fuel component the equipment and measurement technique mentioned were employed. An experimental study was then employed using a variation of important parameters to determine their influence on the mixing performance.

3.1.4.1 Test Cases and overview

Initially a number of parameters were determined to be of interest for their influence on mixing parameters. For this study this included things such as injection type, presence of swirl, and fuel make up. Additionally it was determined that to provide a reference, pure methane fuel was used to provide a baseline. Methane was selected as it is a widely used gaseous hydrocarbon fuel, and has generally well understood mixing characteristics.

Throughout the experimental processes a number of items were chosen to remain constant. In this study the bulk mass flow rate for air was held fixed for all of the various cases, with a flow rate of 1.116 kg/min. The momentum flux ratio (J) was also held as a constant throughout the test as it is controlling term for many jet characteristics. From these considerations a number of test cases were considered and are shown in Table 2. As the bulk mass flow rate and momentum flux ratio were held fixed, these parameters defined the required mass flow rate based on the fuel selection.

Table 2: Experimental Study Test Cases

Case #	Swirl Level	Injection # and type	CH ₄ Fuel Volume [%]	H ₂ Fuel Volume [%]	Fuel Mass Flow [kg/min]·10 ³
1	None	1x Axial	100	-	1.08
2	None	1x Axial	-	100	0.369
3	None	8x Radial	100	-	8.64
4	None	8x Radial	-	100	3.01
5	45° Plate	1x Axial	100	-	1.08
6	45° Plate	1x Axial	-	100	0.369
7	45° Plate	1x Axial	50	50	CH4: 0.742 H2: 0.0867
8	45° Plate	8x Radial	100	-	8.64
9	45° Plate	8x Radial	-	100	2.95
10	45° Plate	8x Radial	50	50	CH4: 5.93 H2: 0.693

* This case consists of hydrogen injection into nitrogen, as opposed to air

3.1.4.1.1 Momentum Flux Ratio

The momentum flux ratio (J) is the ratio of the jet momentum to that of the bulk flow momentum, and is shown in equation 7. Of importance is the density (ρ) and velocity (U) of both the jet and bulk flow.

$$\text{Where } J = (\rho_j U_j^2) / (\rho_b U_b^2) \quad \text{Eq. 7}$$

The momentum flux for the bulk flow (the denominator of equation 7) was established using both the defined bulk mass flow rate and the hardware geometry at the injection. Using the ideal gas behavior of air in tandem with the mass flow rate defined a volumetric flow rate of air. This along with the assumption of incompressibility then allowed the overall bulk velocity to be determined.

As the value of J was desired at a fixed value, and having established the value of the denominator based on the bulk properties, the fuel volume and mass flow rates were then determined. Of importance is that this ratio is on a per jet basis, and as such in the case of radial injection (eight jets), only one eighth of the volume flow is considered.

Important values for the various gases employed as well as hardware geometries of interest are shown in Table 3.

Table 3: Gas and hardware properties of interest for momentum flux ratio

Geometry	Jet	Diameter [mm]	1.194
Dimensions		Area [mm ²]	1.119
	Bulk Flow	Inside diameter [mm]	25.4
		Outside diameter [mm]	63.5
		Flow area [mm ²]	2660
Bulk gas properties	Air	Density (ρ) @ 20 C [kg/m ³]	1.204
		Mass flow rate [kg/min]	1.116
		Velocity (U) [m/s]	5.807
		ρU^2 [kg/ms ²]	40.604
	Nitrogen	Density (ρ) @ 20 C [kg/m ³]	1.16
		Mass flow rate [kg/min]	1.116
		Velocity (U) [m/s]	6.028
		ρU^2 [kg/ms ²]	42.144
Fuel Properties	Methane	Density (ρ) @ 20 C [kg/m ³]	0.667
	Hydrogen	Density (ρ) @ 20 C [kg/m ³]	0.0899

3.1.4.2 Extractive Probe Testing

The extractive probe techniques were crucial for obtaining information on the spatial fuel concentration. Measurements were obtained in three planes downstream of the fuel injection point at distances of 25.4, 76.2, and 152.4 mm respectively. These planes relative to the injection point and hardware can be seen in Figure 36.

Figure 36: Measurement plane locations and important physical dimensions for both axial cases (left) and radial cases (right). Note all dimensions are in mm²

3.1.4.2.1 Non-Swirling Cases

For non-swirling cases the extractive probe was held above the test hardware aligned with the axial direction of the flow. The probe entered the flow field through the exhaust opening, and was extended down such that its tip was in the measurement plane (z coordinate). The test stand, and as a result test hardware, was then moved around the probe to obtain resolution in the measurement plane (x-y plane).

Measurements were taken in a single half geometry of the flow field. This was done after initial tests showed good flow symmetry, which was periodically confirmed, and with the intention of improving measurement density. Initially a matrix of approximately 96 measurement points was implemented at each plane. This grid was then modified to obtain additional detail around fuel jets or regions of high concentration gradients. Typically this involved a doubling of the measurement density within the region of interest. An example of the initial grid density as well as the grid density increase is shown below in Figure 37, where the blue line denotes the area of doubled measurement density.

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Figure 37: Example of the initial measurement grid (left) and refined grid (right)

Additionally for the axial injection cases an axial traverse was taken along the flow centerline. This was a fixed x and y coordinate while varying the z coordinate from injection to exhaust.

3.1.4.2.2 Swirling Cases

Swirling flow cases required the use of an exhaust contraction to prevent suction at the exhaust plane. This contracted prevented the axial probe method that was used in the non-swirling cases because the exhaust opening was now smaller than the flow field area.

As a result the probe was inserted through the exhaust liner side wall to obtain measurements. To avoid flow disturbances where possible these probes were bent into an “L” shape. This had the tip of the probe aligned with the axial direction of the flow field.

The insertion through the liner sidewall also limited the ability to move in a full two dimensional grid. Instead radial measurements along a single axis were taken. For the case of the axial injection this is not much of an issue as it is generally symmetric. In the case of radial injection this may be an issue depending on how well the swirling has mixed the flow. To avoid this, two sets of measurements were taken at each plane for radial injection. This involved one measurement axis which was aligned with the fuel jets, and one which was aligned with the axis between fuel jets.

To support this measurement scheme a series of liners were fabricated. This consisted of a series of three acrylic liners with the same inside diameter and length as the original quartz liner. Each liner had a threaded port drilled and tapped into the side of the liner downstream of one of the measurement planes of interest. A compression fitting was then inserted into

threaded port to provide an air tight seal on the measurement probe. To account for the 25.4 mm difference between the axial and radial injection measurement planes different length measurement probes were used, rather than the fabrication of six liners. The threaded port and compression fitting employed can be seen in Figure 38, with an example of the testing configuration shown in Figure 39.

Figure 38: Threaded port for extractive probe measurements with swirling flows. Threaded hole (left) and with the threaded compression fitting inserted (right)

Figure 39: Extractive probe for swirling cases

3.1.4.3 PLIF Testing

For the PLIF measurements modification of the fuel was required as outline by the acetone seeder unit previously. A methane acetone blend was used. To facilitate the testing special interest was paid to the momentum flux ratio, as well the test hardware. PLIF

measurements were obtained for non swirling cases for both axial and radial injection at the three planes of interest downstream of injection.

As with the standard testing the momentum flux ratio was used as the factor to hold constant. Typically this only involved controlling the mass flow rate of the fuel, but in this case required consideration of fuel flow rate as well as the injection temperature. The temperature of the injection was carefully checked and monitored to ensure the proper momentum flux ratio.

Additionally modifications were made to the liners and test hardware to improve the imaging quality. Initially the quartz liner was going to be used, but this had a large fluorescence signature of its own. To counter this liner fluorescence a series of liners were used which were cut down to the plane of interest. This made the measurement plane the exhaust plane, and had the laser sheet located just above the liner. Four liners were then fabricated for this purpose. These liners were made from acrylic liners with the same inside diameter as the quartz liner which were then cut and filed to the proper height. In total four liners were made for the PLIF testing including liners for both axial and radial injection at 76.2, and 152.4 mm downstream of injection. An example of the liners and their black coating is shown in Figure 40.

Figure 40: Acrylic liners for PLIF measurements

To further improve image quality the liners and edges of the hardware were painted a flat black to reduce light scatter. Also for the measurement plane 25.4 mm downstream of the radial injection plane, which is located within the test hardware, optical access for the laser sheet was not possible. Instead measurements were taken at the plane 50.8 mm downstream, which is located at the top of the quarl.

3.1.4.4 PIV Testing

Velocity field information was important for all of the various test configurations, and as a result was obtained for all ten cases outline earlier in this section. Velocity measurements were obtained in a 2D plane which extended from the top of the quarl to the end of the liner.

As with the PLIF imaging the quartz liner was deemed inappropriate for PIV imaging as the laser sheet illuminated the entire liner, reducing the effectiveness of the PIV imaging. A new liner was then fabricated for the PIV imaging. This liner was fabricated from acrylic, with the same inside diameter as height as the original liner. Two thin slots (5 mm) where then milled into this liner along its height to allow the sheet to pass through (The slot stopped below the height of the quarrel to leave structural integrity for the liner). These two slots were on opposite sides of the liner to provide the inlet and exit for the laser sheet. To keep the air within the liner the slots where then closed through the use of plastic wrap. This thin wrap provided minimal depth for the laser to interact with, provided a flat surface (opposed to curved) which reduces scatter and illumination, and held the flow within the liner.

To further improve image quality the liner was also painted in flat black to reduce light scatter. The inside and outside surface of the liner which was opposite the camera was painted, which had the benefit of reducing internal illumination as well as external stray light sources. This liner is shown in Figure 41.

Figure 41: Slotted acrylic liner for PIV measurements

3.2 Numerical

3.2.1 Geometry

The geometry of the numerical simulations was such that it matched the experimental studies. The details of the test cases are outlined in 3.1.4.1, with details of the various geometries shown in Appendix A.

3.2.2 Grid Generation

Accurate computation of turbulent flows requires careful mesh generation. While high accuracy is desired, turbulent fluctuations play a significant role in the transport of all parameters. Consequently, it is critical to ascertain that the turbulent quantities are suitably resolved. Due to the strong interaction of the mean flow and turbulence, numerical results for turbulent flows, especially mass transport, are more prone to grid quality dependency than those for laminar flows (Fluent 6.3 documentation). As a result, it is very important to assess grid independence of the solutions obtained.

Structured grids are common for 2-D and simple 3-D geometries due to stability and simplicity (Bykovskii et al., 1996). However, for more complex 3-D geometries featuring sharp edges and a wide range of physical dimensions, structured grid generation is quite challenging and inflexible. As a result, considerable effort has been directed towards reliable generation of unstructured grids (Bykovskii et al., 1996). As a result, for the current model premixer geometry, unstructured grids are used (generally tetrahedral mesh elements). To ensure the quality of the numerical predictions, evaluation of grid independence is crucial and is discussed in detail later in this chapter. However, it is important to note that the optimum mesh for grid independence for each turbulent model is different. For instance, it is found that $k - \varepsilon$ turbulence models require less number of grids than RSM turbulent models do. Likewise, LES simulations need a highly refined grid to be accurate. Thus, in the evaluation of the simulations that follow, the numerical results are obtained using an optimized grid for each turbulence model considered. The fact that different optimum meshing is needed depending on which models are used generates an observation that the effect of turbulence model cannot be compared for the same grid; if it were, it would result in misleading results.

An example of grid generation is shown in Figure 42.

Figure 42-mesh generation for the radial injection domain.

Note the range of physical scales that must be resolved as illustrated by the highly refined grid used for the actual fuel injector holes, as it is shown in Figure 43. This illustrates the value and advantage of the unstructured grid in this class of problem which is required in order to resolve the momentum and mixing features of the discrete jets.

Figure 43-grid generation near the injectors of radial injection configuration.

More details about the different grids used for the different turbulence models studied are provided later.

3.2.3 Boundary Condition

To understand the results of numerical analysis, it is crucial to establish proper boundary conditions. For all test cases the selection strategy employed for the mass flow rate was based upon the momentum flux ratio, as defined previously in section 3.1.4.1.1.

On the numerical side, the boundary conditions applied in the 3D model consist of three categories: mass flow inlet, pressure outlet, and walls.

The mass flow inlet boundary conditions apply for both fuel and oxidant. And the appropriate flow rates which were applied are those mentioned in section 3.1.4.1. It is possible to control the boundary conditions by setting mass flow at the fuel and oxidant inlet.

The outlet boundary condition is set at 1 atm. This condition is realistic because the ambient pressure is atmospheric at the outlet.

The wall is assumed to be smooth and adiabatic since the mixing happens in the room temperature and no temperature difference exists.

3.2.4 Simulation Processing and strategies

All computations were carried out on an 8 node Beowulf cluster each with 4 GB RAM. AMD Opteron 2.6GHz CPUs were used with 1MB cache. The operating system is Redhat 4 64 bit OS Advance Server and the nodes are connected via a GigE Nortel switch. Fluent[®] v6.3 is used to solve the flow field governing equations. Since the node-based averaging scheme is known to be more accurate than the default cell-based scheme for unstructured meshes, most notably tetrahedral meshes, this scheme has been applied (Bykovskii et al., 1996). The pressure interpolation scheme, PRESTO (PREssure Stagging Option) has been applied in the present work. Second order accurate, upwind differencing is used for the momentum, species, and elements of turbulence. Under relaxation factors have been chosen to obtain convenient convergence. For unsteady simulations including URANS and LES, the second order implicit scheme has been used. As rule of the thumb, simulation were run at least for 5 flow times to make sure the numerical results are reasonable to make sufficient statistical average of flow field properties.

For LES simulation, the Smagorinsky-Lilly model is utilized for the sub-grid scales. On the solid walls a no-slip condition is applied with no special near-wall treatment for the SGS model.

However, for LES with $y^+ < 5$ at the walls it is presumed that mesh is fine enough to resolve the laminar sublayer. Pressure-velocity coupling is achieved via the SIMPLE procedure. Also, the second order implicit scheme has been used for LES. With respect to large computer memory and CPU requirement, the LES simulation required more than 30 days to achieve the results presented. To be more consistent throughout this thesis, all of the distances are normalized by the main mixing section diameter ($D=81.28$ mm).

4 Results and Discussion

4.1 Presentation of Experimental Data

This section includes and presents the experimental data collected through this study for the various cases investigated. Additionally the raw data are presented in the appendix of this paper. This section is split up first by the type of information, followed by the cases of interest. The types of data collected include coefficient of discharge, spatial fuel concentration, and velocity fields.

4.1.1 Discharge Coefficients

For the non-swirling test cases the discharge coefficient was found experimentally. This coefficient is a ratio of mass flow through an actual opening compared to the ideal flow through that same opening under the same conditions. The coefficient can be determined by knowing the bulk pressure, fuel flow rate, pressure drop of injection, and the actual jet area by using the following relation shown in equation 8 (Holman, 1994).

$$C_d = \frac{\dot{m}_{fuel}}{A_{jet}} \sqrt{\frac{R_{fuel} T_{fuel}}{2P_{bulk}(P_{fuel} - P_{bulk})}} \quad \text{Eq. 8}$$

Where R is the specific gas constant in $\text{J K}^{-1} \text{mol}^{-1}$, T is the temperature in Kelvin, P is pressure in Pascals, A represents area in m^2 , and m represents mass flow per jet in kg min^{-1} . The measurements and final results for radial and axial injection for the non-swirling and swirling cases are shown in Table 4.

Table 4: Coefficient of Discharge for Non-Swirling Cases³

Quarl Module	Straight Barrel, No Contraction			
Flow Swirl	None, Flow Straightener Used			
Bulk Flow Rate [kg/min]	1.116			
Jet Area [m ²]	0.00000112			
Injection Type and #	Radial, 8x		Axial, 1x	
Injection Height	25.4mm below top of centerbody		At top of centerbody	
Case	H ₂ into N ₂	CH ₄ into Air	H ₂ into Air	CH ₄ into Air
H ₂ mass flow per hole [kg/min]	.000376	-	.000369	-
CH ₄ mass flow per hole [kg/min]	-	.00108	-	.00108
R _{fuel} [J/k mol]	8314.47	518.26	8314.47	518.26
Pressure Difference [Pa]	298.7	296.2	358.4	353.4
Bulk Pressure [kPa absolute]	101.698	101.698	101.698	101.698
Fuel Temperature [k]	295.2	293.4	294.3	294.3
Coefficient of discharge C _d	.793	.810	.658	.695

4.1.2 Spatial Fuel Concentration

Spatial fuel concentrations were obtained for all cases. This involved the use of the extractive probe as well as PLIF measurements for a number of the cases. Unless otherwise noted all measurements were obtained through the use of the gas chromatograph (GC) technique. Data are presented in the form of molar fraction in both contour and scatter plots for the various measurement planes.

4.1.2.1 Non-Swirling Axial Injection

This case involves a single fuel jet injected axially from the centerbody in a co-flowing jet configuration. In this case the injection plane is at the top of the quarl, and measurements were obtained at 25.4, 76.2, and 152.4 mm downstream of this injection plane. A section view of this configuration and the measurement planes is shown in Figure 44. Additionally a set of measurements was taken with an axial traverse of the centerline to see how the jet peak dissipates with downstream distance.

For this configuration measurements of both methane and hydrogen were obtained. As a note measurements were obtained in half planes to improve measurement density. Symmetry was verified prior to the reduction to a half plane.

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Figure 44: Non-swirling axial injection hardware cross section view. All dimensions are in mm

4.1.2.1.1 Methane

For methane a total of 90, 122, and 96 points were measured at the 25.4, 76.2, and 152.4 mm planes. The measurement grids employed at each plane are shown in Figure 45. In these plots the red diamonds represent a measurement point, a black line represents a boundary, and blue denotes an area of increased measurement density. Additionally contour plots of fuel concentration, in molar fraction, are shown in Figure 46. Due to the large difference in concentrations the 25.4 mm plane has its own scale, which differ from the one used for the final two planes. A complete table of all raw data collected is presented in the appendices.

Figure 45: Measurement grids for the non-swirling axial injection of methane

Figure 46: Fuel concentration contour plots for the non-swirling axial injection of methane

Additionally plots of fuel concentration versus radius are shown for each measurement plane. As a note multiple points occur at the same radius due to the circular nature of the hardware. These images are shown in Figure 47, Figure 48, and Figure 49 for the 25.4, 76.2, and 152.4 mm planes. Note that the 25.4 mm plane has a different scale due to the large difference in peak fuel concentration between planes.

Figure 47: Fuel concentration versus radius for the non-swirling axial injection of methane at 25.4 mm downstream of injection

Figure 48: Fuel concentration versus radius for the non-swirling axial injection of methane at 76.2 mm downstream of injection

Figure 49: Fuel concentration versus radius for the non-swirling axial injection of methane at 152.4 mm downstream of injection

Finally the axial traverse of the centerline is shown in Figure 50, where concentration is presented as a function of distance downstream of injection.

Figure 50: Fuel concentration at the centerline versus downstream distance for the non-swirling axial injection of methane

4.1.2.1.2 Hydrogen

For hydrogen a total of 305, 122, and 96 points were measured at the 25.4, 76.2, and 152.4 mm planes. The initial plane has a large number of points as the measurements were carried out over a whole plane. The measurement grids employed at each plane are shown in Figure 51. In these plots the red diamonds represent a measurement point, a black line represents a boundary, and blue denotes an area of increased measurement density. Additionally contour plots of fuel concentration, in molar fraction, are shown in Figure 52 and Figure 53. Due to the large difference in concentrations the 25.4 mm plane has its own scale, which differ from the one used for the final two planes. A complete table of all raw data collected is presented in the appendices.

Figure 51: Measurement grids for the non-swirling axial injection of hydrogen

Figure 52: Fuel concentration contour plot for the non-swirling axial injection of hydrogen. 25.4 mm downstream of injection

Figure 53: Fuel concentration contour plots for the non-swirling axial injection of hydrogen. 76.2 and 152.4 mm downstream of injection⁴

Additionally plots of fuel concentration versus radius are shown for each measurement plane. As a note multiple points occur at the same radius due to the circular nature of the hardware. These images are shown in Figure 54, Figure 55, and Figure 56 for the 25.4, 76.2, and 152.4 mm planes. Note that the 25.4 mm plane has a different scale due to the large difference in peak fuel concentration between planes.

Figure 54: Fuel concentration versus radius for the non-swirling axial injection of hydrogen at 25.4 mm downstream of injection

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Figure 55: Fuel concentration versus radius for the non-swirling axial injection of hydrogen at 76.2 mm downstream of injection

Figure 56: Fuel concentration versus radius for the non-swirling axial injection of hydrogen at 152.4 mm downstream of injection

Finally the axial traverse of the centerline is shown in Figure 57, where concentration is presented as a function of distance downstream of injection.

Figure 57: Fuel concentration at the centerline versus downstream distance for the non-swirling axial injection of hydrogen

4.1.2.2 Non-Swirling Radial Injection

This case involves eight fuel jets injected radially outward from the centerbody in a jet in cross flow configuration. Each jet is equally spaced along the circumference of the centerbody, giving an angle separation of 45° . In this case the injection plane is 25.4 mm below the top of the quarl, and measurements were obtained at 25.4, 76.2, and 152.4 mm downstream of this injection plane. A section view of this configuration and the measurement planes is shown in Figure 58 for reference. For this configuration measurements of both methane and hydrogen were obtained. As a note measurements were obtained in half planes to improve measurement density. Symmetry was verified prior to the reduction to a half plane.

Figure 58: Non-swirling radial injection hardware cross section view. All dimensions are in mm⁵

4.1.2.2.1 Methane

Measurements of methane concentration were obtained at a number of points in each plane of interest. Initially 94 points were taken in a half plane, with additional points added near locations of high fuel concentration gradients. The final totals for this case came to 155, 149, and 94 points at the 25.4, 76.2, and 152.4 mm planes respectively. As a note these measurements were obtained through the use of the flame ionization detector (FID). These measurement grids are shown in Figure 59. Black lines denote the physical boundaries while blue denotes area where the measurement density was increased. Additionally contour plots of fuel concentration, in molar fraction, are shown in Figure 60. A complete table of all raw data collected is presented in the appendices.

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Figure 59: Measurement grids for the non-swirling radial injection of methane⁶

Figure 60: Fuel concentration contour plots for the non-swirling radial injection of methane⁷

Additionally plots of fuel concentration versus radius are shown for each measurement plane. As a note multiple points occur at the same radius due to the circular nature of the hardware. These images are shown in Figure 61, Figure 62, and Figure 63 for the 25.4, 76.2, and 152.4 mm planes. Note that the 25.4 mm plane has a different scale due to the large difference in peak fuel concentration between planes.

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Figure 61: Fuel concentration versus radius for the non-swirling radial injection of methane at 25.4 mm downstream of injection

Figure 62: Fuel concentration versus radius for the non-swirling radial injection of methane at 76.2 mm downstream of injection

Figure 63: Fuel concentration versus radius for the non-swirling radial injection of methane at 152.4 mm downstream of injection

4.1.2.2.2 Hydrogen

Hydrogen measurements were obtained in the same manner as methane with an initial grid of 96 points taken in each half plane. Measurement points were again added and resulted in totals of 210, 150, and 96 points at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements were taken through the use of both the hydrogen analyzer and the gas chromatograph (GC). This case also has the bulk fluid of pure nitrogen as opposed to air to allow the use of the hydrogen analyzer. The measurement grids are shown in Figure 64. Black lines denote the physical boundaries while blue denotes area where the measurement density was increased. Additionally contour plots of fuel concentration, in molar fraction, are shown in Figure 65. A complete table of all raw data collected is presented in the appendices.

Figure 64: Measurement grids for the non-swirling radial injection of hydrogen⁸

Figure 65: Fuel concentration contour plots for the non-swirling radial injection of hydrogen⁹

Additionally plots of fuel concentration versus radius are shown for each measurement plane. As a note multiple points occur at the same radius due to the circular nature of the hardware. These images are shown in Figure 66, Figure 67, and Figure 68 for the 25.4, 76.2, and 152.4 mm planes. Note that the 25.4 mm plane has a different scale due to the large difference in peak fuel concentration between planes.

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Figure 66: Fuel concentration versus radius for the non-swirling radial injection of hydrogen at 25.4 mm downstream of injection

Figure 67: Fuel concentration versus radius for the non-swirling radial injection of hydrogen at 76.2 mm downstream of injection

Figure 68: Fuel concentration versus radius for the non-swirling radial injection of hydrogen at 152.4 mm downstream of injection

4.1.2.3 Swirling Axial Injection

This case involves a single fuel jet injected axially from the centerbody into a swirling flow. This flow swirl is generated through the use of a swirler plate. For this case the injection plane is at the top of the quarl, and measurements were obtained at 25.4, 76.2, and 152.4 mm downstream of this injection plane. A section view of this configuration and the measurement planes is shown in Figure 69.

For this configuration measurements of methane, hydrogen, and a methane-hydrogen mix were obtained through the use of the gas chromatography. As a note measurements were obtained by taking measurements along a diameter of the flow geometry.

Figure 69: Swirling axial injection hardware cross section view. All dimensions are in mm

4.1.2.3.1 Methane

Measurements of methane concentration were obtained along a diameter at each plane of interest. A total of 58 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 70, Figure 71, and Figure 72. Each half of the diameter (each radial line) is a separate series to distinguish the data. Note that the scale for the 25.4 mm plane differs from the scale used for the 76.2 and 152.4 mm plane due to the difference in peak concentration.

Figure 70: Fuel concentration versus radius for the swirling axial injection of methane at 25.4 mm downstream of injection

Figure 71: Fuel concentration versus radius for the swirling axial injection of methane at 76.2 mm downstream of injection

Figure 72: Fuel concentration versus radius for the swirling axial injection of methane at 152.4 mm downstream of injection

4.1.2.3.2 Hydrogen

Measurements of hydrogen concentration were obtained along a diameter at each plane of interest. A total of 58 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 73, Figure 74, and Figure 75. Each half of the diameter (each radial line) is a separate series to distinguish the data. Note that the scale for the 25.4 mm plane differs from the scale used for the 76.2 and 152.4 mm plane due to the difference in peak concentration.

Figure 73: Fuel concentration versus radius for the swirling axial injection of hydrogen at 25.4 mm downstream of injection

Figure 74: Fuel concentration versus radius for the swirling axial injection of hydrogen at 76.2 mm downstream of injection

Figure 75: Fuel concentration versus radius for the swirling axial injection of hydrogen at 152.4 mm downstream of injection

4.1.2.3.3 Hydrogen-Methane Blend

Measurements of methane and hydrogen concentration were obtained along a diameter at each plane of interest. For this test case a fuel mixture of 50% methane and 50% hydrogen by volume was used. A total of 58 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 76, Figure 77, and Figure 78. Each half of the diameter (each radial line) is a separate series to distinguish the data.

Figure 76: Fuel concentration versus radius for the swirling axial injection of a methane-hydrogen blend at 25.4 mm downstream of injection

Figure 77: Fuel concentration versus radius for the swirling axial injection of a methane-hydrogen blend at 76.2 mm downstream of injection

Figure 78: Fuel concentration versus radius for the swirling axial injection of a methane-hydrogen blend at 152.4 mm downstream of injection

4.1.2.4 Swirling Radial Injection

This case involves eight fuel jets injected radially outward from the centerbody into a swirling flow. This flow swirl is generated through the use of a swirler plate. Each jet is equally spaced along the circumference of the centerbody, giving an angle separation of 45° . For this case the injection plane is located 25.4mm below the top of the quarl, and measurements were obtained at 25.4, 76.2, and 152.4 mm downstream of this injection plane. A section view of this configuration and the measurement planes is shown in Figure 79.

For this configuration measurements of methane, hydrogen, and a methane-hydrogen mix were obtained. As a note measurements were obtained by taking measurements along a diameter of the flow geometry. Measurements were taken on diameters aligned with the jet as well as diameters located directly between jets.

Figure 79: Swirling radial injection hardware cross section view. All dimensions are in mm

4.1.2.4.1 Methane

Measurements of methane concentration were obtained along a diameter at each plane of interest. A total of 56, 90, and 44 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 80, Figure 81, and Figure 82. Each half of the diameter (each radial line) is a separate series to distinguish the data. Note that the scale for the 25.4 mm plane differs from the scale used for the 76.2 and 152.4 mm plane due to the difference in peak concentration. For the first two planes measurements were taken both along the jet diameter, and on the diameter between jets.

Figure 80: Fuel concentration versus radius for the swirling radial injection of Methane at 25.4 mm downstream of injection

Figure 81: Fuel concentration versus radius for the swirling radial injection of Methane at 76.2 mm downstream of injection

Figure 82: Fuel concentration versus radius for the swirling radial injection of Methane at 152.4 mm downstream of injection

4.1.2.4.2 Hydrogen

Measurements of hydrogen concentration were obtained along a diameter at each plane of interest. A total of 56, 90, and 44 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 83, Figure 84, and Figure 85. Each half of the diameter (each radial line) is a separate series to distinguish the data. Note that the scale for the 25.4 mm plane differs from the scale used for the 76.2 and 152.4 mm plane due to the difference in peak concentration. For the first two planes measurements were taken both along the jet diameter, and on the diameter between jets.

Figure 83: Fuel concentration versus radius for the swirling radial injection of hydrogen at 25.4 mm downstream of injection

Figure 84: Fuel concentration versus radius for the swirling radial injection of hydrogen at 76.2 mm downstream of injection

Figure 85: Fuel concentration versus radius for the swirling radial injection of hydrogen at 152.4 mm downstream of injection

4.1.2.4.3 Hydrogen-Methane Blend

Measurements of methane and hydrogen concentration were obtained along a diameter at each plane of interest. For this test case a fuel mixture of 50% methane and 50% hydrogen by volume was used. A total of 56, 88, and 44 points were taken at the 25.4, 76.2, and 152.4 mm planes respectively. Measurements of fuel concentration, in molar fraction, are shown for each plane in Figure 86, Figure 87, and Figure 88. Each half of the diameter (each radial line) is a separate series to distinguish the data. For the first two planes measurements were taken both along the jet diameter, and on the diameter between jets.

Figure 86: Fuel concentration versus radius for the swirling radial injection of a methane-hydrogen blend at 25.4 mm downstream of injection

Figure 87: Fuel concentration versus radius for the swirling radial injection of a methane-hydrogen blend at 76.2 mm downstream of injection

Figure 88: Fuel concentration versus radius for the swirling radial injection of a methane-hydrogen blend at 152.4 mm downstream of injection

4.1.3 Planar Laser Induced Fluorescence Imaging

Planar laser induced fluorescence was used as additional information for the spatial fuel concentration at the various planes downstream of injection. As mentioned, measurements were taken at the planes 25.4, 76.2, and 152.4 mm downstream of the axial injection, and 50.8, 76.2, and 152.4 mm downstream of the radial injection case. The plane 25.4 mm downstream of the radial injection was not measured as it had no optical access for the laser sheet. Data are presented both through an averaged and processed image at each plane as well as a scatter plot of concentration versus radius. All values are mole fractions of fuel, which was determined from the acetone fuel component. Scatter plot data was obtained from the images by extracting the individual pixel counts and correcting to fuel concentration. At each plane approximately 4000 points are used within the area of interest (radius less than 40 mm). Data above 38 mm was removed due to the light scatter present near the edges from the quarl or liners.

4.1.3.1 Non-Swirling Axial Injection

The results for the non-swirling axial injection of a methane-acetone blend are shown. The scaled images are shown in Figure 89, Figure 91, Figure 93, while the scatter plots are shown in Figure 90, Figure 92, and Figure 94. As a note the 25.4 mm plane has a different scale

then the 76.2 and 152.4 mm planes due to the large change in peak values between the various planes.

Figure 89: PLIF image for the non-swirling axial injection of a methane-acetone blend at the plane 25.4 mm downstream of injection

Figure 90: PLIF derived fuel concentration versus radius for the non-swirling axial injection of a methane-acetone blend at 25.4 mm downstream of injection

Figure 91: PLIF image for the non-swirling axial injection of a methane-acetone blend at the plane 76.2 mm downstream of injection

Figure 92: PLIF derived fuel concentration versus radius for the non-swirling axial injection of a methane-acetone blend at 76.2 mm downstream of injection

Figure 93: PLIF image for the non-swirling axial injection of a methane-acetone blend at the plane 152.4 mm downstream of injection

Figure 94: PLIF derived fuel concentration versus radius for the non-swirling axial injection of a methane-acetone blend at 152.4 mm downstream of injection

4.1.3.2 Non-Swirling Radial Injection

The results for the non-swirling radial injection of a methane-acetone blend are shown. The scaled images are shown in Figure 95, Figure 97, and Figure 99, while the scatter plots are

shown in Figure 96, Figure 98, and Figure 100. As a note the 25.4 mm plane has a different scale than the 76.2 and 152.4 mm planes due to the large change in peak values between the various planes.

Figure 95: PLIF image for the non-swirling radial injection of a methane-acetone blend at the plane 50.8 mm downstream of injection

Figure 96: PLIF derived fuel concentration versus radius for the non-swirling radial injection of a methane-acetone blend at 50.8 mm downstream of injection

Figure 97: PLIF image for the non-swirling axial injection of a methane-acetone blend at the plane 76.2 mm downstream of injection

Figure 98: PLIF derived fuel concentration versus radius for the non-swirling radial injection of a methane-acetone blend at 76.2 mm downstream of injection

Figure 99: PLIF image for the non-swirling axial injection of a methane-acetone blend at the plane 152.4 mm downstream of injection

Figure 100: PLIF derived fuel concentration versus radius for the non-swirling radial injection of a methane-acetone blend at 152.4 mm downstream of injection

4.1.4 Pitot-Static Probe Measurements

A Pitot-Static probe was used to determine the axial velocity for both the axial and radial injection non-swirling cases. For these cases no fuel was injected due to the limited nature of the Pitot probe requiring a known density to perform a proper velocity correlation. Therefore the data presented is simply for a purely bulk flow of air.

For all measurements the temperature was recorded (to determine density), and a minimum of eighteen measurements of pressure difference over 180 seconds was taken to ensure the result was stable and to account for any fluctuations. These pressure differences were then averaged to obtain the velocity. Measurements were obtained in planes 25.4, 76.2, and 152.4 mm downstream of the injection point for each plane.

4.1.4.1 Non-Swirling Axial Injection

Using the strategy mentioned above, a total of 37, 29, and 25 measurement points were taken at the 25.4, 76.2, and 152.4 mm plane respectively. The majority of these points were taken along the X and Y axis with some additional points added off these axes to ensure proper symmetry. The measurement grids for each plane are shown in Figure 101, with axial velocity versus radius present for each plane in Figure 102, Figure 103, and Figure 104.

Figure 101: Measurement grids for Pitot-static probe axial velocity measurements of the non-swirling axial injection measurement planes

Figure 102: Axial velocity versus radius for the plane 25.4 mm downstream of the non-swirling axial injection plane

Figure 103: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling axial injection plane

Figure 104: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling axial injection plane

4.1.4.2 Non-Swirling Radial Injection

Using the strategy mentioned above, a total of 24, 25, and 25 measurement points were taken at the 25.4, 76.2, and 152.4 mm plane respectively. The majority of these points were taken along the X and Y axis with some additional points added off these axes to ensure proper symmetry. The measurement grids for each plane are shown in Figure 105, with axial velocity versus radius present for each plane in Figure 106, Figure 103, and Figure 108.

Figure 105: Measurement grids for Pitot-static probe axial velocity measurements of the non-swirling radial injection measurement planes

Figure 106: Axial velocity versus radius for the plane 25.4 mm downstream of the non-swirling radial injection plane

Figure 107: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling radial injection plane

Figure 108: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling radial injection plane

4.1.5 Velocity Field Measurements

The use of the PIV measurement technique was also employed to measure the velocity for each injection case. Data are presented through both a 2D velocity vector field for the visible flow field of each test case as well as through the use of axial velocity scatter plots for each plane of interest. These plots were generated through extracting the axial velocity component at each plane of interest.

For non-swirling cases 3000 image pairs (1000 at three different heights) were obtained to determine the velocity field. This velocity field is aligned with the X-Z plane of the test hardware, and passes through the center of the hardware.

For the swirling cases 4500 image pairs were used (three sets of 500 at three different heights) to determine the velocity field. For the swirling cases measurements were taken at the central X-Z plane passing through the center of the hardware as well as through two additional planes. These planes were parallel to the first, but one was slightly in front of the initial plane (slightly positive y value) while the other was slightly behind it (slightly negative y value). These planes were only separated by a distance of 0.381 mm. This strategy was employed as the swirling nature of the flow has a large on velocity magnitude near the centerline of the flow field, and the small variation provided a level of averaging to that central region to avoid the skew that a single measurement plane would have generated. These planes and their positions

relative to the test stand are shown in Figure 109. Note that the distance separating the planes has been exaggerated to allow their relative positions to be easily seen.

Figure 109: PIV measurement planes for the swirling flow cases. The central plane is denoted with the dashed line while the two solid lines represent the offset planes

From the 2D velocity field data generated from the PIV measurements images of the flow field are generated. These images contain vectors which are scaled and colored by their velocity magnitude, and their direction shows the direction of the flow field velocity. Additionally for the measurement planes of interest the axial velocity component was extracted along a line of constant axial distance, and used to generated a scatter plot of axial velocity versus radius. For these plots 100 data points were taken at each plane from the PIV data set.

4.1.5.1 Non-Swirling Axial Injection

For the non-swirling axial injection cases the 2D velocity field was measured from the top of the quarl to the end of the exhaust liner (160 mm total height). Additionally the axial velocity at the planes 25.4, 76.2, and 152.4 mm downstream of the injection point were determined and shown in plots of axial velocity versus radius. Data was obtained for both methane and hydrogen fuel injection.

4.1.5.1.1 Methane

Figure 110: Axial velocity versus radius for the plane 25.4 mm downstream of the non-swirling axial injection of methane

Figure 111: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling axial injection of methane

Figure 112: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling axial injection of methane

Figure 113: Velocity field for the non-swirling axial injection of methane

4.1.5.1.2 Hydrogen

Figure 114: Axial velocity versus radius for the plane 25.4 mm downstream of the non-swirling axial injection of hydrogen

Figure 115: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling axial injection of hydrogen

Figure 116: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling axial injection of hydrogen

Figure 117: Velocity field for the non-swirling axial injection of hydrogen

4.1.5.2 Non-Swirling Radial Injection

Again the 2D velocity field was determined as well as the axial velocity versus radius for the 76.2 and 152.4 mm planes for both methane and hydrogen. The 25.4 mm plane was not determined in this manner due to no optical access for the PIV method.

4.1.5.2.1 Methane

Figure 118: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling radial injection of Methane

Figure 119: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling radial injection of Methane

Figure 120: Velocity field for the non-swirling radial injection of methane

4.1.5.2.2 Hydrogen

Figure 121: Axial velocity versus radius for the plane 76.2 mm downstream of the non-swirling radial injection of hydrogen

Figure 122: Axial velocity versus radius for the plane 152.4 mm downstream of the non-swirling radial injection of hydrogen

Figure 123: Velocity field for the non-swirling radial injection of hydrogen

4.1.5.3 Swirling Axial Injection

For methane, hydrogen, and a methane-hydrogen fuel blend the 2D velocity field was determined for the swirling axial injection case. Additionally the axial velocity versus radius for the 25.4, 76.2, and 152.4 mm planes was obtained.

4.1.5.3.1 Methane

Figure 124: Axial velocity versus radius for the plane 25.4 mm downstream of the swirling axial injection of methane

Figure 125: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling axial injection of methane

Figure 126: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling axial injection of methane

Figure 127: Velocity field for the swirling axial injection of methane

4.1.5.3.2 Hydrogen

Figure 128: Axial velocity versus radius for the plane 25.4 mm downstream of the swirling axial injection of hydrogen

Figure 129: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling axial injection of hydrogen

Figure 130: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling axial injection of hydrogen

Figure 131: Velocity field for the swirling axial injection of hydrogen

4.1.5.3.3 Methane-Hydrogen Blend

Figure 132: Axial velocity versus radius for the plane 25.4 mm downstream of the swirling axial injection of a methane-hydrogen blend

Figure 133: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling axial injection of a methane-hydrogen blend

Figure 134: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling axial injection of a methane-hydrogen blend

Figure 135: Velocity field for the swirling axial injection of a methane-hydrogen blend

4.1.5.4 Swirling Radial Injection

Again the 2D velocity field was determined as well as the axial velocity versus radius for the 76.2 and 152.4 mm planes for methane, hydrogen, and a methane-hydrogen blend. The 25.4 mm plane was not determined due to limited optical access.

4.1.5.4.1 Methane

Figure 136: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling radial injection of methane

Figure 137: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling radial injection of methane

Figure 138: Velocity field for the swirling radial injection of methane

4.1.5.4.2 Hydrogen

Figure 139: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling radial injection of hydrogen

Figure 140: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling radial injection of hydrogen

Figure 141: Velocity field for the swirling radial injection of hydrogen

4.1.5.4.3 Methane-Hydrogen Blend

Figure 142: Axial velocity versus radius for the plane 76.2 mm downstream of the swirling radial injection of a methane-hydrogen blend

Figure 143: Axial velocity versus radius for the plane 152.4 mm downstream of the swirling radial injection of a methane-hydrogen blend

Figure 144: Velocity field for the swirling radial injection of a methane-hydrogen blend

4.2 Analysis

4.2.1 Injector Geometry and Fuel Impact

4.2.1.1 Fuel Concentration Comparison

To investigate the effect of fuel properties on the fuel concentration spatial distribution the various cases were compared. Comparisons were carried out on the fuel molar fraction versus radius plots. One issue with direct comparisons is the larger volume of hydrogen (due to its lower density). This resulted in almost three times the volume of hydrogen to that of methane for a comparable jet momentum flux ratio. To facilitate the comparison data was first normalized. This comparison was then carried out for each injection strategy at the three various downstream planes.

4.2.1.1.1 Non-Swirling Axial Injection

Fuel influence was investigated at the planes 25.4, 76.2, and 152.4 mm downstream of the fuel injection for methane, hydrogen, and acetone PLIF. Normalization was carried out by using the centerline value at each plane. Additionally the axial traverse was considered, with each fuel normalized by its molar concentration at the initial measurement point 12.7 mm downstream of injection. The initial planes are shown in Figure 145, Figure 146, and Figure 147, with the axial traverse comparison shown in Figure 148. It is shown that in all planes the fuels have a similar distribution with radius and that the measurements for each fuel as well as the PLIF measurements show good agreement.

Figure 145: Normalized mole fraction of fuel versus radius for the non-swirling axial injection for all fuel types 25.4 mm downstream of injection

Figure 146: Normalized mole fraction of fuel versus radius for the non-swirling axial injection for all fuel types 76.2 mm downstream of injection

Figure 147: Normalized mole fraction of fuel versus radius for the non-swirling axial injection for all fuel types 152.4 mm downstream of injection

Figure 148: Normalized mole fraction of fuel versus downstream for the non-swirling axial injection for methane and hydrogen fuel injection

4.2.1.1.2 Non-Swirling Radial Injection

For this injection strategy the fuel reliance was investigated at the planes 25.4, 76.2, and 152.4 mm downstream of the fuel injection. This involved a comparison of the hydrogen and

methane for all planes as well as the additional of the PLIF result for all but the 25.4 mm plane. Normalization was carried out by using the average molar concentration at each plane, and the results for each plane shown in Figure 149, Figure 150, and Figure 151. At all three planes the methane and hydrogen numbers agree well, though there is disagreement between the PLIF results and the hydrogen and methane results for the final two planes. The PLIF results seem to have the largest disagreement for a radius less than 15 mm. Based on this result, the fact that the axial agreement was good, as well as visual observations of a noticeable ring where the centerbody is located in the PLIF images, it appears that the centerbody reflected the fluoresced light and may have skewed the results by adding an offset. This was not much of a concern for the previous axial cases due to the fact that the majority of the jet was located above the centerbody and most likely resulted in an offset which was removed by the averaging process.

Figure 149: Normalized mole fraction of fuel versus radius for the non-swirling radial injection for all fuel types 25.4 mm downstream of injection

Figure 150: Normalized mole fraction of fuel versus radius for the non-swirling radial injection for all fuel types 25.4 mm downstream of injection

Figure 151: Normalized mole fraction of fuel versus radius for the non-swirling radial injection for all fuel types 152.4 mm downstream of injection

4.2.1.1.3 Swirling Axial Injection

Fuel influence was investigated at the planes 25.4, 76.2, and 152.4 mm downstream of the fuel injection for methane, hydrogen, and a methane-hydrogen blend. Normalization was carried out by using the centerline value at each plane. The planes are shown in Figure 152, Figure 153, and Figure 154. It is shown that in all planes the fuels have a similar distribution with

radius and that the measurements for each fuel show good agreement. Additionally even the individual fuel components of the fuel blend behave as the individual fuels or the total blend, further showing that the fuel type has little impact.

Figure 152: Normalized mole fraction of fuel versus radius for the swirling axial injection for all fuel types 25.4 mm downstream of injection

Figure 153: Normalized mole fraction of fuel versus radius for the swirling axial injection for all fuel types 76.2 mm downstream of injection

Figure 154: Normalized mole fraction of fuel versus radius for the swirling axial injection for all fuel types 152.4 mm downstream of injection

4.2.1.1.4 Swirling Radial Injection

For this injection strategy the fuel reliance was investigated at the planes 25.4, 76.2, and 152.4 mm downstream of the fuel injection. This involved a comparison of the hydrogen, methane, and a methane-hydrogen blend. Normalization was carried out by using the average molar concentration at each plane, and the results for each plane shown in Figure 155, Figure 156, and Figure 157. In the initial plane (25.4 mm) it appears that hydrogen has a higher slope moving towards the center then the fuel blend or pure methane, though the results are still similar. At the planes 76.2 mm and 152.4 mm downstream of the fuel injection all the fuels and individual fuel components have similar distributions with radius, suggesting limited fuel dependence.

Figure 155: Normalized mole fraction of fuel versus radius for the swirling radial injection for all fuel types 25.4 mm downstream of injection

Figure 156: Normalized mole fraction of fuel versus radius for the swirling radial injection for all fuel types 76.2 mm downstream of injection

Figure 157: Normalized mole fraction of fuel versus radius for the swirling radial injection for all fuel types 152.4 mm downstream of injection

4.2.1.2 Jet Penetration

The non-swirling radial injection case initially behaves as a simple jet in cross flow, and for this injection strategy a number of empirical correlations exist. Jet penetration is one of these, and is a measure of how far the jet fluid has traveled, or penetrated, into the cross flow. The effectiveness of these correlations for this study as well as its effectiveness for predicting hydrogen behavior was investigated.

For this study the correlations derived from the work of Holdeman et al. was employed, and is shown in equations 9-11 (Holdeman et al., 2005). In these equations X_{Pen} is jet penetration, S is jet spacing, H is duct width, J is the momentum flux ratio, d is the jet diameter, C_d is the discharge coefficient, Z is downstream distance, and a and b are simple coefficients as defined by equations 10 and 11.

$$X_{Pen}/H = a (0.3575)J^{0.25} \left(\frac{S}{H}\right)^{0.14} \left(\frac{H}{D_{jet}}\right)^{-0.45} (C_d)^{0.155} \left(\frac{Z}{H}\right)^{0.17} e^{-b} \quad \text{Eq. 9}$$

$$a = \min[1 + S/H, 2] \quad \text{Eq. 10}$$

$$b = .091(Z/H)[(H/S) - (J^{0.5})/3.5] \quad \text{Eq. 11}$$

For the non-swirling radial case in the region between the injection point and the plane 25.4 mm downstream of injection the primary values within the correlation, and the derived penetration for each case, are shown in Table 5. As a note in this correlation the jet spacing is

taken as the circumferential distance between the jets on the centerbody, and the jet penetration distance is the distance from the injection point, which occurs at a radius of 12.7 mm from centerline (due to the 25.4 mm diameter centerbody).

Table 5: Jet Penetration empirical correlation summary¹⁰

Parameter		Value
Jet Spacing, S [mm]		9.97
Duct Width, H [mm]		19.05
Jet Diameter, D_{jet} [mm]		1.19
Downstream Distance, Z [mm]		25.4
Methane	Jet-to-mainstream momentum flux ratio, J	9.55
	Coefficient of discharge, C_{D_CH4}	0.81
	Jet Penetration, X_{Pen_CH4} [mm]	6.08
Hydrogen	Jet-to-mainstream momentum flux ratio, J	8.88
	Coefficient of discharge, C_{D_H2}	0.79
	Jet Penetration, X_{Pen_H2} [mm]	5.92

These results were then compared to the measured fuel concentration from the experimental study at the plane 25.4 mm downstream of the injection point. For each fuel the peak value of each jet (corresponding to the four jets in each half plane) were found, and the penetration found (radius of peak minus the radius of the centerbody). For methane all four jets had a maximum value at a radius of 6.0621 mm, while for the hydrogen case three of the peaks occurred at 6.0621 mm, while the fourth was at 5.3724 mm. This gave an average methane penetration of 6.06 mm, while hydrogen had an average of 5.89 mm. These results line up well with the empirical correlation, and the results are within one percent of each other. This jet penetration comparison is summarized in Table 6.

Table 6: Summary of Jet Penetration Results

	Methane	Hydrogen
Empirical Jet Penetration [mm]	6.08	5.92
Measured Jet Penetration [mm]	6.06	5.89
% Difference empirical penetration from measured penetration	0.33%	0.51%

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4.2.1.3 Velocity Comparison

The velocity comparison is of interest for two major reasons. The first to compare the measurement techniques to evaluate their effectiveness, and the second to look at the influence the fuel type would have on the field itself. Data are compared for the various fuel types at each measurement plane for the various hardware configurations tested.

4.2.1.3.1 Non-Swirling Axial Injection

For this test case velocity is compared between measurement obtained with the Pitot-Static probe as well as data obtained for both methane and hydrogen injection through the use of PIV measurements. Comparisons are shown at the 25.4, 76.2, and 152.4 mm planes in Figure 158, Figure 159, and Figure 160 respectively. From these it can be seen that the Pitot-Static probe provides reasonable agreement even without fuel injection, and that the fuel injection itself has little impact on the flow field, especially for the planes further downstream (76.2 and 152.4 mm). At the plane 25.4 mm downstream change is observed between hydrogen and methane injection, so some fuel dependence is present near the jet.

Figure 158: Axial velocity versus radius comparison for the non-swirling axial injection at 25.4 mm downstream of injection

Figure 159: Axial velocity versus radius comparison for the non-swirling axial injection at 76.2 mm downstream of injection

Figure 160: Axial velocity versus radius comparison for the non-swirling axial injection at 152.4 mm downstream of injection

4.2.1.3.2 Non-Swirling Radial Injection

For the non-Swirling radial injection case a similar comparison was done. This included the Pitot-Static velocity measurements as well as PIV measurements for both methane and hydrogen at the planes 76.2 and 152.4 mm downstream of injection. The 25.4 mm plane is not included as no PIV data are available due to the lack of optical access. These comparisons are

shown in Figure 161 and Figure 162. Again these results show that the Pitot-Static probe provides a good measurement of the flow field despite no fuel injection, and that the fuel injection and fuel type have little influence on the flow field.

Figure 161: Axial velocity versus radius comparison for the non-swirling radial injection at 76.2 mm downstream of injection

Figure 162: Axial velocity versus radius comparison for the non-swirling radial injection at 152.4 mm downstream of injection

4.2.1.3.3 Swirling Axial Injection

For the swirling axial injection case only the fuel dependence is investigated through the use of PIV measurements. This included methane, hydrogen, and a methane-hydrogen blend, at the planes 25.4, 76.2, and 152.4 mm downstream of injection. These comparisons are shown in Figure 163, Figure 164, and Figure 165. These results show that at the initial plane (25.4 mm) the fuel has an impact on the velocity field magnitude, while the radial distribution appears to be relatively unchanged. For the planes further downstream no fuel dependence is observed.

Figure 163: Axial velocity versus radius comparison for the swirling axial injection at 25.4 mm downstream of injection

Figure 164: Axial velocity versus radius comparison for the swirling axial injection at 76.4 mm downstream of injection

Figure 165: Axial velocity versus radius comparison for the swirling axial injection at 152.4 mm downstream of injection

4.2.1.3.4 Swirling Radial Injection

The comparison was also carried out for the swirling radial injection for methane, hydrogen, and the methane-hydrogen blend. As with the other radial case only the planes 76.2 and 152.4 mm downstream of injection were considered as the 25.4 mm plane has no optical

access. These comparisons are shown in Figure 166 and Figure 167, and show that the flow field has little dependence on fuel type for these planes downstream of injection.

Figure 166: Axial velocity versus radius comparison for the swirling radial injection at 76.4 mm downstream of injection

Figure 167: Axial velocity versus radius comparison for the swirling radial injection at 152.4 mm downstream of injection

4.2.1.4 Swirl Impact

The influence of the swirling on the profile of fuel distribution was also considered. This was investigated by looking again at the normalized molar fraction of fuel versus radius, but now overlaying the swirling and non swirling cases at each plane downstream of injection.

4.2.1.4.1 Axial Injection

As normal the planes 25.4, 76.2, and 152.4 mm downstream of injection were investigated, and the plots of normalized mole fraction of fuel versus radius are shown in Figure 168, Figure 169, and Figure 170. Normalization was carried out by the centerline mole fraction of fuel for each fuel at each plane. From these it can be seen that the swirling flow sharpened the slope of fuel concentration, and worked to maintain a concentrated high center peak value of fuel in comparison to the non-swirling flow.

Figure 168: Normalized fuel mole fraction versus radius for the swirling and non-swirling axial injection at the plane 25.4 mm downstream of injection

Figure 169: Normalized fuel mole fraction versus radius for the swirling and non-swirling axial injection at the plane 76.2 mm downstream of injection

Figure 170: Normalized fuel mole fraction versus radius for the swirling and non-swirling axial injection at the plane 152.4 mm downstream of injection

4.2.1.4.2 Radial Injection

The influence of swirling on fuel distribution was considered at the planes 25.4, 76.2, and 152.4 mm downstream of injection for radial injection. Both the non-swirling and swirling cases were investigated, and as before fuel normalization was carried out by using the in plane average for each injection case. These planes are shown in Figure 171, Figure 172, and Figure

173. These plots show that the swirling flow worked to change the fuel distribution for radial injection in a number of ways. Firstly it moved the peak concentration towards the inside diameter at the initial plane (25.4 mm), and to the centerline for the remaining downstream planes. This is essentially always moving the peak inward, which differs from the non-swirling cases where the fuel penetration created peaks some distance away from the center. The swirling flow also worked to maintain a larger radial difference in the fuel concentration, particularly at the planes further downstream, as the fuel tended to stay in the central core of the flow.

Figure 171: Normalized fuel mole fraction versus radius for the swirling and non-swirling radial injection at the plane 25.4 mm downstream of injection

Figure 172: Normalized fuel mole fraction versus radius for the swirling and non-swirling radial injection at the plane 76.2 mm downstream of injection

Figure 173: Normalized fuel mole fraction versus radius for the swirling and non-swirling radial injection at the plane 152.4 mm downstream of injection

4.2.2 Numerical Comparisons

4.2.2.1 *Non-Swirling Radial Injection*

4.2.2.1.1 Domain Size Dependency

Due to the apparent planes of symmetry in the premixer hardware, it was thought that solving the flow for one quadrant of the geometry might be sufficient and thus allow a major time savings in the simulations. The grid generated for the quadrant body is shown in Figure 174.

Figure 174: Quadrant body geometry of radial injection configuration

Periodic boundary conditions are applied for the two sides of the quadrant geometry to impose the symmetric physics of the flow field. The motivation for exploring the quadrant body are: 1) saving computation time and cost for solving the equation of the flow field in smaller domain in quadrant body. 2) Avoiding asymmetric result due to the unstructured grid for the entire domain that happens in the entire body analysis.

However, since the accuracy of the numerical solution is the main priority for this study, the results were compared with a full geometry to assess the viability of using the quadrant body. Thus, the numerical results of the quadrant body are compared to those from the entire domain to confirm viability of the quadrant body approach. Results are shown for methane/air ratio contours in Figure 175. In this figure, the right hand side is experimental measurements for the methane air ratio in the first plane downstream of the injection point.

Figure 175: Quadrant body vs. entire body for methane at $Z/D=0.3125$

From Figure 175 it is evident that the simulation with the full geometry resembles the experimental measurement more than the quadrant geometry does. First, the jet dispersion for the quadrant is smaller than either the experimental measurements or the simulations of the entire geometry. Second, the jet penetration is more consistent between the full geometry and the measurements. To explore this more, the radial profile of fuel air ratio is shown in Figure 176 along a jet. As shown, the results using the entire geometry show better agreement with the experimental than the result from the quadrant body.

Figure 176: Quadrant vs. entire body along the jets at $Z/D=0.3125$

The same comparison is made for the second plane downstream of the injection point. The contours of methane to air ratio for entire, quadrant and experimental measurements are shown in Figure 177.

Figure 177: Quadrant body vs. entire body for methane at $Z/D=0.9375$

Radial profiles of fuel to air ratio is shown in Figure 178. This figure presents the fuel to air ratio distribution across the radial distance to show the total trend of mixing in this plane.

Figure 178: Quadrant vs. entire body along the jets at $Z/D=0.9375$

Finally, the same comparison is made for the third plane downstream at $Z/D=1.875$. The results of the comparison are demonstrated in Figure 179 and Figure 180.

Figure 179 presents the contour of fuel to air ratio at the third plane. The side figure shows the location of this plane in the domain.

Figure 179: Quadrant body vs. entire body for methane at $Z/D=1.875$

Figure 180 presents the fuel to air distribution along a radial distance at the third plane. This figure can visualize the mixing trend of fuel into air as the mixture travels downstream.

Figure 180: Quadrant vs. entire body along the jets at $Z/D=1.875$

In conclusion, it seems that although the quadrant body presents relatively efficient predictions of the flow field properties, using the entire domain seems more reliable in general.

Consequently, to evaluate different simulation approaches more fairly, the entire body approach is applied for the entire of this work.

4.2.2.1.2 Coefficient of Discharge Impact

To numerically observe the effect of the C_d , three different cases are studied. The first one is the case with actual injection hole sizes without any modification. In the next case, the size of holes has been decreased to the values obtained by the coefficient of discharge concept to provide the correct velocity fields, while the mass flow rate remains unchanged. The last case includes grid generation for the air plenum with actual hole sizes in order to numerically capture flow field behavior near the injection point.

The schematic of the case with air plenum grid generation is shown in Figure 181.

Figure 181: Grid generation for the air plenum

This case has larger domain and needs more time and consideration to obtain a reliable numerical result compare to typical cases that are shown before. The comparison between these three cases is shown to obtain a better understanding. The contours of these three cases are shown in Figure 182 besides experimental results.

Figure 182: Investigation of effects of C_d at $Z/D=0.3125$

It is relatively hard to see the differences between the predictions of different numerical results. Therefore, the radial profiles of fuel air ratio are shown in Figure 183 for the three cases at $Z/D=0.3125$. The side figure indicates the relative location of current plane to the entire rig.

Figure 183: Effects of C_d along the jets at $Z/D=0.3125$

In Figure 183, it is evident that maximum jet penetration for the case without C_d is less than the one in the experimental analysis. On the other hand, results simulating the entire plenum and fuel passages produces results that are similar to the measured values. . However, it is also apparent that modifying the hole size using the C_d also produces very good results but with much less computational expense. The big conclusion of this section is that it is not necessary to generate grid for the entire plenum to capture details of jet penetration in this geometry. Implication of the appropriate C_d for determination of the modified hole size can actually give rise to better numerical prediction without extension of the main domain which saves us numerical efforts and time. To have a better interpretation into what the effect of the C_d is, Table 7 provides jet penetration distances for the different cases.

Table 7: Jet penetration using various method

Case	Jet Penetration [mm]
Before C_d	4.94
Plenum grid generation	5.91
After C_d	6.16
Experimental	6.06
Emperical	5.94

Based on the data provided in Table 7, it is obvious that C_d has a significant impact on accuracy of the numerical results. For instance, the differences of jet penetrations for various cases compare to the experimental measurement are 18.51%, 2.41%, 4.3%, 1.97% for the case without C_d , plenum grid generation, case after C_d with hole size treatment, and empirical correlations, respectively.

Based on this evaluation, all of the remaining simulations utilize the modified hole size associated with C_d number obtained from the experimental measurements.

4.2.2.1.3 Grid Refinement

To finalize the overall simulation approach, it is critical to establish a grid sufficiently refined so as to demonstrate independence of further refinement. As a result, a grid dependency evaluation was carried out for each turbulence model considered. So far, it is concluded that the entire geometry should be used rather than quadrant body. In addition, it

was shown that for the tiny holes of the injector, implication of the C_d can improve the accuracy of the numerical model. Now, it should be determined how small the grid should be made. It should be considered that the size of the grid depends on the turbulent model. For instance, RSM turbulent model requires more refinement than $k - \varepsilon$ turbulent model. The main point of grid independency study is to make sure that more refinement in a specific geometry will not lead to better accuracy of the results. This step is essential in the CFD simulations. However, it is also evident that too much refinement in the current configuration can lead to less accurate results, especially with respect to mass species transport properties (Wang, 2009). As was mentioned earlier, due to the complexity of the current configuration, tetrahedral unstructured grid is used.

In addition to homogeneous refinement, adaptive local refinement has been implemented for some cases in the grid dependency study. Two main reasons for this strategy are: 1) reduce the required runtime to get appropriate convergence for numerical studies 2) RANS models should not have any grid inside the buffer turbulent sub-layer.

To clarify the last point that was just made the subdivisions of a typical boundary layer for the viscous flow are shown in Figure 184.

Figure 184: Near-wall-region subdivisions

In this discussion, a non-dimensional wall distance for a wall-bounded flow can be defined in the following format.

$$y^+ = \frac{u_* y}{\nu} \quad \text{Eq. 12}$$

In this equation, u_* is the friction velocity at the nearest wall, and y is the distance to the nearest wall. Also ν is the kinematic viscosity of the fluid. Friction velocity is referred to square root of the ratio of the wall shear stress and fluid density in the following way.

$$u_* = \sqrt{\frac{\tau_w}{\rho}} \quad \text{Eq. 13}$$

For the standard wall treatment, as what is done in this study, mesh should be managed to avoid having y^+ between 5 and 30 which occurs in the buffer layer [Fluent 6.3 Documentation].

With respect to the stated reasons, a typical adaptive local refinement is shown in Figure 185 to provide a better understanding of this strategy.

Figure 185: Typical adaptive local refinement

In the present work, a number of cases have been tried for each turbulent model and for each fuel in order to accomplish the grid independency study. For illustrative purposes, only an example of grid dependency study is given in this chapter. It should be noted that

presentation of the grid dependency study for 3D cases is quite challenging. Thus, contours of fuel air ratio and also plots of fuel air ratio along a single jet are shown for three planes downstream of the injection point for the radial injection of methane into air. To be clear, the list of the numerical cases that are subjects of the illustrative example in this section is given in Table 8.

Table 8: Numerical cases for the illustrative grid independency study

Case Name	Fuel	Turbulence Model	Sc_t	Grid Cells ($\times 10^3$)
Coarsened	Methane	RSM	0.7	245
More Refined	Methane	RSM	0.7	1,300
Finalized Case	Methane	RSM	0.7	800

At the first plane downstream of the injection plane, located at $Z/D=0.3125$, the effect of grid refinement is evident. Figure 186 presents the qualitative difference between the coarsened, finalized and more refined cases. It is evident that the coarsened case underestimates the fuel air ratio in this plane. Moreover, after refinement, in the finalized case a good agreement is notable. However, further refinement in this case doesn't lead to better accuracy which is the purpose of grid independency study.

Figure 186: Illustrative grid dependency study for radial injection at $Z/D=0.3125$

To provide a better numerical assessment, Figure 187 presents quantitative comparison between different grid sizes. It is confirmed that more refinement than finalized case doesn't provide any further information. It can be claimed that more refinement for this case is not required due to the fact that desirable accuracy has already been obtained in the finalized case with 8×10^5 grid. In addition, unnecessary refinement after this limit ends in more numerical efforts to solve the equations, spending more time to get the reasonable convergence and potential solution instability (Wang, 2009).

Figure 187: Grid independency study at $Z/D=0.3125$ along the jets

The same analysis is made for the other two planes downstream of the injection points located at $Z/D=0.9375$ and $Z/D=1.875$. The contour and the plot of fuel air ratio at $Z/D=0.9375$ are shown in Figure 188 and Figure 189, respectively. The similar conclusions can be made for the second plane.

Figure 188: Illustrative grid dependency study for radial injection at $Z/D=0.9375$

Figure 189 presents the fuel to air distribution along a radial distance at second plane. This figure gives some insight into the predicted trend of mixing in this plane. The experimental data scatters are shown besides numerical predictions lines.

Figure 189: Grid independency study at $Z/D=0.9375$ along the jets

It is again evident that the finalized case resembles the experimental measurements the best. Same analysis is made for the $Z/D=1.875$ in Figure 190 and Figure 191.

Figure 190 presents the contour of fuel to air ratio for these four cases besides each other. This type of figure facilitates understanding the qualitative mixing level of fuel and air.

Figure 190: Illustrative grid dependency study for radial injection at $Z/D=1.875$

Figure 191 gives quantitative measurement across a line in the third plane. Overall behaviors of jets are apparent in this type of figure for each case. The significance of this figure is that this is related to the last plane downstream which is the closest plane to the exit of the premixer. The level of mixing in this plane can be important for design purposes.

Figure 191: Grid independency study at $Z/D=1.875$ along the jets

Although there are some differences between numerical and experimental analysis at the last plane, the finalized case has a better prediction about the mixing level.

4.2.2.1.4 Evaluation of Numerical Sensitivity to Different Turbulent Models and Sc_t for Radial Injection Cases

In this section, numerical results for the flow field properties of the radial configuration are presented along the experimental measurements. As it was mentioned earlier, numerical cases with entire domain and C_d modification are subjects of study for different turbulent models and different Sc_t . Sensitivity of numerical solutions to turbulent models are verified by studying $k-\varepsilon$, RSM, URANS, and LES turbulent models. Moreover, sensitivity to Sc_t number is tested through examination of four different Sc_t numbers including 0.2, 0.3, 0.4 and 0.7. Furthermore, this study focuses on two different fuels including methane and hydrogen.

To compare numerical and experimental results, momentum fields are compared first. In this part, the axial velocity of the numerical results and experimental measurement are presented along each other. Then, the mixing properties of the fuels are compared within fuel/air ratio comparison. It should be noted that the later task, studying the mixing properties, is the main goal of this thesis. Thus, extensive study is done in this regard including qualitative, quantitative, and statistical comparison.

4.2.2.1.4.1 Momentum Field Comparison

The accuracy of the velocity field is checked at three planes downstream of the injection points. The comparison is taken to the computational simulation to that of the experimental velocity measurements obtained with the Pitot-Static probe.

It should be mentioned that axial velocities are normalized by bulk velocity by the magnitude of 6.21 m/s. The error bars for the experimental measurements are associated with the pressure reading uncertainty of the pressure gauge. The comparison between experimental measurements and different numerical turbulent models at $Z/D=0.3125$ is shown in Figure 192.

Figure 192: Axial velocity comparison at $Z/D=0.3125$

The general agreement between CFD and experiment at this plane is evident. Same comparison is made at $Z/D=0.9375$ which is shown in Figure 193. In Figure 193, the axial velocity is shown along the radial distance at the second plane downstream. The side figure indicates the position of the plane.

Figure 193: Axial velocity comparison at $Z/D=0.9375$

Similar to the previous results, the general agreement between CFD and experiment at this plane is evident at this plane. The axial velocity comparison for the third plane is shown in Figure 194. In Figure 194, axial velocity is shown along the radial distance. This is the closest plane to the exit as it is shown in the side figure.

Figure 194: Axial velocity comparison at $Z/D=1.875$

It can be seen that there is an agreement between numerical results and the experimental within the uncertainty ranges. However, the agreement is poor compared to the first two planes.

4.2.2.1.4.2 Mixing Properties Comparison

In this section, the computed results of fuel to air ratio at 3 axial locations downstream of the injection plane are presented for methane/air and hydrogen/nitrogen cases. These numerical results, based on various combinations of turbulence models and turbulent Schmidt number values are compared with experimental measurements. Both qualitative and quantitative comparison is made based upon planar contour and radial plots of fuel air ratio at different planes. Distances are normalized by the main mixing section diameter ($D=81.28$ mm). The fuel air ratio is reported versus dimensionless radial distances in each plane along a jet. Due to the symmetrical geometry, these figures are representative of the general behavior of each jet in a plane. Moreover, the contours of the different simulations are presented beside the experimental contours. In addition, statistical assessment is made based on the average of the magnitude of fuel air ratio differences between numerical and experimental measurements over the whole plane. It is noted that while the methane and hydrogen cases use about the same momentum flux ratio, the overall ratio of fuel to air based on metered inlet flow rates is different for methane and hydrogen due to different gas properties for different fuels. For methane the overall fuel/air ratio based on inlet mass flow rates is 0.007742, while for hydrogen/nitrogen it is 0.002697. Therefore, to help compare the relative results for the two fuels, the average of the magnitude of fuel air ratio differences between numerical and experimental measurements is normalized by mean measured fuel air ratio in each plane both methane and hydrogen within statistical comparison in this section. To be more consistent, results are presented in two sub-sections for methane and hydrogen.

4.2.2.1.4.2.1 Methane and Air

Before presentation of the comparison of the measured and predicted numerical fuel/air results for methane, an overall view of the fuel distribution in the X-Z plane is presented in Figure 195 for $k - \varepsilon$ and RSM turbulence models with Sc_t of 0.7. As shown, for the condition studied, the fuel remains near the centerbody. In addition, the $k - \varepsilon$ model suggests higher fuel concentration at the centerline of the flow, especially immediately downstream of the centerbody than what RSM model does. The combustion of the fuel/air mixture presented by

these two predictions would differ substantially. Consequently, it should be noted that using numerical prediction without any evaluation is not recommended.

Figure 195: Contours of methane mole-fraction in the plane of $Y/D=0$ for $k-\epsilon$ and RSM simulations¹¹

It should be noted that all of the cases reviewed in this section are summarized in Table 9.

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Table 9: Numerical cases for methane radial injection¹²

Turbulence Model	Fuel	Oxidant	Sc_t	Grid Numbers
k-ε	Methane	Air	0.2	~0.15 x 10 ⁶
k-ε	Methane	Air	0.3	~0.15 x 10 ⁶
k-ε	Methane	Air	0.4	~0.15 x 10 ⁶
k-ε	Methane	Air	0.7	~0.15 x 10 ⁶
RSM	Methane	Air	0.2	~0.80 x 10 ⁶
RSM	Methane	Air	0.3	~0.80 x 10 ⁶
RSM	Methane	Air	0.4	~0.80 x 10 ⁶
RSM	Methane	Air	0.7	~0.80 x 10 ⁶
URANS	Methane	Air	0.7	~1.30 x 10 ⁶
LES	Methane	Air	0.7	~2.20 x 10 ⁶

A comparison of the measured with predicted fuel/air results is now presented for the three planes of interest. The first plane is located 25.4 mm downstream of injection point or Z/D=0.3125. At this point, the 8 jets keep their individual identity. The first comparison is obtained by presenting the fuel air ratio along a jet as a function of radial position. Figure 196 compares all the methane cases with the experiment for this plane along the radial line indicated.

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Figure 196: Comparison of experiment and simulations at $Z/D=0.3125$ ¹³

A wide range of predicted trend is observed, but the radial locations of peaks of different cases generally match measured peak. The URANS and LES approaches result in the highest fidelity with the experimental results. In order to provide qualitative comparison, Figure 197 presents results in contour form for a fixed value of Sc_t of 0.7. In this case, general agreement is reflected with RSM suggesting the most similar fuel concentration distribution compared to the experiment.

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Figure 197: General qualitative comparison at $Z/D = 0.3125$ ¹⁴

In order to investigate the sensitivity of numerical results to different Sc_t numbers, Figure 198 provides the Sc_t variation in $k - \varepsilon$ and RSM models. The RSM results are significantly less affected, but for both simulation approaches, higher values of Sc_t lead to better agreement.

Figure 198: The effect of Sc_t in $k - \varepsilon$ and RSM models¹⁵

The second plane is located in 76.2 mm downstream which is $Z/D=0.9375$. At this plane, the level of mixing of the discrete jets, observed in the first plane, is enhanced by the wake mixing behind the centerbody. Figure 199 presents the comparison between the experimental

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measurements and the predictions of various turbulence models. RSM with $Sc_t = 0.7$ and LES model resemble measured values better than do the URANS and $k - \varepsilon$ models. At this location, the general trends of the fuel distribution are matched in terms of tendency to predict higher fuel concentrations near the centerline. However, $k - \varepsilon$ models show flat behavior near the centerbody.

Figure 199: Comparison between different turbulent models and experiment at $Z/D = 0.9375$ ¹⁶

Similar to the first plane, the planar comparison between experiment and turbulence models with fixed $Sc_t=0.7$ is shown in Figure 200. In this figure, the fuel air distribution is shown along the radial distance. Due to the physical symmetry, it is reasonable to assume that looking into this figure can give insightful information about the trend of mixing in this plane, especially near the discrete jets.

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Figure 200: General qualitative comparison at $Z/D = 0.9375$ ¹⁷

It is again seen that general agreement exists between RSM, URANS, LES and experiment. Results of Figure 201 examine the sensitivity of the solution to the Sc_t for RSM and $k-\varepsilon$ models. In general, the $k-\varepsilon$ modeling approach shows a higher level of mixing compared with the experimental results. On the other hand, $k-\varepsilon$ models typically overpredict the level of mixing.

Note that the results from the RSM model show much higher sensitivity to Sc_t values than does the $k-\varepsilon$ model at this plane. This is in contrast to the results at the first plane, supporting the concept of complexity of trying to establish a general strategy for simulation.

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Figure 201: The effect of Sc_t in $k-\varepsilon$ and RSM models¹⁸

The third plane is located 152.4 mm downstream which is $Z/D=1.875$. Figure 202 presents the comparison between the measured values and the predictions using various turbulence models. It can be seen that again the RSM with $Sc_t = 0.7$ and LES model compare better with the measured values than do the URANS, $k-\varepsilon$, and other RSM models with $Sc_t \neq 0.7$.

At this location, the peak fuel concentration for approaches the centerline and this is captured by all of the simulation approaches considered. At this plane the $k-\varepsilon$ model shows greater sensitivity to Sc_t compared to the RSM, a trend which was observed at the first plane, but opposite again to the trend at the middle plane.

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Figure 202: Comparison between different turbulent models and experiment at $Z/D=1.875$ ¹⁹

The qualitative comparison of contours of concentration between experiment and turbulence models with fixed $Sc_t=0.7$ is shown in Figure 203. As it is evident, at this plane, the RSM with $Sc_t = 0.7$ appears to compare best with the experiment.

The effect of Sc_t values for both $k-\varepsilon$ and RSM simulations are shown in Figure 204. Again it is noted that higher values of Sc_t generally provide better agreement with the experimental results. In the case of methane air, with a Schmidt Number (Sc) number of 0.9, it appears that values of Sc_t closer to the physical property of the gases provide generally better results.

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Figure 203: General qualitative comparisons at $Z/D = 1.875$ ²⁰

Figure 204: The effect of Sc_t in $k-\epsilon$ and RSM models.²¹

As it was mentioned earlier, in order to provide more quantitative assessment of the results, statistics associated with the fuel/air ratio over the plane were calculated for the measurements and simulations. In the present work, the averaged magnitude of the difference between the measured and predicted air/fuel ratio for all points over the plane is used. To provide better comparison between the two fuels, the values are normalized by the overall fuel/air ratio based on mean fuel air ratio measured in each plane. For example, for methane

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the overall fuel/air ratio based on inlet mass flow rates is 0.007742. The results are shown in Figure 205 for each simulation approach for each plane.

Figure 205: Normalized averaged fuel/air differences between experiment and numerical cases over the planes (methane) for radial injection configuration²²

The results shown in Figure 205 indicate the average difference in the context of the overall fuel/air ratio. As shown, typical variations range from 25 to 85% of the overall fuel/air ratio. It is evident that the differences tend to be the greatest for $k-\varepsilon$ models. This is consistent with general observations in the literature that the performance of the turbulence model is sometimes a function of the flowfield itself (e.g., Bradshaw, 1997; Sierra-Espinosa, et al., 2000; El-Beheri, et al., 2011; Bourgeois, et al., 2011). It should be noted that the first plane includes discrete jets while the other two planes involve enhanced mixing level of fuel into air. Hence, the apparent improvement in the agreement at the downstream planes for some cases may be due to the presence of this additional mixing mechanism. In general, the results suggest that RSM with Sc_t between 0.4 and 0.7 and LES provide the best quantitative agreement with experiment at all three planes. It is clear that the results for the first plane are very similar for all of the numerical models. However, as the planes go downstream, the major

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differences between numerical cases appear. For both RANS strategies, higher values of Sc_t improve performance. It is noted that while LES requires significantly more computational resources, the end prediction doesn't necessarily provide significantly better results for the time averaged mixing behavior. This is consistent with other observations comparing LES with other models (e.g., Dejoan, et al., 2005) which find that RANS models can often capture the time averaged structure. Of course if the problem warrants understanding of the dynamics of the process, LES may be required.

4.2.2.1.4.2.2 Hydrogen and Nitrogen

Studying the mixing properties of hydrogen is the main goal of this thesis. So far, mixing properties of methane as the most common fuel for gas turbine applications are studied to provide a baseline for hydrogen properties study. One different though, is that the oxidant for hydrogen is nitrogen for the radial injection configuration. This again is a result of the hydrogen analyzer employed in the experimental measurements.

What is more, due to results of LES for the methane case, it was concluded that the RSM model can predict the mixing properties very well. Also, LES model requires a lot of numerical efforts to provide reasonable results. In addition, primary RSM results for the hydrogen showed promising prediction. Therefore, in the case of hydrogen RSM and $k - \varepsilon$ models are tested. The summary of studied cases in this section is given in Table 10.

Table 10: Numerical cases for hydrogen radial injection²³

Turbulence Model	Fuel	Oxidant	Sc_t	Grid Numbers
k-ε	Hydrogen	Nitrogen	0.2	$\sim 0.18 \times 10^6$
k-ε	Hydrogen	Nitrogen	0.3	$\sim 0.18 \times 10^6$
k-ε	Hydrogen	Nitrogen	0.4	$\sim 0.18 \times 10^6$
k-ε	Hydrogen	Nitrogen	0.7	$\sim 0.18 \times 10^6$
RSM	Hydrogen	Nitrogen	0.2	$\sim 0.90 \times 10^6$
RSM	Hydrogen	Nitrogen	0.3	$\sim 0.90 \times 10^6$
RSM	Hydrogen	Nitrogen	0.4	$\sim 0.90 \times 10^6$
RSM	Hydrogen	Nitrogen	0.7	$\sim 0.90 \times 10^6$

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In this section, results for the mixing of hydrogen are presented following the same organization as used in the 4.2.2.1.4.2.1 section.

The first plane is located 25.4 mm downstream of injection point or $Z/D=0.3125$. The quantitative comparison is made by presenting the data as a function of radial position along an injection jet. In Figure 206 the general comparison is made between different turbulence models and experiment.

Figure 206: Comparison between different turbulent models and experiment at $Z/D=0.3125$ ²⁴

It is evident that the RSM models provide a good level of agreement with experiment in this plane. In addition, the RSM results exhibit less dependency on Sc_t than the $k-\epsilon$ models. The sensitivity of RSM and $k-\epsilon$ models to the Sc_t is shown in Figure 207.

As shown the RSM model provides generally better agreement with the measured values. $k-\epsilon$ models tend to over predict the level of mixing of hydrogen as well as methane.

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Figure 207: The effect of Sc_t in k- ϵ and RSM models²⁵

Looking back to the results for methane into air, penetration for both methane and hydrogen, for a fixed momentum flux ratio is very similar. In this regard, it can be concluded that the selected momentum flux ratio was appropriate. Moreover, the mixing properties of the fuels in the first plane are dominated by turbulent mixing rather than diffusion. As a result, two different fuels with quite different properties show similar trends. With respect to the discussion about the roles of Sc_t in determination of mixing due to either turbulent mixing or diffusion, it can be seen that why higher Sc_t that offers that turbulent mixing is dominant, have generally better results in the prediction of mixing properties of methane and hydrogen. In addition, referring to the data in Figure 181, RSM models provide good level of agreement with experimental that confirms that the need for challenging LES model is not critical.

The second plane is located 76.2 mm downstream ($Z/D=0.9375$). Figure 208 presents the measured and simulation results using various turbulence models. As shown, the predictions, especially k- ϵ models indicate maximum fuel concentrations at the centerline which is not predicted by either RSM or experimental measurement. Again it is crucial to keep in mind that the mixing process at this plane is a combination of discrete jet behavior and wake mixing behind the centerbody.

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Figure 208: Comparison between different turbulent models and experiment at $Z/D=0.9375$ ²⁶

The effect of Sc_t on the numerical results is shown in Figure 209 which indicates that Sc_t has little effect on the results of RSM models, similar to what was presented in Figure 182. This is somewhat in contrast to the results for methane into air, where the Sc_t values did result in an improved general trend for the RSM turbulence models. Higher values of Sc_t improve the performance of the k- ϵ results, but in all cases, this model consistently over predicts the mixing. What is more, in this plane the RSM models can predict the location of jet peak very well. It confirms that the corrections implemented in terms of coefficient of discharge for tiny holes of the injectors are based on actual physical features of the flow field.

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Figure 209: The effect of Sc_t in k- ϵ and RSM models²⁷

The third plane is located 152.4 mm downstream ($Z/D=1.875$). Figure 210 presents the comparison between measured and numerical results. As shown, the simulations again indicate peak levels of fuel at the centerline where as the measurements indicate a small deficit of fuel. The general trends are similar as those at the previous plane located at $Z/D = 0.9375$. The trends away from the centerline seem to be well captured by RSM with higher values of Sc_t . Again, the k- ϵ model over predicts the mixing, especially for low values of Sc_t .

Figure 210: Comparison between different turbulent models and experiment at $Z/D=1.875$ ²⁸

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The effects of various Sc_t values are shown in Figure 211 over the plane for both RSM and $k-\epsilon$ models. In this case, RSM with $Sc_t = 0.2$ shows overall agreement with the measurements near the centerline, while RSM with $Sc_t = 0.2$ and $Sc_t = 0.3$ overpredict the level of mixing near the wall. In this plane it is apparent that all of the numerical cases lose the accuracy, especially near the centerline.

Figure 211: The effect of Sc_t in $k-\epsilon$ and RSM models²⁹

Like the results for methane and air, statistics associated with the fuel/air ratio over the plane were calculated for the measurements and simulations for hydrogen mixture. The average magnitude of differences of air/fuel ratio between numerical cases and experimental measurement over the three planes are normalized by mean measured fuel to air ratio in each plane. To give more insight into the scale of the numbers, the overall fuel-air ratio for hydrogen is 0.002697.

The statistical analysis shown in Figure 212 indicates that RSM simulations provide better agreement with the measurements compared to the $k-\epsilon$ results. This general observation is confirmed with respect to the statistical analysis for the methane cases.

For RSM models, little dependence on Sc_t is noted for the first two planes, but agreement improves at the last plane with decreasing Sc_t . As shown, the average variation is still 20 to 100% of the overall fuel to air ratio even for the most accurate simulation approach. It is again evident that the numbers for the first plane are similar for each turbulent model. Moreover, it seems numerical predictions have the poorest agreement with experimental measurement at the second plane downstream. It could be due to the wake behind the

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centerbody that produced high level of turbulent and makes the measurement test and also numerical prediction quite challenging.

Figure 212: Normalized averaged fuel/air differences between experiment and numerical cases over the planes (hydrogen) for the axial injection configuration³⁰

Based on Figure 205 and Figure 212, the overall fidelity between the simulations and measurements is similar for both methane and hydrogen. The RSM simulations provide the smallest differences with the experimental measurement values. The optimum strategy for minimizing the difference between mixing of hydrogen and methane is different, although if RSM is used with a Sc_t value based on the laminar value (Sc); the best agreement is obtained based on the average difference between measured and predicted fuel concentration over the plane.

4.2.2.1.5 ANOVA Statistical Results for The Radial Injection Cases

In this section, further statistical analysis is accomplished to make final conclusions more confidently. Design-Experiment (DX) v.7 software is utilized to provide ANOVA analysis based on numerical and experimental dataset. In general, this software provides a statistical test to verify the role of various parameters in achievement of higher accuracy in a certain problem.

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For instance, in this work, it is desirable to identify how changing various parameters, such as changing Sc_t and turbulent model can contribute to better numerical solution. As it is indicated so far, different parameters are varying to achieve the best numerical prediction. For instance, four different turbulent Schmidt numbers are tested. In addition, two different RANS models have been compared. Both hydrogen and methane are subjects of numerical and experimental study. What is more, all of the numerical and experimental results are provided for three planes downstream of the injection point. As main comparison in criterion in this work, scaled averaged difference between numerical and experimental measurements in each plane has been selected. This parameter is used as a response in DX software to determine general role of variation of each parameter in agreement of numerical and experimental results for each case. For radial injection, 48 cases exist including combination of 4 Sc_t numbers, 2 fuels, 2 RANS models and 3 different planes.

Based on ANOVA results provided by DX software, it is defined that for radial injection cases variation of turbulent model has the most impact on predictions.

Figure 213: ANOVA analysis for all the RANS radial injection case

The ANOVA analysis for the radial cases is given in Figure 213. In this figure, vertical axis is the normalized averaged differences between numerical results and experimental

measurements. The axial axis is different turbulent models. The lower the vertical value the better the numerical case because lower normalized difference means the experimental measurement is closer to numerical predictions. Moreover, results are shown for averaged values for all of the planes and both fuels. The purpose of the Figure 213 is to investigate the overall sensitivity of numerical predictions to variation of turbulent model and Sc_t .

The big conclusion of this section is that for radial injection cases, high sensitivity to different numerical models is apparent. However, for each numerical model, low sensitivity of numerical predictions to various Sc_t can be seen. This conclusion is consistent with one was drawn in the previous sections as well.

4.2.2.1.6 Effect of Inlet Temperature and Pressure

As shown in Section 4.2.1.2, if conditions are set with matched momentum flux ratio, the overall mixing of the hydrogen and methane appear very similar. To explore this further, consideration was given to a case with elevated temperature and pressure. In this case, the ambient conditions were set to correspond to 17 bar and 700 deg-K. Again, momentum flux was nominally matched at 9.55 for methane and 8.88 for hydrogen. The conditions set resulted in an air flow rate of 7.84 kg/min with methane and hydrogen flows of 0.0859 kg/min and 0.0294 kg/min, respectively.

For these conditions, the comparison of the results for the elevated pressure and temperature case with the standard condition case is shown in Figure 214 for the two fuels. As shown, the results are qualitatively very similar. This suggests that momentum flux matching is a good approach for scaling mixing in this particular case of radial injection into a non-swirling crossflow.

a) Hydrogen

b) Methane

Figure 214: Comparison of Fuel/Air for Elevated Temperature and Pressure Condition and Standard Condition.

To provide a more quantitative comparison between the two conditions, Figure 215 presents radial profiles of the fuel/air ratio for the two conditions at three downstream locations. As shown, the difference between the two conditions is small. This result helps to extend the applicability of the conclusions to realistic engine conditions.

Figure 215: Comparison of Radial Fuel/Air Profiles for Elevated Temperature and Pressure Condition and Standard Condition.

4.2.2.2 Non-Swirling Axial Injection

4.2.2.2.1 Domain Size Dependency

In this section it was investigated if it is possible to provide appropriate numerical predictions using quadrant geometry of the main domain with periodic boundary conditions

instead of grid generation for the entire body which entails more numerical efforts. To provide a better understanding of the quadrant geometry, Figure 216 is provided.

Figure 216: Quadrant body geometry of axial injection configuration

Implementation of quadrant body has some advantages. However, it should be confirmed that the quadrant body has a good level of accuracy in numerical predictions. Therefore, numerical results of quadrant body for axial methane injection into air are compared to those for entire body in this section to present the capabilities or insufficiencies of utilizing quadrant body. Similar to the previous chapter, numerical and experimental results are compared in three different planes downstream of the injection point for each case.

The first figure belongs to the qualitative comparison between entire and quadrant body at the first plane downstream of the injection point located at $Z/D=0.3125$ shown in Figure 217.

Figure 217: Quadrant body vs. entire body for methane at $Z/D=0.3125$

It is evident that the overall agreement is not very good. However, it is clear that the quadrant body results tend to resemble quarter of a square which is far from the intuition. To get more informative figure, the Figure 218 shows the quantitative comparison along a line in this plane.

Figure 218: Quadrant vs entire body for $k - \varepsilon$ turbulent mode at $Z/D=0.3125$

The same comparison is made for the second plane located at $Z/D=0.9375$. This result is shown in Figure 219. In this figure the fast variation of mixing level of mixture can be seen as it travels downstream. The location of this plane is again shown in the side figure. Three contours of fuel to air ratio are shown besides each other to have a better sense of their qualitative agreement.

Figure 219: Quadrant body vs entire body for axial methane case at $Z/D=0.9375$

This contour implies that both quadrant body and entire body have relatively good predictions. More detailed information for this plane can be observed in Figure 220 in which the fuel to air ratio distribution is shown along a radial distance. This line is shown in the side figure. Due to the symmetric physics of this domain it is reasonable to assume that this plot indicates the trend of mixing in the entire plane.

Figure 220: Quadrant vs entire body for $k-\varepsilon$ turbulent mode at $Z/D=0.9375$

To make sure about the sufficiency of the quadrant body approach it is needed to look at the last plane downstream located at $Z/D=1.875$. This plane which is closest to the exit of the premixer is very important. The results for this comparison are shown in Figure 221 and Figure 222.

Figure 221: Quadrant body vs entire body for axial methane case at $Z/D=1.875$

Figure 221 presents the overall qualitative comparison between three cases. The quadrant body approach has lost its accuracy in this plane. However, regarding the selection of ranges for the legend of this contour, it is not quantitatively observable how quadrant body approach predicts the trend of mixing. This can be seen in the radial distribution of fuel to air ratio in Figure 222.

Figure 222: Quadrant vs entire body for $k - \varepsilon$ turbulent mode at $Z/D=1.875$

It is evident that the quadrant body approach is lacking in appropriate accuracy in this plane. It seems this approach tends to over-predict the level of mixing in the downstream of the injection point. As a conclusion, it is decided to do the rest of analysis with entire body approach which is inherently more accurate. To see more details in this regard, the centerline traverse comparison is made along the axial direction of the domain. The result of this comparison is demonstrated in Figure 223.

Figure 223: Centerline traverse comparison for the entire body vs quadrant body

It is clear that the entire body approach is capable of providing an excellent prediction of the trend of mixing as the fuel travels downstream. This result confirms the conclusion of this section in terms of continuing by entire body approach for the rest of the numerical analysis.

4.2.2.2.2 Grid Independency Study

As it was discussed earlier, grid independency study is an essential step in CFD simulations. To prevent discussing the same materials again, grid independency study for different fuels and different turbulent models is comprehensively pointed out.

First, to find appropriate axial methane cases for both $k-\varepsilon$ and RSM eleven different cases with various numbers of cells have been investigated to find suitable case for both $k-\varepsilon$ and RSM turbulent models for both methane and hydrogen. To provide more information in this regard, Table 11 is given.

Table 11: Summary of cases for methane grid independency study

Turbulence Model	Number of Grids×1000
$k - \varepsilon$	217
$k - \varepsilon$	287
$k - \varepsilon$ (refined center)	217 adapted to 290
$k - \varepsilon$ (refined center)	217 adapted to 362
$k - \varepsilon$ (refined center)	287 adapted to 539
$k - \varepsilon$	625
RSM(refined center)	217 adapted to 290
RSM(refined center)	217 adapted to 362
RSM(refined center)	287 adapted to 539
RSM	625
RSM(refined center)	625 adapted to 1400

As a reminder, the refined center cases are referring to making local refinement near the center body as it was demonstrated in Figure 185.

For methane $k - \varepsilon$ cases, the results for the numerical analysis are compared to the experimental measurements in Figure 224 to see how far refinement has a major impact on the accuracy of the results.

Figure 224: Grid independency study for $k-\varepsilon$ models for methane at the second plane downstream

Figure 224 is only an example of this comprehensive study which is shown across a radial distance at the second plane downstream of the injection point. Referring to this set of results and also the results of the other planes, it was concluded that the case with 287,000 cells shows the most promising prediction for $k-\varepsilon$ cases for methane. It is confirmed that more refinement doesn't end in better accuracy.

The results for the RSM turbulent model are shown in Figure 225. Again, this figure is only an example of grid independency study for the RSM models.

Figure 225: Grid independency study for RSM models for methane at the second plane downstream

Based on these results for this geometry, it was concluded that the RSM model with center adaptive refinement including 539,000 cells suggest the best case, confirming the fact that more refinement doesn't obtain better accuracy. The same analysis is made for the hydrogen as a fuel for the axial injection configuration. As it is given in the Table 12, eleven cases have been tested in the grid independency study for hydrogen.

Table 12: Summary of cases for hydrogen grid independency study

Turbulent Model	Number of Grids×1000
$k-\varepsilon$	217
$k-\varepsilon$	287
$k-\varepsilon$ (refined center)	217 adapted to 290
$k-\varepsilon$ (refined center)	217 adapted to 362
$k-\varepsilon$ (refined center)	287 adapted to 539
$k-\varepsilon$	625
RSM(refined center)	217 adapted to 290
RSM(refined center)	217 adapted to 362
RSM(refined center)	287 adapted to 539
RSM	625
RSM(refined center)	625 adapted to 1400

Between $k-\varepsilon$ models, the case with 287,000 cells was selected as the final case due to the results of comparisons in Figure 226 and other data for the other planes.

Figure 226: Grid independency study for $k-\varepsilon$ models for hydrogen at the second plane

The same study is accomplished for RSM turbulent models. In this case, the results of comparison between different numerical predictions and experimental measurements end in selection of RSM model with 625,000 cells. For instance, an example of this study is shown in Figure 227.

Figure 227: Grid independency study for RSM models for hydrogen at the third plane

Therefore, four different cases have been selected for further analysis for axial injection configuration for both methane and hydrogen for both RSM and $k-\varepsilon$ models.

4.2.2.2.3 Evaluation of Numerical Sensitivity to Different Turbulent Models and Sc_t for Axial Injection Cases

In this section, numerical results of CFD simulation are compared to experimental measurements. Sensitivity of CFD simulations to different turbulent models have also been tested. In addition, the impact of various Sc_t number on results is explored. As it was concluded for radial injection case that RSM simulation can provide appropriate predictions, and also based on primary verification of RSM models for axial injection configuration, unsteady turbulent models are not studied again. RANS models including $k-\varepsilon$ and RSM with four different Sc_t numbers, ranging from 0.2 to 0.7, have been tested to present comparison to experimental measurements for both hydrogen and methane.

Mixing properties of methane and hydrogen are reported as fuel to air ratio in the format of qualitative comparison including contours, and also quantitative analysis including radial plots. Finally, the statistical measurement enables drawing better conclusions.

4.2.2.2.3.1 Methane and Air

After taking a number of steps to come up with eight final RANS turbulent models for methane including RSM and $k-\varepsilon$ turbulent models, and four Sc_t numbers, appropriate approaches are necessary to take to provide suitable comparison between experimental and numerical results. In this section methane as a fuel for axial injection configuration will be extensively discussed. Qualitative comparison includes contours of fuel air ratios. Quantitative comparisons include two series of comparisons. The first one is fuel to air ratio plots along the radial distance. The second quantitative comparison includes statistical analysis based on averaged differences of fuel air ratio between numerical models and interpolated experimental measurements in the same plane. The differences are normalized by measured fuel to air at each plane. Before making comparison plane by plane, an overall observation is made for $k-\varepsilon$ and RSM turbulent models. As it is given in Figure 228, the predictions of RSM model and $k-\varepsilon$ model are very similar. This result is different than what was seen in Figure 195. It implies that the impacts of different turbulent models in the final results depend on the configuration. For instance, for the radial injection configurations, different turbulent models have remarkably different trends. However, for the axial injection cases, it is evident that the results of these two turbulent models are very similar.

Figure 228: Contours of methane fuel to air in the plane of $Y/D=0$ for $k-\varepsilon$ and RSM simulations

After providing that overall information, more details about the prediction of different turbulent models can be seen in following figures and plots at three different planes downstream of the injection point.

The first plane is located at $Z/D=0.3125$. The qualitative results for this plane are shown in Figure 229 and Figure 230.

Figure 229: Sensitivity to Sc_t number for $k-\varepsilon$ models at $Z/D=0.3125$

In Figure 229, different $k-\varepsilon$ models with three different Sc_t numbers are shown besides the experimental measurement contours. The position of the plane is given in the side figure. In Figure 230, different RSM models with different Sc_t numbers are drawn next to experimental measurements. It should be noted that the legend for fuel air ratio contours is the same for all the cases in this section.

Figure 230: Sensitivity to Sc_t number for RSM models at $Z/D=0.3125$

It is evident that the jet widths for the above cases are very similar. Also, it is clear that the numerical results in this plane are not similar to the experimental measurements. One reason would be due to the fact that the gradient of change of level of changing is very high near the injection point. This would be demonstrated later in this section.

To obtain better visualization capability, fuel air plots are shown in Figure 231.

Figure 231: Fuel air ratio along radial distance for all cases at $Z/D=0.3125$, $X=0$

In this figure it is apparent that the overall agreement is not good at this plane. However, RSM with standard Sc_t shows promising results. As the Sc_t goes down, the agreement gets worse for both RSM and $k - \varepsilon$ models.

The second plane is located at $Z/D=0.9375$. In this plane jet of fuel has experienced some time to get mixed by co-flow air. The qualitative comparison between numerical cases and experimental measurements are shown in Figure 232 and Figure 233.

Figure 232: Sensitivity to Sc_t number for $k - \varepsilon$ models at $Z/D=0.9375$

In Figure 232, different $k - \varepsilon$ models with three different Sc_t numbers are shown besides the experimental measurement contours. The position of the plane is given in the side figure. In Figure 233, different RSM models with different Sc_t numbers are drawn next to experimental measurements. Due to the fixed legend for all the contours in this section, fuel air ratio distribution could be not visually clear for some cases such as $k - \varepsilon$ with $Sc_t=0.2$ in Figure 232. However, radial distribution of fuel to air ratio is shown in Figure 234.

Figure 233: Sensitivity to Sc_t number for RSM models at $Z/D=0.9375$

It is apparent that the level of agreement is much better than the one in the previous plane. In addition, the effects of Sc_t are strong in this plane for both RANS models. Also, the level of agreement becomes better as Sc_t increases. What is more, the results of $k-\varepsilon$ and RSM models are quite similar. It means that the predictions of CFD are more sensitive to variation of Sc_t rather than variation of turbulent models.

Quantitative comparison for all of the studied cases is given in Figure 234.

Figure 234: Fuel air ratio along radial distance for all cases at $Z/D=0.9375$, $X=0$

It can be seen that the agreement of numerical and experimental measurements across the radial distance is remarkable. This result is consistent to what was shown in the previous plane as well.

The third plane of interest is located at $Z/D=1.875$. The qualitative results for numerical cases are demonstrated in Figure 235 and Figure 236 for $k - \varepsilon$ and RSM, respectively.

Figure 235: Sensitivity to Sc_t number for $k - \varepsilon$ models at $Z/D=1.875$

In Figure 235, different $k - \varepsilon$ models with three different Sc_t numbers are shown besides the experimental measurement contours. The position of the plane is given in the side figure. In Figure 236 different RSM models with different Sc_t numbers are drawn next to experimental measurements. The overall level of fuel to air ratio in this plane is lower than the other planes. Thus, for some cases, especially the ones with low Sc_t , the distribution of fuel to air ratio is not visually distinguishable. However, the quantitative comparison given in Figure 237 can give more insights into the fuel air ratio distribution.

Figure 236: Sensitivity to Sc_t number for RSM models at $Z/D=1.875$

It is again evident that the Sc_t number has a strong impact on numerical prediction in axial injection type premixers. The $Sc_t = 0.7$ has the best agreement with the experimental measurements. Quantitative analysis is made by providing the radial plot of fuel to air ratio in Figure 237. The side figure shown here indicates where the line is located.

Figure 237: Fuel air ratio along radial distance for all cases at $Z/D=1.875$, $X=0$

This set of results confirms that both turbulent models with $Sc_t=0.7$ provide the best agreement with experimental measurements.

Now to indicate what has happened from the first plane downstream to the other planes, Figure 238 is given to explain why the level of agreement has significantly increased. It is apparent that the rate of change is fuel content of the centerline of the traveling jet is very large near the injection point. Thus, the different results of experimental and numerical predictions could be due to insufficiency in accuracy of experimental measurement because slight change in the location of pitot probe can contribute to a huge change of measured values.

Figure 238: Centerline traverse comparison for all of the cases at $X=Y=0$

To help to understand the position of the drawn line, Figure 239 is provided. This line is located at the center of the single jet which is injected through the axial injection. Figure 238 can show the fast variation of mixing level in the centerline.

Figure 239: Cross section of the axial configuration

It is evident that the RSM model with $Sc_t=0.7$ provides excellent agreement with experimental measurement. To present the overall behavior of two RANS models Figure 240 is given. The $k-\varepsilon$ case with $Sc_t=0.7$ suggests the best agreement with experimental measurements between other $k-\varepsilon$ models with lower Sc_t .

Figure 240: Centerline traverse comparison for RANS model with $Sc_t=0.7$ of the cases at $X=Y=0$

It is clear that RSM has the best agreement with the measured trend of mixing as the jet travels downstream.

The statistical analysis, based on difference between interpolated experimental results in each plane with numerical results, is made. In each plane this difference is normalized by the mean measured fuel air ratio to be comparable to the other fuel and also radial configuration results.

Figure 241: Normalized averaged fuel/air differences between experiment and numerical cases over the planes (methane) for axial injection configuration

Figure 241 reveals that both turbulent models with $Sc_t=0.7$ obtain a good level of agreement with experimental measurement. As it is illustrated, as the plane goes toward the exhaust, the level of agreement becomes better. The overall change is between 0.15 and 0.9.

4.2.2.2.3.2 Hydrogen and Air

As it was concluded previously, two numerical cases for hydrogen have been selected after grid independency study. For $k-\varepsilon$ turbulent model, a case with 287,000 cells, and for RSM turbulent model a case with 625,000 cells have been selected. As done for earlier cases, the same approach is taken for making comparison between numerical and experimental results. Similar momentum flux ratios are chosen for hydrogen and methane in this study to facilitate making appropriate comparisons between these two fuels as well. It was again observed that the main characteristics for both $k-\varepsilon$ and RSM models are very similar. In order to demonstrate this observation, the cross section of the domain is shown in Figure 242 for both numerical turbulent models.

Figure 242: Contours of hydrogen fuel to air in the plane of $Y/D=0$ for $k-\varepsilon$ and RSM simulations

In Figure 242 it is evident that the similarity between $k-\varepsilon$ and RSM is even more than the one in Figure 228. This figure demonstrates the overall behavior of mixing properties of hydrogen as the jet travels downstream. To obtain more information in this regard numerical and experimental results for fuel to air ratio are provided in the three planes downstream of the injection point.

First plane is located at $Z/D=0.3125$. The qualitative comparison between $k-\varepsilon$ and RSM models with various Sc_t numbers is provided in Figure 243 and Figure 244.

Figure 243: Sensitivity to Sc_t number for $k-\epsilon$ models at $Z/D=0.3125$

In Figure 243, different $k-\epsilon$ models with three different Sc_t numbers are shown besides the experimental measurement contours. The position of the plane is given in the side figure. In Figure 244, different RSM models with different Sc_t numbers are drawn next to experimental measurements. It should be noted that the legend for fuel air ratio contours is the same for all the cases in this section.

Figure 244: Sensitivity to Sc_t number for RSM models at $Z/D=0.3125$

It is apparent that the width of the jet increased as Sc_t decreases. To see the magnitude of the peaks for each model quantitative comparison is provided in Figure 245 along a line. Due to the symmetric physical condition, the distribution of fuel to air ratio is shown in Figure 245 can be generalized to the entire plane at this location. The side figure shows the location of the line across which the plot is shown.

Figure 245: Fuel air ratio along radial distance for all cases at $Z/D=0.3125$, $X=0$

The result here is consistent with the results of methane in the sense that in both cases the agreement between numerical and experimental results is not very good. The inappropriate in this plane could be because of some experimental measurement issues. In terms of peak magnitude, RSM model with $Sc_t=0.7$ provides the closest result to the experimental measurements.

The second plane is located at $Z/D=0.9375$. The overall agreement in this plane is much better than the one in the previous plane. Qualitative comparison for both RANS models with different Sc_t numbers is given in Figure 246 and Figure 247.

Figure 246: Sensitivity to Sc_t number for $k-\varepsilon$ models at $Z/D=0.9375$

In Figure 246, different $k-\varepsilon$ models with three different Sc_t numbers are shown besides the experimental measurement contours. The position of the plane is given in the side figure. In Figure 247, different RSM models with different Sc_t numbers are drawn next to experimental measurements. The cases that are not visually clear in this figure will be quantitatively shown in Figure 248.

Figure 247: Sensitivity to Sc_t number for RSM models at $Z/D=0.9375$

It is clear that the level of agreement increases with increasing of Sc_t . For instance, in low Sc_t numbers, the CFD results highly overpredict the level of mixing in this plane. However, in cases with higher Sc_t , agreement is desirable. Furthermore, different numerical cases have the same trend of prediction for this configuration. Quantitative comparison is given in Figure 248.

Figure 248: Fuel air ratio along radial distance for all cases at $Z/D=0.9375$, $X=0$.

The best cases based on the experimental measurements are $k-\varepsilon$ and RSM with $Sc_t=0.7$. $k-\varepsilon$ model slightly predicts the experimental measurements better in terms of jet width. Cases with low Sc_t highly over predict the level of mixing as it was apparent in Figure 246, Figure 247 and Figure 248.

The third plane is located at $Z/D=1.875$. Similar to what presented for the other planes, contours of different plane numerical results with different Sc_t numbers are shown in Figure 249 and Figure 250.

Figure 249: Sensitivity to Sc_t number for $k-\varepsilon$ models at $Z/D=1.875$

In Figure 249, different $k-\varepsilon$ models with three different Sc_t numbers are shown next to the experimental measurement contours. The position of the plane is given in the side figure. In Figure 250, different RSM models with different Sc_t numbers are drawn next to experimental measurements. It is apparent that cases with low Sc_t numbers are over predicting the level of mixing. The better visualization of these cases is accomplished in Figure 251.

Figure 250: Sensitivity to Sc_t number for RSM models at $Z/D=1.875$

This is quite remarkable how increasing Sc_t can contribute to increase of level of agreement between numerical predictions and experimental measurements. Low Sc_t extensively overestimates the level of mixing in this plane as well as the previous planes. Quantitative comparison is made in Figure 251.

Figure 251: Fuel air ratio along radial distance for all cases at $Z/D=1.875$, $X=0$

Cases with low Sc_t are far from experimental measurements due to overprediction of the mixing level. It can be due to the fact that in shear flows, turbulence is dominant in determination of flow field properties, and Increasing of Sc_t suggests increase of level of turbulent (Dudukovic et al., 1999) . Both $k-\varepsilon$ and RSM models with $Sc_t=0.7$ have a good prediction in this plane.

The centerline traverse comparison of measured value and numerical results is given here to provide another important aspect of capability of CFD approach.

Figure 252: Centerline traverse comparison for all of the cases at $X=Y=0$

Similar to what presented in Figure 238, RSM model with $Sc_t=0.7$ provides the best agreement with experimental measured fuel content at the centerline of the axial configuration. For both RANS models, increasing Sc_t leads in better agreement which is consistent with previous comparisons in this section. To provide a better understanding of sensitivity of the numerical prediction to different turbulent model, Figure 253 is given.

Figure 253: Centerline traverse comparison for RANS model with $S_{ct}=0.7$ of the cases at $X=Y=0$

Although the results of methane and hydrogen are very similar, the accuracy of $k-\varepsilon$ models in hydrogen is better than the one for methane.

Last quantitative comparison between numerical and experimental results is presented in the form of statistical analysis.

Figure 254: Normalized averaged fuel/air differences between experiment and numerical cases over the planes (methane) for axial injection configuration

This analysis suggests the same trend for agreement of numerical and experimental data. Best Sc_t number for this configuration is undoubtedly 0.7. Moreover, for RANS model with $Sc_t=0.7$ the agreement is worst in the near plane, located at $Z/D=0.3125$.

4.2.2.2.4 ANOVA Statistical Results for Axial Injection Cases

ANOVA results obtained from DX software is used in this work to facilitate making final conclusions more confidently. As it was given in Figure 213, it was concluded that in general the sensitivity of numerical predictions to different Sc_t numbers is low while high sensitivity to different RANS models has been observed. Now, the same analysis is provided for all axial injection cases. Similar to radial case, there are 48 different cases regarding axial injection configuration including 2 fuels, 3 planes, 4 Sc_t numbers, and 2 different RANS models. The result is given in Figure 255.

Figure 255: ANOVA analysis for all the RANS axial injection cases

In Figure 255, it is apparent that the sensitivity of numerical predictions is relatively high to the variation of Sc_t numbers. However, low sensitivity to different RANS models is obvious. This result is opposite to the one that has been obtained for the radial injection cases. Both turbulent models with $Sc_t=0.7$ distinctly provide better predictions compare to the other Sc_t numbers. In general, RSM model with $Sc_t=0.7$ provides the most promising numerical model in

this work. To present the overall advantage of RSM models over $k - \varepsilon$ models, Figure 256 is shown for all 96 cases as inputs of DX software.

Figure 256: ANOVA analysis for all the RANS cases

It is clear that overall prediction of RSM model is better than $k - \varepsilon$ model based on the averaged results of cases with different Sc_t numbers, planes, fuels, and injection types.

4.2.2.3 Non-Swirling Flow Summary

The numerical studies were carried out with a statistically based matrix for both axial and radial injection. In this section the results from both injection types are combined and analyzed together. As a result, the effect of turbulence model, fuel type, axial plane, turbulent Schmidt number, and injection type could be studied using analysis of variance. Figure 257 summarizes the subset of the numerical runs that were isolated for the analysis of variance for the combined axial and radial injection.

Study Type	Factorial	Runs	96				
Design Type	Full Factorial	Blocks	No Blocks				
Center Points	0						
Design Model	2FI	Build Time (ms)	1.2921				
Factor	Name	Type	Subtype	Low Actual	High Actual		
A	Turb Model	Categoric	Nominal	K-E	RSM	Levels:	2
B	Fuel	Categoric	Nominal	Methane	Hydrogen	Levels:	2
C	Plane	Categoric	Nominal	0.3125	1.875	Levels:	3
D	T-Sch	Categoric	Nominal	0.2	0.7	Levels:	4
E	Injection Type	Categoric	Nominal	Axial	Radial	Levels:	2

Figure 257: Summary of the Statistical Design used for Analysis of Variance.

In this analysis, five factors are studied as summarized in Table 13. The rows in bold indicate the statistically significant effects, namely, the turbulence model, the turbulent Schmidt number, and the Injection type. These are the most important factors in determining the relative agreement with the measured values. In addition, interactions are shown between the axial plane and injection type as well as turbulent Schmidt number and injection type. These interactions are due to the fact that the impact of one factor depends on the level of the other. In the case of the injection type and turbulent Schmidt number, it is noted that for radial injection, the value of turbulent Schmidt number doesn't matter very much. However, for axial injection, turbulent Schmidt number is very important. To illustrate this, Figure 258 presents results plotted in a way to see how the turbulent Schmidt number and turbulence model selection impacts the agreement for the two injection types

Table 13: Analysis of Variance for Non-Swirling Cases, Main and 2 Factor Effects.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	3.664	25	0.147	11.438	< 0.0001
A-Turb Model	0.504	1	0.504	39.322	< 0.0001
B-Fuel	0.088	1	0.088	6.896	0.0106
C-Plane	0.053	2	0.027	2.075	0.1332
D-T-Sch	1.162	3	0.387	30.224	< 0.0001
E-Injection Type	0.520	1	0.520	40.566	< 0.0001
CD	0.237	6	0.040	3.085	0.0097
CE	0.475	2	0.237	18.524	< 0.0001
DE	0.467	3	0.156	12.136	< 0.0001
CDE	0.159	6	0.026	2.065	0.0684
Residual	0.897	70	0.013		
Cor Total	4.561	95			

a) Axial Injection

b) Radial Injection

Figure 258: Comparison of Difference between Predicated and Measured Fuel Concentration for different Turbulence Models and Turbulent Schmidt Numbers.

4.2.2.4 Swirling Flow

The simulations for the swirling cases were carried out for a select number of cases. With the swirling cases, much of the experience and methodologies developed for the non-swirling cases were applied. As a result, extensive discussion regarding the approach for domain generation and refinement as well as establishing grid independency is not provided for the swirling cases. Some details are worth noting however and these are discussed before the comparative results are shown. The overall summary of simulations for the swirling flow cases carried out is shown in Table 14. The original plan was to carry out the same parametric variation as was done for the non-swirling cases. Essentially allowing the swirling cases to be added to the overall ANOVA. However, challenges with the swirling cases precluded the entire matrix to be completed. While disappointing from the viewpoint of the ANOVA, valid conclusions can still be drawn. Some details regarding the observations from the cases run are provided in the following sections followed by comparison with measurements for cases which were felt to be the best simulations (noted as “EVALUATED” in Table 14).

Table 14: Summary of Predictions For Swirling Flow.

Turbulent Model & Fuel	Injection type	Fuel mass flow rate kg/min	Air mass flow rate kg/min	Momentum flux ratio	Number of Grids×1000	Note
RSM Methane	Axial	0.00108	1.116	9.5	1300	Convergence problem
RSM Hydrogen	Axial	0.0003693	1.116	8.88	1800	Convergence problem
RSM Mixed 50/50 by volume	Axial	ch4 =0.00068986 h2 =0.000086672	1.116	8.88	1500	Convergence problem
RNG k-ε Methane	Axial	0.00108	1.116	9.5	700	Grid independence study
RNG k-ε Methane	Axial	0.00108	1.116	9.5	920	Grid independence study (EVALUATED)
RNG k-ε Methane	Axial	0.00108	1.116	9.5	1300	Grid independence study
RNG k-ε Hydrogen	Axial	0.0003693	1.116	8.88	1500	Grid independence study
RNG k-ε Hydrogen	Axial	0.0003693	1.116	8.88	1700	Grid independence study(EVALUATED)
RNG k-ε Hydrogen	Axial	0.0003693	1.116	8.88	1900	Grid independence study
RNG k-ε Mixed 50/50 by volume	Axial	ch4 =0.00068986 h2 =0.000086672	1.116	8.88	1100	Grid independence study
RNG k-ε Mixed 50/50 by volume	Axial	ch4 =0.00068986 h2 =0.000086672	1.116	8.88	1450	Grid independence study(EVALUATED)
RNG k-ε Mixed 50/50 by volume	Axial	ch4 =0.00068986 h2 =0.000086672	1.116	8.88	1800	Grid independence study
RSM Methane	Radial	0.00864	1.116	9.5	2400	Convergence problem
RSM Hydrogen	Radial	0.00301	1.116	8.88	2200	Convergence problem
RSM Mixed 50/50 by volume	Radial	ch4 =0.0055189 h2 =0.0006934	1.116	8.88	2900	Convergence problem
RNG k-ε Methane	Radial	0.00864	1.116	9.5	2400	Grid independence study(EVALUATED)
RNG k-ε Methane	Radial	0.00864	1.116	9.5	2800	Grid independence study
RNG k-ε Hydrogen	Radial	0.00301	1.116	8.88	2200	Grid independence study(SELECTED)
RNG k-ε Hydrogen	Radial	0.00301	1.116	8.88	2600	Grid independence study
RNG k-ε Mixed 50/50 by volume	Radial	ch4 =0.0055189 h2 =0.0006934	1.116	8.88	2900	Grid independence study(EVALUATED)
RNG k-ε Mixed 50/50 by volume	Radial	ch4 =0.0055189 h2 =0.0006934	1.116	8.88	3200	Grid independence study

4.2.2.4.1 Radial Injection

4.2.2.4.1.1 Domain and Grid Evaluation.

The inclusion of swirler module creates challenges for mesh generation. For each case, grid independence studies were carried out in a manner similar to that for the non-swirling cases as discussed in Sections 4.2.2.1 and 4.2.2.2. Finer and finer grids were utilized until the results essentially stopped changing. A summary of grid independence studies is shown in Table 14.

4.2.2.4.1.2 Model Sensitivity.

RSM and $k-\varepsilon$ turbulence models were used for the swirling cases, consistent with the goal of evaluating the viability of computationally efficient approaches. Of the possible variants of the $k-\varepsilon$ model, the renormalized group (RNG) $k-\varepsilon$ turbulence model was used for the swirling cases as opposed to the realizable $k-\varepsilon$ for the non-swirling cases based on the literature (e.g., Najafi, et al., (2005); Hou and Zou (2005). After taking all of the mentioned steps, for each fuel combination one numerical case which is RNG $k-\varepsilon$ with appropriate number of grids is presented in this report. The results are shown for both axial and radial injections of fuel into the swirling air.

A fixed value for the turbulence Schmidt number was selected. As shown previously, the mixing results tended to be less sensitive to Schmidt number with high levels of turbulence, hence a value of 0.7 (“the standard value”) was used for the evaluation

4.2.2.4.1.3 Comparison with Measured Results

The cases compared with measured results are summarized in Table 15. The RNG $k-\varepsilon$ turbulence model was used in all case and a turbulent Schmidt number of 0.7 was used.

Table 15: Cases for Radial Injection into Air.

Fuel	Fuel Mass Flow Rate, kg/min	Air Mass Flow Rate, kg/min	Momentum flux Ratio	Grid Cells
Methane	0.00864	1.116	9.5	2,400,000
Hydrogen	0.00301	1.116	8.88	2,200,000
50% Methane	0.005519	1.116	8.88	2,900,000
50% Hydrogen	0.000693			

The comparison between the measured (sample probe) and predicted F/A values are shown in Figure 259. The general agreement is quite poor in trends and magnitudes. Unfortunately, use of the RSM turbulence model, which might be preferred for swirling flow was precluded from this study due to challenges achieving convergence. Second order convergence could not be attained using the convergence criteria sought (e.g., 3 orders of magnitude reduction in the residuals) with a reasonable time period (e.g., < 2 weeks). As a result, despite best effort, no data assessing the reliability for RSM could be attained.

Figure 259: Comparison of Predicted and Measured F/A for Radial Injection into Swirling Flows.

A comparison of the velocity field is shown in Figure 260. As shown the general trends in the flowfield appear to be captured, however regions with significant differences are noted (e.g., the axial velocity at the center of the flow).

Figure 260: Comparison of Measured (LHS) and Predicted Axial Velocity (RHS).

4.2.2.4.2 Axial Injection

In this section, comparison of the predicted fuel concentration with measured values is shown for the axial injection configuration. The summary of the efforts relative to different models and grids is shown in Table 14. A summary of the cases used for the comparison for the axial injection cases is shown in Table 16.

Table 16: Cases for Axial Injection into Swirling Air.

Fuel	Fuel Mass Flow Rate, kg/min	Air Mass Flow Rate, kg/min	Momentum flux Ratio	Grid Cells
Methane	0.00864	1.116	9.5	2,400,000
Hydrogen	0.00301	1.116	8.88	2,200,000
50% Methane	0.005519	1.116	8.88	2,900,000
50% Hydrogen	0.000693			

The comparison of the measured and predicted F/A for the different fuel compositions are shown in Figure 261. Like that for the radial injection, the overall agreement is relatively poor. The CFD strongly overpredicts the mixing of the fuels. As shown Table 14 and discussed in the

section on the radial injection, it was not possible to compare results for RSM turbulence model due to convergence challenges.

Figure 261: Comparison of Predicted and Measured F/A for Axial Injection into Swirling Flows.

In summary, the predictions for the swirling flow cases are considerably different than the measured values. In the present case, it is possible the use of extractive probe causes some additional error in the measured concentration, but it would be expected that the probe would tend to increase the mixing not suppress it. In that case (assuming perturbations would accelerate the mixing), the agreement shown in Figure 259 and Figure 261 would be even poorer. The inability of RANS models to accurately predict complex flows is not unique as evidenced by other comparisons in the literature (e.g., El-Behery and Hamed, 2011; Bourgeois, et al., 2011). Based on the overall poor agreement, it was decided not to add the swirling flow results to the ANOVA already carried out as it would likely decrease the utility of that analysis.

5 Conclusions

A combined experimental and numerical study of fuel mixing processes associated with flows representative of gas turbine premixers has been carried out. The major conclusions of this study are as follows:

In terms of overall observations and insights from the experiments:

- The Pitot-Static probe shows good agreement with more advanced techniques (i.e., Particle Image Velocimetry) even for cases with no fuel injection.
- The use of Laser Raman scattering for measurement of fuel concentration proved challenging in the absence of beam stretching. The available short pulse duration laser systems tried yielded ignition of the hydrogen without attaining sufficient Raman signal.
- The downstream mixing of fuel is determined primarily by the flow field, and has little to no dependence on the fuel section. With use of a constant fuel jet to air momentum flux ratio, hydrogen behaved no differently than methane for all of the cases investigated.
- The result that the mixing behavior was insensitive to fuel type reaffirms that momentum flux ratio (J) is an important parameter for the determination of the spatial fuel distribution. This is evidenced by the ability of existing 1-D correlations in the literature to successfully predict the jet penetration in the near field for the non-swirling cases.
- Measurements of the velocity field with and without the fuel injected suggests that, for the conditions studied, the fuel selection has little effect on the velocity field downstream of the injection point. There is a limited effect near the jet itself.
- Flow swirl improved the symmetry of the flow, and quickly “smeared” any pattern due to distinct individual fuel jets in the case of radial injection.
- For the axial injection cases flow swirl works to decrease the jet area and generated a stronger and sharper peak, effectively making the jet less mixed and more centrally located.
- For radial injection cases flow swirl moved the fuel peaks inward, and reduced the effects of jet.

In terms of observations based on the comparison of the predicted fuel distributions with those measured:

- For the present geometry, use of quarter symmetry to represent the full domain is not appropriate. This is evidenced by the strong periodicity of the results which are not found when the full geometry is considered.
- Improper treatment of the coefficient of discharge for the fuel injection holes has a significant effect on the numerical predictions:
- Local refinement of grid near the centerline can contribute to numerical benefits in both axial and radial geometries:
- For the radial jet configuration, time averaged numerical results using RSM turbulence models are similar to those using LES and URANS, yet with significantly less computational time.
- For radial fuel injection into non-swirling flows, the CFD predictions are sensitive to the turbulence model used, but not to the value of Sc_t .
- For axial fuel injection into non-swirling flows, the CFD predictions are very sensitive to Sc_t values, but are not sensitive to the turbulence model used.
- For non-swirling flows, the RSM turbulent model provides more reliable numerical prediction of mixing properties of fuel and air compared to the $k - \varepsilon$ turbulence model in both axial and radial injection configurations.
- For swirling flows, it was very difficult to get the RSM turbulence model to converge to second order. As a result, the study could only assess the performance of the $k - \varepsilon$ model (in this case the RNG variant of the $k - \varepsilon$ model was expected to provide superior performance for swirling flows).
- The agreement between the RNG $k - \varepsilon$ turbulence model with measured values was poor.
- In general, it was found that the nature of the flowfield influences the performance of the predictions. This result implies that it is difficult to establish apriori the “best” simulation approach to use. The insights from the relative orientation of the jet and flow does offer some guidance for which approach to take. However, the results underscore the importance of model “anchoring” (i.e., “tuning” the model to provide “reasonable” agreement with a well characterized geometry/flow).

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9 Nomenclature

Acronyms

CCD	Charge Coupled Device
CFD	Computational Fluid Dynamics
FID	Flame Ionization Detector
GC	Gas Chromatograph
ICCD	Intensified Charge Coupled Device
IR	Infrared
LES	Large Eddy Simulation
PIV	Particle Image Velocimetry
PLIF	Planar Laser Induced Fluorescence
PRESTO	PREssure Staggering Option
PTU	Programmable Timing Unit
RANS	Reynolds Averaged Navier-Stokes
RSM	Reynolds Stress Model
SCM	Standard Cubic Meter
SCMM	Standard Cubic Meter per minute
SGS	Sub-Grid Scales
UCI	University of California, Irvine
UCICL	University of California, Irvine Combustion Laboratory
URANS	Unsteady Reynolds Averaged Navier-Stokes
UV	Ultraviolet

Symbols

k	Turbulent kinetic energy		
ϵ	Dissipation rate		
Sc_t	Turbulent Schmidt number	ρ	Density [kg/m^3 , lbm/ft^3]
Sc	Schmidt number	P	Pressure
ν_t	Turbulent molecular kinematic viscosity	R_{fuel}	Fuel Specific Gas Constant
D_t	Turbulent molecular mass diffusivity	S	Jet Spacing Distance
y^+	Dimensionless wall distance	S_N	Swirl Number
R	Radius	T	Temperature
X, Y, Z	Spatial coordinate	U	Velocity
A	Area	X_{pen}	Jet Penetration distance
C_d	Coefficient of Discharge	Z	Downstream Distance
D	Diameter		
H	Duct Width		
J	Momentum Flux Ratio		
m	Mass [kg , lbm]		
$\dot{m}$	Mass Flow Rate		
Φ	Equivalence Ratio		

Subscripts

b	Bulk
fuel	Fuel Properties
g	gage
hub	Central Injection Hub
j	Jet
sw	Swirler

A. Schematics of Constructed Components

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		ONE PLACE DECIMAL $\pm .03$	ENG APPR.		
		TWO PLACE DECIMAL $\pm .01$	MFG APPR.		
		THREE PLACE DECIMAL $\pm .001$			
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			
			TITLE: Threaded Centerbody		
			SIZE	DWG. NO.	REV
			A		
			SCALE: 1:1	SHEET 1 OF 1	

Appendix A-1: Threaded centerbody technical drawing

Appendix A-2: Axial injector cap technical drawing

Appendix A-3: Radial injector (8x) cap technical drawing

Appendix A-4: Flow straightener module technical drawing

B. Experimental Database

Experimental Database from

Numerical and Experimental Study of Mixing Processes
Associated with Hydrogen and High Hydrogen Content Fuels

U.S. D.O.E Final Report

2011

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The following database provides information related to the experimental study conducted, and will be presented in the form recommended by Faeth and Sameulsen (Faeth, 1986).

B.1 Experimental Facility

These data were obtained using the modular premixer test stand located at the University of California, Irvine Combustion Lab located at the University of California, Irvine.

B.2 Experimental Configuration

This section includes the test hardware configurations employed. Including detailed information on the geometry of the hardware employed to allow the facilitation of replication through hardware fabrication or CFD simulation. Note that all units are in mm unless otherwise noted.

B.2.1 Basic Configuration and Flow Field

The basic hardware configuration consists of a number of interchangeable hardware modules situated on top of an air plenum. The air plenum is mounted onto a solid plate, which provides the bottom seal, and creates an interface to hold the fuel centerbody. Air initially enters the air plenum through four spokes, which are tangent to the plenum circumference. As this induces a flow swirl the air is then passed through a sintered ring which works to negate the flow swirl and create a radially inward flow. The air then exits through the top of the plenum into the various modules employed.

The initial module is the flow condition module, which can hold either a spacer ring (no change to flow, but maintains constant inside diameter), a flow straightener (aluminum honeycomb section) to further condition the flow, or a swirler plate to induce flow swirl. The flow then continues upward in an annular configuration due to the centerbody. The centerbody is a tube of 25.4 mm diameter located in the center of the flow which allows fuel injection. This centerbody has a threaded cap piece, and by changing this piece the injection type can be changed. The centerbody is also able to traverse in the Z direction, allowing the injection point height to be changed.

The quarl provides a number of functions. The first is to provide a lip to hold a steel plate. This plate is then attached to the bottom plate which the plenum is located, and as

tightened provides a compression which seals all the various modules together. The quarl also provides an interface for the quartz liner section, which contains the flow and allows visual access. Additionally an exhaust section can be mounted atop the liner as needed. The basic flows and hardware components are shown in Appendix B-1, the actual test hardware shown in Appendix B-2, and a detailed cross section with dimensions shown in Appendix B-3.

Appendix B-1: Test hardware section view with air and fuel flows labeled

Appendix B-2: Test hardware

Appendix B-3: Test hardware cross section with dimensions. Note all dimensions are in mm

For the tests conducted four various hardware configurations were employed, and are referred to as configurations A-D. The individual configurations, their injection planes, and the important measurement planes are shown in the following sections.

B.2.2 Configuration A: Non-Swirling Axial Injection

This configuration consists of the axial injection cap and a flow straightening plate located in the flow conditioning module.

Appendix B-4: Non-swirling axial injection hardware configuration

B.2.3 Configuration B: Non-Swirling Radial Injection

This configuration consists of the radial injection cap and a flow straightening plate located in the flow condition module.

Appendix B-5: Non-swirling radial injection hardware configuration

B.2.4 Configuration C: Swirling Axial Injection

This configuration consists of the axial injection cap and the 45° degree swirling plate located in the flow conditioning module. Additionally the exhaust section was installed above the liner.

Appendix B-6: Swirling axial injection hardware configuration

B.2.5 Configuration D: Swirling Radial Injection

This configuration consists of the radial injection cap and the 45° degree swirling plate located in the flow condition module. Additionally the exhaust section was installed above the liner.

Appendix B-7: Swirling radial injection hardware configuration.

B.3 Test Conditions

Data was obtained for the ten cases outline below in Table B-1. For all cases the bulk flow rate was maintained at 1.116 kg/min. Fuel flow rates were determined to maintain a constant momentum flux ratio (J). For Methane injection a J was held at 9.55, while for the hydrogen and methane blend cases the value was 8.88. All cases operate at a standard 101.325 kPa pressure and room temperature.

Table B-1: Experimental Study Test Cases

Case	Hardware Configuration	Swirl Level	Injection # and type	CH ₄ Fuel Volume [%]	H ₂ Fuel Volume [%]	Total Fuel Mass Flow [kg/min]·10 ³
1	A	None	1x Axial	100	-	1.08
2	A	None	1x Axial	-	100	0.369
3	B	None	8x Radial	100	-	8.64
4 [†]	B	None	8x Radial	-	100	3.01
5	C	45° Plate	1x Axial	100	-	1.08
6	C	45° Plate	1x Axial	-	100	0.369
7	C	45° Plate	1x Axial	50	50	CH ₄ : 0.74 H ₂ : 0.087
8	D	45° Plate	8x Radial	100	-	8.64
9	D	45° Plate	8x Radial	-	100	2.95
10	D	45° Plate	8x Radial	50	50	CH ₄ : 5.93 H ₂ : 0.693

[†]This case consists of hydrogen injection into nitrogen, as opposed to air

B.4 Inlet and Boundary Conditions

The mass flow rates of both the bulk air as well as the fuel are important boundary conditions. For all test cases the bulk flow rate of air was 1.116 kg per minute. The fuel flow rate and fuel composition was varied for each test case, and the values are summarized in Table B-1 for each case. As a note the table displayed the total fuel flow rate, not the flow rate through each individual injector.

The bulk pressure was measured in the air plenum (inside the sintered ring) with an absolute pressure gauge (Seegers Standards precision pressure transfer standard, SS-2170-100). For the non-swirling cases it was observed to be 101.698 kPa, an increase of 373 Pa above the room pressure. For the swirling cases it was observed at 102.042 kPa, an increase of 717 Pa above room pressure.

Fuel pressure drop was measured through the use of a differential pressure gauge (Meriam Instrument, 40HE35) and found to 353.4 and 358.4 Pa for methane and hydrogen axial

injection. For the radial cases the pressure drop was observed as 296.2 and 298.7 Pa for methane and hydrogen respectively.

Additionally axial velocity was measured at six planes of the flow field with no fuel injection through the use of a Pitot-Static Probe and these data are presented in section B.13.1.

B.5 Quantities Measured

The quantities measured for the various hardware configuration and test cases are outline in Table B-2. Note GC represents gas chromatograph, FID represents flame ionization detector, HA represents hydrogen analyzer, PIV represents particle image velocimetry, PLIF represents planar laser induced fluorescence, and P-S represents Pitot-static.

Table B-2: Quantities Measured

Quantity Measured	Case Or Configuration	Number and location of Measurements			Diagnostics Employed
Fuel Concentration [Mole fraction]		Downstream Distance [mm]			
		25.4	76.2	152.4	
	1	90, half plane	122, half plane	96, half plane	GC
	2	305, full plane	122, half plane	96, half plane	
	3	155, half plane	149, half plane	94, half plane	FID
	4	210, half plane	150, half plane	96, half plane	HA & GC
	5,6,7	58 across diameter	58 across diameter	58 across diameter	GC
	8,9,10	28 on diameter along jet & 28 on diameter between jets	46 on diameter along jet & 44 on diameter between jets	44 on diameter along jets	GC
Pitot-Static Axial Velocity [m/s] V_z -no fuel injection		Downstream Distance [mm]			
		25.4	76.2	152.4	
	A	16 along both x and y axis, 1 per quadrant (36 total)	12 along both x and y axis, 1 per quadrant (28 total)	11 along both x and y axis, 1 per quadrant (26 total)	P-S
B	10 along both x and y axis, 1 per quadrant (24 total)	10 along both x and y axis, 1 per quadrant (24 total)	10 along both x and y axis, 1 per quadrant (24 total)		
Velocity Field [m/s] V_x & V_z	1-4	Images of X-Z plane through hardware central axis. 1000 image pairs at three downstream distances to cover entire liner (~160 mm of coverage). Total of 3000 image pairs per case			PIV
	5-10	Images of X-Z plane. 500 image pairs at three X-Z planes (central and +/- 0.381 mm) at three downstream distances to cover entire liner (~160 mm of coverage). Total of 4500 image pairs per case.			

Light intensity	A w/ acetone- methane fuel injection	100 images of fluoresced light intensity at the planes 25.4, 76.2, and 152.4 mm downstream of injection. Total of 300 images per case	PLIF
	B 2/ acetone- methane fuel injection		
Pressure [Pa]	A-D	Absolute pressure in air plenum	
	1-4	Fuel pressure drop	

B.6 Diagnostics

B.6.1 Physical Probe

Physical probe measurements were used for both fuel concentration as well as axial velocity. Axial velocity measurements were obtained through the use of a Pitot-Static Probe (United Sensor, PCC-24-KL) and differential pressure gauge (Mid-West Instrument #60001).

Fuel concentration was obtained through the use of an extractive probe tied to a analyzer unit. Three different analysis techniques were employed, including: flame ionization detector (FID), hydrogen analyzer, and a gas chromatograph (GC). For all three techniques a 3.175 mm stainless steel probe was used. This probe was inserted into the flow field and, through the use of a vacuum pump, samples of the flow were extracted. The samples were then passed into one of the analysis techniques.

The first analysis technique is a flame ionization detector. This detector functions by passing the sample through a small hydrogen jet flame which ionizes hydrocarbons. This ionization process produces a measurement signal which is directly related to the concentration of carbon atoms in the sample, and for our study, the direct concentration of methane (due to the single carbon atom). A Horiba FIA-236-1 FID was employed in this study. This detector can work for any hydrocarbon, but cannot measure hydrogen.

A hydrogen analyzer was also employed, and for this study a Horiba TCA 300 hydrogen analyzer was used. A hydrogen analyzer measures concentration of hydrogen through the use of a thermal conductivity detector, and relies on the fact that hydrogen has a thermal conductivity that is approximately seven times that of nitrogen. The limitations of this device are that it can only accept non flammable mixtures, and only measures hydrogen.

The final analysis technique employed was gas chromatography. This technique was used the most extensively as any gas species can be measured, including simultaneous

measurements of methane and hydrogen. In this study an Agilent M200 Micro GC was employed. Gas chromatography measures individual gas species by first separating each species through an internal column packing, and then measuring the individual gas concentration through the use of thermal conductivity. The internal packing effectively separates the individual gas species as each gas has its own affinity for the column. That different affinity results in each gas eluting at a different time, allowing individual measurements.

B.6.2 Planar Laser Induced Fluorescence (PLIF)

Fuel concentration is determined by the fluoresced light emissions induced by an ultraviolet laser sheet. The PLIF diagnostic utilized a laser generated by a Continuum Surelite III-10 Nd:YAG pulsed laser. This laser outputs a beam at 266 nm, with a maximum power output of 100 mJ per pulse. The beam was turned into the sheet through the use of a cylindrical plano-convex lens (Thor Labs, 500 mm focal length, #LA4579), and a plano-concave rectangular lens (CVI Melles Griot, -125mm focal length, #RCC-40.0-25.4-63.6-UV).

Images were obtained through an Andor iStar intensified charge coupled device (ICCD) camera. The camera has a 16 bit resolution with a 1024 by 1024 pixel resolution, with a variable intensifier unit. Additionally a non UV transmitting camera lens (Pentax, 35-70 mm focal length zoom lens, F-mount) was employed to avoid capturing laser light. This camera and lens were mounted above the test hardware, perpendicular to the laser sheet.

To facilitate fluorescence the fuel was seeded with acetone, which emits light when energized by UV light. The fluoresced light is directly and linearly related to laser energy as well as the concentration of acetone. Schematics of the PLIF setup are shown in Appendix B-8.

Appendix B-8: PLIF experimental setup diagram (side view)

B.6.3 Particle Image Velocimetry (PIV)

The velocity field in a 2D plane is determined through imaging light scatter generated by a laser sheet scattered off of particles within the flow field. By taking two images with a small time separation ($\sim 30\mu\text{s}$), a cross correlation technique can be used to track particle movement, and thus the velocity field.

To provide scattered light, a visible laser sheet is required. This sheet is generated through two Surelite III-10 Nd:YAG laser systems operating in the visible spectrum (532 nm, 380 mJ maximum power per pulse). Two systems are needed to allow the small time separation required. The beams are passed through the same optics, to generate an identical laser sheet at the same location. This laser sheet is generated through the use of a plano-convex cylinder lens (Thor Labs, 500 mm focal length, #LA4579), and a plano-concave rectangular lens (CVI Melles Griot, -125mm focal length, #RCC-40.0-25.4-63.6-UV).

The scattered light is then imaged through a frame-straddling charge coupled device (CCD) camera. The frame straddling refers to the fact that two images are obtained with a small time separation. A LaVision Image Intense frame straddling CCD camera using a Pentax F-mount zoom lens (35-70 mm focal length) was employed for the imaging. Additionally a polarization filter (Hoya, Special Effect Filter-PL) was used to reduce any stray light scatter. The camera was mounted perpendicular to the laser sheet.

Flow seeding was achieved through the addition of olive oil droplets into the bulk flow. The droplets were generated by passing a fraction of the total flow through an oil seeder unit,

and remixing the flow in the air plenum post sintered ring, which would remove the droplets. The separate air stream was monitored separately to ensure the same total air flow rate.

Additional equipment was required for the timing of the PIV imaging, and included a programmable timing unit (PTU, LaVision external programming unit). This unit generated the appropriate timing signals needed to coordinate the various pieces of equipment, ensuring the proper time separation as well as successful imaging during the laser pulse.

The velocity field in the X-Z plane was obtained for this study. The overall PIV setup is shown in both top and side views in Appendix B-9, and Appendix B-10.

Appendix B-9: Schematic of PIV setup (Top View)

Appendix B-10: Schematic of PIV optics and imaging (side view)

B.7 Unusual Measurement Methods

For both laser diagnostics modifications were made to reduce light contamination, due to liner fluorescence in the case of PLIF, and liner scatter in the case of PIV.

For the PLIF measurements additional liners were made to remove liner fluorescence. A separate liner was made for each case of interest, with the liner cut such that it ended at the measurement plane. This made any flow downstream of the measurement plane essentially uncontained as the liner was effectively shortened. For the lowest measurement planes no liner was used at all as the measurement plane was the end of the quarl. Additionally the liner and quarl edges were painted in a flat black to reduce any light reflection. An example of the modified exhaust liners are shown in Appendix B-11.

Appendix B-11: Acrylic liners for PLIF measurements

For the PIV measurements a liner was made which contained two slots along its length. These slots were opposite each other, and allowed the laser sheet to travel through. These slots were covered with thin plastic wrap. The goal being that the thin flat surface greatly reduced light scatter, and reduced light traveling through the liner walls, which greatly contaminated any images. Also one half of the liner (far side from the camera) was painted a flat black to reduce internal light scatter, and external light entering the liner. This liner is shown in Appendix B-12.

Appendix B-12: Slotted acrylic liner for PIV measurements

B.8 Experimental Protocols

This study spanned March 2009 to November 2010. Extractive probe measurements were taken over the entirety of this time span, PLIF images were obtained in August 2010, and PIV images were obtained in August to September 2010.

B.9 Quality Control

B.9.1 Fuel and Air Flows

Each fuel and air delivery circuit was calibrated for this testing. With each systems calibration verified with multiple approaches. Typically this involved the standard calibration chart or table, followed by simultaneous measurements by a laminar flow element as well as with a coriolis flow meter (Micro Motions, CMF010).

At the beginning of any testing each flow rate was initially set at the desire value. During testing the values were checked consistently to ensure no fluctuation or drift occurred during testing.

B.9.2 Equipment Spanning

Spanning was critical for all of the extractive probe measurement techniques. For both the FID and Hydrogen analyzer a number of span bottles were used. These gases were produced and measured accurately by the supplier. Multiple bottles were used for each test, with one being used to set the full range, and at least one being used to verify it was measuring properly.

The GC was spanned differently. Initially span bottles were used, but with the wide range of concentration values present, eventually spanning was performed through the use of the fuel circuit, and spanning mixtures were generated. During GC operation a three point calibration was employed for each gas species being measured, as a minimum, and a five point calibration being common. Span gas bottles were used to both verify the performance of the fuel circuit in generating a desired concentration, as well as to double check multi point calibration performance.

B.9.3 Flux balances

Balances were checked in a number of ways. A simple way was to just measure the concentration in an exhaust section (assuming good mixing), to verify that the overall mole fraction agreed well with overall fuel concentration based on the air and fuel streams. This was

found to in general have good agreement. Additionally the volume flux was checked at the upper plane for both a methane and hydrogen case to verify the performance of the measurement technique. By taking the velocity and the area, the total volume flux was found, and by using mole fraction, this was adjusted to fuel flux rate, and compared to the desired input fuel flux. Using curve fits to define the values of functions of radius, and performing integrations to obtain the average velocity and concentration, it was found that the volume flux was within 10% of the ideal gas volume flow rate. As a rough estimate of this flux this showed a good agreement with the desired value. Additionally work alongside another student performing CFD simulations showed good agreement, particularly for non-swirling flows, leading credence to both the measurement and delivery system performance.

B.9.4 Testing Repeatability

The repeatability of the testing was investigated in a number of ways. One such way was that at the end of any test, measurements were repeated from previous in the test. This ensured that the readings did not change over time, which would suggest measurement drift.

Other issues for repeatability focused on measuring the same area if the flow was stopped or changed. It was shown that the flows could be altered or shut off completely, and then brought back to test conditions, and the results would be unchanged. This held on the same day, as well as over gaps multiple days (though equipment often was spanned on a daily basis).

The repeatability held both in regards to time, but also position. Often the equipment would need to be changed, and this required a realignment of the measurement probe. This realignment produced no difference in measurements at a repeated point.

B.9.5 Extractive Probe Testing

For each plane measured a number of points were measured over an extended period of time. At the end of each test a number of random points, typically near the center and near the initial point, were retested. The idea behind the tests was to ensure the measurements were repeatable and no drift occurred in the measurement equipment. Measurements were always found to be the same.

Each measurement also had a form of quality control for concern of settling time. In the case of the FID and hydrogen analyzer this involved a waiting period (for settling), followed by

averaging the measurement over a period of time. If the measurement was still changing at the end of the measurement, the measurement was repeated to ensure the proper point value. For the GC measurements, at least two measurements were taken at each point. If these numbers did not agree a third measurement was taken. This was used to ensure the flow had been given proper time to settle and account for the length of tubing between the probe and measurement hardware.

B.9.6 Extractive Probe Isokinetics

The influence of the pump was also investigated. It was found that altering the pump flow speed produced minimal changes in the readings, and at worst altered the settling times, particularly if the flow was choked. Through an accident it was found that the GC could obtain measurements without the operation of the vacuum pump, and that these results were the same as when the pump was on, though the settling time was also observed to be quite long. This was found as for one test the pump was turned off between spanning and testing, and never turned back on. As the flow had been on for an extended period of time in a single location, the initial reading was fine, but moving the probe had minimal change. Realizing the pump was not running the test was restarted from the beginning, but the initial reading was relatively unchanged (<3% change).

B.9.7 Pitot-Static Probe

Some fluctuations were noted in the Pitot-static probe measurements over time. Typically the fluctuations had a large time scale but small amplitude. To counter their issue measurements were taken at fixed time intervals over an extended period of time to elimination any bias due to a fluctuation.

B.9.8 PIV

Most effort in PIV was directed at removing all light scatter and contamination. This included both light visible through visual inspect, and by checking the quality of the cross correlation through small scale imaging prior to a full test. Prior to any full test a minimum of fifty image pairs was taken to verify the quality of the correlation and images being taken.

Also as the air flow was now separated into two streams this impact was investigated. Testing showed that the orientation of the seeder ports had no impact on the velocity field. The second stream was also monitored in the same way as the primary flow.

B.9.9 PLIF

Throughout imaging of any condition all flow rates and temperatures were monitored to ensure they were consistent. Values had to be the same at the beginning and end of the imaging for the images to be saved, else imaging was restarted. Additionally for the lasers employed time was given for full thermal stabilization before imaging was carried out, to minimize the shot to shot variability.

B.10 Error Analysis

B.10.1 Flow Uncertainty

Each individual flow was verified for accuracy through a number of techniques, but priority was given to the use of a coriolis flow meter, which had an uncertainty of 0.5% for gases. Assuming a worst case scenario of 1% error per flow, and with the maximum number of flows being 3 individual streams, flow uncertainty would <2%, with <1% being within reason.

This flow uncertainty is also important as the fuel circuit was used for the generation of span gases for the gas chromatograph. The low error of the flow is supported by the comparison of measurements of mixtures that were generated to those from span bottles, which showed very good agreement.

B.10.2 Fuel Concentration Measurement Uncertainty

The flame ionization detector has a measurement uncertainty of $\pm 1\%$ of full scale. The two ranges employed in its operation were 0-3.33% and 0-10.0%, giving uncertainties of $\pm 0.033\%$ and $\pm 0.100\%$ respectively. It is worth noting that the FID can measure up to double its range, making the effect range of measurements 0-6.66% and 0-20.0%. The smallest range possible was always employed. This means that the FID uncertainty is inversely related to the measured value, with the greatest uncertainty for low concentrations. Using the instrument error, combined with the flow error (assuming 2 streams, 1% uncertainty each), the overall FID uncertainty would be approximately <2% for 100-200% of the range, <2.5% for the 50%-100%, <4% for the 25-50% range, <10% for the 10-25% range. These numbers are as a percent of the measurement itself, so as the measurement uncertainty percentage increases for low range, the overall change in the value itself is limited.

Measurements with the hydrogen analyzer have an error of 1% of full scale, which corresponds to either $\pm 1\%$ for the 0-100 setting, or $\pm 0.5\%$ for the 0-50% setting. Typically this device was operated in the 0-50% range. Similarly to the FID instrument this lead to a measurement uncertainty which was $<2.5\%$ for the 50-100% portion of range, $<5\%$ for the 25-50% of range, and $<11\%$ for the 10-25% of range. The issue with the hydrogen analyzer is that smallest range being 0-50%, many of the results were well within the low ranges of operation, leading to high uncertainty. This was one of the reasons why the hydrogen analyzer data was verified by the use of the GC, and its operation limited in its scope.

The gas chromatograph has an instrument error from two sources, one being the instrument measurement itself, and the other being spanning error. If the span error is considered the flow error, and at any time at most two streams were used at a time in spanning, the flow error is $<2\%$. The instrument error itself is 1% of the measurement. Including the flow error of the case itself, this gives an overall uncertainty of $<2.5\%$ (including instrument error, flow error of 3 streams, and span error of 2 streams). This uncertainty is unchanged over the whole range. This lower uncertainty over the whole range, combined with the GC being capable of measuring hydrogen and methane simultaneously, is why the GC was used for the vast majority of all measurements.

The PLIF technique is at best a qualitative technique. This is due to the reliance on the data all being normalized to a reference value. In our case this reference value was the concentration at the highest laser peak, and images from a known flow. As before the flow has the uncertainty associated with the flow. This involved the bulk air stream, the methane stream, and the acetone stream. The air and methane stream are the same as mentioned earlier, $<1\%$. The acetone was controlled through a rotameter, which is approximately 3% based on its calibration. This gives the acetone injection a relative uncertainty of roughly 3.5%. Additionally there is the error associated with the laser power variation. For the operating conditions specified, the laser power has an uncertainty of 10%. This is the major reason for the averaging of images. These two factors alone, even with averaging, could still easily impose a measurement uncertainty of 7.5%. Additionally based on the images gathered and the data taken from them, light contamination appears to be an issue, particularly from the centerbody. As the light source of the contamination is the PLIF emission itself reflecting off the metal surfaces (light is essentially counted more than once), this also increases measurement uncertainty. Would say overall this method has an uncertainty in the range of roughly 10-15%.

With better performance for the axial injection as the fuel fluorescence emission occurs further from the metal surfaces due to the injection point being located at the top of the quarl, opposed to 25.4 mm upstream.

B.10.3 Velocity Uncertainty

The Pitot-static probes major sources of uncertainty come in the pressure reading (3% of gauge reading), and by its width. The Pitot-static probe essentially averages the static pressure of its eight ports. Combining just the error in flows with the gauge error gives a <4% measurement uncertainty, but this has no inclusion on the width of the probe. Overall worst case scenario measurement uncertainty is <10%.

The particle image velocimetry method has a number of possible sources of error. Major sources of measurement error include the displacement and magnification, and timing uncertainty. The minimum timing used for the PIV measurements was 27 μ s (27000 ns). With the laser jitter being ± 1 ns and the timing unit jitter being a maximum of ± 1 ns between signals. This gives a timing uncertainty of <0.004% for each laser, and the timing unit. This gives a total timing uncertainty of <0.006%. The displacement error is a result of the distance calibration, and is roughly 0.5%. Combining all of these measurement uncertainties, along with the uncertainties of the flow itself, the overall uncertainty for the PIV data are <2%.

B.11 Availability of Data

Hill, S., (2011). "Experimental Studies of Hydrogen-Air Mixing Processes." M.S. thesis, University of California, Irvine.

B.12 References

Faeth, G., and Samuelson, G., (1986). "Fast Reaction Nonpremixed Combustion." *Progress in Energy and Combustion Science* 12, 1986. Pages 305-372.

B.13 Data

The data collected are presented here in table and image format. Each section of data includes information on the hardware configuration employed.

Pitot-static velocity, plenum total pressure, and fuel pressure drop data are presented in B.13.1. Information related to the hardware configuration for each measurement is included with the data.

For each case studied (1-10) both spatial fuel concentration as well as the 2D velocity components (V_x : tangential and V_z : axial) are presented at a number of planes downstream of fuel injection. The velocity is extracted from the PIV data. These data are presented in sections B.13.2 to B.13.11.

Additionally images are presented for both the PLIF and PIV measurements. The PLIF data are presented as images of the averaged light emission, while the PIV data are presented as an image of the 2D velocity field for the entirety of the visible liner for the cases 1-10. Images have been through post processing.

B.13.1 Initial velocity field and pressure data

B.13.1.1 Pitot-Static Velocity Data

Table B-3: Pitot-Static velocity data. Hardware Configuration A

Hardware Configuration: A Bulk Flow Type: Air Bulk Flow Rate: 1.116 kg/min				Measurement Technique: Pitot-Static Probe Fuel Type: None Fuel Flow Rate: n/a				
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Temperature [K]	Density [kg/m ³]	Delta P average [Pa]	Velocity [m/s]	Error [m/s]
0.0000	0.0000	25.4000	0.0000	294.37	1.202	0.000	0.000	0.000
10.0330	0.0000	25.4000	10.0330	293.82	1.200	11.339	4.345	0.687
16.4465	0.0000	25.4000	16.4465	292.09	1.193	28.503	6.910	1.093
22.4536	0.0000	25.4000	22.4536	291.76	1.191	30.801	7.187	1.136
26.5811	0.0000	25.4000	26.5811	292.21	1.193	20.258	5.824	0.921
29.7180	0.0000	25.4000	29.7180	292.04	1.192	12.445	4.566	0.722
-10.0330	0.0000	25.4000	10.0330	291.48	1.190	7.605	3.573	0.565
-16.4465	0.0000	25.4000	16.4465	291.54	1.190	28.468	6.912	1.093
-22.4536	0.0000	25.4000	22.4536	291.65	1.191	31.769	8.940	1.413
-26.5811	0.0000	25.4000	26.5811	291.54	1.190	21.468	6.002	0.949
-29.7180	0.0000	25.4000	29.7180	291.54	1.190	12.566	4.592	0.726
0.0000	10.0330	25.4000	10.0330	291.48	1.190	9.697	4.034	0.638
0.0000	16.4465	25.4000	16.4465	291.54	1.190	28.191	6.878	1.088
0.0000	22.4536	25.4000	22.4536	291.59	1.191	32.530	7.388	1.168
0.0000	26.5811	25.4000	26.5811	291.54	1.190	23.162	6.235	0.986
0.0000	29.7180	25.4000	29.7180	291.59	1.191	12.376	4.557	0.721
0.0000	-10.0330	25.4000	10.0330	291.48	1.190	7.363	3.516	0.556
0.0000	-16.4465	25.4000	16.4465	291.71	1.191	27.517	6.794	1.074
0.0000	-22.4536	25.4000	22.4536	291.87	1.192	32.443	7.375	1.166
0.0000	-26.5811	25.4000	26.5811	291.71	1.191	23.766	6.314	0.998
0.0000	-29.7180	25.4000	29.7180	291.93	1.192	13.309	4.723	0.747
-6.3500	-19.0500	25.4000	20.0805	291.98	1.192	30.335	7.130	1.127
19.0500	6.3500	25.4000	20.0805	291.93	1.192	30.508	7.151	1.131
-19.0500	12.7000	25.4000	22.8953	291.71	1.191	33.757	7.525	1.190
16.5100	-19.0500	25.4000	25.2088	291.93	1.192	26.325	6.642	1.050
7.6200	0.0000	25.4000	7.6200	291.98	1.192	1.556	1.615	0.255
12.7000	0.0000	25.4000	12.7000	291.93	1.192	21.969	6.068	0.959

-8.2550	0.0000	25.4000	8.2550	291.82	1.191	0.242	0.637	0.101
-12.7000	0.0000	25.4000	12.7000	291.93	1.192	17.423	5.404	0.854
0.0000	7.6200	25.4000	7.6200	291.93	1.192	1.642	1.659	0.262
0.0000	12.7000	25.4000	12.7000	291.93	1.192	20.413	5.849	0.925
0.0000	-8.3185	25.4000	8.3185	291.98	1.192	0.449	0.868	0.137
0.0000	-12.7000	25.4000	12.7000	291.98	1.192	15.625	5.117	0.809
6.3500	0.0000	25.4000	6.3500	292.59	1.195	0.000	0.000	0.000
-6.3500	0.0000	25.4000	6.3500	292.59	1.195	0.000	0.000	0.000
0.0000	6.3500	25.4000	6.3500	292.59	1.195	0.000	0.000	0.000
0.0000	-6.3500	25.4000	6.3500	292.59	1.195	0.000	0.000	0.000
0.0000	0.0000	76.2000	0.0000	292.15	1.193	9.641	4.019	0.635
12.4460	0.0000	76.2000	12.4460	292.32	1.193	22.219	6.100	0.964
21.8440	0.0000	76.2000	21.8440	292.54	1.194	22.703	6.163	0.974
27.9400	0.0000	76.2000	27.9400	292.43	1.194	6.583	3.319	0.525
33.2740	0.0000	76.2000	33.2740	292.65	1.195	0.622	1.020	0.161
37.2110	0.0000	76.2000	37.2110	292.71	1.195	0.000	0.000	0.000
-12.4460	0.0000	76.2000	12.4460	292.21	1.193	20.336	5.836	0.923
-21.8440	0.0000	76.2000	21.8440	292.15	1.193	27.368	6.771	1.071
-27.9400	0.0000	76.2000	27.9400	292.21	1.193	11.196	4.331	0.685
-33.2740	0.0000	76.2000	33.2740	292.21	1.193	1.607	1.641	0.259
-37.2110	0.0000	76.2000	37.2110	292.15	1.193	0.000	0.000	0.000
0.0000	12.4460	76.2000	12.4460	292.65	1.195	22.064	6.075	0.960
0.0000	21.8440	76.2000	21.8440	292.71	1.195	27.005	6.720	1.063
0.0000	27.9400	76.2000	27.9400	292.54	1.194	10.436	4.179	0.661
0.0000	33.2740	76.2000	33.2740	292.71	1.195	1.244	1.442	0.228
0.0000	37.2110	76.2000	37.2110	292.71	1.195	0.000	0.000	0.000
0.0000	-12.4460	76.2000	12.4460	292.65	1.195	17.658	5.434	0.859
0.0000	-21.8440	76.2000	21.8440	292.71	1.195	27.783	6.816	1.078
0.0000	-27.9400	76.2000	27.9400	292.71	1.195	13.632	4.775	0.755
0.0000	-33.2740	76.2000	33.2740	292.76	1.195	2.367	1.989	0.315
0.0000	-37.2110	76.2000	37.2110	292.76	1.195	0.000	0.000	0.000
-8.8900	-19.9517	76.2000	21.8427	292.76	1.195	22.530	6.137	0.970
19.9517	8.8900	76.2000	21.8427	292.82	1.195	25.191	6.489	1.026
19.0500	-27.2796	76.2000	33.2728	292.87	1.196	1.728	1.699	0.269
-20.4343	19.0500	76.2000	27.9368	292.93	1.196	9.002	3.878	0.613
6.3500	0.0000	76.2000	6.3500	292.93	1.196	14.928	4.994	0.790
-6.3500	0.0000	76.2000	6.3500	292.93	1.196	13.218	4.700	0.743
0.0000	6.3500	76.2000	6.3500	292.98	1.196	14.410	4.906	0.776
0.0000	-6.3500	76.2000	6.3500	292.98	1.196	12.388	4.549	0.719
0.0000	0.0000	76.2000	0.0000	295.04	1.205	11.628	4.392	0.694
0.0000	12.4460	76.2000	12.4460	294.59	1.203	14.617	4.928	0.779
0.0000	21.8440	76.2000	21.8440	294.21	1.201	17.883	5.454	0.862
0.0000	27.9400	76.2000	27.9400	293.98	1.200	11.041	4.287	0.678
0.0000	33.2740	76.2000	33.2740	293.93	1.200	4.751	2.813	0.445
0.0000	37.5920	76.2000	37.5920	293.59	1.199	1.987	1.820	0.288
0.0000	-12.4460	76.2000	12.4460	293.71	1.199	17.623	5.419	0.857
0.0000	-21.8440	76.2000	21.8440	293.71	1.199	19.420	5.689	0.900
0.0000	-27.9400	76.2000	27.9400	293.48	1.198	10.315	4.148	0.656
0.0000	-33.2740	76.2000	33.2740	293.43	1.198	3.922	2.558	0.404
0.0000	-37.5920	76.2000	37.5920	293.48	1.198	1.866	1.764	0.279
12.4460	0.0000	76.2000	12.4460	293.48	1.198	17.779	5.445	0.861
21.8440	0.0000	76.2000	21.8440	293.48	1.198	15.636	5.107	0.807
27.9400	0.0000	76.2000	27.9400	293.48	1.198	8.449	3.754	0.594
33.2740	0.0000	76.2000	33.2740	293.48	1.198	2.730	2.134	0.337
36.8300	0.0000	76.2000	36.8300	293.43	1.198	1.175	1.400	0.221
-12.4460	0.0000	76.2000	12.4460	293.43	1.198	17.226	5.360	0.848
-21.8440	0.0000	76.2000	21.8440	293.43	1.198	18.349	5.532	0.875
-27.9400	0.0000	76.2000	27.9400	293.43	1.198	8.397	3.743	0.592
-33.2740	0.0000	76.2000	33.2740	293.43	1.198	2.868	2.187	0.346
-37.2110	0.0000	76.2000	37.2110	293.37	1.198	1.209	1.421	0.225
-8.8900	-19.9517	76.2000	21.8427	293.37	1.198	18.090	5.494	0.869
19.9517	8.8900	76.2000	21.8427	293.43	1.198	18.038	5.485	0.867
-27.2796	19.0500	76.2000	33.2728	293.48	1.198	4.682	2.794	0.442
-20.4343	19.0500	76.2000	27.9368	293.43	1.198	10.937	4.271	0.675

Table B-4: Pitot-Static velocity data. Hardware Configuration B

Hardware Configuration: B				Measurement Technique: Pitot-Static Probe				
Bulk Flow Type: Air				Fuel Type: None				
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: n/a				
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Temperature [K]	Density [kg/m ³]	Delta P average [Pa]	Velocity [m/s]	Error [m/s]
13.9700	0.0000	25.4000	13.9700	295.32	1.198	23.195	6.220	0.983
17.5260	0.0000	25.4000	17.5260	295.18	1.199	31.193	7.211	1.140
22.3520	0.0000	25.4000	22.3520	295.05	1.199	34.334	7.564	1.196
26.6700	0.0000	25.4000	26.6700	294.92	1.200	29.410	6.999	1.107
29.8450	0.0000	25.4000	29.8450	294.78	1.200	15.581	5.093	0.805

-13.9700	0.0000	25.4000	13.9700	294.65	1.201	22.506	6.120	0.968
-17.5260	0.0000	25.4000	17.5260	294.61	1.201	32.261	7.326	1.158
-22.3520	0.0000	25.4000	22.3520	294.56	1.201	35.247	7.657	1.211
-26.6700	0.0000	25.4000	26.6700	294.52	1.201	29.690	7.027	1.111
-29.8450	0.0000	25.4000	29.8450	294.47	1.202	15.115	5.014	0.793
0.0000	13.9700	25.4000	13.9700	294.43	1.202	22.091	6.061	0.958
0.0000	17.5260	25.4000	17.5260	294.29	1.202	34.640	7.588	1.200
0.0000	22.3520	25.4000	22.3520	294.16	1.203	36.335	7.769	1.228
0.0000	26.6700	25.4000	26.6700	294.03	1.203	28.415	6.869	1.086
0.0000	29.8450	25.4000	29.8450	293.89	1.204	12.761	4.602	0.728
0.0000	-13.9700	25.4000	13.9700	293.76	1.205	24.953	6.434	1.017
0.0000	-17.5260	25.4000	17.5260	293.69	1.205	34.044	7.515	1.188
0.0000	-22.3520	25.4000	22.3520	293.63	1.205	36.625	7.793	1.232
0.0000	-26.6700	25.4000	26.6700	293.56	1.205	30.945	7.163	1.133
0.0000	-29.8450	25.4000	29.8450	293.49	1.206	15.384	5.050	0.798
6.3500	21.4249	25.4000	22.3461	293.43	1.206	36.553	7.783	1.231
-21.4249	6.3500	25.4000	22.3461	293.47	1.206	36.377	7.765	1.228
-7.6200	-25.5524	25.4000	26.6644	293.55	1.205	28.384	6.860	1.085
23.4569	-12.7000	25.4000	26.6743	293.59	1.205	27.907	6.802	1.076
0.0000	0.0000	76.2000	0.0000	292.21	1.207	7.153	3.442	0.544
12.4460	0.0000	76.2000	12.4460	292.02	1.208	23.418	6.225	0.984
21.8440	0.0000	76.2000	21.8440	291.84	1.208	28.558	6.872	1.087
27.9400	0.0000	76.2000	27.9400	291.65	1.209	14.068	4.822	0.762
33.2740	0.0000	76.2000	33.2740	291.46	1.210	1.254	1.439	0.228
37.5920	0.0000	76.2000	37.5920	291.28	1.211	0.000	0.000	0.000
-12.4460	0.0000	76.2000	12.4460	291.09	1.211	22.402	6.079	0.961
-21.8440	0.0000	76.2000	21.8440	291.12	1.211	29.234	6.945	1.098
-27.9400	0.0000	76.2000	27.9400	291.14	1.211	12.875	4.609	0.729
-33.2740	0.0000	76.2000	33.2740	291.16	1.211	1.192	1.403	0.222
-37.5920	0.0000	76.2000	37.5920	291.18	1.211	0.000	0.000	0.000
0.0000	12.4460	76.2000	12.4460	291.21	1.211	24.486	6.357	1.005
0.0000	21.8440	76.2000	21.8440	291.35	1.210	29.317	6.957	1.100
0.0000	27.9400	76.2000	27.9400	291.49	1.210	13.352	4.696	0.743
0.0000	33.2740	76.2000	33.2740	291.64	1.209	1.887	1.766	0.279
0.0000	37.5920	76.2000	37.5920	291.78	1.209	0.000	0.000	0.000
0.0000	-12.4460	76.2000	12.4460	291.93	1.208	21.013	5.896	0.932
0.0000	-21.8440	76.2000	21.8440	291.99	1.208	31.059	7.169	1.134
0.0000	-27.9400	76.2000	27.9400	292.06	1.207	15.602	5.082	0.803
0.0000	-33.2740	76.2000	33.2740	292.13	1.207	1.731	1.693	0.268
0.0000	-37.5920	76.2000	37.5920	292.19	1.207	0.000	0.000	0.000
-8.8900	-19.9517	76.2000	21.8427	292.26	1.207	31.038	7.170	1.134
19.9517	8.8900	76.2000	21.8427	292.14	1.207	30.789	7.139	1.129
-19.0500	27.2796	76.2000	33.2728	291.89	1.208	1.037	1.309	0.207
20.4343	-19.0500	76.2000	27.9368	291.76	1.209	14.548	4.904	0.775
0.0000	0.0000	152.4000	0.0000	290.43	1.214	11.196	4.293	0.679
0.0000	12.4460	152.4000	12.4460	290.50	1.214	17.692	5.397	0.853
0.0000	21.8440	152.4000	21.8440	290.58	1.214	25.917	6.533	1.033
0.0000	27.9400	152.4000	27.9400	290.65	1.213	9.330	3.920	0.620
0.0000	33.2740	152.4000	33.2740	290.72	1.213	2.747	2.127	0.336
0.0000	37.5920	152.4000	37.5920	290.80	1.213	0.363	0.773	0.122
0.0000	-12.4460	152.4000	12.4460	290.87	1.212	14.721	4.926	0.779
0.0000	-21.8440	152.4000	21.8440	290.98	1.212	21.079	5.896	0.932
0.0000	-27.9400	152.4000	27.9400	291.09	1.211	11.369	4.331	0.685
0.0000	-33.2740	152.4000	33.2740	291.21	1.211	3.386	2.364	0.374
0.0000	-37.5920	152.4000	37.5920	291.32	1.210	0.726	1.095	0.173
12.4460	0.0000	152.4000	12.4460	293.48	1.202	18.453	5.540	0.876
21.8440	0.0000	152.4000	21.8440	293.32	1.202	25.191	6.471	1.023
27.9400	0.0000	152.4000	27.9400	293.15	1.203	8.570	3.773	0.597
33.2740	0.0000	152.4000	33.2740	292.98	1.204	2.453	2.018	0.319
37.5920	0.0000	152.4000	37.5920	292.82	1.204	0.104	0.415	0.066
-12.4460	0.0000	152.4000	12.4460	292.65	1.205	16.742	5.269	0.833
-21.8440	0.0000	152.4000	21.8440	292.58	1.205	25.709	6.529	1.032
-27.9400	0.0000	152.4000	27.9400	292.52	1.206	7.931	3.626	0.573
-33.2740	0.0000	152.4000	33.2740	292.45	1.206	1.970	1.807	0.286
-37.5920	0.0000	152.4000	37.5920	292.38	1.206	0.138	0.479	0.076
-8.8900	-19.9517	152.4000	21.8427	292.32	1.206	21.649	5.989	0.947
19.9517	8.8900	152.4000	21.8427	292.22	1.207	21.148	5.918	0.936
-19.0500	27.2796	152.4000	33.2728	292.03	1.208	2.333	1.965	0.311
20.4343	-19.0500	152.4000	27.9368	291.93	1.208	10.885	4.244	0.671

B.13.1.2 Pressure Data

Table B-5: Air plenum total pressure

Hardware Configuration	Bulk Total Pressure [kPa]	Pressure above atmospheric [pa]
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A, B	101.698	373
C, D	102.042	717

Table B-6: Fuel pressure drop at injection

Case	Hardware Configuration	Fuel Pressure Drop [pa]
1	A	353.4
2		358.4
3		296.2
4	B	298.7

B.13.2 Case 1: Non-Swirling Axial Injection of Methane

Table B-7: Spatial fuel concentration data. Case 1

Hardware Configuration: A				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00108 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
0.0000	31.7500	25.4000	31.7500	0.000	0.00000
0.0000	26.4541	25.4000	26.4541	0.000	0.00000
0.0000	21.1709	25.4000	21.1709	0.000	0.00000
0.0000	15.8750	25.4000	15.8750	0.016	0.00016
0.0000	10.5791	25.4000	10.5791	2.111	0.02111
0.0000	5.2959	25.4000	5.2959	8.448	0.08448
0.0000	0.0000	25.4000	0.0000	12.966	0.12966
0.0000	-5.2959	25.4000	5.2959	10.616	0.10616
0.0000	-10.5791	25.4000	10.5791	4.136	0.04136
0.0000	-15.8750	25.4000	15.8750	0.077	0.00077
0.0000	-21.1709	25.4000	21.1709	0.000	0.00000
0.0000	-26.4541	25.4000	26.4541	0.000	0.00000
0.0000	-31.7500	25.4000	31.7500	0.000	0.00000
-5.2959	-26.4541	25.4000	26.9790	0.000	0.00000
-5.2959	-21.1709	25.4000	21.8232	0.000	0.00000
-5.2959	-15.8750	25.4000	16.7351	0.030	0.00030
-5.2959	-10.5791	25.4000	11.8306	2.527	0.02527
-5.2959	-5.2959	25.4000	7.4895	8.390	0.08390
-5.2959	0.0000	25.4000	5.2959	10.029	0.10029
-5.2959	5.2959	25.4000	7.4895	7.020	0.07020
-5.2959	10.5791	25.4000	11.8306	1.470	0.01470
-5.2959	15.8750	25.4000	16.7351	0.000	0.00000
-5.2959	21.1709	25.4000	21.8232	0.000	0.00000
-5.2959	26.4541	25.4000	26.9790	0.000	0.00000
-10.5791	26.4541	25.4000	28.4910	0.000	0.00000
-10.5791	21.1709	25.4000	23.6669	0.000	0.00000
-10.5791	15.8750	25.4000	19.0770	0.000	0.00000
-10.5791	10.5791	25.4000	14.9611	0.163	0.00163
-10.5791	5.2959	25.4000	11.8306	1.898	0.01898
-10.5791	0.0000	25.4000	10.5791	4.234	0.04234
-10.5791	-5.2959	25.4000	11.8306	2.405	0.02405
-10.5791	-10.5791	25.4000	14.9611	0.282	0.00282
-10.5791	-15.8750	25.4000	19.0770	0.000	0.00000
-10.5791	-21.1709	25.4000	23.6669	0.000	0.00000
-10.5791	-26.4541	25.4000	28.4910	0.000	0.00000
-15.8750	-26.4541	25.4000	30.8518	0.000	0.00000
-15.8750	-21.1709	25.4000	26.4617	0.000	0.00000
-15.8750	-15.8750	25.4000	22.4506	0.000	0.00000
-15.8750	-10.5791	25.4000	19.0770	0.000	0.00000
-15.8750	-5.2959	25.4000	16.7351	0.040	0.00040
-15.8750	0.0000	25.4000	15.8750	0.141	0.00141
-15.8750	5.2959	25.4000	16.7351	0.017	0.00017
-15.8750	10.5791	25.4000	19.0770	0.000	0.00000
-15.8750	15.8750	25.4000	22.4506	0.000	0.00000
-15.8750	21.1709	25.4000	26.4617	0.000	0.00000
-15.8750	26.4541	25.4000	30.8518	0.000	0.00000
-21.1709	21.1709	25.4000	29.9402	0.000	0.00000
-21.1709	15.8750	25.4000	26.4617	0.000	0.00000
-21.1709	10.5791	25.4000	23.6669	0.000	0.00000
-21.1709	5.2959	25.4000	21.8232	0.000	0.00000
-21.1709	0.0000	25.4000	21.1709	0.000	0.00000
-21.1709	-5.2959	25.4000	21.8232	0.000	0.00000

-21.1709	-10.5791	25.4000	23.6669	0.000	0.00000
-21.1709	-15.8750	25.4000	26.4617	0.000	0.00000
-21.1709	-21.1709	25.4000	29.9402	0.000	0.00000
-26.4541	-15.8750	25.4000	30.8518	0.000	0.00000
-26.4541	-10.5791	25.4000	28.4910	0.000	0.00000
-26.4541	-5.2959	25.4000	26.9790	0.000	0.00000
-26.4541	0.0000	25.4000	26.4541	0.000	0.00000
-26.4541	5.2959	25.4000	26.9790	0.000	0.00000
-26.4541	10.5791	25.4000	28.4910	0.000	0.00000
-26.4541	15.8750	25.4000	30.8518	0.000	0.00000
-31.7500	0.0000	25.4000	31.7500	0.000	0.00000
0.0000	7.9502	25.4000	7.9502	5.949	0.05949
0.0000	2.6543	25.4000	2.6543	11.870	0.11870
0.0000	-2.6543	25.4000	2.6543	13.204	0.13204
0.0000	-7.9502	25.4000	7.9502	7.312	0.07312
-2.6543	-10.5791	25.4000	10.9070	2.983	0.02983
-2.6543	-7.9502	25.4000	8.3816	7.110	0.07110
-2.6543	-5.2959	25.4000	5.9238	9.912	0.09912
-2.6543	-2.6543	25.4000	3.7537	12.548	0.12548
-2.6543	0.0000	25.4000	2.6543	12.796	0.12796
-2.6543	2.6543	25.4000	3.7537	11.084	0.11084
-2.6543	5.2959	25.4000	5.9238	8.591	0.08591
-2.6543	7.9502	25.4000	8.3816	5.568	0.05568
-2.6543	10.5791	25.4000	10.9070	2.211	0.02211
-5.2959	7.9502	25.4000	9.5526	4.176	0.04176
-5.2959	2.6543	25.4000	5.9238	9.048	0.09048
-5.2959	-2.6543	25.4000	5.9238	9.935	0.09935
-5.2959	-7.9502	25.4000	9.5526	5.659	0.05659
-7.9502	-7.9502	25.4000	11.2433	3.102	0.03102
-7.9502	-5.2959	25.4000	9.5526	5.566	0.05566
-7.9502	-2.6543	25.4000	8.3816	7.125	0.07125
-7.9502	0.0000	25.4000	7.9502	7.341	0.07341
-7.9502	2.6543	25.4000	8.3816	6.513	0.06513
-7.9502	5.2959	25.4000	9.5526	4.704	0.04704
-7.9502	7.9502	25.4000	11.2433	2.281	0.02281
-10.5791	2.6543	25.4000	10.9070	3.259	0.03259
-10.5791	-2.6543	25.4000	10.9070	3.723	0.03723
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
0.0000	37.0459	76.2000	37.0459	0.000	0.00000
0.0000	31.7500	76.2000	31.7500	0.000	0.00000
0.0000	26.4541	76.2000	26.4541	0.000	0.00000
0.0000	21.1709	76.2000	21.1709	0.000	0.00000
0.0000	15.8750	76.2000	15.8750	0.118	0.00118
0.0000	10.5791	76.2000	10.5791	0.714	0.00714
0.0000	5.2959	76.2000	5.2959	1.511	0.01511
0.0000	0.0000	76.2000	0.0000	1.922	0.01922
0.0000	-5.2959	76.2000	5.2959	1.709	0.01709
0.0000	-10.5791	76.2000	10.5791	0.930	0.00930
0.0000	-15.8750	76.2000	15.8750	0.208	0.00208
0.0000	-21.1709	76.2000	21.1709	0.000	0.00000
0.0000	-26.4541	76.2000	26.4541	0.000	0.00000
0.0000	-31.7500	76.2000	31.7500	0.000	0.00000
0.0000	-37.0459	76.2000	37.0459	0.000	0.00000
-5.2959	-37.0459	76.2000	37.4225	0.000	0.00000
-5.2959	-31.7500	76.2000	32.1886	0.000	0.00000
-5.2959	-26.4541	76.2000	26.9790	0.000	0.00000
-5.2959	-21.1709	76.2000	21.8232	0.000	0.00000
-5.2959	-15.8750	76.2000	16.7351	0.167	0.00167
-5.2959	-10.5791	76.2000	11.8306	0.805	0.00805
-5.2959	-5.2959	76.2000	7.4895	1.483	0.01483
-5.2959	0.0000	76.2000	5.2959	1.679	0.01679
-5.2959	5.2959	76.2000	7.4895	1.321	0.01321
-5.2959	10.5791	76.2000	11.8306	0.626	0.00626
-5.2959	15.8750	76.2000	16.7351	0.096	0.00096
-5.2959	21.1709	76.2000	21.8232	0.000	0.00000
-5.2959	26.4541	76.2000	26.9790	0.000	0.00000
-5.2959	31.7500	76.2000	32.1886	0.000	0.00000
-5.2959	37.0459	76.2000	37.4225	0.000	0.00000
-10.5791	37.0459	76.2000	38.5268	0.000	0.00000
-10.5791	31.7500	76.2000	33.4661	0.000	0.00000
-10.5791	26.4541	76.2000	28.4910	0.000	0.00000
-10.5791	21.1709	76.2000	23.6669	0.000	0.00000
-10.5791	15.8750	76.2000	19.0770	0.018	0.00018
-10.5791	10.5791	76.2000	14.9611	0.225	0.00225
-10.5791	5.2959	76.2000	11.8306	0.578	0.00578
-10.5791	0.0000	76.2000	10.5791	0.929	0.00929
-10.5791	-5.2959	76.2000	11.8306	0.752	0.00752
-10.5791	-10.5791	76.2000	14.9611	0.291	0.00291
-10.5791	-15.8750	76.2000	19.0770	0.033	0.00033

-10.5791	-21.1709	76.2000	23.6669	0.000	0.00000
-10.5791	-26.4541	76.2000	28.4910	0.000	0.00000
-10.5791	-31.7500	76.2000	33.4661	0.000	0.00000
-10.5791	-37.0459	76.2000	38.5268	0.000	0.00000
-15.8750	-31.7500	76.2000	35.4976	0.000	0.00000
-15.8750	-26.4541	76.2000	30.8518	0.000	0.00000
-15.8750	-21.1709	76.2000	26.4617	0.000	0.00000
-15.8750	-15.8750	76.2000	22.4506	0.000	0.00000
-15.8750	-10.5791	76.2000	19.0770	0.024	0.00024
-15.8750	-5.2959	76.2000	16.7351	0.143	0.00143
-15.8750	0.0000	76.2000	15.8750	0.217	0.00217
-15.8750	5.2959	76.2000	16.7351	0.096	0.00096
-15.8750	10.5791	76.2000	19.0770	0.013	0.00013
-15.8750	15.8750	76.2000	22.4506	0.000	0.00000
-15.8750	21.1709	76.2000	26.4617	0.000	0.00000
-15.8750	26.4541	76.2000	30.8518	0.000	0.00000
-15.8750	31.7500	76.2000	35.4976	0.000	0.00000
-21.1709	31.7500	76.2000	38.1611	0.000	0.00000
-21.1709	26.4541	76.2000	33.8825	0.000	0.00000
-21.1709	21.1709	76.2000	29.9402	0.000	0.00000
-21.1709	15.8750	76.2000	26.4617	0.000	0.00000
-21.1709	10.5791	76.2000	23.6669	0.000	0.00000
-21.1709	5.2959	76.2000	21.8232	0.000	0.00000
-21.1709	0.0000	76.2000	21.1709	0.000	0.00000
-21.1709	-5.2959	76.2000	21.8232	0.000	0.00000
-21.1709	-10.5791	76.2000	23.6669	0.000	0.00000
-21.1709	-15.8750	76.2000	26.4617	0.000	0.00000
-21.1709	-21.1709	76.2000	29.9402	0.000	0.00000
-21.1709	-26.4541	76.2000	33.8825	0.000	0.00000
-21.1709	-31.7500	76.2000	38.1611	0.000	0.00000
-26.4541	-26.4541	76.2000	37.4117	0.000	0.00000
-26.4541	-21.1709	76.2000	33.8825	0.000	0.00000
-26.4541	-15.8750	76.2000	30.8518	0.000	0.00000
-26.4541	-10.5791	76.2000	28.4910	0.000	0.00000
-26.4541	-5.2959	76.2000	26.9790	0.000	0.00000
-26.4541	0.0000	76.2000	26.4541	0.000	0.00000
-26.4541	5.2959	76.2000	26.9790	0.000	0.00000
-26.4541	10.5791	76.2000	28.4910	0.000	0.00000
-26.4541	15.8750	76.2000	30.8518	0.000	0.00000
-26.4541	21.1709	76.2000	33.8825	0.000	0.00000
-26.4541	26.4541	76.2000	37.4117	0.000	0.00000
-31.7500	21.1709	76.2000	38.1611	0.000	0.00000
-31.7500	15.8750	76.2000	35.4976	0.000	0.00000
-31.7500	10.5791	76.2000	33.4661	0.000	0.00000
-31.7500	5.2959	76.2000	32.1886	0.000	0.00000
-31.7500	0.0000	76.2000	31.7500	0.000	0.00000
-31.7500	-5.2959	76.2000	32.1886	0.000	0.00000
-31.7500	-10.5791	76.2000	33.4661	0.000	0.00000
-31.7500	-15.8750	76.2000	35.4976	0.000	0.00000
-31.7500	-21.1709	76.2000	38.1611	0.000	0.00000
-37.0459	-10.5791	76.2000	38.5268	0.000	0.00000
-37.0459	-5.2959	76.2000	37.4225	0.000	0.00000
-37.0459	0.0000	76.2000	37.0459	0.000	0.00000
-37.0459	5.2959	76.2000	37.4225	0.000	0.00000
-37.0459	10.5791	76.2000	38.5268	0.000	0.00000
0.0000	7.9502	76.2000	7.9502	1.118	0.01118
0.0000	2.6543	76.2000	2.6543	1.786	0.01786
0.0000	-2.6543	76.2000	2.6543	1.911	0.01911
0.0000	-7.9502	76.2000	7.9502	1.370	0.01370
-2.6543	-10.5791	76.2000	10.9070	0.953	0.00953
-2.6543	-7.9502	76.2000	8.3816	1.360	0.01360
-2.6543	-5.2959	76.2000	5.9238	1.697	0.01697
-2.6543	-2.6543	76.2000	3.7537	1.869	0.01869
-2.6543	0.0000	76.2000	2.6543	1.910	0.01910
-2.6543	2.6543	76.2000	3.7537	1.762	0.01762
-2.6543	5.2959	76.2000	5.9238	1.495	0.01495
-2.6543	7.9502	76.2000	8.3816	1.131	0.01131
-2.6543	10.5791	76.2000	10.9070	0.750	0.00750
-5.2959	7.9502	76.2000	9.5526	0.970	0.00970
-5.2959	2.6543	76.2000	5.9238	1.538	0.01538
-5.2959	-2.6543	76.2000	5.9238	1.696	0.01696
-5.2959	-7.9502	76.2000	9.5526	1.155	0.01155
-7.9502	-7.9502	76.2000	11.2433	0.866	0.00866
-7.9502	-5.2959	76.2000	9.5526	1.149	0.01149
-7.9502	-2.6543	76.2000	8.3816	1.332	0.01332
-7.9502	0.0000	76.2000	7.9502	1.380	0.01380
-7.9502	2.6543	76.2000	8.3816	1.181	0.01181
-7.9502	5.2959	76.2000	9.5526	0.972	0.00972
-7.9502	7.9502	76.2000	11.2433	0.698	0.00698
-10.5791	2.6543	76.2000	10.9070	0.786	0.00786

-10.5791	-2.6543	76.2000	10.9070	0.923	0.00923
Plane: 152.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
0.0000	37.0459	25.4000	37.0459	0.000	0.00000
0.0000	31.7500	25.4000	31.7500	0.000	0.00000
0.0000	26.4541	25.4000	26.4541	0.000	0.00000
0.0000	21.1709	25.4000	21.1709	0.042	0.00042
0.0000	15.8750	25.4000	15.8750	0.212	0.00212
0.0000	10.5791	25.4000	10.5791	0.518	0.00518
0.0000	5.2959	25.4000	5.2959	0.764	0.00764
0.0000	0.0000	25.4000	0.0000	0.859	0.00859
0.0000	-5.2959	25.4000	5.2959	0.845	0.00845
0.0000	-10.5791	25.4000	10.5791	0.720	0.00720
0.0000	-15.8750	25.4000	15.8750	0.452	0.00452
0.0000	-21.1709	25.4000	21.1709	0.157	0.00157
0.0000	-26.4541	25.4000	26.4541	0.020	0.00020
0.0000	-31.7500	25.4000	31.7500	0.000	0.00000
0.0000	-37.0459	25.4000	37.0459	0.000	0.00000
-5.2959	-37.0459	25.4000	37.4225	0.000	0.00000
-5.2959	-31.7500	25.4000	32.1886	0.000	0.00000
-5.2959	-26.4541	25.4000	26.9790	0.020	0.00020
-5.2959	-21.1709	25.4000	21.8232	0.162	0.00162
-5.2959	-15.8750	25.4000	16.7351	0.468	0.00468
-5.2959	-10.5791	25.4000	11.8306	0.733	0.00733
-5.2959	-5.2959	25.4000	7.4895	0.899	0.00899
-5.2959	0.0000	25.4000	5.2959	0.895	0.00895
-5.2959	5.2959	25.4000	7.4895	0.763	0.00763
-5.2959	10.5791	25.4000	11.8306	0.523	0.00523
-5.2959	15.8750	25.4000	16.7351	0.243	0.00243
-5.2959	21.1709	25.4000	21.8232	0.052	0.00052
-5.2959	26.4541	25.4000	26.9790	0.008	0.00008
-5.2959	31.7500	25.4000	32.1886	0.000	0.00000
-5.2959	37.0459	25.4000	37.4225	0.000	0.00000
-10.5791	37.0459	25.4000	38.5268	0.000	0.00000
-10.5791	31.7500	25.4000	33.4661	0.000	0.00000
-10.5791	26.4541	25.4000	28.4910	0.000	0.00000
-10.5791	21.1709	25.4000	23.6669	0.040	0.00040
-10.5791	15.8750	25.4000	19.0770	0.157	0.00157
-10.5791	10.5791	25.4000	14.9611	0.381	0.00381
-10.5791	5.2959	25.4000	11.8306	0.596	0.00596
-10.5791	0.0000	25.4000	10.5791	0.738	0.00738
-10.5791	-5.2959	25.4000	11.8306	0.749	0.00749
-10.5791	-10.5791	25.4000	14.9611	0.581	0.00581
-10.5791	-15.8750	25.4000	19.0770	0.311	0.00311
-10.5791	-21.1709	25.4000	23.6669	0.088	0.00088
-10.5791	-26.4541	25.4000	28.4910	0.013	0.00013
-10.5791	-31.7500	25.4000	33.4661	0.000	0.00000
-10.5791	-37.0459	25.4000	38.5268	0.000	0.00000
-15.8750	-31.7500	25.4000	35.4976	0.000	0.00000
-15.8750	-26.4541	25.4000	30.8518	0.000	0.00000
-15.8750	-21.1709	25.4000	26.4617	0.028	0.00028
-15.8750	-15.8750	25.4000	22.4506	0.126	0.00126
-15.8750	-10.5791	25.4000	19.0770	0.305	0.00305
-15.8750	-5.2959	25.4000	16.7351	0.452	0.00452
-15.8750	0.0000	25.4000	15.8750	0.454	0.00454
-15.8750	5.2959	25.4000	16.7351	0.330	0.00330
-15.8750	10.5791	25.4000	19.0770	0.170	0.00170
-15.8750	15.8750	25.4000	22.4506	0.063	0.00063
-15.8750	21.1709	25.4000	26.4617	0.016	0.00016
-15.8750	26.4541	25.4000	30.8518	0.000	0.00000
-15.8750	31.7500	25.4000	35.4976	0.000	0.00000
-21.1709	31.7500	25.4000	38.1611	0.000	0.00000
-21.1709	26.4541	25.4000	33.8825	0.000	0.00000
-21.1709	21.1709	25.4000	29.9402	0.000	0.00000
-21.1709	15.8750	25.4000	26.4617	0.017	0.00017
-21.1709	10.5791	25.4000	23.6669	0.044	0.00044
-21.1709	5.2959	25.4000	21.8232	0.096	0.00096
-21.1709	0.0000	25.4000	21.1709	0.147	0.00147
-21.1709	-5.2959	25.4000	21.8232	0.139	0.00139
-21.1709	-10.5791	25.4000	23.6669	0.085	0.00085
-21.1709	-15.8750	25.4000	26.4617	0.029	0.00029
-21.1709	-21.1709	25.4000	29.9402	0.000	0.00000
-21.1709	-26.4541	25.4000	33.8825	0.000	0.00000
-21.1709	-31.7500	25.4000	38.1611	0.000	0.00000
-26.4541	-26.4541	25.4000	37.4117	0.000	0.00000
-26.4541	-21.1709	25.4000	33.8825	0.000	0.00000
-26.4541	-15.8750	25.4000	30.8518	0.000	0.00000
-26.4541	-10.5791	25.4000	28.4910	0.013	0.00013
-26.4541	-5.2959	25.4000	26.9790	0.021	0.00021
-26.4541	0.0000	25.4000	26.4541	0.023	0.00023

-26.4541	5.2959	25.4000	26.9790	0.015	0.00015
-26.4541	10.5791	25.4000	28.4910	0.000	0.00000
-26.4541	15.8750	25.4000	30.8518	0.000	0.00000
-26.4541	21.1709	25.4000	33.8825	0.000	0.00000
-26.4541	26.4541	25.4000	37.4117	0.000	0.00000
-31.7500	21.1709	25.4000	38.1611	0.000	0.00000
-31.7500	15.8750	25.4000	35.4976	0.000	0.00000
-31.7500	10.5791	25.4000	33.4661	0.000	0.00000
-31.7500	5.2959	25.4000	32.1886	0.000	0.00000
-31.7500	0.0000	25.4000	31.7500	0.000	0.00000
-31.7500	-5.2959	25.4000	32.1886	0.000	0.00000
-31.7500	-10.5791	25.4000	33.4661	0.000	0.00000
-31.7500	-15.8750	25.4000	35.4976	0.000	0.00000
-31.7500	-21.1709	25.4000	38.1611	0.000	0.00000
-37.0459	-10.5791	25.4000	38.5268	0.000	0.00000
-37.0459	-5.2959	25.4000	37.4225	0.000	0.00000
-37.0459	0.0000	25.4000	37.0459	0.000	0.00000
-37.0459	5.2959	25.4000	37.4225	0.000	0.00000
-37.0459	10.5791	25.4000	38.5268	0.000	0.00000
Case: Axial traverse data					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
0.0000	0.0000	6.3500	0.0000	28.304	0.28304
0.0000	0.0000	12.7000	0.0000	25.668	0.25668
0.0000	0.0000	19.0500	0.0000	21.841	0.21841
0.0000	0.0000	25.4000	0.0000	14.318	0.14318
0.0000	0.0000	31.7500	0.0000	8.774	0.08774
0.0000	0.0000	38.1000	0.0000	5.679	0.05679
0.0000	0.0000	44.4500	0.0000	4.179	0.04179
0.0000	0.0000	50.8000	0.0000	3.364	0.03364
0.0000	0.0000	57.1500	0.0000	2.788	0.02788
0.0000	0.0000	63.5000	0.0000	2.419	0.02419
0.0000	0.0000	69.8500	0.0000	2.154	0.02154
0.0000	0.0000	76.2000	0.0000	1.942	0.01942
0.0000	0.0000	82.5500	0.0000	1.765	0.01765
0.0000	0.0000	88.9000	0.0000	1.684	0.01684
0.0000	0.0000	95.2500	0.0000	1.505	0.01505
0.0000	0.0000	101.6000	0.0000	1.383	0.01383
0.0000	0.0000	107.9500	0.0000	1.326	0.01326
0.0000	0.0000	114.3000	0.0000	1.231	0.01231
0.0000	0.0000	120.6500	0.0000	1.140	0.01140
0.0000	0.0000	127.0000	0.0000	1.095	0.01095
0.0000	0.0000	133.3500	0.0000	1.034	0.01034
0.0000	0.0000	139.7000	0.0000	1.000	0.01000
0.0000	0.0000	146.0500	0.0000	0.952	0.00952
0.0000	0.0000	152.4000	0.0000	0.906	0.00906

Table B-8: Velocity field data. Case 1

Hardware Configuration: A				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00108 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-40.2759	0.0000	25.4853	40.2759	0.0366	-0.0803
-39.4479	0.0000	25.4853	39.4479	0.0354	-0.1550
-38.6200	0.0000	25.4853	38.6200	0.0844	-0.1267
-37.7920	0.0000	25.4853	37.7920	0.1132	-0.0497
-36.9641	0.0000	25.4853	36.9641	0.1386	-0.0153
-36.1361	0.0000	25.4853	36.1361	0.2014	-0.0437
-35.3082	0.0000	25.4853	35.3082	0.2551	-0.0841
-34.4802	0.0000	25.4853	34.4802	0.2822	-0.0640
-33.6523	0.0000	25.4853	33.6523	0.2667	-0.0035
-32.8243	0.0000	25.4853	32.8243	0.1925	0.0185
-31.9964	0.0000	25.4853	31.9964	0.0924	0.0747
-31.1684	0.0000	25.4853	31.1684	0.0812	0.3315
-30.3405	0.0000	25.4853	30.3405	0.1530	0.8730
-29.5125	0.0000	25.4853	29.5125	0.1874	1.7415
-28.6846	0.0000	25.4853	28.6846	0.2031	2.5021
-27.8566	0.0000	25.4853	27.8566	0.2269	3.0020
-27.0286	0.0000	25.4853	27.0286	0.2485	3.3814
-26.2007	0.0000	25.4853	26.2007	0.2544	3.8965
-25.3727	0.0000	25.4853	25.3727	0.3008	4.6096
-24.5448	0.0000	25.4853	24.5448	0.3941	5.2590
-23.7168	0.0000	25.4853	23.7168	0.3225	5.2982
-22.8889	0.0000	25.4853	22.8889	0.2600	5.2062
-22.0609	0.0000	25.4853	22.0609	0.3000	5.4201
-21.2330	0.0000	25.4853	21.2330	0.3724	5.7549

-20.4050	0.0000	25.4853	20.4050	0.4057	6.0336
-19.5771	0.0000	25.4853	19.5771	0.4226	6.2425
-18.7491	0.0000	25.4853	18.7491	0.4486	6.3776
-17.9212	0.0000	25.4853	17.9212	0.4903	6.3569
-17.0932	0.0000	25.4853	17.0932	0.5122	6.2000
-16.2653	0.0000	25.4853	16.2653	0.5840	6.1590
-15.4373	0.0000	25.4853	15.4373	0.6812	6.1682
-14.6094	0.0000	25.4853	14.6094	0.7529	6.0728
-13.7814	0.0000	25.4853	13.7814	0.7863	5.7710
-12.9535	0.0000	25.4853	12.9535	0.8091	5.2861
-12.1255	0.0000	25.4853	12.1255	0.7846	4.6677
-11.2976	0.0000	25.4853	11.2976	0.7350	3.9077
-10.4696	0.0000	25.4853	10.4696	0.6937	3.1721
-9.6417	0.0000	25.4853	9.6417	0.6215	2.4786
-8.8137	0.0000	25.4853	8.8137	0.5049	1.8468
-7.9858	0.0000	25.4853	7.9858	0.3529	1.2992
-7.1578	0.0000	25.4853	7.1578	0.1789	0.8531
-6.3299	0.0000	25.4853	6.3299	-0.0058	0.5223
-5.5019	0.0000	25.4853	5.5019	-0.1877	0.3290
-4.6740	0.0000	25.4853	4.6740	-0.3588	0.3032
-3.8460	0.0000	25.4853	3.8460	-0.4729	0.4625
-3.0180	0.0000	25.4853	3.0180	-0.5423	0.7369
-2.1901	0.0000	25.4853	2.1901	-0.5680	1.0254
-1.3621	0.0000	25.4853	1.3621	-0.5332	1.2170
-0.5342	0.0000	25.4853	0.5342	-0.4431	1.2384
0.2938	0.0000	25.4853	0.2938	-0.3442	1.0844
1.1217	0.0000	25.4853	1.1217	-0.2874	0.8069
1.9497	0.0000	25.4853	1.9497	-0.3047	0.5297
2.7776	0.0000	25.4853	2.7776	-0.3863	0.3708
3.6056	0.0000	25.4853	3.6056	-0.4675	0.3684
4.4335	0.0000	25.4853	4.4335	-0.5380	0.4899
5.2615	0.0000	25.4853	5.2615	-0.6094	0.7032
6.0894	0.0000	25.4853	6.0894	-0.6828	0.9856
6.9174	0.0000	25.4853	6.9174	-0.7519	1.3249
7.7453	0.0000	25.4853	7.7453	-0.8231	1.7258
8.5733	0.0000	25.4853	8.5733	-0.8791	2.2144
9.4012	0.0000	25.4853	9.4012	-0.9093	2.7749
10.2292	0.0000	25.4853	10.2292	-0.9069	3.3436
11.0571	0.0000	25.4853	11.0571	-0.8683	3.8783
11.8851	0.0000	25.4853	11.8851	-0.8252	4.3419
12.7130	0.0000	25.4853	12.7130	-0.7991	4.7199
13.5410	0.0000	25.4853	13.5410	-0.7785	5.0320
14.3689	0.0000	25.4853	14.3689	-0.7365	5.3076
15.1969	0.0000	25.4853	15.1969	-0.7049	5.5334
16.0248	0.0000	25.4853	16.0248	-0.6632	5.7059
16.8528	0.0000	25.4853	16.8528	-0.6273	5.8193
17.6807	0.0000	25.4853	17.6807	-0.6067	5.8707
18.5087	0.0000	25.4853	18.5087	-0.5767	5.9570
19.3366	0.0000	25.4853	19.3366	-0.5298	6.1305
20.1646	0.0000	25.4853	20.1646	-0.4977	6.3197
20.9925	0.0000	25.4853	20.9925	-0.4916	6.3523
21.8205	0.0000	25.4853	21.8205	-0.4601	6.2271
22.6485	0.0000	25.4853	22.6485	-0.3886	6.0822
23.4764	0.0000	25.4853	23.4764	-0.3478	5.9008
24.3044	0.0000	25.4853	24.3044	-0.2991	5.5732
25.1323	0.0000	25.4853	25.1323	-0.2176	4.9699
25.9603	0.0000	25.4853	25.9603	-0.1568	4.3170
26.7882	0.0000	25.4853	26.7882	-0.1798	3.9960
27.6162	0.0000	25.4853	27.6162	-0.2061	3.9851
28.4441	0.0000	25.4853	28.4441	-0.1882	3.6517
29.2721	0.0000	25.4853	29.2721	-0.1760	3.1054
30.1000	0.0000	25.4853	30.1000	-0.1531	2.0983
30.9280	0.0000	25.4853	30.9280	-0.0732	0.9302
31.7559	0.0000	25.4853	31.7559	-0.0443	0.1214
32.5839	0.0000	25.4853	32.5839	-0.1061	-0.1126
33.4118	0.0000	25.4853	33.4118	-0.1715	-0.0363
34.2398	0.0000	25.4853	34.2398	-0.1772	-0.1145
35.0677	0.0000	25.4853	35.0677	-0.1423	-0.1958
35.8957	0.0000	25.4853	35.8957	-0.0543	-0.1931
36.7236	0.0000	25.4853	36.7236	-0.0075	-0.2363
37.5516	0.0000	25.4853	37.5516	-0.0001	-0.2079
38.3795	0.0000	25.4853	38.3795	-0.0245	-0.1092
39.2075	0.0000	25.4853	39.2075	-0.1316	-0.0088
Plane: 76.2 mm downstream of injection					
-40.2784	0.0000	76.3197	40.2784	-0.0417	-0.1483
-39.4530	0.0000	76.3197	39.4530	-0.0573	-0.2049
-38.6276	0.0000	76.3197	38.6276	-0.1567	-0.7892
-37.8022	0.0000	76.3197	37.8022	-0.1600	-1.7263
-36.9768	0.0000	76.3197	36.9768	-0.1069	-1.7153
-36.1514	0.0000	76.3197	36.1514	-0.0697	-0.8381

-35.3260	0.0000	76.3197	35.3260	0.0373	-0.2222
-34.5006	0.0000	76.3197	34.5006	0.0947	0.0165
-33.6752	0.0000	76.3197	33.6752	0.0438	0.1914
-32.8498	0.0000	76.3197	32.8498	0.0093	0.3619
-32.0244	0.0000	76.3197	32.0244	0.0030	0.5987
-31.1990	0.0000	76.3197	31.1990	0.0207	0.9004
-30.3736	0.0000	76.3197	30.3736	0.0317	1.1995
-29.5482	0.0000	76.3197	29.5482	0.0208	1.5592
-28.7228	0.0000	76.3197	28.7228	0.0050	1.9693
-27.8974	0.0000	76.3197	27.8974	-0.0162	2.4008
-27.0720	0.0000	76.3197	27.0720	-0.0448	2.8440
-26.2466	0.0000	76.3197	26.2466	-0.0669	3.3096
-25.4211	0.0000	76.3197	25.4211	-0.0829	3.7596
-24.5957	0.0000	76.3197	24.5957	-0.0779	4.2173
-23.7703	0.0000	76.3197	23.7703	-0.0790	4.7182
-22.9449	0.0000	76.3197	22.9449	-0.1084	5.2001
-22.1195	0.0000	76.3197	22.1195	-0.1458	5.6181
-21.2941	0.0000	76.3197	21.2941	-0.1683	5.9607
-20.4687	0.0000	76.3197	20.4687	-0.1705	6.2279
-19.6433	0.0000	76.3197	19.6433	-0.1642	6.4248
-18.8179	0.0000	76.3197	18.8179	-0.1588	6.5256
-17.9925	0.0000	76.3197	17.9925	-0.1566	6.4929
-17.1671	0.0000	76.3197	17.1671	-0.1504	6.3969
-16.3417	0.0000	76.3197	16.3417	-0.1397	6.2576
-15.5163	0.0000	76.3197	15.5163	-0.1301	6.0909
-14.6909	0.0000	76.3197	14.6909	-0.1263	5.8927
-13.8655	0.0000	76.3197	13.8655	-0.1308	5.6466
-13.0401	0.0000	76.3197	13.0401	-0.1390	5.3652
-12.2147	0.0000	76.3197	12.2147	-0.1444	5.1276
-11.3893	0.0000	76.3197	11.3893	-0.1435	4.9309
-10.5639	0.0000	76.3197	10.5639	-0.1435	4.7340
-9.7385	0.0000	76.3197	9.7385	-0.1451	4.5292
-8.9131	0.0000	76.3197	8.9131	-0.1489	4.3332
-8.0877	0.0000	76.3197	8.0877	-0.1549	4.1559
-7.2623	0.0000	76.3197	7.2623	-0.1601	3.9991
-6.4369	0.0000	76.3197	6.4369	-0.1555	3.8590
-5.6114	0.0000	76.3197	5.6114	-0.1479	3.7392
-4.7860	0.0000	76.3197	4.7860	-0.1701	3.6155
-3.9606	0.0000	76.3197	3.9606	-0.1849	3.5039
-3.1352	0.0000	76.3197	3.1352	-0.1762	3.4308
-2.3098	0.0000	76.3197	2.3098	-0.1577	3.3912
-1.4844	0.0000	76.3197	1.4844	-0.1463	3.3665
-0.6590	0.0000	76.3197	0.6590	-0.1404	3.3442
0.1664	0.0000	76.3197	0.1664	-0.1286	3.3394
0.9918	0.0000	76.3197	0.9918	-0.1117	3.3868
1.8172	0.0000	76.3197	1.8172	-0.1049	3.4536
2.6426	0.0000	76.3197	2.6426	-0.0976	3.5226
3.4680	0.0000	76.3197	3.4680	-0.0763	3.6015
4.2934	0.0000	76.3197	4.2934	-0.0524	3.7029
5.1188	0.0000	76.3197	5.1188	-0.0395	3.8222
5.9442	0.0000	76.3197	5.9442	-0.0292	3.9600
6.7696	0.0000	76.3197	6.7696	-0.0220	4.1043
7.5950	0.0000	76.3197	7.5950	-0.0130	4.2486
8.4204	0.0000	76.3197	8.4204	-0.0044	4.4018
9.2458	0.0000	76.3197	9.2458	0.0051	4.5668
10.0712	0.0000	76.3197	10.0712	0.0159	4.7403
10.8966	0.0000	76.3197	10.8966	0.0269	4.9122
11.7220	0.0000	76.3197	11.7220	0.0405	5.0855
12.5474	0.0000	76.3197	12.5474	0.0632	5.2780
13.3728	0.0000	76.3197	13.3728	0.0755	5.4731
14.1982	0.0000	76.3197	14.1982	0.0733	5.6416
15.0237	0.0000	76.3197	15.0237	0.0792	5.8255
15.8491	0.0000	76.3197	15.8491	0.0968	6.0168
16.6745	0.0000	76.3197	16.6745	0.1191	6.2039
17.4999	0.0000	76.3197	17.4999	0.1431	6.3843
18.3253	0.0000	76.3197	18.3253	0.1751	6.5452
19.1507	0.0000	76.3197	19.1507	0.2111	6.6465
19.9761	0.0000	76.3197	19.9761	0.2233	6.6480
20.8015	0.0000	76.3197	20.8015	0.2058	6.5446
21.6269	0.0000	76.3197	21.6269	0.2080	6.3471
22.4523	0.0000	76.3197	22.4523	0.2143	6.0572
23.2777	0.0000	76.3197	23.2777	0.2119	5.7054
24.1031	0.0000	76.3197	24.1031	0.1994	5.3127
24.9285	0.0000	76.3197	24.9285	0.1840	4.8921
25.7539	0.0000	76.3197	25.7539	0.1752	4.4541
26.5793	0.0000	76.3197	26.5793	0.1650	3.9786
27.4047	0.0000	76.3197	27.4047	0.1503	3.5129
28.2301	0.0000	76.3197	28.2301	0.1433	3.0627
29.0555	0.0000	76.3197	29.0555	0.1340	2.6324
29.8809	0.0000	76.3197	29.8809	0.1212	2.2257

30.7063	0.0000	76.3197	30.7063	0.1035	1.8388
31.5317	0.0000	76.3197	31.5317	0.0866	1.4659
32.3571	0.0000	76.3197	32.3571	0.0723	1.1075
33.1825	0.0000	76.3197	33.1825	0.0425	0.7902
34.0079	0.0000	76.3197	34.0079	0.0190	0.5124
34.8334	0.0000	76.3197	34.8334	0.0110	0.2648
35.6588	0.0000	76.3197	35.6588	-0.0014	0.0498
36.4842	0.0000	76.3197	36.4842	-0.0283	-0.1146
37.3096	0.0000	76.3197	37.3096	-0.0287	-0.1954
38.1350	0.0000	76.3197	38.1350	0.0185	-0.1761
38.9604	0.0000	76.3197	38.9604	0.0161	-0.1455
39.7858	0.0000	76.3197	39.7858	-0.0068	-0.1324
Plane: 152.4 mm Downstream of injection					
-40.2784	0.0000	152.3093	40.2784	0.0772	0.3196
-39.4530	0.0000	152.3093	39.4530	0.0158	0.0647
-38.6276	0.0000	152.3093	38.6276	-0.0636	0.1284
-37.8022	0.0000	152.3093	37.8022	-0.0945	0.5295
-36.9768	0.0000	152.3093	36.9768	-0.0956	-0.1102
-36.1514	0.0000	152.3093	36.1514	-0.0957	0.2048
-35.3260	0.0000	152.3093	35.3260	-0.0995	0.7177
-34.5006	0.0000	152.3093	34.5006	-0.0998	1.1499
-33.6752	0.0000	152.3093	33.6752	-0.0836	1.4522
-32.8498	0.0000	152.3093	32.8498	-0.0450	1.5893
-32.0244	0.0000	152.3093	32.0244	-0.0244	1.6947
-31.1990	0.0000	152.3093	31.1990	-0.0108	1.8264
-30.3736	0.0000	152.3093	30.3736	-0.0146	2.0078
-29.5482	0.0000	152.3093	29.5482	-0.0377	2.1981
-28.7228	0.0000	152.3093	28.7228	-0.0594	2.3865
-27.8974	0.0000	152.3093	27.8974	-0.0681	2.5768
-27.0720	0.0000	152.3093	27.0720	-0.0686	2.7694
-26.2466	0.0000	152.3093	26.2466	-0.0768	2.9508
-25.4211	0.0000	152.3093	25.4211	-0.0834	3.1354
-24.5957	0.0000	152.3093	24.5957	-0.1072	3.3326
-23.7703	0.0000	152.3093	23.7703	-0.1136	3.5174
-22.9449	0.0000	152.3093	22.9449	-0.1060	3.7386
-22.1195	0.0000	152.3093	22.1195	-0.0936	3.9747
-21.2941	0.0000	152.3093	21.2941	-0.0878	4.2010
-20.4687	0.0000	152.3093	20.4687	-0.0919	4.3975
-19.6433	0.0000	152.3093	19.6433	-0.0922	4.5368
-18.8179	0.0000	152.3093	18.8179	-0.0689	4.5752
-17.9925	0.0000	152.3093	17.9925	-0.0581	4.5422
-17.1671	0.0000	152.3093	17.1671	-0.0632	4.5529
-16.3417	0.0000	152.3093	16.3417	-0.0772	4.5964
-15.5163	0.0000	152.3093	15.5163	-0.0820	4.6106
-14.6909	0.0000	152.3093	14.6909	-0.0723	4.5601
-13.8655	0.0000	152.3093	13.8655	-0.0570	4.4643
-13.0401	0.0000	152.3093	13.0401	-0.0399	4.3881
-12.2147	0.0000	152.3093	12.2147	-0.0255	4.3403
-11.3893	0.0000	152.3093	11.3893	-0.0293	4.3255
-10.5639	0.0000	152.3093	10.5639	-0.0381	4.2761
-9.7385	0.0000	152.3093	9.7385	-0.0451	4.1988
-8.9131	0.0000	152.3093	8.9131	-0.0410	4.0913
-8.0877	0.0000	152.3093	8.0877	-0.0338	3.9582
-7.2623	0.0000	152.3093	7.2623	-0.0326	3.8211
-6.4369	0.0000	152.3093	6.4369	-0.0132	3.7275
-5.6114	0.0000	152.3093	5.6114	0.0124	3.7085
-4.7860	0.0000	152.3093	4.7860	0.0219	3.6655
-3.9606	0.0000	152.3093	3.9606	0.0207	3.6159
-3.1352	0.0000	152.3093	3.1352	0.0258	3.5564
-2.3098	0.0000	152.3093	2.3098	0.0326	3.5047
-1.4844	0.0000	152.3093	1.4844	0.0345	3.4767
-0.6590	0.0000	152.3093	0.6590	0.0314	3.4804
0.1664	0.0000	152.3093	0.1664	0.0289	3.5283
0.9918	0.0000	152.3093	0.9918	0.0524	3.5671
1.8172	0.0000	152.3093	1.8172	0.0667	3.5676
2.6426	0.0000	152.3093	2.6426	0.0887	3.5769
3.4680	0.0000	152.3093	3.4680	0.0983	3.5943
4.2934	0.0000	152.3093	4.2934	0.0897	3.6173
5.1188	0.0000	152.3093	5.1188	0.0724	3.6580
5.9442	0.0000	152.3093	5.9442	0.0607	3.7345
6.7696	0.0000	152.3093	6.7696	0.0593	3.8317
7.5950	0.0000	152.3093	7.5950	0.0748	3.9357
8.4204	0.0000	152.3093	8.4204	0.0936	4.0353
9.2458	0.0000	152.3093	9.2458	0.0968	4.1312
10.0712	0.0000	152.3093	10.0712	0.0886	4.2266
10.8966	0.0000	152.3093	10.8966	0.0756	4.3307
11.7220	0.0000	152.3093	11.7220	0.0632	4.4461
12.5474	0.0000	152.3093	12.5474	0.0569	4.5604
13.3728	0.0000	152.3093	13.3728	0.0663	4.6600
14.1982	0.0000	152.3093	14.1982	0.0906	4.7562

15.0237	0.0000	152.3093	15.0237	0.0943	4.8585
15.8491	0.0000	152.3093	15.8491	0.0867	4.9538
16.6745	0.0000	152.3093	16.6745	0.0903	5.0482
17.4999	0.0000	152.3093	17.4999	0.0952	5.1474
18.3253	0.0000	152.3093	18.3253	0.0906	5.2462
19.1507	0.0000	152.3093	19.1507	0.1025	5.3273
19.9761	0.0000	152.3093	19.9761	0.1363	5.3631
20.8015	0.0000	152.3093	20.8015	0.1363	5.3188
21.6269	0.0000	152.3093	21.6269	0.1350	5.2249
22.4523	0.0000	152.3093	22.4523	0.1504	5.1243
23.2777	0.0000	152.3093	23.2777	0.1673	5.0037
24.1031	0.0000	152.3093	24.1031	0.1813	4.8476
24.9285	0.0000	152.3093	24.9285	0.1962	4.6627
25.7539	0.0000	152.3093	25.7539	0.2073	4.4776
26.5793	0.0000	152.3093	26.5793	0.2203	4.2766
27.4047	0.0000	152.3093	27.4047	0.2182	4.0438
28.2301	0.0000	152.3093	28.2301	0.2042	3.7851
29.0555	0.0000	152.3093	29.0555	0.1779	3.5228
29.8809	0.0000	152.3093	29.8809	0.1487	3.2724
30.7063	0.0000	152.3093	30.7063	0.1234	3.0367
31.5317	0.0000	152.3093	31.5317	0.1004	2.8071
32.3571	0.0000	152.3093	32.3571	0.0705	2.5675
33.1825	0.0000	152.3093	33.1825	0.0483	2.3486
34.0079	0.0000	152.3093	34.0079	0.0493	2.1514
34.8334	0.0000	152.3093	34.8334	0.0544	1.9690
35.6588	0.0000	152.3093	35.6588	0.0635	1.8069
36.4842	0.0000	152.3093	36.4842	0.0697	1.5525
37.3096	0.0000	152.3093	37.3096	0.0521	1.0311
38.1350	0.0000	152.3093	38.1350	0.0062	0.2866
38.9604	0.0000	152.3093	38.9604	-0.0267	-0.1365
39.7858	0.0000	152.3093	39.7858	-0.0206	-0.1555

B.13.3 Case 2: Non-Swirling Axial Injection of Hydrogen

Table B-9: Spatial fuel concentration data. Case 2

Hardware Configuration: A				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.000369 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
0.0000	-30.4800	25.4000	30.4800	0.000	0.00000
0.0000	-26.6700	25.4000	26.6700	0.000	0.00000
0.0000	-22.8600	25.4000	22.8600	0.000	0.00000
0.0000	-19.0500	25.4000	19.0500	0.005	0.00005
0.0000	-15.2400	25.4000	15.2400	0.239	0.00239
0.0000	-11.4300	25.4000	11.4300	8.163	0.08163
0.0000	-7.6200	25.4000	7.6200	21.699	0.21699
0.0000	-3.8100	25.4000	3.8100	31.208	0.31208
0.0000	0.0000	25.4000	0.0000	33.431	0.33431
0.0000	3.8100	25.4000	3.8100	18.596	0.18596
0.0000	7.6200	25.4000	7.6200	15.209	0.15209
0.0000	11.4300	25.4000	11.4300	3.669	0.03669
0.0000	15.2400	25.4000	15.2400	0.091	0.00091
0.0000	19.0500	25.4000	19.0500	0.000	0.00000
0.0000	22.8600	25.4000	22.8600	0.000	0.00000
0.0000	26.6700	25.4000	26.6700	0.000	0.00000
0.0000	30.4800	25.4000	30.4800	0.000	0.00000
-3.8100	30.4800	25.4000	30.7172	0.000	0.00000
-3.8100	26.6700	25.4000	26.9408	0.000	0.00000
-3.8100	22.8600	25.4000	23.1753	0.000	0.00000
-3.8100	19.0500	25.4000	19.4273	0.007	0.00007
-3.8100	15.2400	25.4000	15.7090	0.057	0.00057
-3.8100	11.4300	25.4000	12.0483	2.764	0.02764
-3.8100	7.6200	25.4000	8.5194	13.723	0.13723
-3.8100	3.8100	25.4000	5.3882	19.555	0.19555
-3.8100	0.0000	25.4000	3.8100	23.680	0.23680
-3.8100	-3.8100	25.4000	5.3882	27.369	0.27369
-3.8100	-7.6200	25.4000	8.5194	20.312	0.20312
-3.8100	-11.4300	25.4000	12.0483	5.988	0.05988
-3.8100	-15.2400	25.4000	15.7090	0.209	0.00209
-3.8100	-19.0500	25.4000	19.4273	0.000	0.00000
-3.8100	-22.8600	25.4000	23.1753	0.000	0.00000
-3.8100	-26.6700	25.4000	26.9408	0.000	0.00000
-3.8100	-30.4800	25.4000	30.7172	0.000	0.00000
-7.6200	-30.4800	25.4000	31.4181	0.000	0.00000
-7.6200	-26.6700	25.4000	27.7372	0.000	0.00000

-7.6200	-22.8600	25.4000	24.0966	0.000	0.00000
-7.6200	-19.0500	25.4000	20.5175	0.000	0.00000
-7.6200	-15.2400	25.4000	17.0388	0.019	0.00019
-7.6200	-11.4300	25.4000	13.7372	1.015	0.01015
-7.6200	-7.6200	25.4000	10.7763	11.264	0.11264
-7.6200	-3.8100	25.4000	8.5194	17.563	0.17563
-7.6200	0.0000	25.4000	7.6200	17.152	0.17152
-7.6200	3.8100	25.4000	8.5194	14.998	0.14998
-7.6200	7.6200	25.4000	10.7763	4.990	0.04990
-7.6200	11.4300	25.4000	13.7372	0.470	0.00470
-7.6200	15.2400	25.4000	17.0388	0.012	0.00012
-7.6200	19.0500	25.4000	20.5175	0.000	0.00000
-7.6200	22.8600	25.4000	24.0966	0.000	0.00000
-7.6200	26.6700	25.4000	27.7372	0.000	0.00000
-7.6200	30.4800	25.4000	31.4181	0.000	0.00000
-11.4300	26.6700	25.4000	29.0161	0.000	0.00000
-11.4300	22.8600	25.4000	25.5583	0.000	0.00000
-11.4300	19.0500	25.4000	22.2159	0.000	0.00000
-11.4300	15.2400	25.4000	19.0500	0.000	0.00000
-11.4300	11.4300	25.4000	16.1645	0.026	0.00026
-11.4300	7.6200	25.4000	13.7372	0.380	0.00380
-11.4300	3.8100	25.4000	12.0483	2.902	0.02902
-11.4300	0.0000	25.4000	11.4300	5.983	0.05983
-11.4300	-3.8100	25.4000	12.0483	5.155	0.05155
-11.4300	-7.6200	25.4000	13.7372	0.970	0.00970
-11.4300	-11.4300	25.4000	16.1645	0.072	0.00072
-11.4300	-15.2400	25.4000	19.0500	0.000	0.00000
-11.4300	-19.0500	25.4000	22.2159	0.000	0.00000
-11.4300	-22.8600	25.4000	25.5583	0.000	0.00000
-11.4300	-26.6700	25.4000	29.0161	0.000	0.00000
-15.2400	-26.6700	25.4000	30.7172	0.000	0.00000
-15.2400	-22.8600	25.4000	27.4743	0.000	0.00000
-15.2400	-19.0500	25.4000	24.3959	0.000	0.00000
-15.2400	-15.2400	25.4000	21.5526	0.000	0.00000
-15.2400	-11.4300	25.4000	19.0500	0.000	0.00000
-15.2400	-7.6200	25.4000	17.0388	0.019	0.00019
-15.2400	-3.8100	25.4000	15.7090	0.141	0.00141
-15.2400	0.0000	25.4000	15.2400	0.178	0.00178
-15.2400	3.8100	25.4000	15.7090	0.060	0.00060
-15.2400	7.6200	25.4000	17.0388	0.000	0.00000
-15.2400	11.4300	25.4000	19.0500	0.000	0.00000
-15.2400	15.2400	25.4000	21.5526	0.000	0.00000
-15.2400	19.0500	25.4000	24.3959	0.000	0.00000
-15.2400	22.8600	25.4000	27.4743	0.000	0.00000
-15.2400	26.6700	25.4000	30.7172	0.000	0.00000
-19.0500	22.8600	25.4000	29.7571	0.000	0.00000
-19.0500	19.0500	25.4000	26.9408	0.000	0.00000
-19.0500	15.2400	25.4000	24.3959	0.000	0.00000
-19.0500	11.4300	25.4000	22.2159	0.000	0.00000
-19.0500	7.6200	25.4000	20.5175	0.000	0.00000
-19.0500	3.8100	25.4000	19.4273	0.000	0.00000
-19.0500	0.0000	25.4000	19.0500	0.000	0.00000
-19.0500	-3.8100	25.4000	19.4273	0.000	0.00000
-19.0500	-7.6200	25.4000	20.5175	0.000	0.00000
-19.0500	-11.4300	25.4000	22.2159	0.000	0.00000
-19.0500	-15.2400	25.4000	24.3959	0.000	0.00000
-19.0500	-19.0500	25.4000	26.9408	0.000	0.00000
-19.0500	-22.8600	25.4000	29.7571	0.000	0.00000
-22.8600	-19.0500	25.4000	29.7571	0.000	0.00000
-22.8600	-15.2400	25.4000	27.4743	0.000	0.00000
-22.8600	-11.4300	25.4000	25.5583	0.000	0.00000
-22.8600	-7.6200	25.4000	24.0966	0.000	0.00000
-22.8600	-3.8100	25.4000	23.1753	0.000	0.00000
-22.8600	0.0000	25.4000	22.8600	0.000	0.00000
-22.8600	3.8100	25.4000	23.1753	0.000	0.00000
-22.8600	7.6200	25.4000	24.0966	0.000	0.00000
-22.8600	11.4300	25.4000	25.5583	0.000	0.00000
-22.8600	15.2400	25.4000	27.4743	0.000	0.00000
-22.8600	19.0500	25.4000	29.7571	0.000	0.00000
-26.6700	15.2400	25.4000	30.7172	0.000	0.00000
-26.6700	11.4300	25.4000	29.0161	0.000	0.00000
-26.6700	7.6200	25.4000	27.7372	0.000	0.00000
-26.6700	3.8100	25.4000	26.9408	0.000	0.00000
-26.6700	0.0000	25.4000	26.6700	0.000	0.00000
-26.6700	-3.8100	25.4000	26.9408	0.000	0.00000
-26.6700	-7.6200	25.4000	27.7372	0.000	0.00000
-26.6700	-11.4300	25.4000	29.0161	0.000	0.00000
-26.6700	-15.2400	25.4000	30.7172	0.000	0.00000
-30.4800	-7.6200	25.4000	31.4181	0.000	0.00000
-30.4800	-3.8100	25.4000	30.7172	0.000	0.00000

-30.4800	0.0000	25.4000	30.4800	0.000	0.00000
-30.4800	3.8100	25.4000	30.7172	0.000	0.00000
-30.4800	7.6200	25.4000	31.4181	0.000	0.00000
3.8100	-30.4800	25.4000	30.7172	0.000	0.00000
3.8100	-26.6700	25.4000	26.9408	0.000	0.00000
3.8100	-22.8600	25.4000	23.1753	0.000	0.00000
3.8100	-19.0500	25.4000	19.4273	0.000	0.00000
3.8100	-15.2400	25.4000	15.7090	0.102	0.00102
3.8100	-11.4300	25.4000	12.0483	3.876	0.03876
3.8100	-7.6200	25.4000	8.5194	23.421	0.23421
3.8100	-3.8100	25.4000	5.3882	27.522	0.27522
3.8100	0.0000	25.4000	3.8100	24.184	0.24184
3.8100	3.8100	25.4000	5.3882	19.177	0.19177
3.8100	7.6200	25.4000	8.5194	14.425	0.14425
3.8100	11.4300	25.4000	12.0483	2.084	0.02084
3.8100	15.2400	25.4000	15.7090	0.043	0.00043
3.8100	19.0500	25.4000	19.4273	0.000	0.00000
3.8100	22.8600	25.4000	23.1753	0.000	0.00000
3.8100	26.6700	25.4000	26.9408	0.000	0.00000
3.8100	30.4800	25.4000	30.7172	0.000	0.00000
7.6200	30.4800	25.4000	31.4181	0.000	0.00000
7.6200	26.6700	25.4000	27.7372	0.000	0.00000
7.6200	22.8600	25.4000	24.0966	0.000	0.00000
7.6200	19.0500	25.4000	20.5175	0.000	0.00000
7.6200	15.2400	25.4000	17.0388	0.000	0.00000
7.6200	11.4300	25.4000	13.7372	0.270	0.00270
7.6200	7.6200	25.4000	10.7763	6.095	0.06095
7.6200	3.8100	25.4000	8.5194	17.228	0.17228
7.6200	0.0000	25.4000	7.6200	20.728	0.20728
7.6200	-3.8100	25.4000	8.5194	21.569	0.21569
7.6200	-7.6200	25.4000	10.7763	8.692	0.08692
7.6200	-11.4300	25.4000	13.7372	0.791	0.00791
7.6200	-15.2400	25.4000	17.0388	0.023	0.00023
7.6200	-19.0500	25.4000	20.5175	0.000	0.00000
7.6200	-22.8600	25.4000	24.0966	0.000	0.00000
7.6200	-26.6700	25.4000	27.7372	0.000	0.00000
7.6200	-30.4800	25.4000	31.4181	0.000	0.00000
11.4300	-26.6700	25.4000	29.0161	0.000	0.00000
11.4300	-22.8600	25.4000	25.5583	0.000	0.00000
11.4300	-19.0500	25.4000	22.2159	0.000	0.00000
11.4300	-15.2400	25.4000	19.0500	0.000	0.00000
11.4300	-11.4300	25.4000	16.1645	0.033	0.00033
11.4300	-7.6200	25.4000	13.7372	0.571	0.00571
11.4300	-3.8100	25.4000	12.0483	2.683	0.02683
11.4300	0.0000	25.4000	11.4300	5.297	0.05297
11.4300	3.8100	25.4000	12.0483	2.462	0.02462
11.4300	7.6200	25.4000	13.7372	0.382	0.00382
11.4300	11.4300	25.4000	16.1645	0.014	0.00014
11.4300	15.2400	25.4000	19.0500	0.000	0.00000
11.4300	19.0500	25.4000	22.2159	0.000	0.00000
11.4300	22.8600	25.4000	25.5583	0.000	0.00000
11.4300	26.6700	25.4000	29.0161	0.000	0.00000
15.2400	26.6700	25.4000	30.7172	0.000	0.00000
15.2400	22.8600	25.4000	27.4743	0.000	0.00000
15.2400	19.0500	25.4000	24.3959	0.000	0.00000
15.2400	15.2400	25.4000	21.5526	0.000	0.00000
15.2400	11.4300	25.4000	19.0500	0.000	0.00000
15.2400	7.6200	25.4000	17.0388	0.000	0.00000
15.2400	3.8100	25.4000	15.7090	0.046	0.00046
15.2400	0.0000	25.4000	15.2400	0.090	0.00090
15.2400	-3.8100	25.4000	15.7090	0.042	0.00042
15.2400	-7.6200	25.4000	17.0388	0.000	0.00000
15.2400	-11.4300	25.4000	19.0500	0.000	0.00000
15.2400	-15.2400	25.4000	21.5526	0.000	0.00000
15.2400	-19.0500	25.4000	24.3959	0.000	0.00000
15.2400	-22.8600	25.4000	27.4743	0.000	0.00000
15.2400	-26.6700	25.4000	30.7172	0.000	0.00000
19.0500	22.8600	25.4000	29.7571	0.000	0.00000
19.0500	19.0500	25.4000	26.9408	0.000	0.00000
19.0500	15.2400	25.4000	24.3959	0.000	0.00000
19.0500	11.4300	25.4000	22.2159	0.000	0.00000
19.0500	7.6200	25.4000	20.5175	0.000	0.00000
19.0500	3.8100	25.4000	19.4273	0.000	0.00000
19.0500	0.0000	25.4000	19.0500	0.000	0.00000
19.0500	-3.8100	25.4000	19.4273	0.000	0.00000
19.0500	-7.6200	25.4000	20.5175	0.000	0.00000
19.0500	-11.4300	25.4000	22.2159	0.000	0.00000
19.0500	-15.2400	25.4000	24.3959	0.000	0.00000
19.0500	-19.0500	25.4000	26.9408	0.000	0.00000
19.0500	-22.8600	25.4000	29.7571	0.000	0.00000

22.8600	-19.0500	25.4000	29.7571	0.000	0.00000
22.8600	-15.2400	25.4000	27.4743	0.000	0.00000
22.8600	-11.4300	25.4000	25.5583	0.000	0.00000
22.8600	-7.6200	25.4000	24.0966	0.000	0.00000
22.8600	-3.8100	25.4000	23.1753	0.000	0.00000
22.8600	0.0000	25.4000	22.8600	0.000	0.00000
22.8600	3.8100	25.4000	23.1753	0.000	0.00000
22.8600	7.6200	25.4000	24.0966	0.000	0.00000
22.8600	11.4300	25.4000	25.5583	0.000	0.00000
22.8600	15.2400	25.4000	27.4743	0.000	0.00000
22.8600	19.0500	25.4000	29.7571	0.000	0.00000
26.6700	15.2400	25.4000	30.7172	0.000	0.00000
26.6700	11.4300	25.4000	29.0161	0.000	0.00000
26.6700	7.6200	25.4000	27.7372	0.000	0.00000
26.6700	3.8100	25.4000	26.9408	0.000	0.00000
26.6700	0.0000	25.4000	26.6700	0.000	0.00000
26.6700	-3.8100	25.4000	26.9408	0.000	0.00000
26.6700	-7.6200	25.4000	27.7372	0.000	0.00000
26.6700	-11.4300	25.4000	29.0161	0.000	0.00000
26.6700	-15.2400	25.4000	30.7172	0.000	0.00000
30.4800	-7.6200	25.4000	31.4181	0.000	0.00000
30.4800	-3.8100	25.4000	30.7172	0.000	0.00000
30.4800	0.0000	25.4000	30.4800	0.000	0.00000
30.4800	3.8100	25.4000	30.7172	0.000	0.00000
30.4800	7.6200	25.4000	31.4181	0.000	0.00000
0.0000	9.5250	25.4000	9.5250	10.024	0.10024
0.0000	5.7150	25.4000	5.7150	18.093	0.18093
0.0000	1.9050	25.4000	1.9050	25.107	0.25107
0.0000	-1.9050	25.4000	1.9050	39.079	0.39079
0.0000	-5.7150	25.4000	5.7150	27.315	0.27315
0.0000	-9.5250	25.4000	9.5250	19.014	0.19014
1.9050	9.5250	25.4000	9.7136	9.437	0.09437
1.9050	7.6200	25.4000	7.8545	15.633	0.15633
1.9050	5.7150	25.4000	6.0241	18.066	0.18066
1.9050	3.8100	25.4000	4.2597	19.811	0.19811
1.9050	1.9050	25.4000	2.6941	24.349	0.24349
1.9050	0.0000	25.4000	1.9050	30.508	0.30508
1.9050	-1.9050	25.4000	2.6941	35.308	0.35308
1.9050	-3.8100	25.4000	4.2597	33.104	0.33104
1.9050	-5.7150	25.4000	6.0241	28.536	0.28536
1.9050	-7.6200	25.4000	7.8545	24.007	0.24007
1.9050	-9.5250	25.4000	9.7136	18.248	0.18248
-1.9050	9.5250	25.4000	9.7136	9.729	0.09729
-1.9050	7.6200	25.4000	7.8545	14.998	0.14998
-1.9050	5.7150	25.4000	6.0241	18.204	0.18204
-1.9050	3.8100	25.4000	4.2597	20.135	0.20135
-1.9050	1.9050	25.4000	2.6941	25.189	0.25189
-1.9050	0.0000	25.4000	1.9050	34.701	0.34701
-1.9050	-1.9050	25.4000	2.6941	36.145	0.36145
-1.9050	-3.8100	25.4000	4.2597	30.352	0.30352
-1.9050	-5.7150	25.4000	6.0241	26.298	0.26298
-1.9050	-7.6200	25.4000	7.8545	21.879	0.21879
-1.9050	-9.5250	25.4000	9.7136	18.048	0.18048
3.8100	9.5250	25.4000	10.2587	6.772	0.06772
3.8100	5.7150	25.4000	6.8686	17.466	0.17466
3.8100	1.9050	25.4000	4.2597	21.840	0.21840
3.8100	-1.9050	25.4000	4.2597	27.654	0.27654
3.8100	-5.7150	25.4000	6.8686	25.499	0.25499
3.8100	-9.5250	25.4000	10.2587	14.696	0.14696
-3.8100	9.5250	25.4000	10.2587	7.309	0.07309
-3.8100	5.7150	25.4000	6.8686	16.796	0.16796
-3.8100	1.9050	25.4000	4.2597	21.841	0.21841
-3.8100	-1.9050	25.4000	4.2597	27.301	0.27301
-3.8100	-5.7150	25.4000	6.8686	23.924	0.23924
-3.8100	-9.5250	25.4000	10.2587	15.181	0.15181
5.7150	9.5250	25.4000	11.1080	4.129	0.04129
5.7150	7.6200	25.4000	9.5250	11.051	0.11051
5.7150	5.7150	25.4000	8.0822	16.895	0.16895
5.7150	3.8100	25.4000	6.8686	18.261	0.18261
5.7150	1.9050	25.4000	6.0241	19.113	0.19113
5.7150	0.0000	25.4000	5.7150	20.508	0.20508
5.7150	-1.9050	25.4000	6.0241	21.634	0.21634
5.7150	-3.8100	25.4000	6.8686	22.182	0.22182
5.7150	-5.7150	25.4000	8.0822	23.760	0.23760
5.7150	-7.6200	25.4000	9.5250	18.640	0.18640
5.7150	-9.5250	25.4000	11.1080	7.583	0.07583
-5.7150	9.5250	25.4000	11.1080	4.042	0.04042
-5.7150	7.6200	25.4000	9.5250	10.476	0.10476
-5.7150	5.7150	25.4000	8.0822	15.305	0.15305
-5.7150	3.8100	25.4000	6.8686	18.012	0.18012

-5.7150	1.9050	25.4000	6.0241	20.609	0.20609
-5.7150	0.0000	25.4000	5.7150	21.731	0.21731
-5.7150	-1.9050	25.4000	6.0241	22.788	0.22788
-5.7150	-3.8100	25.4000	6.8686	21.586	0.21586
-5.7150	-5.7150	25.4000	8.0822	20.110	0.20110
-5.7150	-7.6200	25.4000	9.5250	17.534	0.17534
-5.7150	-9.5250	25.4000	11.1080	9.520	0.09520
-7.6200	5.7150	25.4000	9.5250	11.154	0.11154
-7.6200	1.9050	25.4000	7.8545	16.489	0.16489
-7.6200	-1.9050	25.4000	7.8545	17.910	0.17910
-7.6200	-5.7150	25.4000	9.5250	15.596	0.15596
7.6200	5.7150	25.4000	9.5250	11.860	0.11860
7.6200	1.9050	25.4000	7.8545	18.854	0.18854
7.6200	-1.9050	25.4000	7.8545	22.145	0.22145
7.6200	-5.7150	25.4000	9.5250	18.524	0.18524
-9.5250	5.7150	25.4000	11.1080	7.701	0.07701
-9.5250	3.8100	25.4000	0.0000	11.828	0.11828
-9.5250	1.9050	25.4000	9.7136	14.015	0.14015
-9.5250	0.0000	25.4000	9.5250	14.387	0.14387
-9.5250	-1.9050	25.4000	9.7136	12.227	0.12227
-9.5250	-3.8100	25.4000	10.2587	8.472	0.08472
-9.5250	-5.7150	25.4000	11.1080	4.163	0.04163
9.5250	5.7150	25.4000	11.1080	4.878	0.04878
9.5250	3.8100	25.4000	10.2587	8.177	0.08177
9.5250	1.9050	25.4000	9.7136	12.111	0.12111
9.5250	0.0000	25.4000	9.5250	14.369	0.14369
9.5250	-1.9050	25.4000	9.7136	13.961	0.13961
9.5250	-3.8100	25.4000	10.2587	11.057	0.11057
9.5250	-5.7150	25.4000	11.1080	6.282	0.06282
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
0.0000	37.0459	76.2000	37.0459	0.000	0.00000
0.0000	31.7500	76.2000	31.7500	0.000	0.00000
0.0000	26.4541	76.2000	26.4541	0.000	0.00000
0.0000	21.1709	76.2000	21.1709	0.000	0.00000
0.0000	15.8750	76.2000	15.8750	0.439	0.00439
0.0000	10.5791	76.2000	10.5791	2.448	0.02448
0.0000	5.2959	76.2000	5.2959	4.428	0.04428
0.0000	0.0000	76.2000	0.0000	5.278	0.05278
0.0000	-5.2959	76.2000	5.2959	4.538	0.04538
0.0000	-10.5791	76.2000	10.5791	2.451	0.02451
0.0000	-15.8750	76.2000	15.8750	0.420	0.00420
0.0000	-21.1709	76.2000	21.1709	0.000	0.00000
0.0000	-26.4541	76.2000	26.4541	0.000	0.00000
0.0000	-31.7500	76.2000	31.7500	0.000	0.00000
0.0000	-37.0459	76.2000	37.0459	0.000	0.00000
-5.2959	-37.0459	76.2000	37.4225	0.000	0.00000
-5.2959	-31.7500	76.2000	32.1886	0.000	0.00000
-5.2959	-26.4541	76.2000	26.9790	0.000	0.00000
-5.2959	-21.1709	76.2000	21.8232	0.000	0.00000
-5.2959	-15.8750	76.2000	16.7351	0.257	0.00257
-5.2959	-10.5791	76.2000	11.8306	1.810	0.01810
-5.2959	-5.2959	76.2000	7.4895	3.837	0.03837
-5.2959	0.0000	76.2000	5.2959	4.702	0.04702
-5.2959	5.2959	76.2000	7.4895	3.864	0.03864
-5.2959	10.5791	76.2000	11.8306	2.082	0.02082
-5.2959	15.8750	76.2000	16.7351	0.358	0.00358
-5.2959	21.1709	76.2000	21.8232	0.000	0.00000
-5.2959	26.4541	76.2000	26.9790	0.000	0.00000
-5.2959	31.7500	76.2000	32.1886	0.000	0.00000
-5.2959	37.0459	76.2000	37.4225	0.000	0.00000
-10.5791	37.0459	76.2000	38.5268	0.000	0.00000
-10.5791	31.7500	76.2000	33.4661	0.000	0.00000
-10.5791	26.4541	76.2000	28.4910	0.000	0.00000
-10.5791	21.1709	76.2000	23.6669	0.000	0.00000
-10.5791	15.8750	76.2000	19.0770	0.071	0.00071
-10.5791	10.5791	76.2000	14.9611	0.643	0.00643
-10.5791	5.2959	76.2000	11.8306	1.834	0.01834
-10.5791	0.0000	76.2000	10.5791	2.768	0.02768
-10.5791	-5.2959	76.2000	11.8306	1.912	0.01912
-10.5791	-10.5791	76.2000	14.9611	0.598	0.00598
-10.5791	-15.8750	76.2000	19.0770	0.036	0.00036
-10.5791	-21.1709	76.2000	23.6669	0.000	0.00000
-10.5791	-26.4541	76.2000	28.4910	0.000	0.00000
-10.5791	-31.7500	76.2000	33.4661	0.000	0.00000
-10.5791	-37.0459	76.2000	38.5268	0.000	0.00000
-15.8750	-31.7500	76.2000	35.4976	0.000	0.00000
-15.8750	-26.4541	76.2000	30.8518	0.000	0.00000
-15.8750	-21.1709	76.2000	26.4617	0.000	0.00000
-15.8750	-15.8750	76.2000	22.4506	0.000	0.00000

-15.8750	-10.5791	76.2000	19.0770	0.039	0.00039
-15.8750	-5.2959	76.2000	16.7351	0.311	0.00311
-15.8750	0.0000	76.2000	15.8750	0.538	0.00538
-15.8750	5.2959	76.2000	16.7351	0.250	0.00250
-15.8750	10.5791	76.2000	19.0770	0.034	0.00034
-15.8750	15.8750	76.2000	22.4506	0.000	0.00000
-15.8750	21.1709	76.2000	26.4617	0.000	0.00000
-15.8750	26.4541	76.2000	30.8518	0.000	0.00000
-15.8750	31.7500	76.2000	35.4976	0.000	0.00000
-21.1709	31.7500	76.2000	38.1611	0.000	0.00000
-21.1709	26.4541	76.2000	33.8825	0.000	0.00000
-21.1709	21.1709	76.2000	29.9402	0.000	0.00000
-21.1709	15.8750	76.2000	26.4617	0.000	0.00000
-21.1709	10.5791	76.2000	23.6669	0.000	0.00000
-21.1709	5.2959	76.2000	21.8232	0.000	0.00000
-21.1709	0.0000	76.2000	21.1709	0.011	0.00011
-21.1709	-5.2959	76.2000	21.8232	0.000	0.00000
-21.1709	-10.5791	76.2000	23.6669	0.000	0.00000
-21.1709	-15.8750	76.2000	26.4617	0.000	0.00000
-21.1709	-21.1709	76.2000	29.9402	0.000	0.00000
-21.1709	-26.4541	76.2000	33.8825	0.000	0.00000
-21.1709	-31.7500	76.2000	38.1611	0.000	0.00000
-26.4541	-26.4541	76.2000	37.4117	0.000	0.00000
-26.4541	-21.1709	76.2000	33.8825	0.000	0.00000
-26.4541	-15.8750	76.2000	30.8518	0.000	0.00000
-26.4541	-10.5791	76.2000	28.4910	0.000	0.00000
-26.4541	-5.2959	76.2000	26.9790	0.000	0.00000
-26.4541	0.0000	76.2000	26.4541	0.000	0.00000
-26.4541	5.2959	76.2000	26.9790	0.000	0.00000
-26.4541	10.5791	76.2000	28.4910	0.000	0.00000
-26.4541	15.8750	76.2000	30.8518	0.000	0.00000
-26.4541	21.1709	76.2000	33.8825	0.000	0.00000
-26.4541	26.4541	76.2000	37.4117	0.000	0.00000
-31.7500	21.1709	76.2000	38.1611	0.000	0.00000
-31.7500	15.8750	76.2000	35.4976	0.000	0.00000
-31.7500	10.5791	76.2000	33.4661	0.000	0.00000
-31.7500	5.2959	76.2000	32.1886	0.000	0.00000
-31.7500	0.0000	76.2000	31.7500	0.000	0.00000
-31.7500	-5.2959	76.2000	32.1886	0.000	0.00000
-31.7500	-10.5791	76.2000	33.4661	0.000	0.00000
-31.7500	-15.8750	76.2000	35.4976	0.000	0.00000
-31.7500	-21.1709	76.2000	38.1611	0.000	0.00000
-37.0459	-10.5791	76.2000	38.5268	0.000	0.00000
-37.0459	-5.2959	76.2000	37.4225	0.000	0.00000
-37.0459	0.0000	76.2000	37.0459	0.000	0.00000
-37.0459	5.2959	76.2000	37.4225	0.000	0.00000
-37.0459	10.5791	76.2000	38.5268	0.000	0.00000
0.0000	7.9502	76.2000	7.9502	3.662	0.03662
0.0000	2.6543	76.2000	2.6543	5.079	0.05079
0.0000	-2.6543	76.2000	2.6543	5.051	0.05051
0.0000	-7.9502	76.2000	7.9502	3.521	0.03521
-2.6543	-10.5791	76.2000	10.9070	2.432	0.02432
-2.6543	-7.9502	76.2000	8.3816	3.521	0.03521
-2.6543	-5.2959	76.2000	5.9238	4.351	0.04351
-2.6543	-2.6543	76.2000	3.7537	4.940	0.04940
-2.6543	0.0000	76.2000	2.6543	5.208	0.05208
-2.6543	2.6543	76.2000	3.7537	5.032	0.05032
-2.6543	5.2959	76.2000	5.9238	4.420	0.04420
-2.6543	7.9502	76.2000	8.3816	3.558	0.03558
-2.6543	10.5791	76.2000	10.9070	2.402	0.02402
-5.2959	7.9502	76.2000	9.5526	2.963	0.02963
-5.2959	2.6543	76.2000	5.9238	4.460	0.04460
-5.2959	-2.6543	76.2000	5.9238	4.467	0.04467
-5.2959	-7.9502	76.2000	9.5526	3.006	0.03006
-7.9502	-7.9502	76.2000	11.2433	2.161	0.02161
-7.9502	-5.2959	76.2000	9.5526	2.942	0.02942
-7.9502	-2.6543	76.2000	8.3816	3.555	0.03555
-7.9502	0.0000	76.2000	7.9502	3.913	0.03913
-7.9502	2.6543	76.2000	8.3816	3.687	0.03687
-7.9502	5.2959	76.2000	9.5526	3.008	0.03008
-7.9502	7.9502	76.2000	11.2433	2.099	0.02099
-10.5791	2.6543	76.2000	10.9070	2.572	0.02572
-10.5791	-2.6543	76.2000	10.9070	2.475	0.02475
Plane: 152.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
0.0000	37.0459	152.4000	37.0459	0.000	0.00000
0.0000	31.7500	152.4000	31.7500	0.000	0.00000
0.0000	26.4541	152.4000	26.4541	0.034	0.00034
0.0000	21.1709	152.4000	21.1709	0.228	0.00228
0.0000	15.8750	152.4000	15.8750	0.912	0.00912

0.0000	10.5791	152.4000	10.5791	1.839	0.01839
0.0000	5.2959	152.4000	5.2959	2.496	0.02496
0.0000	0.0000	152.4000	0.0000	2.781	0.02781
0.0000	-5.2959	152.4000	5.2959	2.552	0.02552
0.0000	-10.5791	152.4000	10.5791	2.004	0.02004
0.0000	-15.8750	152.4000	15.8750	1.117	0.01117
0.0000	-21.1709	152.4000	21.1709	0.298	0.00298
0.0000	-26.4541	152.4000	26.4541	0.030	0.00030
0.0000	-31.7500	152.4000	31.7500	0.000	0.00000
0.0000	-37.0459	152.4000	37.0459	0.000	0.00000
-5.2959	-37.0459	152.4000	37.4225	0.000	0.00000
-5.2959	-31.7500	152.4000	32.1886	0.000	0.00000
-5.2959	-26.4541	152.4000	26.9790	0.025	0.00025
-5.2959	-21.1709	152.4000	21.8232	0.252	0.00252
-5.2959	-15.8750	152.4000	16.7351	0.995	0.00995
-5.2959	-10.5791	152.4000	11.8306	1.927	0.01927
-5.2959	-5.2959	152.4000	7.4895	2.535	0.02535
-5.2959	0.0000	152.4000	5.2959	2.681	0.02681
-5.2959	5.2959	152.4000	7.4895	2.402	0.02402
-5.2959	10.5791	152.4000	11.8306	1.776	0.01776
-5.2959	15.8750	152.4000	16.7351	0.892	0.00892
-5.2959	21.1709	152.4000	21.8232	0.244	0.00244
-5.2959	26.4541	152.4000	26.9790	0.041	0.00041
-5.2959	31.7500	152.4000	32.1886	0.000	0.00000
-5.2959	37.0459	152.4000	37.4225	0.000	0.00000
-10.5791	37.0459	152.4000	38.5268	0.000	0.00000
-10.5791	31.7500	152.4000	33.4661	0.000	0.00000
-10.5791	26.4541	152.4000	28.4910	0.025	0.00025
-10.5791	21.1709	152.4000	23.6669	0.139	0.00139
-10.5791	15.8750	152.4000	19.0770	0.541	0.00541
-10.5791	10.5791	152.4000	14.9611	1.115	0.01115
-10.5791	5.2959	152.4000	11.8306	1.761	0.01761
-10.5791	0.0000	152.4000	10.5791	2.080	0.02080
-10.5791	-5.2959	152.4000	11.8306	1.901	0.01901
-10.5791	-10.5791	152.4000	14.9611	1.318	0.01318
-10.5791	-15.8750	152.4000	19.0770	0.554	0.00554
-10.5791	-21.1709	152.4000	23.6669	0.120	0.00120
-10.5791	-26.4541	152.4000	28.4910	0.013	0.00013
-10.5791	-31.7500	152.4000	33.4661	0.000	0.00000
-10.5791	-37.0459	152.4000	38.5268	0.000	0.00000
-15.8750	-31.7500	152.4000	35.4976	0.000	0.00000
-15.8750	-26.4541	152.4000	30.8518	0.000	0.00000
-15.8750	-21.1709	152.4000	26.4617	0.028	0.00028
-15.8750	-15.8750	152.4000	22.4506	0.179	0.00179
-15.8750	-10.5791	152.4000	19.0770	0.538	0.00538
-15.8750	-5.2959	152.4000	16.7351	0.945	0.00945
-15.8750	0.0000	152.4000	15.8750	1.084	0.01084
-15.8750	5.2959	152.4000	16.7351	0.828	0.00828
-15.8750	10.5791	152.4000	19.0770	0.449	0.00449
-15.8750	15.8750	152.4000	22.4506	0.179	0.00179
-15.8750	21.1709	152.4000	26.4617	0.050	0.00050
-15.8750	26.4541	152.4000	30.8518	0.000	0.00000
-15.8750	31.7500	152.4000	35.4976	0.000	0.00000
-21.1709	31.7500	152.4000	38.1611	0.000	0.00000
-21.1709	26.4541	152.4000	33.8825	0.000	0.00000
-21.1709	21.1709	152.4000	29.9402	0.006	0.00006
-21.1709	15.8750	152.4000	26.4617	0.040	0.00040
-21.1709	10.5791	152.4000	23.6669	0.092	0.00092
-21.1709	5.2959	152.4000	21.8232	0.204	0.00204
-21.1709	0.0000	152.4000	21.1709	0.284	0.00284
-21.1709	-5.2959	152.4000	21.8232	0.231	0.00231
-21.1709	-10.5791	152.4000	23.6669	0.113	0.00113
-21.1709	-15.8750	152.4000	26.4617	0.030	0.00030
-21.1709	-21.1709	152.4000	29.9402	0.000	0.00000
-21.1709	-26.4541	152.4000	33.8825	0.000	0.00000
-21.1709	-31.7500	152.4000	38.1611	0.000	0.00000
-26.4541	-26.4541	152.4000	37.4117	0.000	0.00000
-26.4541	-21.1709	152.4000	33.8825	0.000	0.00000
-26.4541	-15.8750	152.4000	30.8518	0.000	0.00000
-26.4541	-10.5791	152.4000	28.4910	0.017	0.00017
-26.4541	-5.2959	152.4000	26.9790	0.029	0.00029
-26.4541	0.0000	152.4000	26.4541	0.033	0.00033
-26.4541	5.2959	152.4000	26.9790	0.025	0.00025
-26.4541	10.5791	152.4000	28.4910	0.014	0.00014
-26.4541	15.8750	152.4000	30.8518	0.000	0.00000
-26.4541	21.1709	152.4000	33.8825	0.000	0.00000
-26.4541	26.4541	152.4000	37.4117	0.000	0.00000
-31.7500	21.1709	152.4000	38.1611	0.000	0.00000
-31.7500	15.8750	152.4000	35.4976	0.000	0.00000
-31.7500	10.5791	152.4000	33.4661	0.000	0.00000

-31.7500	5.2959	152.4000	32.1886	0.000	0.00000
-31.7500	0.0000	152.4000	31.7500	0.000	0.00000
-31.7500	-5.2959	152.4000	32.1886	0.000	0.00000
-31.7500	-10.5791	152.4000	33.4661	0.000	0.00000
-31.7500	-15.8750	152.4000	35.4976	0.000	0.00000
-31.7500	-21.1709	152.4000	38.1611	0.000	0.00000
-37.0459	-10.5791	152.4000	38.5268	0.000	0.00000
-37.0459	-5.2959	152.4000	37.4225	0.000	0.00000
-37.0459	0.0000	152.4000	37.0459	0.000	0.00000
-37.0459	5.2959	152.4000	37.4225	0.000	0.00000
-37.0459	10.5791	152.4000	38.5268	0.000	0.00000
Case: Axial Traverse					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 [%]	Mole Fraction
0.0000	0.0000	12.7000	0.0000	49.803	0.49803
0.0000	0.0000	19.0500	0.0000	45.521	0.45521
0.0000	0.0000	25.4000	0.0000	38.425	0.38425
0.0000	0.0000	31.7500	0.0000	26.340	0.26340
0.0000	0.0000	38.1000	0.0000	16.583	0.16583
0.0000	0.0000	44.4500	0.0000	11.546	0.11546
0.0000	0.0000	50.8000	0.0000	8.818	0.08818
0.0000	0.0000	57.1500	0.0000	7.394	0.07394
0.0000	0.0000	63.5000	0.0000	6.459	0.06459
0.0000	0.0000	69.8500	0.0000	5.767	0.05767
0.0000	0.0000	76.2000	0.0000	5.050	0.05050
0.0000	0.0000	82.5500	0.0000	4.767	0.04767
0.0000	0.0000	88.9000	0.0000	4.449	0.04449
0.0000	0.0000	95.2500	0.0000	4.141	0.04141
0.0000	0.0000	101.6000	0.0000	3.977	0.03977
0.0000	0.0000	107.9500	0.0000	3.664	0.03664
0.0000	0.0000	114.3000	0.0000	3.521	0.03521
0.0000	0.0000	120.6500	0.0000	3.333	0.03333
0.0000	0.0000	127.0000	0.0000	3.180	0.03180
0.0000	0.0000	133.3500	0.0000	3.000	0.03000
0.0000	0.0000	139.7000	0.0000	2.929	0.02929
0.0000	0.0000	146.0500	0.0000	2.778	0.02778
0.0000	0.0000	152.4000	0.0000	2.652	0.02652

Table B-10: Velocity field data. Case 2

Hardware Configuration: A				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.000369 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.5294	0.0000	25.4853	39.5294	0.2947	-0.0746
-38.7117	0.0000	25.4853	38.7117	0.0940	-0.0686
-37.8939	0.0000	25.4853	37.8939	-0.0059	-0.0695
-37.0762	0.0000	25.4853	37.0762	-0.0999	-0.0489
-36.2584	0.0000	25.4853	36.2584	-0.1379	-0.0085
-35.4406	0.0000	25.4853	35.4406	-0.0508	-0.0018
-34.6229	0.0000	25.4853	34.6229	0.0451	-0.0126
-33.8051	0.0000	25.4853	33.8051	0.0056	-0.0495
-32.9874	0.0000	25.4853	32.9874	-0.1421	-0.1638
-32.1696	0.0000	25.4853	32.1696	-0.1004	-0.3340
-31.3518	0.0000	25.4853	31.3518	-0.1997	-0.1579
-30.5341	0.0000	25.4853	30.5341	-0.1513	0.8022
-29.7163	0.0000	25.4853	29.7163	0.2057	0.9785
-28.8985	0.0000	25.4853	28.8985	0.3791	1.1747
-28.0808	0.0000	25.4853	28.0808	0.3542	1.8061
-27.2630	0.0000	25.4853	27.2630	0.3205	2.7631
-26.4453	0.0000	25.4853	26.4453	0.2987	3.8434
-25.6275	0.0000	25.4853	25.6275	0.3395	4.6993
-24.8097	0.0000	25.4853	24.8097	0.3763	5.1722
-23.9920	0.0000	25.4853	23.9920	0.3783	5.5979
-23.1742	0.0000	25.4853	23.1742	0.4027	5.9908
-22.3565	0.0000	25.4853	22.3565	0.4641	6.3870
-21.5387	0.0000	25.4853	21.5387	0.5223	6.7839
-20.7209	0.0000	25.4853	20.7209	0.5492	7.1302
-19.9032	0.0000	25.4853	19.9032	0.5811	7.3577
-19.0854	0.0000	25.4853	19.0854	0.6366	7.4866
-18.2676	0.0000	25.4853	18.2676	0.6853	7.6053
-17.4499	0.0000	25.4853	17.4499	0.7131	7.6514
-16.6321	0.0000	25.4853	16.6321	0.7674	7.6515
-15.8144	0.0000	25.4853	15.8144	0.8452	7.6185
-14.9966	0.0000	25.4853	14.9966	0.9255	7.5390
-14.1788	0.0000	25.4853	14.1788	0.9962	7.3825
-13.3611	0.0000	25.4853	13.3611	1.0673	7.1163

-12.5433	0.0000	25.4853	12.5433	1.1122	6.6500
-11.7256	0.0000	25.4853	11.7256	1.0972	5.9619
-10.9078	0.0000	25.4853	10.9078	1.0488	5.1093
-10.0900	0.0000	25.4853	10.0900	0.9510	4.1368
-9.2723	0.0000	25.4853	9.2723	0.8194	3.1326
-8.4545	0.0000	25.4853	8.4545	0.6779	2.2102
-7.6367	0.0000	25.4853	7.6367	0.5305	1.4596
-6.8190	0.0000	25.4853	6.8190	0.3553	0.8805
-6.0012	0.0000	25.4853	6.0012	0.1701	0.4476
-5.1835	0.0000	25.4853	5.1835	-0.0389	0.1697
-4.3657	0.0000	25.4853	4.3657	-0.2322	0.0850
-3.5479	0.0000	25.4853	3.5479	-0.3872	0.2156
-2.7302	0.0000	25.4853	2.7302	-0.4886	0.5243
-1.9124	0.0000	25.4853	1.9124	-0.5267	0.8843
-1.0947	0.0000	25.4853	1.0947	-0.4887	1.1163
-0.2769	0.0000	25.4853	0.2769	-0.3416	1.1290
0.5409	0.0000	25.4853	0.5409	-0.2205	0.9009
1.3586	0.0000	25.4853	1.3586	-0.1271	0.5537
2.1764	0.0000	25.4853	2.1764	-0.0886	0.2532
2.9942	0.0000	25.4853	2.9942	-0.1436	0.0630
3.8119	0.0000	25.4853	3.8119	-0.2856	0.0323
4.6297	0.0000	25.4853	4.6297	-0.4637	0.1764
5.4474	0.0000	25.4853	5.4474	-0.6193	0.4572
6.2652	0.0000	25.4853	6.2652	-0.7282	0.8124
7.0830	0.0000	25.4853	7.0830	-0.8853	1.2259
7.9007	0.0000	25.4853	7.9007	-0.9801	1.7066
8.7185	0.0000	25.4853	8.7185	-0.9958	2.2209
9.5362	0.0000	25.4853	9.5362	-0.9994	2.7542
10.3540	0.0000	25.4853	10.3540	-0.9970	3.2701
11.1718	0.0000	25.4853	11.1718	-0.9645	3.7482
11.9895	0.0000	25.4853	11.9895	-0.9279	4.2145
12.8073	0.0000	25.4853	12.8073	-0.9128	4.6531
13.6251	0.0000	25.4853	13.6251	-0.8558	5.0131
14.4428	0.0000	25.4853	14.4428	-0.7948	5.2855
15.2606	0.0000	25.4853	15.2606	-0.7186	5.4985
16.0783	0.0000	25.4853	16.0783	-0.6240	5.6439
16.8961	0.0000	25.4853	16.8961	-0.5416	5.7586
17.7139	0.0000	25.4853	17.7139	-0.5051	5.9041
18.5316	0.0000	25.4853	18.5316	-0.4975	6.0562
19.3494	0.0000	25.4853	19.3494	-0.5344	6.1873
20.1671	0.0000	25.4853	20.1671	-0.5466	6.2483
20.9849	0.0000	25.4853	20.9849	-0.5362	6.2787
21.8027	0.0000	25.4853	21.8027	-0.5058	6.2965
22.6204	0.0000	25.4853	22.6204	-0.4477	6.2830
23.4382	0.0000	25.4853	23.4382	-0.3778	6.2055
24.2560	0.0000	25.4853	24.2560	-0.3246	6.0444
25.0737	0.0000	25.4853	25.0737	-0.3079	5.8306
25.8915	0.0000	25.4853	25.8915	-0.3752	5.5508
26.7092	0.0000	25.4853	26.7092	-0.3844	5.2012
27.5270	0.0000	25.4853	27.5270	-0.3386	4.7728
28.3448	0.0000	25.4853	28.3448	-0.2876	4.2509
29.1625	0.0000	25.4853	29.1625	-0.2463	3.6132
29.9803	0.0000	25.4853	29.9803	-0.1961	2.7810
30.7980	0.0000	25.4853	30.7980	-0.1122	1.6629
31.6158	0.0000	25.4853	31.6158	0.0022	0.5491
32.4336	0.0000	25.4853	32.4336	0.0160	0.1132
33.2513	0.0000	25.4853	33.2513	0.0958	-0.0183
34.0691	0.0000	25.4853	34.0691	0.0886	-0.0759
34.8869	0.0000	25.4853	34.8869	-0.0178	-0.1207
35.7046	0.0000	25.4853	35.7046	-0.0879	-0.1532
36.5224	0.0000	25.4853	36.5224	-0.0482	-0.1704
37.3401	0.0000	25.4853	37.3401	-0.0342	-0.1786
38.1579	0.0000	25.4853	38.1579	0.0054	-0.1518
38.9757	0.0000	25.4853	38.9757	0.0495	-0.0725
39.7934	0.0000	25.4853	39.7934	0.0699	0.0637
Plane: 76.2 mm downstream of injection					
-39.5243	0.0000	76.3197	39.5243	-0.0381	-0.9814
-38.7015	0.0000	76.3197	38.7015	0.0285	-0.7203
-37.8786	0.0000	76.3197	37.8786	0.2264	-1.6296
-37.0558	0.0000	76.3197	37.0558	0.3335	-1.5012
-36.2329	0.0000	76.3197	36.2329	0.1876	-0.4883
-35.4101	0.0000	76.3197	35.4101	0.0976	-0.0533
-34.5872	0.0000	76.3197	34.5872	0.0225	0.1468
-33.7644	0.0000	76.3197	33.7644	-0.0682	0.4358
-32.9415	0.0000	76.3197	32.9415	-0.1113	0.7333
-32.1186	0.0000	76.3197	32.1186	-0.1174	1.0240
-31.2958	0.0000	76.3197	31.2958	-0.1439	1.3258
-30.4729	0.0000	76.3197	30.4729	-0.1735	1.6639
-29.6501	0.0000	76.3197	29.6501	-0.2080	2.0397
-28.8272	0.0000	76.3197	28.8272	-0.2389	2.4540

-28.0044	0.0000	76.3197	28.0044	-0.2586	2.8960
-27.1815	0.0000	76.3197	27.1815	-0.2652	3.3387
-26.3586	0.0000	76.3197	26.3586	-0.2659	3.7640
-25.5358	0.0000	76.3197	25.5358	-0.2737	4.1872
-24.7129	0.0000	76.3197	24.7129	-0.2660	4.5869
-23.8901	0.0000	76.3197	23.8901	-0.2479	4.9649
-23.0672	0.0000	76.3197	23.0672	-0.2408	5.3057
-22.2444	0.0000	76.3197	22.2444	-0.2288	5.6492
-21.4215	0.0000	76.3197	21.4215	-0.2059	5.9813
-20.5986	0.0000	76.3197	20.5986	-0.1801	6.2770
-19.7758	0.0000	76.3197	19.7758	-0.1624	6.5312
-18.9529	0.0000	76.3197	18.9529	-0.1484	6.7577
-18.1301	0.0000	76.3197	18.1301	-0.1355	6.9358
-17.3072	0.0000	76.3197	17.3072	-0.1265	7.0214
-16.4844	0.0000	76.3197	16.4844	-0.1144	7.0327
-15.6615	0.0000	76.3197	15.6615	-0.0839	6.9645
-14.8387	0.0000	76.3197	14.8387	-0.0487	6.8398
-14.0158	0.0000	76.3197	14.0158	-0.0215	6.6883
-13.1929	0.0000	76.3197	13.1929	0.0003	6.5217
-12.3701	0.0000	76.3197	12.3701	0.0297	6.3226
-11.5472	0.0000	76.3197	11.5472	0.0441	6.0880
-10.7244	0.0000	76.3197	10.7244	0.0390	5.8324
-9.9015	0.0000	76.3197	9.9015	0.0391	5.6034
-9.0787	0.0000	76.3197	9.0787	0.0473	5.4008
-8.2558	0.0000	76.3197	8.2558	0.0450	5.2025
-7.4329	0.0000	76.3197	7.4329	0.0259	5.0039
-6.6101	0.0000	76.3197	6.6101	-0.0004	4.8104
-5.7872	0.0000	76.3197	5.7872	-0.0182	4.6247
-4.9644	0.0000	76.3197	4.9644	-0.0341	4.4391
-4.1415	0.0000	76.3197	4.1415	-0.0435	4.2899
-3.3187	0.0000	76.3197	3.3187	-0.0443	4.1687
-2.4958	0.0000	76.3197	2.4958	-0.0510	4.0633
-1.6729	0.0000	76.3197	1.6729	-0.0625	3.9774
-0.8501	0.0000	76.3197	0.8501	-0.0638	3.9163
-0.0272	0.0000	76.3197	0.0272	-0.0519	3.8837
0.7956	0.0000	76.3197	0.7956	-0.0416	3.8773
1.6185	0.0000	76.3197	1.6185	-0.0387	3.8861
2.4413	0.0000	76.3197	2.4413	-0.0321	3.9158
3.2642	0.0000	76.3197	3.2642	-0.0138	3.9550
4.0870	0.0000	76.3197	4.0870	0.0149	4.0025
4.9099	0.0000	76.3197	4.9099	0.0444	4.0512
5.7328	0.0000	76.3197	5.7328	0.0713	4.0974
6.5556	0.0000	76.3197	6.5556	0.0991	4.1485
7.3785	0.0000	76.3197	7.3785	0.1269	4.2159
8.2013	0.0000	76.3197	8.2013	0.1376	4.2975
9.0242	0.0000	76.3197	9.0242	0.1499	4.3921
9.8470	0.0000	76.3197	9.8470	0.1644	4.5156
10.6699	0.0000	76.3197	10.6699	0.1647	4.6429
11.4928	0.0000	76.3197	11.4928	0.1656	4.7744
12.3156	0.0000	76.3197	12.3156	0.1690	4.9240
13.1385	0.0000	76.3197	13.1385	0.1690	5.1009
13.9613	0.0000	76.3197	13.9613	0.1614	5.2975
14.7842	0.0000	76.3197	14.7842	0.1467	5.4885
15.6070	0.0000	76.3197	15.6070	0.1500	5.6732
16.4299	0.0000	76.3197	16.4299	0.1562	5.8646
17.2528	0.0000	76.3197	17.2528	0.1509	6.0544
18.0756	0.0000	76.3197	18.0756	0.1487	6.2213
18.8985	0.0000	76.3197	18.8985	0.1460	6.3649
19.7213	0.0000	76.3197	19.7213	0.1407	6.4836
20.5442	0.0000	76.3197	20.5442	0.1391	6.5633
21.3670	0.0000	76.3197	21.3670	0.1511	6.5840
22.1899	0.0000	76.3197	22.1899	0.1540	6.4911
23.0128	0.0000	76.3197	23.0128	0.1419	6.2833
23.8356	0.0000	76.3197	23.8356	0.1320	6.0147
24.6585	0.0000	76.3197	24.6585	0.1209	5.6700
25.4813	0.0000	76.3197	25.4813	0.1134	5.2604
26.3042	0.0000	76.3197	26.3042	0.1085	4.8078
27.1270	0.0000	76.3197	27.1270	0.1005	4.3294
27.9499	0.0000	76.3197	27.9499	0.0882	3.8365
28.7727	0.0000	76.3197	28.7727	0.0787	3.3470
29.5956	0.0000	76.3197	29.5956	0.0614	2.8751
30.4185	0.0000	76.3197	30.4185	0.0368	2.4151
31.2413	0.0000	76.3197	31.2413	0.0278	1.9948
32.0642	0.0000	76.3197	32.0642	0.0399	1.6271
32.8870	0.0000	76.3197	32.8870	0.0508	1.2965
33.7099	0.0000	76.3197	33.7099	0.0431	0.9817
34.5327	0.0000	76.3197	34.5327	0.0377	0.6815
35.3556	0.0000	76.3197	35.3556	0.0420	0.4135
36.1785	0.0000	76.3197	36.1785	0.0540	0.2077
37.0013	0.0000	76.3197	37.0013	0.0434	-0.0288

37.8242	0.0000	76.3197	37.8242	0.0133	-0.2759
38.6470	0.0000	76.3197	38.6470	-0.0146	-0.3411
39.4699	0.0000	76.3197	39.4699	-0.0333	-0.2521
Plane: 152.4 mm downstream of injection					
-39.2059	0.0000	152.3093	39.2059	-0.0480	0.1245
-38.3830	0.0000	152.3093	38.3830	-0.0189	-0.0699
-37.5602	0.0000	152.3093	37.5602	-0.0901	-0.0265
-36.7373	0.0000	152.3093	36.7373	-0.1920	0.0903
-35.9145	0.0000	152.3093	35.9145	-0.1344	0.4103
-35.0916	0.0000	152.3093	35.0916	-0.0262	0.4504
-34.2688	0.0000	152.3093	34.2688	0.0025	0.8742
-33.4459	0.0000	152.3093	33.4459	-0.0186	1.5964
-32.6231	0.0000	152.3093	32.6231	-0.0407	2.0782
-31.8002	0.0000	152.3093	31.8002	-0.0758	2.3434
-30.9773	0.0000	152.3093	30.9773	-0.1213	2.5696
-30.1545	0.0000	152.3093	30.1545	-0.1535	2.7894
-29.3316	0.0000	152.3093	29.3316	-0.2045	2.9907
-28.5088	0.0000	152.3093	28.5088	-0.2458	3.1970
-27.6859	0.0000	152.3093	27.6859	-0.2729	3.4198
-26.8631	0.0000	152.3093	26.8631	-0.2849	3.6524
-26.0402	0.0000	152.3093	26.0402	-0.2848	3.8931
-25.2173	0.0000	152.3093	25.2173	-0.2817	4.1324
-24.3945	0.0000	152.3093	24.3945	-0.2795	4.3542
-23.5716	0.0000	152.3093	23.5716	-0.2742	4.5490
-22.7488	0.0000	152.3093	22.7488	-0.2623	4.7351
-21.9259	0.0000	152.3093	21.9259	-0.2402	4.9198
-21.1031	0.0000	152.3093	21.1031	-0.2241	5.0888
-20.2802	0.0000	152.3093	20.2802	-0.2116	5.2455
-19.4573	0.0000	152.3093	19.4573	-0.1997	5.3869
-18.6345	0.0000	152.3093	18.6345	-0.1827	5.5077
-17.8116	0.0000	152.3093	17.8116	-0.1622	5.6042
-16.9888	0.0000	152.3093	16.9888	-0.1476	5.6648
-16.1659	0.0000	152.3093	16.1659	-0.1505	5.6637
-15.3431	0.0000	152.3093	15.3431	-0.1503	5.6471
-14.5202	0.0000	152.3093	14.5202	-0.1289	5.6324
-13.6974	0.0000	152.3093	13.6974	-0.1160	5.5854
-12.8745	0.0000	152.3093	12.8745	-0.0990	5.5209
-12.0516	0.0000	152.3093	12.0516	-0.0699	5.4581
-11.2288	0.0000	152.3093	11.2288	-0.0442	5.4021
-10.4059	0.0000	152.3093	10.4059	-0.0399	5.3429
-9.5831	0.0000	152.3093	9.5831	-0.0461	5.2662
-8.7602	0.0000	152.3093	8.7602	-0.0332	5.1727
-7.9374	0.0000	152.3093	7.9374	-0.0413	5.0689
-7.1145	0.0000	152.3093	7.1145	-0.0555	4.9719
-6.2916	0.0000	152.3093	6.2916	-0.0546	4.8934
-5.4688	0.0000	152.3093	5.4688	-0.0370	4.8244
-4.6459	0.0000	152.3093	4.6459	-0.0164	4.7574
-3.8231	0.0000	152.3093	3.8231	-0.0055	4.6935
-3.0002	0.0000	152.3093	3.0002	-0.0047	4.6355
-2.1774	0.0000	152.3093	2.1774	-0.0056	4.5937
-1.3545	0.0000	152.3093	1.3545	-0.0049	4.5627
-0.5316	0.0000	152.3093	0.5316	-0.0156	4.5397
0.2912	0.0000	152.3093	0.2912	-0.0119	4.5146
1.1141	0.0000	152.3093	1.1141	0.0067	4.4894
1.9369	0.0000	152.3093	1.9369	0.0223	4.4649
2.7598	0.0000	152.3093	2.7598	0.0288	4.4399
3.5826	0.0000	152.3093	3.5826	0.0407	4.4146
4.4055	0.0000	152.3093	4.4055	0.0443	4.3918
5.2283	0.0000	152.3093	5.2283	0.0597	4.3725
6.0512	0.0000	152.3093	6.0512	0.0644	4.3532
6.8741	0.0000	152.3093	6.8741	0.0694	4.3432
7.6969	0.0000	152.3093	7.6969	0.0940	4.3414
8.5198	0.0000	152.3093	8.5198	0.1187	4.3390
9.3426	0.0000	152.3093	9.3426	0.1208	4.3383
10.1655	0.0000	152.3093	10.1655	0.1085	4.3574
10.9883	0.0000	152.3093	10.9883	0.1035	4.4081
11.8112	0.0000	152.3093	11.8112	0.0935	4.4723
12.6341	0.0000	152.3093	12.6341	0.0873	4.5299
13.4569	0.0000	152.3093	13.4569	0.0957	4.5995
14.2798	0.0000	152.3093	14.2798	0.1024	4.6835
15.1026	0.0000	152.3093	15.1026	0.0971	4.7784
15.9255	0.0000	152.3093	15.9255	0.0859	4.8835
16.7483	0.0000	152.3093	16.7483	0.0821	4.9930
17.5712	0.0000	152.3093	17.5712	0.0791	5.0885
18.3941	0.0000	152.3093	18.3941	0.0688	5.1558
19.2169	0.0000	152.3093	19.2169	0.0607	5.2215
20.0398	0.0000	152.3093	20.0398	0.0621	5.2791
20.8626	0.0000	152.3093	20.8626	0.0638	5.3088
21.6855	0.0000	152.3093	21.6855	0.0575	5.3068
22.5083	0.0000	152.3093	22.5083	0.0520	5.2801

23.3312	0.0000	152.3093	23.3312	0.0638	5.2329
24.1540	0.0000	152.3093	24.1540	0.0887	5.1517
24.9769	0.0000	152.3093	24.9769	0.1083	5.0023
25.7998	0.0000	152.3093	25.7998	0.1122	4.7992
26.6226	0.0000	152.3093	26.6226	0.1103	4.5727
27.4455	0.0000	152.3093	27.4455	0.1119	4.3391
28.2683	0.0000	152.3093	28.2683	0.1108	4.1115
29.0912	0.0000	152.3093	29.0912	0.1058	3.8882
29.9140	0.0000	152.3093	29.9140	0.1050	3.6572
30.7369	0.0000	152.3093	30.7369	0.1051	3.4066
31.5598	0.0000	152.3093	31.5598	0.0758	3.1326
32.3826	0.0000	152.3093	32.3826	0.0542	2.8759
33.2055	0.0000	152.3093	33.2055	0.0354	2.6404
34.0283	0.0000	152.3093	34.0283	0.0224	2.4204
34.8512	0.0000	152.3093	34.8512	0.0136	2.2157
35.6740	0.0000	152.3093	35.6740	0.0078	2.0286
36.4969	0.0000	152.3093	36.4969	0.0102	1.8562
37.3198	0.0000	152.3093	37.3198	0.0241	1.6659
38.1426	0.0000	152.3093	38.1426	0.0092	1.2894
38.9655	0.0000	152.3093	38.9655	-0.0219	0.5180
39.7883	0.0000	152.3093	39.7883	-0.0145	0.0399

B.13.4 Case 3: Non-Swirling Radial Injection of Methane

Table B-11: Spatial fuel concentration data. Case 3

Hardware Configuration: B
Bulk Flow Type: Air
Bulk Flow Rate: 1.116 kg/min
Plane: 25.4 mm downstream of injection

Measurement Technique: Flame Ionization Detector
Fuel Type: Methane
Fuel Flow Rate: 0.00864 kg/min

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Voltage [V]	Volume CH ₄	
					[%]	Mole Fraction
0.0000	30.4800	25.4000	30.4800	0.000	0.00	0.0000
0.0000	26.6700	25.4000	26.6700	0.000	0.00	0.0000
0.0000	22.8600	25.4000	22.8600	0.008	0.08	0.0008
0.0000	19.0500	25.4000	19.0500	0.145	1.45	0.0145
0.0000	15.2400	25.4000	15.2400	0.150	1.50	0.0150
0.0000	14.2875	25.4000	14.2875	0.123	1.23	0.0123
0.0000	-14.2875	25.4000	14.2875	0.071	0.71	0.0071
0.0000	-15.2400	25.4000	15.2400	0.092	0.92	0.0092
0.0000	-19.0500	25.4000	19.0500	0.044	0.44	0.0044
0.0000	-22.8600	25.4000	22.8600	0.002	0.02	0.0002
0.0000	-26.6700	25.4000	26.6700	0.000	0.00	0.0000
0.0000	-30.4800	25.4000	30.4800	0.000	0.00	0.0000
-3.8100	-30.4800	25.4000	30.7172	0.000	0.00	0.0000
-3.8100	-26.6700	25.4000	26.9408	0.000	0.00	0.0000
-3.8100	-22.8600	25.4000	23.1753	0.048	0.48	0.0048
-3.8100	-19.0500	25.4000	19.4273	0.657	6.57	0.0657
-3.8100	-15.2400	25.4000	15.7090	0.676	6.76	0.0676
-3.8100	-13.7033	25.4000	14.2231	0.399	3.99	0.0399
-3.8100	13.7033	25.4000	14.2231	0.325	3.25	0.0325
-3.8100	15.2400	25.4000	15.7090	0.614	6.14	0.0614
-3.8100	19.0500	25.4000	19.4273	0.511	5.11	0.0511
-3.8100	22.8600	25.4000	23.1753	0.021	0.21	0.0021
-3.8100	26.6700	25.4000	26.9408	0.000	0.00	0.0000
-3.8100	30.4800	25.4000	30.7172	0.000	0.00	0.0000
-7.6200	26.6700	25.4000	27.7372	0.000	0.00	0.0000
-7.6200	22.8600	25.4000	24.0966	0.054	0.54	0.0054
-7.6200	19.0500	25.4000	20.5175	0.787	7.87	0.0787
-7.6200	15.2400	25.4000	17.0388	0.727	7.27	0.0727
-7.6200	11.4300	25.4000	13.7372	0.166	1.66	0.0166
-7.6200	-11.4300	25.4000	13.7372	0.229	2.29	0.0229
-7.6200	-15.2400	25.4000	17.0388	0.832	8.32	0.0832
-7.6200	-19.0500	25.4000	20.5175	0.727	7.27	0.0727
-7.6200	-22.8600	25.4000	24.0966	0.063	0.63	0.0063
-7.6200	-26.6700	25.4000	27.7372	0.000	0.00	0.0000
-10.1092	-10.1092	25.4000	14.2966	0.090	0.90	0.0090
-10.1092	10.1092	25.4000	14.2966	0.080	0.80	0.0080
-11.4300	-26.6700	25.4000	29.0161	0.000	0.00	0.0000
-11.4300	-22.8600	25.4000	25.5583	0.011	0.11	0.0011
-11.4300	-19.0500	25.4000	22.2159	0.182	1.82	0.0182
-11.4300	-15.2400	25.4000	19.0500	0.288	2.88	0.0288
-11.4300	-11.4300	25.4000	16.1645	0.110	1.10	0.0110
-11.4300	-7.6200	25.4000	13.7372	0.157	1.57	0.0157
-11.4300	7.6200	25.4000	13.7372	0.175	1.75	0.0175
-11.4300	11.4300	25.4000	16.1645	0.102	1.02	0.0102
-11.4300	15.2400	25.4000	19.0500	0.485	4.85	0.0485

-11.4300	19.0500	25.4000	22.2159	0.307	3.07	0.0307
-11.4300	22.8600	25.4000	25.5583	0.010	0.10	0.0010
-11.4300	26.6700	25.4000	29.0161	0.000	0.00	0.0000
-13.7033	3.8100	25.4000	14.2231	0.436	4.36	0.0436
-13.7033	-3.8100	25.4000	14.2231	0.404	4.04	0.0404
-14.2875	0.0000	25.4000	14.2875	0.089	0.89	0.0089
-15.2400	26.6700	25.4000	30.7172	0.000	0.00	0.0000
-15.2400	22.8600	25.4000	27.4743	0.000	0.00	0.0000
-15.2400	19.0500	25.4000	24.3959	0.001	0.01	0.0001
-15.2400	15.2400	25.4000	21.5526	0.003	0.03	0.0003
-15.2400	11.4300	25.4000	19.0500	0.246	2.46	0.0246
-15.2400	7.6200	25.4000	17.0388	0.887	8.87	0.0887
-15.2400	3.8100	25.4000	15.7090	0.665	6.65	0.0665
-15.2400	0.0000	25.4000	15.2400	0.110	1.10	0.0110
-15.2400	-3.8100	25.4000	15.7090	0.581	5.81	0.0581
-15.2400	-7.6200	25.4000	17.0388	0.878	8.78	0.0878
-15.2400	-11.4300	25.4000	19.0500	0.463	4.63	0.0463
-15.2400	-15.2400	25.4000	21.5526	0.014	0.14	0.0014
-15.2400	-19.0500	25.4000	24.3959	0.001	0.01	0.0001
-15.2400	-22.8600	25.4000	27.4743	0.000	0.00	0.0000
-15.2400	-26.6700	25.4000	30.7172	0.000	0.00	0.0000
-19.0500	-22.8600	25.4000	29.7571	0.000	0.00	0.0000
-19.0500	-19.0500	25.4000	26.9408	0.000	0.00	0.0000
-19.0500	-15.2400	25.4000	24.3959	0.004	0.04	0.0004
-19.0500	-11.4300	25.4000	22.2159	0.204	2.04	0.0204
-19.0500	-7.6200	25.4000	20.5175	0.613	6.13	0.0613
-19.0500	-3.8100	25.4000	19.4273	0.291	2.91	0.0291
-19.0500	0.0000	25.4000	19.0500	0.047	0.47	0.0047
-19.0500	3.8100	25.4000	19.4273	0.580	5.80	0.0580
-19.0500	7.6200	25.4000	20.5175	0.677	6.77	0.0677
-19.0500	11.4300	25.4000	22.2159	0.130	1.30	0.0130
-19.0500	15.2400	25.4000	24.3959	0.001	0.01	0.0001
-19.0500	19.0500	25.4000	26.9408	0.000	0.00	0.0000
-19.0500	22.8600	25.4000	29.7571	0.000	0.00	0.0000
-22.8600	19.0500	25.4000	29.7571	0.000	0.00	0.0000
-22.8600	15.2400	25.4000	27.4743	0.000	0.00	0.0000
-22.8600	11.4300	25.4000	25.5583	0.005	0.05	0.0005
-22.8600	7.6200	25.4000	24.0966	0.044	0.44	0.0044
-22.8600	3.8100	25.4000	23.1753	0.037	0.37	0.0037
-22.8600	0.0000	25.4000	22.8600	0.002	0.02	0.0002
-22.8600	-3.8100	25.4000	23.1753	0.016	0.16	0.0016
-22.8600	-7.6200	25.4000	24.0966	0.039	0.39	0.0039
-22.8600	-11.4300	25.4000	25.5583	0.008	0.08	0.0008
-22.8600	-15.2400	25.4000	27.4743	0.000	0.00	0.0000
-22.8600	-19.0500	25.4000	29.7571	0.000	0.00	0.0000
-26.6700	-15.2400	25.4000	30.7172	0.000	0.00	0.0000
-26.6700	-11.4300	25.4000	29.0161	0.000	0.00	0.0000
-26.6700	-7.6200	25.4000	27.7372	0.000	0.00	0.0000
-26.6700	-3.8100	25.4000	26.9408	0.000	0.00	0.0000
-26.6700	0.0000	25.4000	26.6700	0.000	0.00	0.0000
-26.6700	3.8100	25.4000	26.9408	0.000	0.00	0.0000
-26.6700	7.6200	25.4000	27.7372	0.000	0.00	0.0000
-26.6700	11.4300	25.4000	29.0161	0.000	0.00	0.0000
-26.6700	15.2400	25.4000	30.7172	0.000	0.00	0.0000
-30.4800	3.8100	25.4000	30.7172	0.000	0.00	0.0000
-30.4800	0.0000	25.4000	30.4800	0.000	0.00	0.0000
-30.4800	-3.8100	25.4000	30.7172	0.000	0.00	0.0000
-19.0500	-5.7150	25.4000	19.8888	0.752	7.52	0.0752
-19.0500	-1.9050	25.4000	19.1450	0.145	1.45	0.0145
-19.0500	1.9050	25.4000	19.1450	0.305	3.05	0.0305
-19.0500	5.7150	25.4000	19.8888	0.812	8.12	0.0812
-17.1450	9.5250	25.4000	19.6132	0.660	6.60	0.0660
-17.1450	7.6200	25.4000	18.7621	0.911	9.11	0.0911
-17.1450	5.7150	25.4000	18.0724	0.886	8.86	0.0886
-17.1450	3.8100	25.4000	17.5632	0.734	7.34	0.0734
-17.1450	1.9050	25.4000	17.2505	0.382	3.82	0.0382
-17.1450	0.0000	25.4000	17.1450	0.109	1.09	0.0109
-17.1450	-1.9050	25.4000	17.2505	0.216	2.16	0.0216
-17.1450	-3.8100	25.4000	17.5632	0.607	6.07	0.0607
-17.1450	-5.7150	25.4000	18.0724	0.875	8.75	0.0875
-17.1450	-7.6200	25.4000	18.7621	0.936	9.36	0.0936
-17.1450	-9.5250	25.4000	19.6132	0.916	9.16	0.0916
-15.2400	-13.3350	25.4000	20.2504	0.115	1.15	0.0115
-15.2400	-9.5250	25.4000	17.9717	0.825	8.25	0.0825
-15.2400	-5.7150	25.4000	16.2763	0.802	8.02	0.0802
-15.2400	-1.9050	25.4000	15.3586	0.210	2.10	0.0210
-15.2400	1.9050	25.4000	15.3586	0.362	3.62	0.0362
-15.2400	5.7150	25.4000	16.2763	0.816	8.16	0.0816
-15.2400	9.5250	25.4000	17.9717	0.640	6.40	0.0640
-15.2400	13.3350	25.4000	20.2504	0.035	0.35	0.0035

-13.3350	13.3350	25.4000	18.8585	0.084	0.84	0.0084
-13.3350	11.4300	25.4000	17.5632	0.107	1.07	0.0107
-13.3350	9.5250	25.4000	16.3874	0.325	3.25	0.0325
-13.3350	-9.5250	25.4000	16.3874	0.396	3.96	0.0396
-13.3350	-11.4300	25.4000	17.5632	0.213	2.13	0.0213
-13.3350	-13.3350	25.4000	18.8585	0.078	0.78	0.0078
-11.4300	-13.3350	25.4000	17.5632	0.205	2.05	0.0205
-11.4300	13.3350	25.4000	17.5632	0.330	3.30	0.0330
-9.5250	17.1450	25.4000	19.6132	0.870	8.70	0.0870
-9.5250	15.2400	25.4000	17.9717	0.795	7.95	0.0795
-9.5250	13.3350	25.4000	16.3874	0.520	5.20	0.0520
-9.5250	-13.3350	25.4000	16.3874	0.476	4.76	0.0476
-9.5250	-15.2400	25.4000	17.9717	0.741	7.41	0.0741
-9.5250	-17.1450	25.4000	19.6132	0.780	7.80	0.0780
-7.6200	-17.1450	25.4000	18.7621	0.932	9.32	0.0932
-7.6200	17.1450	25.4000	18.7621	0.929	9.29	0.0929
-5.7150	19.0500	25.4000	19.8888	0.575	5.75	0.0575
-5.7150	17.1450	25.4000	18.0724	0.839	8.39	0.0839
-5.7150	15.2400	25.4000	16.2763	0.679	6.79	0.0679
-5.7150	-15.2400	25.4000	16.2763	0.686	6.86	0.0686
-5.7150	-17.1450	25.4000	18.0724	0.903	9.03	0.0903
-5.7150	-19.0500	25.4000	19.8888	0.757	7.57	0.0757
-3.8100	-17.1450	25.4000	17.5632	0.680	6.80	0.0680
-3.8100	17.1450	25.4000	17.5632	0.450	4.50	0.0450
-1.9050	-19.0500	25.4000	19.1450	0.152	1.52	0.0152
-1.9050	-17.1450	25.4000	17.2505	0.268	2.68	0.0268
-1.9050	17.1450	25.4000	17.2505	0.127	1.27	0.0127
-1.9050	19.0500	25.4000	19.1450	0.057	0.57	0.0057
0.0000	17.1450	25.4000	17.1450	0.205	2.05	0.0205
0.0000	-17.1450	25.4000	17.1450	0.093	0.93	0.0093

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Voltage [V]	Volume CH4 [%]	Mole Fraction
-37.0459	-10.5791	76.2000	38.5268	0.048	0.158	0.0016
-37.0459	-5.2959	76.2000	37.4225	0.041	0.135	0.0014
-37.0459	0.0000	76.2000	37.0459	0.038	0.125	0.0013
-37.0459	5.2959	76.2000	37.4225	0.032	0.106	0.0011
-37.0459	10.5791	76.2000	38.5268	0.036	0.119	0.0012
-31.7500	-21.1709	76.2000	38.1611	0.032	0.106	0.0011
-31.7500	-15.8750	76.2000	35.4976	0.038	0.125	0.0013
-31.7500	-10.5791	76.2000	33.4661	0.040	0.132	0.0013
-31.7500	-5.2959	76.2000	32.1886	0.039	0.129	0.0013
-31.7500	0.0000	76.2000	31.7500	0.036	0.119	0.0012
-31.7500	5.2959	76.2000	32.1886	0.035	0.116	0.0012
-31.7500	10.5791	76.2000	33.4661	0.033	0.109	0.0011
-31.7500	15.8750	76.2000	35.4976	0.028	0.092	0.0009
-31.7500	21.1709	76.2000	38.1611	0.025	0.083	0.0008
-26.4541	-26.4541	76.2000	37.4117	0.023	0.076	0.0008
-26.4541	-21.1709	76.2000	33.8825	0.029	0.096	0.0010
-26.4541	-15.8750	76.2000	30.8518	0.032	0.106	0.0011
-26.4541	-10.5791	76.2000	28.4910	0.034	0.112	0.0011
-26.4541	-5.2959	76.2000	26.9790	0.031	0.102	0.0010
-26.4541	0.0000	76.2000	26.4541	0.021	0.069	0.0007
-26.4541	5.2959	76.2000	26.9790	0.026	0.086	0.0009
-26.4541	10.5791	76.2000	28.4910	0.027	0.089	0.0009
-26.4541	15.8750	76.2000	30.8518	0.024	0.079	0.0008
-26.4541	21.1709	76.2000	33.8825	0.023	0.076	0.0008
-26.4541	26.4541	76.2000	37.4117	0.020	0.066	0.0007
-23.8133	-13.2334	76.2000	27.2433	0.050	0.165	0.0017
-23.8133	-7.9375	76.2000	25.1014	0.086	0.284	0.0028
-23.8133	-2.6416	76.2000	23.9594	0.066	0.218	0.0022
-23.8133	0.0000	76.2000	23.8133	0.056	0.185	0.0018
-23.8133	2.6416	76.2000	23.9594	0.082	0.271	0.0027
-23.8133	7.9375	76.2000	25.1014	0.105	0.347	0.0035
-23.8133	13.2334	76.2000	27.2433	0.033	0.109	0.0011
-21.1709	-26.4541	76.2000	33.8825	0.025	0.083	0.0008
-21.1709	-21.1709	76.2000	29.9402	0.019	0.063	0.0006
-21.1709	-15.8750	76.2000	26.4617	0.043	0.142	0.0014
-21.1709	-10.5791	76.2000	23.6669	0.269	0.888	0.0089
-21.1709	-5.2959	76.2000	21.8232	0.378	1.247	0.0125
-21.1709	0.0000	76.2000	21.1709	0.229	0.756	0.0076
-21.1709	5.2959	76.2000	21.8232	0.405	1.337	0.0134
-21.1709	10.5791	76.2000	23.6669	0.217	0.716	0.0072
-21.1709	15.8750	76.2000	26.4617	0.024	0.079	0.0008
-21.1709	21.1709	76.2000	29.9402	0.010	0.033	0.0003
-21.1709	26.4541	76.2000	33.8825	0.012	0.040	0.0004
-18.5166	-18.5166	76.2000	26.1864	0.033	0.109	0.0011
-18.5166	-13.2334	76.2000	22.7593	0.282	0.931	0.0093
-18.5166	-7.9375	76.2000	20.1462	0.697	2.300	0.0230
-18.5166	-2.6416	76.2000	18.7041	0.474	1.564	0.0156

-18.5166	0.0000	76.2000	18.5166	0.407	1.343	0.0134
-18.5166	2.6416	76.2000	18.7041	0.677	2.234	0.0223
-18.5166	7.9375	76.2000	20.1462	0.820	2.706	0.0271
-18.5166	13.2334	76.2000	22.7593	0.196	0.647	0.0065
-18.5166	18.5166	76.2000	26.1864	0.023	0.076	0.0008
-15.8750	-31.7500	76.2000	35.4976	0.018	0.059	0.0006
-15.8750	-26.4541	76.2000	30.8518	0.013	0.043	0.0004
-15.8750	-21.1709	76.2000	26.4617	0.016	0.053	0.0005
-15.8750	-15.8750	76.2000	22.4506	0.175	0.578	0.0058
-15.8750	-10.5791	76.2000	19.0770	0.959	3.165	0.0316
-15.8750	-5.2959	76.2000	16.7351	1.215	4.010	0.0401
-15.8750	0.0000	76.2000	15.8750	0.821	2.709	0.0271
-15.8750	5.2959	76.2000	16.7351	1.281	4.227	0.0423
-15.8750	10.5791	76.2000	19.0770	0.727	2.399	0.0240
-15.8750	15.8750	76.2000	22.4506	0.164	0.541	0.0054
-15.8750	21.1709	76.2000	26.4617	0.048	0.158	0.0016
-15.8750	26.4541	76.2000	30.8518	0.012	0.040	0.0004
-15.8750	31.7500	76.2000	35.4976	0.012	0.040	0.0004
-13.2334	-18.5166	76.2000	22.7593	0.140	0.462	0.0046
-13.2334	-13.2334	76.2000	18.7149	0.584	1.927	0.0193
-13.2334	-7.9375	76.2000	15.4314	1.289	4.254	0.0425
-13.2334	-2.6416	76.2000	13.4945	1.039	3.429	0.0343
-13.2334	0.0000	76.2000	13.2334	0.945	3.119	0.0312
-13.2334	2.6416	76.2000	13.4945	1.147	3.785	0.0379
-13.2334	7.9375	76.2000	15.4314	1.156	3.815	0.0381
-13.2334	13.2334	76.2000	18.7149	0.541	1.785	0.0179
-13.2334	18.5166	76.2000	22.7593	0.331	1.092	0.0109
-10.5791	-31.7500	76.2000	33.4661	0.014	0.046	0.0005
-10.5791	-26.4541	76.2000	28.4910	0.017	0.056	0.0006
-10.5791	-21.1709	76.2000	23.6669	0.216	0.713	0.0071
-10.5791	-15.8750	76.2000	19.0770	0.589	1.944	0.0194
-10.5791	-10.5791	76.2000	14.9611	0.898	2.963	0.0296
-10.5791	-5.2959	76.2000	11.8306	1.133	3.739	0.0374
-10.5791	0.0000	76.2000	10.5791	0.938	3.095	0.0310
-10.5791	5.2959	76.2000	11.8306	1.114	3.676	0.0368
-10.5791	10.5791	76.2000	14.9611	0.919	3.033	0.0303
-10.5791	15.8750	76.2000	19.0770	1.020	3.366	0.0337
-10.5791	21.1709	76.2000	23.6669	0.364	1.201	0.0120
-10.5791	26.4541	76.2000	28.4910	0.013	0.043	0.0004
-10.5791	31.7500	76.2000	33.4661	0.010	0.033	0.0003
-7.9375	-18.5166	76.2000	20.1462	0.881	2.907	0.0291
-7.9375	-13.2334	76.2000	15.4314	1.011	3.336	0.0334
-7.9375	-7.9375	76.2000	11.2253	0.962	3.175	0.0317
-7.9375	-2.6416	76.2000	8.3655	0.865	2.855	0.0285
-7.9375	0.0000	76.2000	7.9375	0.827	2.729	0.0273
-7.9375	2.6416	76.2000	8.3655	0.867	2.861	0.0286
-7.9375	7.9375	76.2000	11.2253	0.944	3.115	0.0312
-7.9375	13.2334	76.2000	15.4314	1.236	4.079	0.0408
-7.9375	18.5166	76.2000	20.1462	1.016	3.353	0.0335
-5.2959	-37.0459	76.2000	37.4225	0.013	0.043	0.0004
-5.2959	-31.7500	76.2000	32.1886	0.010	0.033	0.0003
-5.2959	-26.4541	76.2000	26.9790	0.033	0.109	0.0011
-5.2959	-23.8125	76.2000	24.3943	0.212	0.700	0.0070
-5.2959	-21.1709	76.2000	21.8232	0.593	1.957	0.0196
-5.2959	-15.8750	76.2000	16.7351	1.313	4.333	0.0433
-5.2959	-10.5791	76.2000	11.8306	1.050	3.465	0.0347
-5.2959	-5.2959	76.2000	7.4895	0.823	2.716	0.0272
-5.2959	0.0000	76.2000	5.2959	0.713	2.353	0.0235
-5.2959	5.2959	76.2000	7.4895	0.765	2.525	0.0252
-5.2959	10.5791	76.2000	11.8306	1.070	3.531	0.0353
-5.2959	15.8750	76.2000	16.7351	1.212	4.000	0.0400
-5.2959	21.1709	76.2000	21.8232	0.391	1.290	0.0129
-5.2959	23.8125	76.2000	24.3943	0.123	0.406	0.0041
-5.2959	26.4541	76.2000	26.9790	0.014	0.046	0.0005
-5.2959	31.7500	76.2000	32.1886	0.007	0.023	0.0002
-5.2959	37.0459	76.2000	37.4225	0.009	0.030	0.0003
-2.6416	-23.8125	76.2000	23.9586	0.146	0.482	0.0048
-2.6416	-18.5166	76.2000	18.7041	0.895	2.954	0.0295
-2.6416	-13.2334	76.2000	13.4945	1.148	3.788	0.0379
-2.6416	-7.9375	76.2000	8.3655	0.867	2.861	0.0286
-2.6416	-2.6416	76.2000	3.7358	0.690	2.277	0.0228
-2.6416	0.0000	76.2000	2.6416	0.660	2.178	0.0218
-2.6416	2.6416	76.2000	3.7358	0.654	2.158	0.0216
-2.6416	7.9375	76.2000	8.3655	0.810	2.673	0.0267
-2.6416	13.2334	76.2000	13.4945	1.018	3.359	0.0336
-2.6416	18.5166	76.2000	18.7041	0.564	1.861	0.0186
-2.6416	23.8125	76.2000	23.9586	0.057	0.188	0.0019
0.0000	-37.0459	76.2000	37.0459	0.011	0.036	0.0004
0.0000	-31.7500	76.2000	31.7500	0.008	0.026	0.0003
0.0000	-26.4541	76.2000	26.4541	0.013	0.043	0.0004

0.0000	-23.8133	76.2000	23.8133	0.088	0.290	0.0029
0.0000	-21.1709	76.2000	21.1709	0.290	0.957	0.0096
0.0000	-18.5166	76.2000	18.5166	0.572	1.888	0.0189
0.0000	-15.8750	76.2000	15.8750	0.896	2.957	0.0296
0.0000	-13.2334	76.2000	13.2334	0.911	3.006	0.0301
0.0000	-10.5791	76.2000	10.5791	0.935	3.086	0.0309
0.0000	-7.9375	76.2000	7.9375	0.819	2.703	0.0270
0.0000	-5.2959	76.2000	5.2959	0.757	2.498	0.0250
0.0000	-2.6416	76.2000	2.6416	0.671	2.214	0.0221
0.0000	0.0000	76.2000	0.0000	0.653	2.155	0.0215
0.0000	2.6416	76.2000	2.6416	0.649	2.142	0.0214
0.0000	5.2959	76.2000	5.2959	0.694	2.290	0.0229
0.0000	7.9375	76.2000	7.9375	0.786	2.594	0.0259
0.0000	10.5791	76.2000	10.5791	0.919	3.033	0.0303
0.0000	13.2334	76.2000	13.2334	0.991	3.270	0.0327
0.0000	15.8750	76.2000	15.8750	0.858	2.831	0.0283
0.0000	18.5166	76.2000	18.5166	0.682	2.251	0.0225
0.0000	21.1709	76.2000	21.1709	0.137	0.452	0.0045
0.0000	23.8133	76.2000	23.8133	0.103	0.340	0.0034
0.0000	26.4541	76.2000	26.4541	0.007	0.023	0.0002
0.0000	31.7500	76.2000	31.7500	0.005	0.017	0.0002
0.0000	37.0459	76.2000	37.0459	0.007	0.023	0.0002

Plane: 152.4 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Voltage [V]	Volume CH4	Mole Fraction
					[%]	
0.0000	37.6142	152.4000	37.6142	0.054	0.178	0.0018
0.0000	32.3183	152.4000	32.3183	0.084	0.277	0.0028
0.0000	27.0224	152.4000	27.0224	0.212	0.700	0.0070
0.0000	21.7392	152.4000	21.7392	0.544	1.795	0.0180
0.0000	16.4433	152.4000	16.4433	0.813	2.683	0.0268
0.0000	11.1474	152.4000	11.1474	0.887	2.927	0.0293
0.0000	5.8642	152.4000	5.8642	0.875	2.888	0.0289
0.0000	0.5683	152.4000	0.5683	0.866	2.858	0.0286
0.0000	-4.7276	152.4000	4.7276	0.882	2.911	0.0291
0.0000	-10.0108	152.4000	10.0108	0.893	2.947	0.0295
0.0000	-15.3067	152.4000	15.3067	0.839	2.769	0.0277
0.0000	-20.6026	152.4000	20.6026	0.620	2.046	0.0205
0.0000	-25.8858	152.4000	25.8858	0.305	1.007	0.0101
0.0000	-31.1817	152.4000	31.1817	0.123	0.406	0.0041
0.0000	-36.4776	152.4000	36.4776	0.091	0.300	0.0030
-5.2959	-36.4776	152.4000	36.8600	0.082	0.271	0.0027
-5.2959	-31.1817	152.4000	31.6282	0.131	0.432	0.0043
-5.2959	-25.8858	152.4000	26.4220	0.313	1.033	0.0103
-5.2959	-20.6026	152.4000	21.2723	0.620	2.046	0.0205
-5.2959	-15.3067	152.4000	16.1969	0.830	2.739	0.0274
-5.2959	-10.0108	152.4000	11.3253	0.897	2.960	0.0296
-5.2959	-4.7276	152.4000	7.0991	0.891	2.940	0.0294
-5.2959	0.5683	152.4000	5.3263	0.881	2.907	0.0291
-5.2959	5.8642	152.4000	7.9016	0.901	2.973	0.0297
-5.2959	11.1474	152.4000	12.3415	0.913	3.013	0.0301
-5.2959	16.4433	152.4000	17.2751	0.810	2.673	0.0267
-5.2959	21.7392	152.4000	22.3750	0.485	1.601	0.0160
-5.2959	27.0224	152.4000	27.5365	0.192	0.634	0.0063
-5.2959	32.3183	152.4000	32.7494	0.093	0.307	0.0031
-5.2959	37.6142	152.4000	37.9852	0.069	0.228	0.0023
-10.5791	32.3183	152.4000	34.0058	0.103	0.340	0.0034
-10.5791	27.0224	152.4000	29.0195	0.192	0.634	0.0063
-10.5791	21.7392	152.4000	24.1767	0.446	1.472	0.0147
-10.5791	16.4433	152.4000	19.5525	0.773	2.551	0.0255
-10.5791	11.1474	152.4000	15.3682	0.901	2.973	0.0297
-10.5791	5.8642	152.4000	12.0957	0.917	3.026	0.0303
-10.5791	0.5683	152.4000	10.5944	0.898	2.963	0.0296
-10.5791	-4.7276	152.4000	11.5874	0.887	2.927	0.0293
-10.5791	-10.0108	152.4000	14.5648	0.846	2.792	0.0279
-10.5791	-15.3067	152.4000	18.6068	0.719	2.373	0.0237
-10.5791	-20.6026	152.4000	23.1600	0.486	1.604	0.0160
-10.5791	-25.8858	152.4000	27.9641	0.249	0.822	0.0082
-10.5791	-31.1817	152.4000	32.9274	0.138	0.455	0.0046
-15.8750	-31.1817	152.4000	34.9902	0.134	0.442	0.0044
-15.8750	-25.8858	152.4000	30.3659	0.201	0.663	0.0066
-15.8750	-20.6026	152.4000	26.0093	0.348	1.148	0.0115
-15.8750	-15.3067	152.4000	22.0524	0.548	1.808	0.0181
-15.8750	-10.0108	152.4000	18.7678	0.707	2.333	0.0233
-15.8750	-4.7276	152.4000	16.5640	0.780	2.574	0.0257
-15.8750	0.5683	152.4000	15.8852	0.819	2.703	0.0270
-15.8750	5.8642	152.4000	16.9235	0.829	2.736	0.0274
-15.8750	11.1474	152.4000	19.3980	0.734	2.422	0.0242
-15.8750	16.4433	152.4000	22.8560	0.545	1.799	0.0180
-15.8750	21.7392	152.4000	26.9186	0.327	1.079	0.0108
-15.8750	27.0224	152.4000	31.3405	0.173	0.571	0.0057

-15.8750	32.3183	152.4000	36.0068	0.112	0.370	0.0037
-21.1709	32.3183	152.4000	38.6352	0.121	0.399	0.0040
-21.1709	27.0224	152.4000	34.3281	0.148	0.488	0.0049
-21.1709	21.7392	152.4000	30.3447	0.210	0.693	0.0069
-21.1709	16.4433	152.4000	26.8065	0.315	1.040	0.0104
-21.1709	11.1474	152.4000	23.9264	0.450	1.485	0.0149
-21.1709	5.8642	152.4000	21.9681	0.553	1.825	0.0182
-21.1709	0.5683	152.4000	21.1785	0.562	1.855	0.0185
-21.1709	-4.7276	152.4000	21.6923	0.535	1.766	0.0177
-21.1709	-10.0108	152.4000	23.4184	0.488	1.610	0.0161
-21.1709	-15.3067	152.4000	26.1247	0.383	1.264	0.0126
-21.1709	-20.6026	152.4000	29.5410	0.266	0.878	0.0088
-21.1709	-25.8858	152.4000	33.4407	0.184	0.607	0.0061
-21.1709	-31.1817	152.4000	37.6896	0.144	0.475	0.0048
-26.4541	-25.8858	152.4000	37.0121	0.186	0.614	0.0061
-26.4541	-20.6026	152.4000	33.5304	0.225	0.743	0.0074
-26.4541	-15.3067	152.4000	30.5633	0.285	0.941	0.0094
-26.4541	-10.0108	152.4000	28.2849	0.322	1.063	0.0106
-26.4541	-4.7276	152.4000	26.8732	0.343	1.132	0.0113
-26.4541	0.5683	152.4000	26.4602	0.347	1.145	0.0115
-26.4541	5.8642	152.4000	27.0963	0.326	1.076	0.0108
-26.4541	11.1474	152.4000	28.7069	0.274	0.904	0.0090
-26.4541	16.4433	152.4000	31.1481	0.210	0.693	0.0069
-26.4541	21.7392	152.4000	34.2405	0.168	0.554	0.0055
-26.4541	27.0224	152.4000	37.8157	0.140	0.462	0.0046
-31.7500	21.7392	152.4000	38.4793	0.158	0.521	0.0052
-31.7500	16.4433	152.4000	35.7554	0.178	0.587	0.0059
-31.7500	11.1474	152.4000	33.6501	0.204	0.673	0.0067
-31.7500	5.8642	152.4000	32.2870	0.230	0.759	0.0076
-31.7500	0.5683	152.4000	31.7551	0.248	0.818	0.0082
-31.7500	-4.7276	152.4000	32.1000	0.256	0.845	0.0084
-31.7500	-10.0108	152.4000	33.2908	0.240	0.792	0.0079
-31.7500	-15.3067	152.4000	35.2471	0.234	0.772	0.0077
-31.7500	-20.6026	152.4000	37.8488	0.213	0.703	0.0070
-37.0459	-11.1474	152.4000	38.6867	0.225	0.743	0.0074
-37.0459	-4.7276	152.4000	37.3463	0.226	0.746	0.0075
-37.0459	0.5683	152.4000	37.0503	0.215	0.710	0.0071
-37.0459	5.8642	152.4000	37.5072	0.203	0.670	0.0067
-37.0459	11.1474	152.4000	38.6867	0.187	0.617	0.0062

Table B-12: Velocity field data. Case 3

Hardware Configuration: B				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00864 kg/min	
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-40.0313	0.0000	76.3025	40.0313	-0.1125	0.5825
-39.2110	0.0000	76.3025	39.2110	-0.0816	0.2987
-38.3907	0.0000	76.3025	38.3907	0.1014	0.5834
-37.5704	0.0000	76.3025	37.5704	0.0367	0.0073
-36.7501	0.0000	76.3025	36.7501	-0.1270	-1.0520
-35.9298	0.0000	76.3025	35.9298	-0.1661	-1.3998
-35.1095	0.0000	76.3025	35.1095	-0.0520	-0.7907
-34.2891	0.0000	76.3025	34.2891	0.0103	-0.4933
-33.4688	0.0000	76.3025	33.4688	0.0151	-0.2126
-32.6485	0.0000	76.3025	32.6485	-0.0063	0.0756
-31.8282	0.0000	76.3025	31.8282	-0.0329	0.4091
-31.0079	0.0000	76.3025	31.0079	-0.0719	0.7806
-30.1876	0.0000	76.3025	30.1876	-0.1071	1.1744
-29.3673	0.0000	76.3025	29.3673	-0.1254	1.5824
-28.5470	0.0000	76.3025	28.5470	-0.1278	2.0115
-27.7267	0.0000	76.3025	27.7267	-0.1288	2.4757
-26.9064	0.0000	76.3025	26.9064	-0.1362	2.9664
-26.0861	0.0000	76.3025	26.0861	-0.1498	3.4738
-25.2657	0.0000	76.3025	25.2657	-0.1690	3.9490
-24.4454	0.0000	76.3025	24.4454	-0.1701	4.3656
-23.6251	0.0000	76.3025	23.6251	-0.1494	4.7216
-22.8048	0.0000	76.3025	22.8048	-0.1264	5.0284
-21.9845	0.0000	76.3025	21.9845	-0.1133	5.2977
-21.1642	0.0000	76.3025	21.1642	-0.1038	5.5300
-20.3439	0.0000	76.3025	20.3439	-0.0903	5.7281
-19.5236	0.0000	76.3025	19.5236	-0.0618	5.8954
-18.7033	0.0000	76.3025	18.7033	-0.0224	6.0354
-17.8830	0.0000	76.3025	17.8830	0.0253	6.1622
-17.0627	0.0000	76.3025	17.0627	0.0544	6.2860
-16.2423	0.0000	76.3025	16.2423	0.0590	6.3846

-15.4220	0.0000	76.3025	15.4220	0.0679	6.4271
-14.6017	0.0000	76.3025	14.6017	0.1188	6.4150
-13.7814	0.0000	76.3025	13.7814	0.1845	6.3881
-12.9611	0.0000	76.3025	12.9611	0.2333	6.3584
-12.1408	0.0000	76.3025	12.1408	0.2819	6.3255
-11.3205	0.0000	76.3025	11.3205	0.3392	6.2516
-10.5002	0.0000	76.3025	10.5002	0.3936	6.1376
-9.6799	0.0000	76.3025	9.6799	0.4373	5.9915
-8.8596	0.0000	76.3025	8.8596	0.4740	5.8144
-8.0393	0.0000	76.3025	8.0393	0.5083	5.6110
-7.2189	0.0000	76.3025	7.2189	0.5411	5.4365
-6.3986	0.0000	76.3025	6.3986	0.5824	5.2896
-5.5783	0.0000	76.3025	5.5783	0.6066	5.1192
-4.7580	0.0000	76.3025	4.7580	0.5965	4.9593
-3.9377	0.0000	76.3025	3.9377	0.5625	4.8248
-3.1174	0.0000	76.3025	3.1174	0.5263	4.7066
-2.2971	0.0000	76.3025	2.2971	0.4926	4.5768
-1.4768	0.0000	76.3025	1.4768	0.4297	4.4098
-0.6565	0.0000	76.3025	0.6565	0.3275	4.2600
0.1638	0.0000	76.3025	0.1638	0.2411	4.1627
0.9841	0.0000	76.3025	0.9841	0.1327	4.1006
1.8045	0.0000	76.3025	1.8045	0.0320	4.0702
2.6248	0.0000	76.3025	2.6248	-0.0565	4.0828
3.4451	0.0000	76.3025	3.4451	-0.1297	4.1413
4.2654	0.0000	76.3025	4.2654	-0.1874	4.2345
5.0857	0.0000	76.3025	5.0857	-0.2333	4.3494
5.9060	0.0000	76.3025	5.9060	-0.2800	4.5012
6.7263	0.0000	76.3025	6.7263	-0.3140	4.6793
7.5466	0.0000	76.3025	7.5466	-0.3127	4.8616
8.3669	0.0000	76.3025	8.3669	-0.2694	5.0494
9.1872	0.0000	76.3025	9.1872	-0.2128	5.2282
10.0075	0.0000	76.3025	10.0075	-0.1608	5.3819
10.8278	0.0000	76.3025	10.8278	-0.1125	5.5055
11.6482	0.0000	76.3025	11.6482	-0.0648	5.6080
12.4685	0.0000	76.3025	12.4685	-0.0161	5.6921
13.2888	0.0000	76.3025	13.2888	0.0095	5.7570
14.1091	0.0000	76.3025	14.1091	0.0260	5.8174
14.9294	0.0000	76.3025	14.9294	0.0330	5.8877
15.7497	0.0000	76.3025	15.7497	0.0347	5.9910
16.5700	0.0000	76.3025	16.5700	0.0362	6.1393
17.3903	0.0000	76.3025	17.3903	0.0361	6.3271
18.2106	0.0000	76.3025	18.2106	0.0159	6.5370
19.0309	0.0000	76.3025	19.0309	-0.0276	6.7975
19.8512	0.0000	76.3025	19.8512	-0.0728	7.0405
20.6716	0.0000	76.3025	20.6716	-0.1104	7.1766
21.4919	0.0000	76.3025	21.4919	-0.1210	7.1741
22.3122	0.0000	76.3025	22.3122	-0.1150	7.0168
23.1325	0.0000	76.3025	23.1325	-0.1081	6.7241
23.9528	0.0000	76.3025	23.9528	-0.1048	6.3378
24.7731	0.0000	76.3025	24.7731	-0.0955	5.8941
25.5934	0.0000	76.3025	25.5934	-0.0838	5.3660
26.4137	0.0000	76.3025	26.4137	-0.0882	4.7524
27.2340	0.0000	76.3025	27.2340	-0.1074	4.0840
28.0543	0.0000	76.3025	28.0543	-0.1233	3.4021
28.8746	0.0000	76.3025	28.8746	-0.1250	2.7256
29.6950	0.0000	76.3025	29.6950	-0.1137	2.0824
30.5153	0.0000	76.3025	30.5153	-0.0991	1.5093
31.3356	0.0000	76.3025	31.3356	-0.0902	1.0093
32.1559	0.0000	76.3025	32.1559	-0.0904	0.5204
32.9762	0.0000	76.3025	32.9762	-0.1035	0.0743
33.7965	0.0000	76.3025	33.7965	-0.1088	-0.2936
34.6168	0.0000	76.3025	34.6168	-0.1122	-0.5823
35.4371	0.0000	76.3025	35.4371	-0.1022	-0.8033
36.2574	0.0000	76.3025	36.2574	-0.0828	-0.9828
37.0777	0.0000	76.3025	37.0777	-0.0729	-1.0978
37.8980	0.0000	76.3025	37.8980	-0.0813	-1.0060
38.7184	0.0000	76.3025	38.7184	-0.0195	-0.4728
39.5387	0.0000	76.3025	39.5387	0.0147	-0.1508
Plane: 152.4 mm downstream of injection					
-40.0237	0.0000	152.2921	40.0237	0.0698	-0.1208
-39.1957	0.0000	152.2921	39.1957	0.0463	0.1210
-38.3678	0.0000	152.2921	38.3678	0.2108	0.3653
-37.5398	0.0000	152.2921	37.5398	0.3560	0.4435
-36.7119	0.0000	152.2921	36.7119	0.3146	0.2893
-35.8839	0.0000	152.2921	35.8839	0.1511	0.1501
-35.0560	0.0000	152.2921	35.0560	-0.0075	0.2644
-34.2280	0.0000	152.2921	34.2280	-0.0940	0.6582
-33.4001	0.0000	152.2921	33.4001	-0.0913	1.2190
-32.5721	0.0000	152.2921	32.5721	-0.0734	1.5059
-31.7442	0.0000	152.2921	31.7442	-0.1333	1.6311

-30.9162	0.0000	152.2921	30.9162	-0.1812	1.7946
-30.0882	0.0000	152.2921	30.0882	-0.2103	1.9835
-29.2603	0.0000	152.2921	29.2603	-0.2277	2.1794
-28.4323	0.0000	152.2921	28.4323	-0.2409	2.3872
-27.6044	0.0000	152.2921	27.6044	-0.2533	2.6080
-26.7764	0.0000	152.2921	26.7764	-0.2629	2.8273
-25.9485	0.0000	152.2921	25.9485	-0.2758	3.0515
-25.1205	0.0000	152.2921	25.1205	-0.2862	3.2708
-24.2926	0.0000	152.2921	24.2926	-0.2927	3.4596
-23.4646	0.0000	152.2921	23.4646	-0.2969	3.6437
-22.6367	0.0000	152.2921	22.6367	-0.2985	3.8370
-21.8087	0.0000	152.2921	21.8087	-0.2866	4.0333
-20.9808	0.0000	152.2921	20.9808	-0.2654	4.2229
-20.1528	0.0000	152.2921	20.1528	-0.2497	4.4034
-19.3249	0.0000	152.2921	19.3249	-0.2398	4.5834
-18.4969	0.0000	152.2921	18.4969	-0.2402	4.7427
-17.6690	0.0000	152.2921	17.6690	-0.2520	4.8722
-16.8410	0.0000	152.2921	16.8410	-0.2427	5.0038
-16.0131	0.0000	152.2921	16.0131	-0.2207	5.1218
-15.1851	0.0000	152.2921	15.1851	-0.1966	5.2217
-14.3572	0.0000	152.2921	14.3572	-0.1722	5.2944
-13.5292	0.0000	152.2921	13.5292	-0.1438	5.3405
-12.7013	0.0000	152.2921	12.7013	-0.1126	5.3749
-11.8733	0.0000	152.2921	11.8733	-0.0854	5.4066
-11.0454	0.0000	152.2921	11.0454	-0.0569	5.4108
-10.2174	0.0000	152.2921	10.2174	-0.0314	5.4143
-9.3895	0.0000	152.2921	9.3895	-0.0078	5.4157
-8.5615	0.0000	152.2921	8.5615	0.0177	5.3990
-7.7336	0.0000	152.2921	7.7336	0.0405	5.3636
-6.9056	0.0000	152.2921	6.9056	0.0556	5.3186
-6.0776	0.0000	152.2921	6.0776	0.0633	5.2748
-5.2497	0.0000	152.2921	5.2497	0.0715	5.2368
-4.4217	0.0000	152.2921	4.4217	0.0880	5.2072
-3.5938	0.0000	152.2921	3.5938	0.1054	5.1683
-2.7658	0.0000	152.2921	2.7658	0.1097	5.1163
-1.9379	0.0000	152.2921	1.9379	0.1069	5.0648
-1.1099	0.0000	152.2921	1.1099	0.1004	5.0110
-0.2820	0.0000	152.2921	0.2820	0.0902	4.9617
0.5460	0.0000	152.2921	0.5460	0.0786	4.9274
1.3739	0.0000	152.2921	1.3739	0.0715	4.9074
2.2019	0.0000	152.2921	2.2019	0.0711	4.8766
3.0298	0.0000	152.2921	3.0298	0.0647	4.8509
3.8578	0.0000	152.2921	3.8578	0.0591	4.8520
4.6857	0.0000	152.2921	4.6857	0.0545	4.8577
5.5137	0.0000	152.2921	5.5137	0.0391	4.8686
6.3416	0.0000	152.2921	6.3416	0.0127	4.8955
7.1696	0.0000	152.2921	7.1696	-0.0134	4.9457
7.9975	0.0000	152.2921	7.9975	-0.0260	5.0147
8.8255	0.0000	152.2921	8.8255	-0.0178	5.0940
9.6534	0.0000	152.2921	9.6534	0.0037	5.1750
10.4814	0.0000	152.2921	10.4814	0.0065	5.2473
11.3093	0.0000	152.2921	11.3093	-0.0005	5.3103
12.1373	0.0000	152.2921	12.1373	-0.0041	5.3759
12.9652	0.0000	152.2921	12.9652	-0.0075	5.4468
13.7932	0.0000	152.2921	13.7932	-0.0075	5.5162
14.6211	0.0000	152.2921	14.6211	0.0019	5.5802
15.4491	0.0000	152.2921	15.4491	0.0175	5.6423
16.2770	0.0000	152.2921	16.2770	0.0315	5.7021
17.1050	0.0000	152.2921	17.1050	0.0364	5.7477
17.9329	0.0000	152.2921	17.9329	0.0390	5.7730
18.7609	0.0000	152.2921	18.7609	0.0458	5.7688
19.5889	0.0000	152.2921	19.5889	0.0566	5.7265
20.4168	0.0000	152.2921	20.4168	0.0729	5.6464
21.2448	0.0000	152.2921	21.2448	0.0970	5.5366
22.0727	0.0000	152.2921	22.0727	0.1211	5.4046
22.9007	0.0000	152.2921	22.9007	0.1193	5.2451
23.7286	0.0000	152.2921	23.7286	0.1130	5.0465
24.5566	0.0000	152.2921	24.5566	0.1123	4.7911
25.3845	0.0000	152.2921	25.3845	0.1038	4.5133
26.2125	0.0000	152.2921	26.2125	0.1002	4.2383
27.0404	0.0000	152.2921	27.0404	0.1092	3.9583
27.8684	0.0000	152.2921	27.8684	0.1156	3.6543
28.6963	0.0000	152.2921	28.6963	0.1040	3.3316
29.5243	0.0000	152.2921	29.5243	0.0785	3.0278
30.3522	0.0000	152.2921	30.3522	0.0439	2.7485
31.1802	0.0000	152.2921	31.1802	0.0160	2.4639
32.0081	0.0000	152.2921	32.0081	-0.0167	2.2004
32.8361	0.0000	152.2921	32.8361	-0.0389	1.9612
33.6640	0.0000	152.2921	33.6640	-0.0408	1.7603
34.4920	0.0000	152.2921	34.4920	-0.0289	1.5923

35.3199	0.0000	152.2921	35.3199	-0.0081	1.4421
36.1479	0.0000	152.2921	36.1479	0.0173	1.2842
36.9758	0.0000	152.2921	36.9758	0.0308	1.0711
37.8038	0.0000	152.2921	37.8038	0.0618	0.6972
38.6317	0.0000	152.2921	38.6317	0.1357	0.3355
39.4597	0.0000	152.2921	39.4597	0.2548	0.1947

B.13.5 Case 4: Non-Swirling Radial Injection of Hydrogen

Table B-13: Spatial fuel concentration data. Case 4

Hardware Configuration: B Bulk Flow Type: Nitrogen Bulk Flow Rate: 1.116 kg/min Plane: 25.4 mm downstream of injection				Measurement Technique: Gas Chromatography (25.4 mm), H2 analyzer (76.2 and 152.4 mm) Fuel Type: Hydrogen Fuel Flow Rate: 0.00301 kg/min	
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
0.0000	29.8450	25.4000	29.8450	0.000	0.00000
0.0000	26.6700	25.4000	26.6700	0.000	0.00000
0.0000	22.8600	25.4000	22.8600	0.000	0.00000
0.0000	19.0500	25.4000	19.0500	0.762	0.00762
0.0000	15.2400	25.4000	15.2400	1.639	0.01639
0.0000	-15.2400	25.4000	15.2400	1.465	0.01465
0.0000	-19.0500	25.4000	19.0500	1.224	0.01224
0.0000	-22.8600	25.4000	22.8600	0.000	0.00000
0.0000	-26.6700	25.4000	26.6700	0.000	0.00000
0.0000	-29.8450	25.4000	29.8450	0.000	0.00000
-3.8100	-29.8450	25.4000	30.0872	0.000	0.00000
-3.8100	-26.6700	25.4000	26.9408	0.000	0.00000
-3.8100	-22.8600	25.4000	23.1753	1.579	0.01579
-3.8100	-19.0500	25.4000	19.4273	13.727	0.13727
-3.8100	-15.2400	25.4000	15.7090	10.067	0.10067
-3.8100	15.2400	25.4000	15.7090	8.963	0.08963
-3.8100	19.0500	25.4000	19.4273	6.460	0.06460
-3.8100	22.8600	25.4000	23.1753	0.084	0.00084
-3.8100	26.6700	25.4000	26.9408	0.000	0.00000
-3.8100	29.8450	25.4000	30.0872	0.000	0.00000
-7.6200	29.8450	25.4000	30.8024	0.000	0.00000
-7.6200	26.6700	25.4000	27.7372	0.000	0.00000
-7.6200	22.8600	25.4000	24.0966	0.763	0.00763
-7.6200	19.0500	25.4000	20.5175	15.072	0.15072
-7.6200	15.2400	25.4000	17.0388	17.003	0.17003
-7.6200	11.4300	25.4000	13.7372	5.591	0.05591
-7.6200	-11.4300	25.4000	13.7372	3.630	0.03630
-7.6200	-15.2400	25.4000	17.0388	14.241	0.14241
-7.6200	-19.0500	25.4000	20.5175	16.592	0.16592
-7.6200	-22.8600	25.4000	24.0966	2.865	0.02865
-7.6200	-26.6700	25.4000	27.7372	0.000	0.00000
-7.6200	-29.8450	25.4000	30.8024	0.000	0.00000
-11.4300	-26.6700	25.4000	29.0161	0.000	0.00000
-11.4300	-22.8600	25.4000	25.5583	0.138	0.00138
-11.4300	-19.0500	25.4000	22.2159	3.458	0.03458
-11.4300	-15.2400	25.4000	19.0500	3.320	0.03320
-11.4300	-11.4300	25.4000	16.1645	1.860	0.01860
-11.4300	-7.6200	25.4000	13.7372	5.166	0.05166
-11.4300	7.6200	25.4000	13.7372	4.926	0.04926
-11.4300	11.4300	25.4000	16.1645	2.382	0.02382
-11.4300	15.2400	25.4000	19.0500	10.887	0.10887
-11.4300	19.0500	25.4000	22.2159	7.543	0.07543
-11.4300	22.8600	25.4000	25.5583	0.183	0.00183
-11.4300	26.6700	25.4000	29.0161	0.000	0.00000
-15.2400	26.6700	25.4000	30.7172	0.000	0.00000
-15.2400	22.8600	25.4000	27.4743	0.000	0.00000
-15.2400	19.0500	25.4000	24.3959	0.081	0.00081
-15.2400	15.2400	25.4000	21.5526	0.151	0.00151
-15.2400	11.4300	25.4000	19.0500	4.692	0.04692
-15.2400	7.6200	25.4000	17.0388	16.128	0.16128
-15.2400	3.8100	25.4000	15.7090	12.579	0.12579
-15.2400	0.0000	25.4000	15.2400	3.100	0.03100
-15.2400	-3.8100	25.4000	15.7090	8.871	0.08871
-15.2400	-7.6200	25.4000	17.0388	17.023	0.17023
-15.2400	-11.4300	25.4000	19.0500	10.057	0.10057
-15.2400	-15.2400	25.4000	21.5526	0.089	0.00089
-15.2400	-19.0500	25.4000	24.3959	0.000	0.00000
-15.2400	-22.8600	25.4000	27.4743	0.000	0.00000
-15.2400	-26.6700	25.4000	30.7172	0.000	0.00000

-19.0500	-22.8600	25.4000	29.7571	0.000	0.00000
-19.0500	-19.0500	25.4000	26.9408	0.000	0.00000
-19.0500	-15.2400	25.4000	24.3959	0.033	0.00033
-19.0500	-11.4300	25.4000	22.2159	7.348	0.07348
-19.0500	-7.6200	25.4000	20.5175	16.905	0.16905
-19.0500	-3.8100	25.4000	19.4273	6.547	0.06547
-19.0500	0.0000	25.4000	19.0500	2.263	0.02263
-19.0500	3.8100	25.4000	19.4273	13.205	0.13205
-19.0500	7.6200	25.4000	20.5175	14.062	0.14062
-19.0500	11.4300	25.4000	22.2159	2.427	0.02427
-19.0500	15.2400	25.4000	24.3959	0.000	0.00000
-19.0500	19.0500	25.4000	26.9408	0.000	0.00000
-19.0500	22.8600	25.4000	29.7571	0.000	0.00000
-22.8600	19.0500	25.4000	29.7571	0.000	0.00000
-22.8600	15.2400	25.4000	27.4743	0.000	0.00000
-22.8600	11.4300	25.4000	25.5583	0.000	0.00000
-22.8600	7.6200	25.4000	24.0966	0.849	0.00849
-22.8600	3.8100	25.4000	23.1753	0.869	0.00869
-22.8600	0.0000	25.4000	22.8600	0.000	0.00000
-22.8600	-3.8100	25.4000	23.1753	0.108	0.00108
-22.8600	-7.6200	25.4000	24.0966	1.438	0.01438
-22.8600	-11.4300	25.4000	25.5583	0.216	0.00216
-22.8600	-15.2400	25.4000	27.4743	0.000	0.00000
-22.8600	-19.0500	25.4000	29.7571	0.000	0.00000
-26.6700	-15.2400	25.4000	30.7172	0.000	0.00000
-26.6700	-11.4300	25.4000	29.0161	0.000	0.00000
-26.6700	-7.6200	25.4000	27.7372	0.000	0.00000
-26.6700	-3.8100	25.4000	26.9408	0.000	0.00000
-26.6700	0.0000	25.4000	26.6700	0.000	0.00000
-26.6700	3.8100	25.4000	26.9408	0.000	0.00000
-26.6700	7.6200	25.4000	27.7372	0.000	0.00000
-26.6700	11.4300	25.4000	29.0161	0.000	0.00000
-26.6700	15.2400	25.4000	30.7172	0.000	0.00000
-29.8450	7.6200	25.4000	30.8024	0.000	0.00000
-29.8450	3.8100	25.4000	30.0872	0.000	0.00000
-29.8450	0.0000	25.4000	29.8450	0.000	0.00000
-29.8450	-3.8100	25.4000	30.0872	0.000	0.00000
-29.8450	-7.6200	25.4000	30.8024	0.000	0.00000
-17.1450	-7.6200	25.4000	18.7621	20.112	0.20112
-17.1450	-5.7150	25.4000	18.0724	16.884	0.16884
-17.1450	-3.8100	25.4000	17.5632	9.571	0.09571
-17.1450	0.0000	25.4000	17.1450	3.893	0.03893
-17.1450	3.8100	25.4000	17.5632	16.267	0.16267
-17.1450	5.7150	25.4000	18.0724	18.397	0.18397
-17.1450	7.6200	25.4000	18.7621	17.520	0.17520
-15.2400	9.5250	25.4000	17.9717	11.824	0.11824
-15.2400	5.7150	25.4000	16.2763	15.336	0.15336
-15.2400	1.9050	25.4000	15.3586	8.920	0.08920
-15.2400	-1.9050	25.4000	15.3586	2.706	0.02706
-15.2400	-5.7150	25.4000	16.2763	14.094	0.14094
-15.2400	-9.5250	25.4000	17.9717	16.879	0.16879
-13.3350	-13.3350	25.4000	18.8585	1.412	0.01412
-13.3350	-11.4300	25.4000	17.5632	6.405	0.06405
-13.3350	-9.5250	25.4000	16.3874	10.190	0.10190
-13.3350	-7.6200	25.4000	15.3586	9.995	0.09995
-13.3350	-5.7150	25.4000	14.5080	8.570	0.08570
-13.3350	-3.8100	25.4000	13.8686	5.935	0.05935
-13.3350	-1.9050	25.4000	13.4704	2.868	0.02868
-13.3350	0.0000	25.4000	13.3350	2.842	0.02842
-13.3350	1.9050	25.4000	13.4704	5.498	0.05498
-13.3350	3.8100	25.4000	13.8686	7.741	0.07741
-13.3350	5.7150	25.4000	14.5080	9.352	0.09352
-13.3350	7.6200	25.4000	15.3586	10.265	0.10265
-13.3350	9.5250	25.4000	16.3874	7.642	0.07642
-13.3350	11.4300	25.4000	17.5632	2.720	0.02720
-13.3350	13.3350	25.4000	18.8585	1.365	0.01365
-11.4300	13.3350	25.4000	17.5632	6.224	0.06224
-11.4300	9.5250	25.4000	14.8785	2.647	0.02647
-11.4300	5.7150	25.4000	12.7791	4.708	0.04708
-11.4300	-5.7150	25.4000	12.7791	4.672	0.04672
-11.4300	-9.5250	25.4000	14.8785	3.563	0.03563
-11.4300	-13.3350	25.4000	17.5632	1.388	0.01388
-9.5250	-15.2400	25.4000	17.9717	10.198	0.10198
-9.5250	-13.3350	25.4000	16.3874	4.738	0.04738
-9.5250	-11.4300	25.4000	14.8785	1.470	0.01470
-9.5250	-9.5250	25.4000	13.4704	1.705	0.01705
-9.5250	9.5250	25.4000	13.4704	2.075	0.02075
-9.5250	11.4300	25.4000	14.8785	4.260	0.04260
-9.5250	13.3350	25.4000	16.3874	10.624	0.10624
-9.5250	15.2400	25.4000	17.9717	16.776	0.16776

-7.6200	17.1450	25.4000	18.7621	19.544	0.19544
-7.6200	13.3350	25.4000	15.3586	10.720	0.10720
-7.6200	-13.3350	25.4000	15.3586	7.761	0.07761
-7.6200	-17.1450	25.4000	18.7621	18.222	0.18222
-5.7150	-17.1450	25.4000	18.0724	18.198	0.18198
-5.7150	-15.2400	25.4000	16.2763	13.398	0.13398
-5.7150	-13.3350	25.4000	14.5080	7.845	0.07845
-5.7150	13.3350	25.4000	14.5080	8.782	0.08782
-5.7150	15.2400	25.4000	16.2763	14.307	0.14307
-5.7150	17.1450	25.4000	18.0724	16.614	0.16614
-3.8100	17.1450	25.4000	17.5632	9.644	0.09644
-3.8100	13.3350	25.4000	13.8686	5.508	0.05508
-3.8100	-13.3350	25.4000	13.8686	6.095	0.06095
-3.8100	-17.1450	25.4000	17.5632	14.605	0.14605
-1.9050	-17.1450	25.4000	17.2505	8.205	0.08205
-1.9050	-13.3350	25.4000	13.4704	3.342	0.03342
-1.9050	13.3350	25.4000	13.4704	2.459	0.02459
-1.9050	17.1450	25.4000	17.2505	2.426	0.02426
0.0000	17.1450	25.4000	17.1450	1.699	0.01699
0.0000	13.3350	25.4000	13.3350	2.180	0.02180
0.0000	-13.3350	25.4000	13.3350	1.606	0.01606
0.0000	-17.1450	25.4000	17.1450	1.929	0.01929
0.0000	-20.9550	25.4000	20.9550	0.251	0.00251
0.0000	20.9550	25.4000	20.9550	0.127	0.00127
-1.9050	20.9550	25.4000	21.0414	0.209	0.00209
-1.9050	-20.9550	25.4000	21.0414	2.776	0.02776
-3.8100	-20.9550	25.4000	21.2985	7.611	0.07611
-3.8100	20.9550	25.4000	21.2985	1.567	0.01567
-5.7150	19.0500	25.4000	19.8888	12.374	0.12374
-5.7150	-19.0500	25.4000	19.8888	17.402	0.17402
-9.5250	-19.0500	25.4000	21.2985	10.950	0.10950
-9.5250	-17.1450	25.4000	19.6132	12.886	0.12886
-9.5250	17.1450	25.4000	19.6132	17.909	0.17909
-9.5250	19.0500	25.4000	21.2985	12.536	0.12536
-11.4300	17.1450	25.4000	20.6057	11.423	0.11423
-11.4300	-17.1450	25.4000	20.6057	4.633	0.04633
-13.3350	-15.2400	25.4000	20.2504	0.270	0.00270
-13.3350	15.2400	25.4000	20.2504	2.699	0.02699
-15.2400	13.3350	25.4000	20.2504	0.465	0.00465
-15.2400	-13.3350	25.4000	20.2504	3.262	0.03262
-17.1450	-11.4300	25.4000	20.6057	12.465	0.12465
-17.1450	-9.5250	25.4000	19.6132	19.072	0.19072
-17.1450	9.5250	25.4000	19.6132	11.586	0.11586
-17.1450	11.4300	25.4000	20.6057	4.041	0.04041
-19.0500	9.5250	25.4000	21.2985	7.694	0.07694
-19.0500	5.7150	25.4000	19.8888	15.206	0.15206
-19.0500	1.9050	25.4000	19.1450	7.216	0.07216
-19.0500	-1.9050	25.4000	19.1450	0.923	0.00923
-19.0500	-5.7150	25.4000	19.8888	12.548	0.12548
-19.0500	-9.5250	25.4000	21.2985	14.356	0.14356
-20.9550	-1.9050	25.4000	21.0414	0.123	0.00123
-20.9550	0.0000	25.4000	20.9550	0.485	0.00485
-20.9550	19.0500	25.4000	28.3199	2.776	0.02776
-20.9550	-7.6200	25.4000	22.2975	8.067	0.08067
-20.9550	-5.7150	25.4000	21.7203	5.500	0.05500
-20.9550	5.7150	25.4000	21.7203	7.696	0.07696
-20.9550	7.6200	25.4000	22.2975	6.193	0.06193
-17.1450	13.3350	25.4000	21.7203	0.320	0.00320
-17.1450	-13.3350	25.4000	21.7203	3.863	0.03863
-15.2400	-17.1450	25.4000	22.9392	0.000	0.00000
-15.2400	17.1450	25.4000	22.9392	0.126	0.00126
-13.3350	17.1450	25.4000	21.7203	3.140	0.03140
-13.3350	-17.1450	25.4000	21.7203	0.322	0.00322
-7.6200	-20.9550	25.4000	22.2975	9.925	0.09925
-7.6200	20.9550	25.4000	22.2975	5.953	0.05953
-5.7150	20.9550	25.4000	21.7203	4.444	0.04444
-5.7150	-20.9550	25.4000	21.7203	10.508	0.10508
-9.5250	-22.8600	25.4000	24.7650	1.070	0.01070
-9.5250	-20.9550	25.4000	23.0182	5.565	0.05565
-9.5250	20.9550	25.4000	23.0182	4.656	0.04656
-9.5250	22.8600	25.4000	24.7650	0.447	0.00447

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Voltage [V]	Volume H2 [%]	Mole Fraction
0.0000	37.0459	76.2000	37.0459	0.000	0.000	0.0000
0.0000	31.7500	76.2000	31.7500	0.000	0.000	0.0000
0.0000	26.4541	76.2000	26.4541	0.000	0.000	0.0000
0.0000	21.1709	76.2000	21.1709	0.002	0.387	0.0039
0.0000	15.8750	76.2000	15.8750	0.016	2.979	0.0298
0.0000	10.5791	76.2000	10.5791	0.026	4.704	0.0470
0.0000	5.2959	76.2000	5.2959	0.024	4.367	0.0437

0.0000	0.0000	76.2000	0.0000	0.024	4.367	0.0437
0.0000	-5.2959	76.2000	5.2959	0.025	4.536	0.0454
0.0000	-10.5791	76.2000	10.5791	0.026	4.704	0.0470
0.0000	-15.8750	76.2000	15.8750	0.023	4.197	0.0420
0.0000	-21.1709	76.2000	21.1709	0.004	0.770	0.0077
0.0000	-26.4541	76.2000	26.4541	0.000	0.000	0.0000
0.0000	-31.7500	76.2000	31.7500	0.000	0.000	0.0000
0.0000	-37.0459	76.2000	37.0459	0.000	0.000	0.0000
-5.2959	-37.0459	76.2000	37.4225	0.000	0.000	0.0000
-5.2959	-31.7500	76.2000	32.1886	0.000	0.000	0.0000
-5.2959	-26.4541	76.2000	26.9790	0.000	0.000	0.0000
-5.2959	-21.1709	76.2000	21.8232	0.029	5.201	0.0520
-5.2959	-15.8750	76.2000	16.7351	0.063	10.175	0.1017
-5.2959	-10.5791	76.2000	11.8306	0.038	6.636	0.0664
-5.2959	-5.2959	76.2000	7.4895	0.026	4.704	0.0470
-5.2959	0.0000	76.2000	5.2959	0.027	4.871	0.0487
-5.2959	5.2959	76.2000	7.4895	0.028	5.036	0.0504
-5.2959	10.5791	76.2000	11.8306	0.040	6.943	0.0694
-5.2959	15.8750	76.2000	16.7351	0.053	8.838	0.0884
-5.2959	21.1709	76.2000	21.8232	0.018	3.332	0.0333
-5.2959	26.4541	76.2000	26.9790	0.001	0.194	0.0019
-5.2959	31.7500	76.2000	32.1886	0.000	0.000	0.0000
-5.2959	37.0459	76.2000	37.4225	0.000	0.000	0.0000
-10.5791	37.0459	76.2000	38.5268	0.000	0.000	0.0000
-10.5791	31.7500	76.2000	33.4661	0.000	0.000	0.0000
-10.5791	26.4541	76.2000	28.4910	0.001	0.194	0.0019
-10.5791	21.1709	76.2000	23.6669	0.017	3.156	0.0316
-10.5791	15.8750	76.2000	19.0770	0.050	8.416	0.0842
-10.5791	10.5791	76.2000	14.9611	0.030	5.365	0.0536
-10.5791	5.2959	76.2000	11.8306	0.040	6.943	0.0694
-10.5791	0.0000	76.2000	10.5791	0.032	5.689	0.0569
-10.5791	-5.2959	76.2000	11.8306	0.041	7.095	0.0709
-10.5791	-10.5791	76.2000	14.9611	0.030	5.365	0.0536
-10.5791	-15.8750	76.2000	19.0770	0.026	4.704	0.0470
-10.5791	-21.1709	76.2000	23.6669	0.010	1.893	0.0189
-10.5791	-26.4541	76.2000	28.4910	0.000	0.000	0.0000
-10.5791	-31.7500	76.2000	33.4661	0.000	0.000	0.0000
-10.5791	-37.0459	76.2000	38.5268	0.000	0.000	0.0000
-15.8750	-31.7500	76.2000	35.4976	0.000	0.000	0.0000
-15.8750	-26.4541	76.2000	30.8518	0.000	0.000	0.0000
-15.8750	-21.1709	76.2000	26.4617	0.000	0.000	0.0000
-15.8750	-15.8750	76.2000	22.4506	0.002	0.387	0.0039
-15.8750	-10.5791	76.2000	19.0770	0.053	8.838	0.0884
-15.8750	-5.2959	76.2000	16.7351	0.055	9.113	0.0911
-15.8750	0.0000	76.2000	15.8750	0.027	4.871	0.0487
-15.8750	5.2959	76.2000	16.7351	0.057	9.385	0.0939
-15.8750	10.5791	76.2000	19.0770	0.031	5.527	0.0553
-15.8750	15.8750	76.2000	22.4506	0.002	0.387	0.0039
-15.8750	21.1709	76.2000	26.4617	0.000	0.000	0.0000
-15.8750	26.4541	76.2000	30.8518	0.000	0.000	0.0000
-15.8750	31.7500	76.2000	35.4976	0.000	0.000	0.0000
-21.1709	31.7500	76.2000	38.1611	0.000	0.000	0.0000
-21.1709	26.4541	76.2000	33.8825	0.000	0.000	0.0000
-21.1709	21.1709	76.2000	29.9402	0.000	0.000	0.0000
-21.1709	15.8750	76.2000	26.4617	0.000	0.000	0.0000
-21.1709	10.5791	76.2000	23.6669	0.012	2.259	0.0226
-21.1709	5.2959	76.2000	21.8232	0.029	5.201	0.0520
-21.1709	0.0000	76.2000	21.1709	0.005	0.960	0.0096
-21.1709	-5.2959	76.2000	21.8232	0.019	3.507	0.0351
-21.1709	-10.5791	76.2000	23.6669	0.016	2.979	0.0298
-21.1709	-15.8750	76.2000	26.4617	0.000	0.000	0.0000
-21.1709	-21.1709	76.2000	29.9402	0.000	0.000	0.0000
-21.1709	-26.4541	76.2000	33.8825	0.000	0.000	0.0000
-21.1709	-31.7500	76.2000	38.1611	0.000	0.000	0.0000
-26.4541	-26.4541	76.2000	37.4117	0.000	0.000	0.0000
-26.4541	-21.1709	76.2000	33.8825	0.000	0.000	0.0000
-26.4541	-15.8750	76.2000	30.8518	0.000	0.000	0.0000
-26.4541	-10.5791	76.2000	28.4910	0.000	0.000	0.0000
-26.4541	-5.2959	76.2000	26.9790	0.000	0.000	0.0000
-26.4541	0.0000	76.2000	26.4541	0.000	0.000	0.0000
-26.4541	5.2959	76.2000	26.9790	0.000	0.000	0.0000
-26.4541	10.5791	76.2000	28.4910	0.000	0.000	0.0000
-26.4541	15.8750	76.2000	30.8518	0.000	0.000	0.0000
-26.4541	21.1709	76.2000	33.8825	0.000	0.000	0.0000
-26.4541	26.4541	76.2000	37.4117	0.000	0.000	0.0000
-31.7500	21.1709	76.2000	38.1611	0.000	0.000	0.0000
-31.7500	15.8750	76.2000	35.4976	0.000	0.000	0.0000
-31.7500	10.5791	76.2000	33.4661	0.000	0.000	0.0000
-31.7500	5.2959	76.2000	32.1886	0.000	0.000	0.0000
-31.7500	0.0000	76.2000	31.7500	0.000	0.000	0.0000

-31.7500	-5.2959	76.2000	32.1886	0.000	0.000	0.0000
-31.7500	-10.5791	76.2000	33.4661	0.000	0.000	0.0000
-31.7500	-15.8750	76.2000	35.4976	0.000	0.000	0.0000
-31.7500	-21.1709	76.2000	38.1611	0.000	0.000	0.0000
-37.0459	-10.5791	76.2000	38.5268	0.000	0.000	0.0000
-37.0459	-5.2959	76.2000	37.4225	0.000	0.000	0.0000
-37.0459	0.0000	76.2000	37.0459	0.000	0.000	0.0000
-37.0459	5.2959	76.2000	37.4225	0.000	0.000	0.0000
-37.0459	10.5791	76.2000	38.5268	0.000	0.000	0.0000
0.0000	18.5166	76.2000	18.5166	0.008	1.523	0.0152
0.0000	13.2207	76.2000	13.2207	0.024	4.367	0.0437
0.0000	-13.2207	76.2000	13.2207	0.028	5.036	0.0504
0.0000	-18.5166	76.2000	18.5166	0.015	2.800	0.0280
-2.6416	-18.5166	76.2000	18.7041	0.039	6.790	0.0679
-2.6416	-15.8750	76.2000	16.0933	0.050	8.416	0.0842
-2.6416	-13.2207	76.2000	13.4820	0.046	7.839	0.0784
-2.6416	-10.5791	76.2000	10.9039	0.036	6.324	0.0632
-2.6416	10.5791	76.2000	10.9039	0.034	6.008	0.0601
-2.6416	13.2207	76.2000	13.4820	0.035	6.167	0.0617
-2.6416	15.8750	76.2000	16.0933	0.030	5.365	0.0536
-2.6416	18.5166	76.2000	18.7041	0.018	3.332	0.0333
-5.2959	18.5166	76.2000	19.2591	0.038	6.636	0.0664
-5.2959	13.3350	76.2000	14.3481	0.050	8.416	0.0842
-5.2959	-13.3350	76.2000	14.3481	0.052	8.698	0.0870
-5.2959	-18.5166	76.2000	19.2591	0.054	8.976	0.0898
-7.9375	-18.5166	76.2000	20.1462	0.047	7.985	0.0799
-7.9375	-15.8750	76.2000	17.7488	0.054	8.976	0.0898
-7.9375	-13.2207	76.2000	15.4205	0.043	7.396	0.0740
-7.9375	-10.5791	76.2000	13.2258	0.029	5.201	0.0520
-7.9375	-7.9375	76.2000	11.2253	0.029	5.201	0.0520
-7.9375	7.9375	76.2000	11.2253	0.032	5.689	0.0569
-7.9375	10.5791	76.2000	13.2258	0.040	6.943	0.0694
-7.9375	13.2207	76.2000	15.4205	0.055	9.113	0.0911
-7.9375	15.8750	76.2000	17.7488	0.062	10.046	0.1005
-7.9375	18.5166	76.2000	20.1462	0.048	8.130	0.0813
-10.5791	13.2207	76.2000	16.9323	0.042	7.246	0.0725
-10.5791	7.9375	76.2000	13.2258	0.034	6.008	0.0601
-10.5791	2.6416	76.2000	10.9039	0.037	6.480	0.0648
-10.5791	-2.6416	76.2000	10.9039	0.032	5.689	0.0569
-10.5791	-7.9375	76.2000	13.2258	0.041	7.095	0.0709
-10.5791	-13.2207	76.2000	16.9323	0.023	4.197	0.0420
-13.2207	-13.2207	76.2000	18.6969	0.019	3.507	0.0351
-13.2207	-10.5791	76.2000	16.9323	0.045	7.693	0.0769
-13.2207	-7.9375	76.2000	15.4205	0.057	9.385	0.0939
-13.2207	-5.2959	76.2000	14.2420	0.049	8.274	0.0827
-13.2207	-2.6416	76.2000	13.4820	0.034	6.008	0.0601
-13.2207	0.0000	76.2000	13.2207	0.032	5.689	0.0569
-13.2207	2.6416	76.2000	13.4820	0.044	7.545	0.0754
-13.2207	5.2959	76.2000	14.2420	0.050	8.416	0.0842
-13.2207	7.9375	76.2000	15.4205	0.044	7.545	0.0754
-13.2207	10.5791	76.2000	16.9323	0.019	3.507	0.0351
-13.2207	13.2207	76.2000	18.6969	0.018	3.332	0.0333
-15.8750	7.9375	76.2000	17.7488	0.053	8.838	0.0884
-15.8750	2.6416	76.2000	16.0933	0.046	7.839	0.0784
-15.8750	-2.6416	76.2000	16.0933	0.029	5.201	0.0520
-15.8750	-7.9375	76.2000	17.7488	0.066	10.555	0.1056
-18.5166	-7.9375	76.2000	20.1462	0.055	9.113	0.0911
-18.5166	-5.2959	76.2000	19.2591	0.044	7.545	0.0754
-18.5166	-2.6416	76.2000	18.7041	0.017	3.156	0.0316
-18.5166	0.0000	76.2000	18.5166	0.017	3.156	0.0316
-18.5166	2.6416	76.2000	18.7041	0.038	6.636	0.0664
-18.5166	5.2959	76.2000	19.2591	0.053	8.838	0.0884
-18.5166	7.9375	76.2000	20.1462	0.049	8.274	0.0827
Plane: 152.4 mm downstream of injection						
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Voltage [V]	Volume h2 [%]	Mole Fraction
0.0000	37.0459	152.4000	37.0459	0.007	1.236	0.0124
0.0000	31.7500	152.4000	31.7500	0.008	1.409	0.0141
0.0000	26.4541	152.4000	26.4541	0.011	1.921	0.0192
0.0000	21.1709	152.4000	21.1709	0.020	3.405	0.0341
0.0000	15.8750	152.4000	15.8750	0.030	4.962	0.0496
0.0000	10.5791	152.4000	10.5791	0.035	5.704	0.0570
0.0000	5.2959	152.4000	5.2959	0.034	5.558	0.0556
0.0000	0.0000	152.4000	0.0000	0.034	5.558	0.0556
0.0000	-5.2959	152.4000	5.2959	0.034	5.558	0.0556
0.0000	-10.5791	152.4000	10.5791	0.036	5.850	0.0585
0.0000	-15.8750	152.4000	15.8750	0.034	5.558	0.0556
0.0000	-21.1709	152.4000	21.1709	0.019	3.244	0.0324
0.0000	-26.4541	152.4000	26.4541	0.006	1.062	0.0106
0.0000	-31.7500	152.4000	31.7500	0.003	0.536	0.0054
0.0000	-37.0459	152.4000	37.0459	0.002	0.358	0.0036

-5.2959	-37.0459	152.4000	37.4225	0.002	0.358	0.0036
-5.2959	-31.7500	152.4000	32.1886	0.004	0.712	0.0071
-5.2959	-26.4541	152.4000	26.9790	0.010	1.751	0.0175
-5.2959	-21.1709	152.4000	21.8232	0.027	4.505	0.0451
-5.2959	-15.8750	152.4000	16.7351	0.038	6.138	0.0614
-5.2959	-10.5791	152.4000	11.8306	0.036	5.850	0.0585
-5.2959	-5.2959	152.4000	7.4895	0.034	5.558	0.0556
-5.2959	0.0000	152.4000	5.2959	0.034	5.558	0.0556
-5.2959	5.2959	152.4000	7.4895	0.034	5.558	0.0556
-5.2959	10.5791	152.4000	11.8306	0.036	5.850	0.0585
-5.2959	15.8750	152.4000	16.7351	0.034	5.558	0.0556
-5.2959	21.1709	152.4000	21.8232	0.024	4.040	0.0404
-5.2959	26.4541	152.4000	26.9790	0.013	2.258	0.0226
-5.2959	31.7500	152.4000	32.1886	0.008	1.409	0.0141
-5.2959	37.0459	152.4000	37.4225	0.006	1.062	0.0106
-10.5791	37.0459	152.4000	38.5268	0.007	1.236	0.0124
-10.5791	31.7500	152.4000	33.4661	0.008	1.409	0.0141
-10.5791	26.4541	152.4000	28.4910	0.013	2.258	0.0226
-10.5791	21.1709	152.4000	23.6669	0.024	4.040	0.0404
-10.5791	15.8750	152.4000	19.0770	0.033	5.410	0.0541
-10.5791	10.5791	152.4000	14.9611	0.035	5.704	0.0570
-10.5791	5.2959	152.4000	11.8306	0.036	5.850	0.0585
-10.5791	0.0000	152.4000	10.5791	0.035	5.704	0.0570
-10.5791	-5.2959	152.4000	11.8306	0.037	5.994	0.0599
-10.5791	-10.5791	152.4000	14.9611	0.036	5.850	0.0585
-10.5791	-15.8750	152.4000	19.0770	0.030	4.962	0.0496
-10.5791	-21.1709	152.4000	23.6669	0.019	3.244	0.0324
-10.5791	-26.4541	152.4000	28.4910	0.008	1.409	0.0141
-10.5791	-31.7500	152.4000	33.4661	0.004	0.712	0.0071
-10.5791	-37.0459	152.4000	38.5268	0.002	0.358	0.0036
-15.8750	-31.7500	152.4000	35.4976	0.003	0.536	0.0054
-15.8750	-26.4541	152.4000	30.8518	0.004	0.712	0.0071
-15.8750	-21.1709	152.4000	26.4617	0.008	1.409	0.0141
-15.8750	-15.8750	152.4000	22.4506	0.019	3.244	0.0324
-15.8750	-10.5791	152.4000	19.0770	0.036	5.850	0.0585
-15.8750	-5.2959	152.4000	16.7351	0.037	5.994	0.0599
-15.8750	0.0000	152.4000	15.8750	0.034	5.558	0.0556
-15.8750	5.2959	152.4000	16.7351	0.036	5.850	0.0585
-15.8750	10.5791	152.4000	19.0770	0.031	5.113	0.0511
-15.8750	15.8750	152.4000	22.4506	0.021	3.565	0.0357
-15.8750	21.1709	152.4000	26.4617	0.014	2.424	0.0242
-15.8750	26.4541	152.4000	30.8518	0.009	1.580	0.0158
-15.8750	31.7500	152.4000	35.4976	0.007	1.236	0.0124
-21.1709	31.7500	152.4000	38.1611	0.006	1.062	0.0106
-21.1709	26.4541	152.4000	33.8825	0.006	1.062	0.0106
-21.1709	21.1709	152.4000	29.9402	0.007	1.236	0.0124
-21.1709	15.8750	152.4000	26.4617	0.012	2.090	0.0209
-21.1709	10.5791	152.4000	23.6669	0.023	3.882	0.0388
-21.1709	5.2959	152.4000	21.8232	0.028	4.659	0.0466
-21.1709	0.0000	152.4000	21.1709	0.024	4.040	0.0404
-21.1709	-5.2959	152.4000	21.8232	0.026	4.351	0.0435
-21.1709	-10.5791	152.4000	23.6669	0.025	4.196	0.0420
-21.1709	-15.8750	152.4000	26.4617	0.013	2.258	0.0226
-21.1709	-21.1709	152.4000	29.9402	0.006	1.062	0.0106
-21.1709	-26.4541	152.4000	33.8825	0.003	0.536	0.0054
-21.1709	-31.7500	152.4000	38.1611	0.002	0.358	0.0036
-26.4541	-26.4541	152.4000	37.4117	0.003	0.536	0.0054
-26.4541	-21.1709	152.4000	33.8825	0.004	0.712	0.0071
-26.4541	-15.8750	152.4000	30.8518	0.007	1.236	0.0124
-26.4541	-10.5791	152.4000	28.4910	0.011	1.921	0.0192
-26.4541	-5.2959	152.4000	26.9790	0.011	1.921	0.0192
-26.4541	0.0000	152.4000	26.4541	0.011	1.921	0.0192
-26.4541	5.2959	152.4000	26.9790	0.014	2.424	0.0242
-26.4541	10.5791	152.4000	28.4910	0.012	2.090	0.0209
-26.4541	15.8750	152.4000	30.8518	0.008	1.409	0.0141
-26.4541	21.1709	152.4000	33.8825	0.006	1.062	0.0106
-26.4541	26.4541	152.4000	37.4117	0.005	0.888	0.0089
-31.7500	21.1709	152.4000	38.1611	0.005	0.888	0.0089
-31.7500	15.8750	152.4000	35.4976	0.006	1.062	0.0106
-31.7500	10.5791	152.4000	33.4661	0.007	1.236	0.0124
-31.7500	5.2959	152.4000	32.1886	0.007	1.236	0.0124
-31.7500	0.0000	152.4000	31.7500	0.005	0.888	0.0089
-31.7500	-5.2959	152.4000	32.1886	0.005	0.888	0.0089
-31.7500	-10.5791	152.4000	33.4661	0.005	0.888	0.0089
-31.7500	-15.8750	152.4000	35.4976	0.004	0.712	0.0071
-31.7500	-21.1709	152.4000	38.1611	0.004	0.712	0.0071
-37.0459	-10.5791	152.4000	38.5268	0.004	0.712	0.0071
-37.0459	-5.2959	152.4000	37.4225	0.004	0.712	0.0071
-37.0459	0.0000	152.4000	37.0459	0.004	0.712	0.0071
-37.0459	5.2959	152.4000	37.4225	0.005	0.888	0.0089

-37.0459 10.5791 152.4000 38.5268 0.005 0.888 0.0089

Table B-14: Velocity field data. Case 4

Hardware Configuration: B				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.002952 kg/min	
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.7867	0.0000	76.3025	39.7867	0.0733	0.2151
-38.9741	0.0000	76.3025	38.9741	0.0414	0.1679
-38.1614	0.0000	76.3025	38.1614	-0.0041	-0.0238
-37.3487	0.0000	76.3025	37.3487	-0.0880	0.0428
-36.5361	0.0000	76.3025	36.5361	-0.1455	0.0081
-35.7234	0.0000	76.3025	35.7234	-0.1721	-0.1793
-34.9107	0.0000	76.3025	34.9107	-0.1526	-0.1863
-34.0981	0.0000	76.3025	34.0981	-0.0934	0.0747
-33.2854	0.0000	76.3025	33.2854	-0.0380	0.3744
-32.4727	0.0000	76.3025	32.4727	-0.0488	0.6932
-31.6601	0.0000	76.3025	31.6601	-0.0802	1.0926
-30.8474	0.0000	76.3025	30.8474	-0.1076	1.5134
-30.0347	0.0000	76.3025	30.0347	-0.1331	1.9658
-29.2221	0.0000	76.3025	29.2221	-0.1472	2.4635
-28.4094	0.0000	76.3025	28.4094	-0.1565	2.9834
-27.5967	0.0000	76.3025	27.5967	-0.1742	3.4942
-26.7841	0.0000	76.3025	26.7841	-0.1988	3.9918
-25.9714	0.0000	76.3025	25.9714	-0.2054	4.4423
-25.1588	0.0000	76.3025	25.1588	-0.2149	4.8286
-24.3461	0.0000	76.3025	24.3461	-0.2254	5.1347
-23.5334	0.0000	76.3025	23.5334	-0.2162	5.3963
-22.7208	0.0000	76.3025	22.7208	-0.1884	5.6414
-21.9081	0.0000	76.3025	21.9081	-0.1574	5.8665
-21.0954	0.0000	76.3025	21.0954	-0.1347	6.0539
-20.2828	0.0000	76.3025	20.2828	-0.1122	6.2332
-19.4701	0.0000	76.3025	19.4701	-0.1195	6.3839
-18.6574	0.0000	76.3025	18.6574	-0.1155	6.5010
-17.8448	0.0000	76.3025	17.8448	-0.0731	6.6144
-17.0321	0.0000	76.3025	17.0321	-0.0251	6.7213
-16.2194	0.0000	76.3025	16.2194	0.0060	6.8023
-15.4068	0.0000	76.3025	15.4068	0.0350	6.8284
-14.5941	0.0000	76.3025	14.5941	0.1044	6.7707
-13.7814	0.0000	76.3025	13.7814	0.1691	6.6336
-12.9688	0.0000	76.3025	12.9688	0.2318	6.4826
-12.1561	0.0000	76.3025	12.1561	0.2974	6.3362
-11.3434	0.0000	76.3025	11.3434	0.3481	6.1514
-10.5308	0.0000	76.3025	10.5308	0.3747	5.9233
-9.7181	0.0000	76.3025	9.7181	0.3872	5.6735
-8.9054	0.0000	76.3025	8.9054	0.4054	5.4313
-8.0928	0.0000	76.3025	8.0928	0.4232	5.2125
-7.2801	0.0000	76.3025	7.2801	0.4311	5.0498
-6.4674	0.0000	76.3025	6.4674	0.4507	4.9264
-5.6548	0.0000	76.3025	5.6548	0.4432	4.7917
-4.8421	0.0000	76.3025	4.8421	0.4073	4.6354
-4.0294	0.0000	76.3025	4.0294	0.3662	4.4822
-3.2168	0.0000	76.3025	3.2168	0.3392	4.3617
-2.4041	0.0000	76.3025	2.4041	0.3117	4.2708
-1.5914	0.0000	76.3025	1.5914	0.2494	4.1532
-0.7788	0.0000	76.3025	0.7788	0.1979	4.0304
0.0339	0.0000	76.3025	0.0339	0.1587	3.9426
0.8466	0.0000	76.3025	0.8466	0.1013	3.8827
1.6592	0.0000	76.3025	1.6592	0.0282	3.8629
2.4719	0.0000	76.3025	2.4719	-0.0374	3.8953
3.2846	0.0000	76.3025	3.2846	-0.0760	3.9689
4.0972	0.0000	76.3025	4.0972	-0.0946	4.0366
4.9099	0.0000	76.3025	4.9099	-0.1501	4.1349
5.7226	0.0000	76.3025	5.7226	-0.2103	4.3006
6.5352	0.0000	76.3025	6.5352	-0.2337	4.5041
7.3479	0.0000	76.3025	7.3479	-0.2290	4.7185
8.1606	0.0000	76.3025	8.1606	-0.2080	4.9216
8.9732	0.0000	76.3025	8.9732	-0.1701	5.0994
9.7859	0.0000	76.3025	9.7859	-0.1155	5.2476
10.5986	0.0000	76.3025	10.5986	-0.0606	5.3986
11.4112	0.0000	76.3025	11.4112	0.0084	5.5480
12.2239	0.0000	76.3025	12.2239	0.0605	5.6664
13.0366	0.0000	76.3025	13.0366	0.0949	5.7481
13.8492	0.0000	76.3025	13.8492	0.1163	5.8095
14.6619	0.0000	76.3025	14.6619	0.1302	5.8731

15.4746	0.0000	76.3025	15.4746	0.1428	5.9481
16.2872	0.0000	76.3025	16.2872	0.1524	6.0183
17.0999	0.0000	76.3025	17.0999	0.1497	6.1108
17.9126	0.0000	76.3025	17.9126	0.1167	6.2389
18.7252	0.0000	76.3025	18.7252	0.0573	6.4330
19.5379	0.0000	76.3025	19.5379	-0.0004	6.6765
20.3506	0.0000	76.3025	20.3506	-0.0443	6.9201
21.1632	0.0000	76.3025	21.1632	-0.0763	7.1024
21.9759	0.0000	76.3025	21.9759	-0.0842	7.1736
22.7886	0.0000	76.3025	22.7886	-0.0858	7.0486
23.6012	0.0000	76.3025	23.6012	-0.0926	6.7795
24.4139	0.0000	76.3025	24.4139	-0.0841	6.4327
25.2266	0.0000	76.3025	25.2266	-0.0738	5.9932
26.0392	0.0000	76.3025	26.0392	-0.0860	5.4370
26.8519	0.0000	76.3025	26.8519	-0.1219	4.7708
27.6646	0.0000	76.3025	27.6646	-0.1442	4.0448
28.4772	0.0000	76.3025	28.4772	-0.1308	3.3100
29.2899	0.0000	76.3025	29.2899	-0.1093	2.6211
30.1026	0.0000	76.3025	30.1026	-0.1007	1.9842
30.9152	0.0000	76.3025	30.9152	-0.1118	1.4002
31.7279	0.0000	76.3025	31.7279	-0.1333	0.8522
32.5406	0.0000	76.3025	32.5406	-0.1535	0.3412
33.3532	0.0000	76.3025	33.3532	-0.1640	-0.1062
34.1659	0.0000	76.3025	34.1659	-0.1589	-0.4649
34.9786	0.0000	76.3025	34.9786	-0.1403	-0.7244
35.7912	0.0000	76.3025	35.7912	-0.1137	-0.9171
36.6039	0.0000	76.3025	36.6039	-0.0918	-1.0926
37.4166	0.0000	76.3025	37.4166	-0.0534	-1.1353
38.2292	0.0000	76.3025	38.2292	-0.0041	-0.9442
Plane: 152.4 mm downstream of injection					
-39.4581	0.0000	152.2921	39.4581	-0.0286	0.0999
-38.6353	0.0000	152.2921	38.6353	-0.0402	0.4500
-37.8124	0.0000	152.2921	37.8124	-0.0475	0.7996
-36.9895	0.0000	152.2921	36.9895	-0.0827	0.7791
-36.1667	0.0000	152.2921	36.1667	-0.1206	0.2528
-35.3438	0.0000	152.2921	35.3438	-0.1236	0.0482
-34.5210	0.0000	152.2921	34.5210	-0.1131	0.3137
-33.6981	0.0000	152.2921	33.6981	-0.1004	0.9384
-32.8753	0.0000	152.2921	32.8753	-0.0999	1.6454
-32.0524	0.0000	152.2921	32.0524	-0.1420	2.0940
-31.2295	0.0000	152.2921	31.2295	-0.2064	2.2946
-30.4067	0.0000	152.2921	30.4067	-0.2537	2.4727
-29.5838	0.0000	152.2921	29.5838	-0.2894	2.7011
-28.7610	0.0000	152.2921	28.7610	-0.3164	2.9564
-27.9381	0.0000	152.2921	27.9381	-0.3211	3.2150
-27.1153	0.0000	152.2921	27.1153	-0.3301	3.4402
-26.2924	0.0000	152.2921	26.2924	-0.3375	3.6600
-25.4696	0.0000	152.2921	25.4696	-0.3370	3.8734
-24.6467	0.0000	152.2921	24.6467	-0.3313	4.0636
-23.8238	0.0000	152.2921	23.8238	-0.3233	4.2318
-23.0010	0.0000	152.2921	23.0010	-0.3085	4.4123
-22.1781	0.0000	152.2921	22.1781	-0.2952	4.6101
-21.3553	0.0000	152.2921	21.3553	-0.2643	4.7813
-20.5324	0.0000	152.2921	20.5324	-0.2398	4.9218
-19.7096	0.0000	152.2921	19.7096	-0.2326	5.0521
-18.8867	0.0000	152.2921	18.8867	-0.2195	5.1627
-18.0638	0.0000	152.2921	18.0638	-0.2029	5.2491
-17.2410	0.0000	152.2921	17.2410	-0.1890	5.3171
-16.4181	0.0000	152.2921	16.4181	-0.1639	5.3745
-15.5953	0.0000	152.2921	15.5953	-0.1431	5.4199
-14.7724	0.0000	152.2921	14.7724	-0.1334	5.4428
-13.9496	0.0000	152.2921	13.9496	-0.1159	5.4317
-13.1267	0.0000	152.2921	13.1267	-0.0902	5.4121
-12.3038	0.0000	152.2921	12.3038	-0.0679	5.3950
-11.4810	0.0000	152.2921	11.4810	-0.0492	5.3839
-10.6581	0.0000	152.2921	10.6581	-0.0288	5.3813
-9.8353	0.0000	152.2921	9.8353	-0.0085	5.3823
-9.0124	0.0000	152.2921	9.0124	0.0003	5.3521
-8.1896	0.0000	152.2921	8.1896	0.0099	5.2900
-7.3667	0.0000	152.2921	7.3667	0.0238	5.2300
-6.5438	0.0000	152.2921	6.5438	0.0292	5.1814
-5.7210	0.0000	152.2921	5.7210	0.0389	5.1527
-4.8981	0.0000	152.2921	4.8981	0.0534	5.1346
-4.0753	0.0000	152.2921	4.0753	0.0691	5.1114
-3.2524	0.0000	152.2921	3.2524	0.0884	5.0728
-2.4296	0.0000	152.2921	2.4296	0.1113	5.0132
-1.6067	0.0000	152.2921	1.6067	0.1098	4.9565
-0.7839	0.0000	152.2921	0.7839	0.1023	4.9165
0.0390	0.0000	152.2921	0.0390	0.1005	4.8952
0.8619	0.0000	152.2921	0.8619	0.0959	4.8746

1.6847	0.0000	152.2921	1.6847	0.0810	4.8375
2.5076	0.0000	152.2921	2.5076	0.0573	4.7910
3.3304	0.0000	152.2921	3.3304	0.0370	4.7633
4.1533	0.0000	152.2921	4.1533	0.0339	4.7684
4.9761	0.0000	152.2921	4.9761	0.0364	4.7827
5.7990	0.0000	152.2921	5.7990	0.0320	4.7949
6.6219	0.0000	152.2921	6.6219	0.0239	4.8202
7.4447	0.0000	152.2921	7.4447	0.0206	4.8704
8.2676	0.0000	152.2921	8.2676	0.0261	4.9391
9.0904	0.0000	152.2921	9.0904	0.0391	5.0187
9.9133	0.0000	152.2921	9.9133	0.0510	5.1074
10.7361	0.0000	152.2921	10.7361	0.0443	5.1970
11.5590	0.0000	152.2921	11.5590	0.0323	5.2689
12.3819	0.0000	152.2921	12.3819	0.0379	5.3278
13.2047	0.0000	152.2921	13.2047	0.0521	5.3859
14.0276	0.0000	152.2921	14.0276	0.0649	5.4426
14.8504	0.0000	152.2921	14.8504	0.0739	5.4950
15.6733	0.0000	152.2921	15.6733	0.0843	5.5430
16.4961	0.0000	152.2921	16.4961	0.0956	5.5870
17.3190	0.0000	152.2921	17.3190	0.0916	5.6223
18.1418	0.0000	152.2921	18.1418	0.0788	5.6478
18.9647	0.0000	152.2921	18.9647	0.0821	5.6437
19.7876	0.0000	152.2921	19.7876	0.0831	5.6034
20.6104	0.0000	152.2921	20.6104	0.1001	5.5493
21.4333	0.0000	152.2921	21.4333	0.1291	5.4797
22.2561	0.0000	152.2921	22.2561	0.1390	5.3788
23.0790	0.0000	152.2921	23.0790	0.1099	5.2332
23.9018	0.0000	152.2921	23.9018	0.0753	5.0423
24.7247	0.0000	152.2921	24.7247	0.0790	4.8017
25.5476	0.0000	152.2921	25.5476	0.0915	4.5422
26.3704	0.0000	152.2921	26.3704	0.0925	4.2849
27.1933	0.0000	152.2921	27.1933	0.0864	4.0241
28.0161	0.0000	152.2921	28.0161	0.0728	3.7383
28.8390	0.0000	152.2921	28.8390	0.0571	3.4280
29.6618	0.0000	152.2921	29.6618	0.0459	3.1151
30.4847	0.0000	152.2921	30.4847	0.0359	2.8177
31.3076	0.0000	152.2921	31.3076	0.0138	2.5309
32.1304	0.0000	152.2921	32.1304	0.0076	2.2846
32.9533	0.0000	152.2921	32.9533	0.0022	2.0703
33.7761	0.0000	152.2921	33.7761	-0.0068	1.8631
34.5990	0.0000	152.2921	34.5990	-0.0100	1.6598
35.4218	0.0000	152.2921	35.4218	-0.0020	1.4730
36.2447	0.0000	152.2921	36.2447	0.0172	1.3013
37.0675	0.0000	152.2921	37.0675	0.0511	1.0919
37.8904	0.0000	152.2921	37.8904	0.1203	0.7155
38.7133	0.0000	152.2921	38.7133	0.3760	0.2446

B.13.6 Case 5: Swirling Axial Injection of Methane

Table B-15: Spatial fuel concentration data. Case 5

Hardware Configuration: C				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00108 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
-36.1950	0.0000	25.4000	36.1950	0.000	0.00000
-34.9250	0.0000	25.4000	34.9250	0.000	0.00000
-33.6550	0.0000	25.4000	33.6550	0.000	0.00000
-32.3850	0.0000	25.4000	32.3850	0.000	0.00000
-31.1150	0.0000	25.4000	31.1150	0.000	0.00000
-29.8450	0.0000	25.4000	29.8450	0.000	0.00000
-28.5750	0.0000	25.4000	28.5750	0.000	0.00000
-27.3050	0.0000	25.4000	27.3050	0.000	0.00000
-26.0350	0.0000	25.4000	26.0350	0.006	0.00006
-23.4950	0.0000	25.4000	23.4950	0.012	0.00012
-22.2250	0.0000	25.4000	22.2250	0.014	0.00014
-20.9550	0.0000	25.4000	20.9550	0.016	0.00016
-19.6850	0.0000	25.4000	19.6850	0.019	0.00019
-18.4150	0.0000	25.4000	18.4150	0.021	0.00021
-17.1450	0.0000	25.4000	17.1450	0.024	0.00024
-15.8750	0.0000	25.4000	15.8750	0.024	0.00024
-14.6050	0.0000	25.4000	14.6050	0.024	0.00024
-13.3350	0.0000	25.4000	13.3350	0.026	0.00026
-12.0650	0.0000	25.4000	12.0650	0.044	0.00044
-10.7950	0.0000	25.4000	10.7950	0.136	0.00136
-9.5250	0.0000	25.4000	9.5250	0.531	0.00531

-8.2550	0.0000	25.4000	8.2550	1.284	0.01284
-6.9850	0.0000	25.4000	6.9850	2.344	0.02344
-5.7150	0.0000	25.4000	5.7150	3.331	0.03331
-4.4450	0.0000	25.4000	4.4450	3.874	0.03874
-3.1750	0.0000	25.4000	3.1750	4.353	0.04353
-1.9050	0.0000	25.4000	1.9050	4.827	0.04827
-0.6350	0.0000	25.4000	0.6350	5.315	0.05315
0.6350	0.0000	25.4000	0.6350	5.598	0.05598
1.9050	0.0000	25.4000	1.9050	5.206	0.05206
3.1750	0.0000	25.4000	3.1750	4.523	0.04523
4.4450	0.0000	25.4000	4.4450	3.971	0.03971
5.7150	0.0000	25.4000	5.7150	3.372	0.03372
6.9850	0.0000	25.4000	6.9850	2.266	0.02266
8.2550	0.0000	25.4000	8.2550	0.813	0.00813
9.5250	0.0000	25.4000	9.5250	0.327	0.00327
10.7950	0.0000	25.4000	10.7950	0.190	0.00190
12.0650	0.0000	25.4000	12.0650	0.102	0.00102
13.3350	0.0000	25.4000	13.3350	0.063	0.00063
14.6050	0.0000	25.4000	14.6050	0.049	0.00049
15.8750	0.0000	25.4000	15.8750	0.045	0.00045
17.1450	0.0000	25.4000	17.1450	0.038	0.00038
18.4150	0.0000	25.4000	18.4150	0.032	0.00032
19.6850	0.0000	25.4000	19.6850	0.026	0.00026
20.9550	0.0000	25.4000	20.9550	0.019	0.00019
22.2250	0.0000	25.4000	22.2250	0.014	0.00014
23.4950	0.0000	25.4000	23.4950	0.009	0.00009
24.7650	0.0000	25.4000	24.7650	0.000	0.00000
26.0350	0.0000	25.4000	26.0350	0.000	0.00000
27.3050	0.0000	25.4000	27.3050	0.000	0.00000
28.5750	0.0000	25.4000	28.5750	0.000	0.00000
29.8450	0.0000	25.4000	29.8450	0.000	0.00000
31.1150	0.0000	25.4000	31.1150	0.000	0.00000
32.3850	0.0000	25.4000	32.3850	0.000	0.00000
33.6550	0.0000	25.4000	33.6550	0.000	0.00000
34.9250	0.0000	25.4000	34.9250	0.000	0.00000
36.1950	0.0000	25.4000	36.1950	0.000	0.00000

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
-36.1950	0.0000	76.2000	36.1950	0.000	0.00000
-34.9250	0.0000	76.2000	34.9250	0.000	0.00000
-33.6550	0.0000	76.2000	33.6550	0.000	0.00000
-32.3850	0.0000	76.2000	32.3850	0.000	0.00000
-31.1150	0.0000	76.2000	31.1150	0.000	0.00000
-29.8450	0.0000	76.2000	29.8450	0.000	0.00000
-28.5750	0.0000	76.2000	28.5750	0.000	0.00000
-27.3050	0.0000	76.2000	27.3050	0.000	0.00000
-26.0350	0.0000	76.2000	26.0350	0.008	0.00008
-24.7650	0.0000	76.2000	24.7650	0.008	0.00008
-23.4950	0.0000	76.2000	23.4950	0.008	0.00008
-22.2250	0.0000	76.2000	22.2250	0.009	0.00009
-20.9550	0.0000	76.2000	20.9550	0.011	0.00011
-19.6850	0.0000	76.2000	19.6850	0.011	0.00011
-18.4150	0.0000	76.2000	18.4150	0.013	0.00013
-17.1450	0.0000	76.2000	17.1450	0.018	0.00018
-15.8750	0.0000	76.2000	15.8750	0.027	0.00027
-14.6050	0.0000	76.2000	14.6050	0.048	0.00048
-13.3350	0.0000	76.2000	13.3350	0.090	0.00090
-12.0650	0.0000	76.2000	12.0650	0.182	0.00182
-10.7950	0.0000	76.2000	10.7950	0.403	0.00403
-9.5250	0.0000	76.2000	9.5250	0.753	0.00753
-8.2550	0.0000	76.2000	8.2550	1.227	0.01227
-6.9850	0.0000	76.2000	6.9850	1.722	0.01722
-5.7150	0.0000	76.2000	5.7150	2.079	0.02079
-4.4450	0.0000	76.2000	4.4450	2.198	0.02198
-3.1750	0.0000	76.2000	3.1750	2.242	0.02242
-1.9050	0.0000	76.2000	1.9050	2.384	0.02384
-0.6350	0.0000	76.2000	0.6350	2.791	0.02791
0.6350	0.0000	76.2000	0.6350	2.795	0.02795
1.9050	0.0000	76.2000	1.9050	2.696	0.02696
3.1750	0.0000	76.2000	3.1750	2.529	0.02529
4.4450	0.0000	76.2000	4.4450	2.335	0.02335
5.7150	0.0000	76.2000	5.7150	2.090	0.02090
6.9850	0.0000	76.2000	6.9850	1.555	0.01555
8.2550	0.0000	76.2000	8.2550	1.088	0.01088
9.5250	0.0000	76.2000	9.5250	0.694	0.00694
10.7950	0.0000	76.2000	10.7950	0.379	0.00379
12.0650	0.0000	76.2000	12.0650	0.202	0.00202
13.3350	0.0000	76.2000	13.3350	0.111	0.00111
14.6050	0.0000	76.2000	14.6050	0.066	0.00066
15.8750	0.0000	76.2000	15.8750	0.043	0.00043

17.1450	0.0000	76.2000	17.1450	0.030	0.00030
18.4150	0.0000	76.2000	18.4150	0.022	0.00022
19.6850	0.0000	76.2000	19.6850	0.016	0.00016
20.9550	0.0000	76.2000	20.9550	0.013	0.00013
22.2250	0.0000	76.2000	22.2250	0.011	0.00011
23.4950	0.0000	76.2000	23.4950	0.011	0.00011
24.7650	0.0000	76.2000	24.7650	0.010	0.00010
26.0350	0.0000	76.2000	26.0350	0.009	0.00009
27.3050	0.0000	76.2000	27.3050	0.008	0.00008
28.5750	0.0000	76.2000	28.5750	0.008	0.00008
29.8450	0.0000	76.2000	29.8450	0.008	0.00008
31.1150	0.0000	76.2000	31.1150	0.007	0.00007
32.3850	0.0000	76.2000	32.3850	0.006	0.00006
33.6550	0.0000	76.2000	33.6550	0.000	0.00000
34.9250	0.0000	76.2000	34.9250	0.000	0.00000
36.1950	0.0000	76.2000	36.1950	0.000	0.00000
Plane: 152.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
-37.4650	0.0000	152.4000	37.4650	0.000	0.00000
-36.1950	0.0000	152.4000	36.1950	0.000	0.00000
-34.9250	0.0000	152.4000	34.9250	0.000	0.00000
-33.6550	0.0000	152.4000	33.6550	0.000	0.00000
-32.3850	0.0000	152.4000	32.3850	0.000	0.00000
-31.1150	0.0000	152.4000	31.1150	0.000	0.00000
-29.8450	0.0000	152.4000	29.8450	0.000	0.00000
-28.5750	0.0000	152.4000	28.5750	0.000	0.00000
-27.3050	0.0000	152.4000	27.3050	0.000	0.00000
-26.0350	0.0000	152.4000	26.0350	0.000	0.00000
-24.7650	0.0000	152.4000	24.7650	0.000	0.00000
-23.4950	0.0000	152.4000	23.4950	0.000	0.00000
-22.2250	0.0000	152.4000	22.2250	0.000	0.00000
-20.9550	0.0000	152.4000	20.9550	0.008	0.00008
-19.6850	0.0000	152.4000	19.6850	0.009	0.00009
-18.4150	0.0000	152.4000	18.4150	0.014	0.00014
-17.1450	0.0000	152.4000	17.1450	0.024	0.00024
-15.8750	0.0000	152.4000	15.8750	0.037	0.00037
-14.6050	0.0000	152.4000	14.6050	0.050	0.00050
-13.3350	0.0000	152.4000	13.3350	0.074	0.00074
-12.0650	0.0000	152.4000	12.0650	0.126	0.00126
-10.7950	0.0000	152.4000	10.7950	0.288	0.00288
-9.5250	0.0000	152.4000	9.5250	0.697	0.00697
-8.2550	0.0000	152.4000	8.2550	1.076	0.01076
-6.9850	0.0000	152.4000	6.9850	1.314	0.01314
-5.7150	0.0000	152.4000	5.7150	1.405	0.01405
-4.4450	0.0000	152.4000	4.4450	1.400	0.01400
-3.1750	0.0000	152.4000	3.1750	1.408	0.01408
-1.9050	0.0000	152.4000	1.9050	1.391	0.01391
-0.6350	0.0000	152.4000	0.6350	1.358	0.01358
0.6350	0.0000	152.4000	0.6350	1.362	0.01362
1.9050	0.0000	152.4000	1.9050	1.393	0.01393
3.1750	0.0000	152.4000	3.1750	1.405	0.01405
4.4450	0.0000	152.4000	4.4450	1.390	0.01390
5.7150	0.0000	152.4000	5.7150	1.379	0.01379
6.9850	0.0000	152.4000	6.9850	1.347	0.01347
8.2550	0.0000	152.4000	8.2550	1.271	0.01271
9.5250	0.0000	152.4000	9.5250	1.169	0.01169
10.7950	0.0000	152.4000	10.7950	1.015	0.01015
12.0650	0.0000	152.4000	12.0650	0.682	0.00682
13.3350	0.0000	152.4000	13.3350	0.346	0.00346
14.6050	0.0000	152.4000	14.6050	0.171	0.00171
15.8750	0.0000	152.4000	15.8750	0.117	0.00117
17.1450	0.0000	152.4000	17.1450	0.090	0.00090
18.4150	0.0000	152.4000	18.4150	0.062	0.00062
19.6850	0.0000	152.4000	19.6850	0.032	0.00032
20.9550	0.0000	152.4000	20.9550	0.016	0.00016
22.2250	0.0000	152.4000	22.2250	0.010	0.00010
23.4950	0.0000	152.4000	23.4950	0.009	0.00009
24.7650	0.0000	152.4000	24.7650	0.008	0.00008
26.0350	0.0000	152.4000	26.0350	0.008	0.00008
27.3050	0.0000	152.4000	27.3050	0.008	0.00008
28.5750	0.0000	152.4000	28.5750	0.008	0.00008
29.8450	0.0000	152.4000	29.8450	0.008	0.00008
31.1150	0.0000	152.4000	31.1150	0.000	0.00000
32.3850	0.0000	152.4000	32.3850	0.000	0.00000
33.6550	0.0000	152.4000	33.6550	0.000	0.00000
34.9250	0.0000	152.4000	34.9250	0.000	0.00000

Table B-16: Velocity field data. Case 5

Hardware Configuration: C				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00108 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-38.9588	0.0000	25.4853	38.9588	0.1630	-0.0210
-38.1385	0.0000	25.4853	38.1385	0.2119	-0.1971
-37.3182	0.0000	25.4853	37.3182	0.2299	-0.2626
-36.4979	0.0000	25.4853	36.4979	0.2186	-0.1827
-35.6776	0.0000	25.4853	35.6776	0.2302	-0.0834
-34.8572	0.0000	25.4853	34.8572	0.2010	-0.0773
-34.0369	0.0000	25.4853	34.0369	0.3215	-0.1951
-33.2166	0.0000	25.4853	33.2166	0.2380	-0.2498
-32.3963	0.0000	25.4853	32.3963	-0.2030	-0.3099
-31.5760	0.0000	25.4853	31.5760	-0.6304	-0.2328
-30.7557	0.0000	25.4853	30.7557	-0.8322	0.2563
-29.9354	0.0000	25.4853	29.9354	-0.8342	1.7935
-29.1151	0.0000	25.4853	29.1151	-0.8242	3.6921
-28.2948	0.0000	25.4853	28.2948	-0.8449	4.2250
-27.4745	0.0000	25.4853	27.4745	-0.8239	4.1119
-26.6542	0.0000	25.4853	26.6542	-0.8386	3.8636
-25.8338	0.0000	25.4853	25.8338	-0.8585	3.5370
-25.0135	0.0000	25.4853	25.0135	-0.8638	3.0696
-24.1932	0.0000	25.4853	24.1932	-0.7778	2.4074
-23.3729	0.0000	25.4853	23.3729	-0.6473	1.6907
-22.5526	0.0000	25.4853	22.5526	-0.5520	1.0825
-21.7323	0.0000	25.4853	21.7323	-0.4997	0.6114
-20.9120	0.0000	25.4853	20.9120	-0.4369	0.2272
-20.0917	0.0000	25.4853	20.0917	-0.4066	-0.0380
-19.2714	0.0000	25.4853	19.2714	-0.3358	-0.1287
-18.4511	0.0000	25.4853	18.4511	-0.2008	-0.1212
-17.6308	0.0000	25.4853	17.6308	-0.0058	-0.0769
-16.8105	0.0000	25.4853	16.8105	0.1706	-0.0261
-15.9901	0.0000	25.4853	15.9901	0.1965	0.0317
-15.1698	0.0000	25.4853	15.1698	0.0621	0.1118
-14.3495	0.0000	25.4853	14.3495	-0.0540	0.2739
-13.5292	0.0000	25.4853	13.5292	-0.0246	0.6886
-12.7089	0.0000	25.4853	12.7089	0.0479	1.3153
-11.8886	0.0000	25.4853	11.8886	0.1691	1.9170
-11.0683	0.0000	25.4853	11.0683	0.2993	2.5278
-10.2480	0.0000	25.4853	10.2480	0.4145	3.3062
-9.4277	0.0000	25.4853	9.4277	0.5241	4.3533
-8.6074	0.0000	25.4853	8.6074	0.6522	5.5640
-7.7871	0.0000	25.4853	7.7871	0.7988	6.7123
-6.9667	0.0000	25.4853	6.9667	0.9693	7.6626
-6.1464	0.0000	25.4853	6.1464	1.1845	8.3231
-5.3261	0.0000	25.4853	5.3261	1.4661	8.4476
-4.5058	0.0000	25.4853	4.5058	1.8580	7.5000
-3.6855	0.0000	25.4853	3.6855	2.3351	5.3984
-2.8652	0.0000	25.4853	2.8652	2.8296	2.7990
-2.0449	0.0000	25.4853	2.0449	3.3027	0.6268
-1.2246	0.0000	25.4853	1.2246	3.7357	-0.5815
-0.4043	0.0000	25.4853	0.4043	4.0978	-0.8342
0.4160	0.0000	25.4853	0.4160	4.2365	-0.4365
1.2363	0.0000	25.4853	1.2363	4.1897	0.4639
2.0567	0.0000	25.4853	2.0567	4.0124	2.0509
2.8770	0.0000	25.4853	2.8770	3.7958	4.2669
3.6973	0.0000	25.4853	3.6973	3.5532	6.6173
4.5176	0.0000	25.4853	4.5176	3.2133	8.3452
5.3379	0.0000	25.4853	5.3379	2.6845	8.9846
6.1582	0.0000	25.4853	6.1582	2.0038	8.6228
6.9785	0.0000	25.4853	6.9785	1.4241	7.8144
7.7988	0.0000	25.4853	7.7988	0.9606	6.8708
8.6191	0.0000	25.4853	8.6191	0.5757	5.9024
9.4394	0.0000	25.4853	9.4394	0.3260	4.8098
10.2597	0.0000	25.4853	10.2597	0.1327	3.4705
11.0801	0.0000	25.4853	11.0801	-0.0583	2.2415
11.9004	0.0000	25.4853	11.9004	-0.1968	1.6234
12.7207	0.0000	25.4853	12.7207	-0.2675	1.5865
13.5410	0.0000	25.4853	13.5410	-0.3465	1.6304
14.3613	0.0000	25.4853	14.3613	-0.3532	1.4436
15.1816	0.0000	25.4853	15.1816	-0.3103	1.1247
16.0019	0.0000	25.4853	16.0019	-0.2688	0.8545
16.8222	0.0000	25.4853	16.8222	-0.2606	0.7363
17.6425	0.0000	25.4853	17.6425	-0.3105	0.7919
18.4628	0.0000	25.4853	18.4628	-0.4059	0.9918
19.2831	0.0000	25.4853	19.2831	-0.4910	1.3000
20.1035	0.0000	25.4853	20.1035	-0.5398	1.6524
20.9238	0.0000	25.4853	20.9238	-0.6012	1.9180
21.7441	0.0000	25.4853	21.7441	-0.6052	2.1661

22.5644	0.0000	25.4853	22.5644	-0.6333	2.4360
23.3847	0.0000	25.4853	23.3847	-0.6694	2.7651
24.2050	0.0000	25.4853	24.2050	-0.7250	3.1284
25.0253	0.0000	25.4853	25.0253	-0.8118	3.5033
25.8456	0.0000	25.4853	25.8456	-0.8736	3.9395
26.6659	0.0000	25.4853	26.6659	-0.9656	4.4424
27.4862	0.0000	25.4853	27.4862	-1.0573	4.7554
28.3065	0.0000	25.4853	28.3065	-1.1393	5.0482
29.1269	0.0000	25.4853	29.1269	-1.2111	5.2460
29.9472	0.0000	25.4853	29.9472	-1.1013	4.5368
30.7675	0.0000	25.4853	30.7675	-0.8204	2.6061
31.5878	0.0000	25.4853	31.5878	-0.7456	0.6666
32.4081	0.0000	25.4853	32.4081	-1.2982	-0.1224
33.2284	0.0000	25.4853	33.2284	-2.3167	0.1171
34.0487	0.0000	25.4853	34.0487	-1.9138	0.1571
34.8690	0.0000	25.4853	34.8690	-1.0308	0.0804
35.6893	0.0000	25.4853	35.6893	-0.3930	0.0011
36.5096	0.0000	25.4853	36.5096	-0.1608	-0.0819
37.3299	0.0000	25.4853	37.3299	-0.0889	-0.1047
38.1503	0.0000	25.4853	38.1503	-0.0251	-0.0449
38.9706	0.0000	25.4853	38.9706	-0.0452	0.0565
Plane: 76.2 mm downstream of injection					
-39.5294	0.0000	76.3197	39.5294	0.1816	-0.3090
-38.7117	0.0000	76.3197	38.7117	-0.0362	-0.5253
-37.8939	0.0000	76.3197	37.8939	0.1868	0.0384
-37.0762	0.0000	76.3197	37.0762	0.2079	0.3312
-36.2584	0.0000	76.3197	36.2584	-0.0269	0.4880
-35.4406	0.0000	76.3197	35.4406	-0.3228	1.1305
-34.6229	0.0000	76.3197	34.6229	-0.6234	2.1763
-33.8051	0.0000	76.3197	33.8051	-1.0064	3.1045
-32.9874	0.0000	76.3197	32.9874	-1.4791	3.6327
-32.1696	0.0000	76.3197	32.1696	-1.7038	3.5604
-31.3518	0.0000	76.3197	31.3518	-1.7361	3.3151
-30.5341	0.0000	76.3197	30.5341	-1.7234	3.0055
-29.7163	0.0000	76.3197	29.7163	-1.6983	2.6664
-28.8985	0.0000	76.3197	28.8985	-1.6527	2.3358
-28.0808	0.0000	76.3197	28.0808	-1.6084	2.0266
-27.2630	0.0000	76.3197	27.2630	-1.6032	1.7394
-26.4453	0.0000	76.3197	26.4453	-1.6310	1.4705
-25.6275	0.0000	76.3197	25.6275	-1.6551	1.2174
-24.8097	0.0000	76.3197	24.8097	-1.6578	0.9967
-23.9920	0.0000	76.3197	23.9920	-1.6501	0.8088
-23.1742	0.0000	76.3197	23.1742	-1.6520	0.6645
-22.3565	0.0000	76.3197	22.3565	-1.6675	0.5724
-21.5387	0.0000	76.3197	21.5387	-1.7026	0.5367
-20.7209	0.0000	76.3197	20.7209	-1.7562	0.5640
-19.9032	0.0000	76.3197	19.9032	-1.8151	0.6717
-19.0854	0.0000	76.3197	19.0854	-1.8562	0.9111
-18.2676	0.0000	76.3197	18.2676	-1.8617	1.2714
-17.4499	0.0000	76.3197	17.4499	-1.8672	1.7261
-16.6321	0.0000	76.3197	16.6321	-1.8767	2.2526
-15.8144	0.0000	76.3197	15.8144	-1.8897	2.7996
-14.9966	0.0000	76.3197	14.9966	-1.9007	3.3552
-14.1788	0.0000	76.3197	14.1788	-1.9097	3.9408
-13.3611	0.0000	76.3197	13.3611	-1.9294	4.5787
-12.5433	0.0000	76.3197	12.5433	-1.9613	5.2857
-11.7256	0.0000	76.3197	11.7256	-1.9974	6.1070
-10.9078	0.0000	76.3197	10.9078	-2.0075	6.9910
-10.0900	0.0000	76.3197	10.0900	-2.0232	7.8851
-9.2723	0.0000	76.3197	9.2723	-2.0604	8.7571
-8.4545	0.0000	76.3197	8.4545	-2.1171	9.5878
-7.6367	0.0000	76.3197	7.6367	-2.1686	10.3808
-6.8190	0.0000	76.3197	6.8190	-2.1846	11.1050
-6.0012	0.0000	76.3197	6.0012	-2.1655	11.5051
-5.1835	0.0000	76.3197	5.1835	-2.2136	11.0770
-4.3657	0.0000	76.3197	4.3657	-2.3169	9.6747
-3.5479	0.0000	76.3197	3.5479	-2.4199	7.4933
-2.7302	0.0000	76.3197	2.7302	-2.5283	4.9551
-1.9124	0.0000	76.3197	1.9124	-2.6506	2.5056
-1.0947	0.0000	76.3197	1.0947	-2.7969	0.5076
-0.2769	0.0000	76.3197	0.2769	-2.9640	-0.8250
0.5409	0.0000	76.3197	0.5409	-3.0780	-1.4837
1.3586	0.0000	76.3197	1.3586	-2.6260	-1.3766
2.1764	0.0000	76.3197	2.1764	-2.1183	-0.6071
2.9942	0.0000	76.3197	2.9942	-1.7435	0.8812
3.8119	0.0000	76.3197	3.8119	-1.4802	2.9902
4.6297	0.0000	76.3197	4.6297	-1.2669	5.4223
5.4474	0.0000	76.3197	5.4474	-1.0954	7.7737
6.2652	0.0000	76.3197	6.2652	-1.0086	9.6291
7.0830	0.0000	76.3197	7.0830	-0.9815	10.6310

7.9007	0.0000	76.3197	7.9007	-1.0334	10.6013
8.7185	0.0000	76.3197	8.7185	-1.1475	9.9545
9.5362	0.0000	76.3197	9.5362	-1.2408	9.0657
10.3540	0.0000	76.3197	10.3540	-1.2994	8.0960
11.1718	0.0000	76.3197	11.1718	-1.3384	7.1093
11.9895	0.0000	76.3197	11.9895	-1.3697	6.1493
12.8073	0.0000	76.3197	12.8073	-1.3893	5.2802
13.6251	0.0000	76.3197	13.6251	-1.4029	4.5295
14.4428	0.0000	76.3197	14.4428	-1.4066	3.9053
15.2606	0.0000	76.3197	15.2606	-1.4072	3.3347
16.0783	0.0000	76.3197	16.0783	-1.4150	2.7725
16.8961	0.0000	76.3197	16.8961	-1.4088	2.2167
17.7139	0.0000	76.3197	17.7139	-1.3983	1.6824
18.5316	0.0000	76.3197	18.5316	-1.4004	1.1980
19.3494	0.0000	76.3197	19.3494	-1.4187	0.8057
20.1671	0.0000	76.3197	20.1671	-1.4300	0.5339
20.9849	0.0000	76.3197	20.9849	-1.4352	0.4072
21.8027	0.0000	76.3197	21.8027	-1.4317	0.4044
22.6204	0.0000	76.3197	22.6204	-1.4531	0.4810
23.4382	0.0000	76.3197	23.4382	-1.4817	0.6077
24.2560	0.0000	76.3197	24.2560	-1.5047	0.7639
25.0737	0.0000	76.3197	25.0737	-1.5267	0.9432
25.8915	0.0000	76.3197	25.8915	-1.5590	1.1458
26.7092	0.0000	76.3197	26.7092	-1.5908	1.3648
27.5270	0.0000	76.3197	27.5270	-1.6403	1.6064
28.3448	0.0000	76.3197	28.3448	-1.7253	1.8520
29.1625	0.0000	76.3197	29.1625	-1.8173	2.0988
29.9803	0.0000	76.3197	29.9803	-1.8805	2.3656
30.7980	0.0000	76.3197	30.7980	-1.9200	2.6494
31.6158	0.0000	76.3197	31.6158	-1.9466	2.9463
32.4336	0.0000	76.3197	32.4336	-1.9691	3.2672
33.2513	0.0000	76.3197	33.2513	-2.0070	3.6057
34.0691	0.0000	76.3197	34.0691	-2.0645	3.9563
34.8869	0.0000	76.3197	34.8869	-2.0883	4.3414
35.7046	0.0000	76.3197	35.7046	-1.9888	4.6889
36.5224	0.0000	76.3197	36.5224	-1.6500	4.7996
37.3401	0.0000	76.3197	37.3401	-1.1362	4.3308
38.1579	0.0000	76.3197	38.1579	-0.6412	3.1588
38.9757	0.0000	76.3197	38.9757	-0.3009	1.6643
Plane: 152.4 mm downstream of injection					
-38.9537	0.0000	152.3093	38.9537	0.0324	-0.9690
-38.1308	0.0000	152.3093	38.1308	-0.0100	-0.6612
-37.3080	0.0000	152.3093	37.3080	0.1614	0.3361
-36.4851	0.0000	152.3093	36.4851	0.2929	0.9214
-35.6623	0.0000	152.3093	35.6623	0.0983	0.6898
-34.8394	0.0000	152.3093	34.8394	-0.3226	0.1364
-34.0166	0.0000	152.3093	34.0166	-0.5502	0.8812
-33.1937	0.0000	152.3093	33.1937	-0.8442	2.6669
-32.3708	0.0000	152.3093	32.3708	-1.2320	3.1923
-31.5480	0.0000	152.3093	31.5480	-1.3944	3.1882
-30.7251	0.0000	152.3093	30.7251	-1.3628	3.0731
-29.9023	0.0000	152.3093	29.9023	-1.3372	2.9571
-29.0794	0.0000	152.3093	29.0794	-1.3874	2.8286
-28.2566	0.0000	152.3093	28.2566	-1.4117	2.7007
-27.4337	0.0000	152.3093	27.4337	-1.4003	2.5523
-26.6108	0.0000	152.3093	26.6108	-1.3994	2.3533
-25.7880	0.0000	152.3093	25.7880	-1.3820	2.2128
-24.9651	0.0000	152.3093	24.9651	-1.3408	2.0838
-24.1423	0.0000	152.3093	24.1423	-1.3322	1.9371
-23.3194	0.0000	152.3093	23.3194	-1.3474	1.7853
-22.4966	0.0000	152.3093	22.4966	-1.3677	1.6565
-21.6737	0.0000	152.3093	21.6737	-1.3908	1.5660
-20.8509	0.0000	152.3093	20.8509	-1.4372	1.5086
-20.0280	0.0000	152.3093	20.0280	-1.4750	1.4801
-19.2051	0.0000	152.3093	19.2051	-1.5079	1.5568
-18.3823	0.0000	152.3093	18.3823	-1.5707	1.7248
-17.5594	0.0000	152.3093	17.5594	-1.6194	1.9717
-16.7366	0.0000	152.3093	16.7366	-1.6543	2.3119
-15.9137	0.0000	152.3093	15.9137	-1.6855	2.7765
-15.0909	0.0000	152.3093	15.0909	-1.7152	3.4014
-14.2680	0.0000	152.3093	14.2680	-1.7537	4.2062
-13.4451	0.0000	152.3093	13.4451	-1.8273	5.1512
-12.6223	0.0000	152.3093	12.6223	-1.8958	6.2193
-11.7994	0.0000	152.3093	11.7994	-1.9047	7.3498
-10.9766	0.0000	152.3093	10.9766	-1.9222	8.4290
-10.1537	0.0000	152.3093	10.1537	-1.9789	9.4305
-9.3309	0.0000	152.3093	9.3309	-2.0639	10.4335
-8.5080	0.0000	152.3093	8.5080	-2.1623	11.4967
-7.6851	0.0000	152.3093	7.6851	-2.2617	12.5645
-6.8623	0.0000	152.3093	6.8623	-2.3409	13.4513

-6.0394	0.0000	152.3093	6.0394	-2.4233	13.7406
-5.2166	0.0000	152.3093	5.2166	-2.5252	12.8666
-4.3937	0.0000	152.3093	4.3937	-2.6605	10.9300
-3.5709	0.0000	152.3093	3.5709	-2.8600	8.3691
-2.7480	0.0000	152.3093	2.7480	-3.1149	5.6286
-1.9252	0.0000	152.3093	1.9252	-3.4470	2.9678
-1.1023	0.0000	152.3093	1.1023	-3.8669	0.5580
-0.2794	0.0000	152.3093	0.2794	-4.3191	-1.3854
0.5434	0.0000	152.3093	0.5434	-4.6592	-2.6960
1.3663	0.0000	152.3093	1.3663	-4.5482	-2.9619
2.1891	0.0000	152.3093	2.1891	-4.0882	-2.2490
3.0120	0.0000	152.3093	3.0120	-3.4834	-0.8430
3.8348	0.0000	152.3093	3.8348	-2.9600	1.1569
4.6577	0.0000	152.3093	4.6577	-2.5514	3.5058
5.4806	0.0000	152.3093	5.4806	-2.2118	5.9710
6.3034	0.0000	152.3093	6.3034	-1.9149	8.4005
7.1263	0.0000	152.3093	7.1263	-1.6689	10.5687
7.9491	0.0000	152.3093	7.9491	-1.5428	11.8494
8.7720	0.0000	152.3093	8.7720	-1.5188	11.9037
9.5948	0.0000	152.3093	9.5948	-1.5266	11.1980
10.4177	0.0000	152.3093	10.4177	-1.5497	10.1911
11.2406	0.0000	152.3093	11.2406	-1.5701	9.1165
12.0634	0.0000	152.3093	12.0634	-1.5844	8.0326
12.8863	0.0000	152.3093	12.8863	-1.5945	6.9200
13.7091	0.0000	152.3093	13.7091	-1.5864	5.7789
14.5320	0.0000	152.3093	14.5320	-1.5854	4.6818
15.3548	0.0000	152.3093	15.3548	-1.5799	3.7062
16.1777	0.0000	152.3093	16.1777	-1.6119	2.8691
17.0005	0.0000	152.3093	17.0005	-1.6342	2.1536
17.8234	0.0000	152.3093	17.8234	-1.6317	1.5615
18.6463	0.0000	152.3093	18.6463	-1.6165	1.1085
19.4691	0.0000	152.3093	19.4691	-1.6027	0.7967
20.2920	0.0000	152.3093	20.2920	-1.5805	0.5986
21.1148	0.0000	152.3093	21.1148	-1.5702	0.4827
21.9377	0.0000	152.3093	21.9377	-1.5536	0.4201
22.7605	0.0000	152.3093	22.7605	-1.5423	0.4595
23.5834	0.0000	152.3093	23.5834	-1.5589	0.5645
24.4063	0.0000	152.3093	24.4063	-1.5770	0.6758
25.2291	0.0000	152.3093	25.2291	-1.5828	0.7937
26.0520	0.0000	152.3093	26.0520	-1.5787	0.9424
26.8748	0.0000	152.3093	26.8748	-1.5803	1.1276
27.6977	0.0000	152.3093	27.6977	-1.5875	1.3220
28.5205	0.0000	152.3093	28.5205	-1.5739	1.5264
29.3434	0.0000	152.3093	29.3434	-1.5611	1.7537
30.1663	0.0000	152.3093	30.1663	-1.5636	2.0164
30.9891	0.0000	152.3093	30.9891	-1.5392	2.3066
31.8120	0.0000	152.3093	31.8120	-1.5122	2.6010
32.6348	0.0000	152.3093	32.6348	-1.4962	2.8870
33.4577	0.0000	152.3093	33.4577	-1.4824	3.1788
34.2805	0.0000	152.3093	34.2805	-1.4642	3.4957
35.1034	0.0000	152.3093	35.1034	-1.4147	3.7787
35.9262	0.0000	152.3093	35.9262	-1.4625	3.9962
36.7491	0.0000	152.3093	36.7491	-1.6039	4.2472
37.5720	0.0000	152.3093	37.5720	-1.4923	3.9706
38.3948	0.0000	152.3093	38.3948	-0.8390	2.3359
39.2177	0.0000	152.3093	39.2177	-0.1526	0.6322

B.13.7 Case 6: Swirling Axial Injection of Hydrogen

Table B-17: Spatial fuel concentration data. Case 6

Hardware Configuration: C				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.000369 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-36.1950	0.0000	25.4000	36.1950	0.000	0.00000
-34.9250	0.0000	25.4000	34.9250	0.000	0.00000
-33.6550	0.0000	25.4000	33.6550	0.000	0.00000
-32.3850	0.0000	25.4000	32.3850	0.000	0.00000
-31.1150	0.0000	25.4000	31.1150	0.000	0.00000
-29.8450	0.0000	25.4000	29.8450	0.000	0.00000
-28.5750	0.0000	25.4000	28.5750	0.000	0.00000
-27.3050	0.0000	25.4000	27.3050	0.008	0.00008
-26.0350	0.0000	25.4000	26.0350	0.014	0.00014
-24.7650	0.0000	25.4000	24.7650	0.020	0.00020
-23.4950	0.0000	25.4000	23.4950	0.026	0.00026

-22.2250	0.0000	25.4000	22.2250	0.032	0.00032
-20.9550	0.0000	25.4000	20.9550	0.038	0.00038
-19.6850	0.0000	25.4000	19.6850	0.042	0.00042
-18.4150	0.0000	25.4000	18.4150	0.048	0.00048
-17.1450	0.0000	25.4000	17.1450	0.050	0.00050
-15.8750	0.0000	25.4000	15.8750	0.053	0.00053
-14.6050	0.0000	25.4000	14.6050	0.053	0.00053
-13.3350	0.0000	25.4000	13.3350	0.054	0.00054
-12.0650	0.0000	25.4000	12.0650	0.079	0.00079
-10.7950	0.0000	25.4000	10.7950	0.216	0.00216
-9.5250	0.0000	25.4000	9.5250	0.906	0.00906
-8.2550	0.0000	25.4000	8.2550	2.403	0.02403
-6.9850	0.0000	25.4000	6.9850	5.038	0.05038
-5.7150	0.0000	25.4000	5.7150	8.934	0.08934
-4.4450	0.0000	25.4000	4.4450	12.324	0.12324
-3.1750	0.0000	25.4000	3.1750	14.285	0.14285
-1.9050	0.0000	25.4000	1.9050	15.789	0.15789
-0.6350	0.0000	25.4000	0.6350	18.058	0.18058
0.6350	0.0000	25.4000	0.6350	17.712	0.17712
1.9050	0.0000	25.4000	1.9050	16.118	0.16118
3.1750	0.0000	25.4000	3.1750	14.172	0.14172
4.4450	0.0000	25.4000	4.4450	12.242	0.12242
5.7150	0.0000	25.4000	5.7150	9.435	0.09435
6.9850	0.0000	25.4000	6.9850	4.667	0.04667
8.2550	0.0000	25.4000	8.2550	1.337	0.01337
9.5250	0.0000	25.4000	9.5250	0.591	0.00591
10.7950	0.0000	25.4000	10.7950	0.327	0.00327
12.0650	0.0000	25.4000	12.0650	0.179	0.00179
13.3350	0.0000	25.4000	13.3350	0.129	0.00129
14.6050	0.0000	25.4000	14.6050	0.103	0.00103
15.8750	0.0000	25.4000	15.8750	0.096	0.00096
17.1450	0.0000	25.4000	17.1450	0.087	0.00087
18.4150	0.0000	25.4000	18.4150	0.073	0.00073
19.6850	0.0000	25.4000	19.6850	0.057	0.00057
20.9550	0.0000	25.4000	20.9550	0.046	0.00046
22.2250	0.0000	25.4000	22.2250	0.035	0.00035
23.4950	0.0000	25.4000	23.4950	0.023	0.00023
24.7650	0.0000	25.4000	24.7650	0.014	0.00014
26.0350	0.0000	25.4000	26.0350	0.008	0.00008
27.3050	0.0000	25.4000	27.3050	0.000	0.00000
28.5750	0.0000	25.4000	28.5750	0.000	0.00000
29.8450	0.0000	25.4000	29.8450	0.000	0.00000
31.1150	0.0000	25.4000	31.1150	0.000	0.00000
32.3850	0.0000	25.4000	32.3850	0.000	0.00000
33.6550	0.0000	25.4000	33.6550	0.000	0.00000
34.9250	0.0000	25.4000	34.9250	0.000	0.00000
36.1950	0.0000	25.4000	36.1950	0.000	0.00000

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-36.1950	0.0000	76.2000	36.1950	0.000	0.00000
-34.9250	0.0000	76.2000	34.9250	0.000	0.00000
-33.6550	0.0000	76.2000	33.6550	0.000	0.00000
-32.3850	0.0000	76.2000	32.3850	0.000	0.00000
-31.1150	0.0000	76.2000	31.1150	0.000	0.00000
-29.8450	0.0000	76.2000	29.8450	0.000	0.00000
-28.5750	0.0000	76.2000	28.5750	0.000	0.00000
-27.3050	0.0000	76.2000	27.3050	0.000	0.00000
-26.0350	0.0000	76.2000	26.0350	0.000	0.00000
-24.7650	0.0000	76.2000	24.7650	0.000	0.00000
-23.4950	0.0000	76.2000	23.4950	0.000	0.00000
-22.2250	0.0000	76.2000	22.2250	0.000	0.00000
-20.9550	0.0000	76.2000	20.9550	0.000	0.00000
-19.6850	0.0000	76.2000	19.6850	0.000	0.00000
-18.4150	0.0000	76.2000	18.4150	0.000	0.00000
-17.1450	0.0000	76.2000	17.1450	0.028	0.00028
-15.8750	0.0000	76.2000	15.8750	0.052	0.00052
-14.6050	0.0000	76.2000	14.6050	0.099	0.00099
-13.3350	0.0000	76.2000	13.3350	0.196	0.00196
-12.0650	0.0000	76.2000	12.0650	0.422	0.00422
-10.7950	0.0000	76.2000	10.7950	1.046	0.01046
-9.5250	0.0000	76.2000	9.5250	1.914	0.01914
-8.2550	0.0000	76.2000	8.2550	3.233	0.03233
-6.9850	0.0000	76.2000	6.9850	4.998	0.04998
-5.7150	0.0000	76.2000	5.7150	6.639	0.06639
-4.4450	0.0000	76.2000	4.4450	6.996	0.06996
-3.1750	0.0000	76.2000	3.1750	7.219	0.07219
-1.9050	0.0000	76.2000	1.9050	8.105	0.08105
-1.2700	0.0000	76.2000	1.2700	10.016	0.10016
-0.6350	0.0000	76.2000	0.6350	10.779	0.10779
0.0000	0.0000	76.2000	0.0000	10.291	0.10291

0.6350	0.0000	76.2000	0.6350	9.781	0.09781
1.9050	0.0000	76.2000	1.9050	9.269	0.09269
3.1750	0.0000	76.2000	3.1750	8.858	0.08858
4.4450	0.0000	76.2000	4.4450	7.944	0.07944
5.7150	0.0000	76.2000	5.7150	5.499	0.05499
6.9850	0.0000	76.2000	6.9850	3.712	0.03712
8.2550	0.0000	76.2000	8.2550	2.527	0.02527
9.5250	0.0000	76.2000	9.5250	1.513	0.01513
10.7950	0.0000	76.2000	10.7950	0.819	0.00819
12.0650	0.0000	76.2000	12.0650	0.408	0.00408
13.3350	0.0000	76.2000	13.3350	0.216	0.00216
14.6050	0.0000	76.2000	14.6050	0.124	0.00124
15.8750	0.0000	76.2000	15.8750	0.079	0.00079
17.1450	0.0000	76.2000	17.1450	0.052	0.00052
18.4150	0.0000	76.2000	18.4150	0.037	0.00037
19.6850	0.0000	76.2000	19.6850	0.026	0.00026
20.9550	0.0000	76.2000	20.9550	0.019	0.00019
22.2250	0.0000	76.2000	22.2250	0.014	0.00014
23.4950	0.0000	76.2000	23.4950	0.000	0.00000
24.7650	0.0000	76.2000	24.7650	0.000	0.00000
26.0350	0.0000	76.2000	26.0350	0.000	0.00000
27.3050	0.0000	76.2000	27.3050	0.000	0.00000
28.5750	0.0000	76.2000	28.5750	0.000	0.00000
29.8450	0.0000	76.2000	29.8450	0.000	0.00000
31.1150	0.0000	76.2000	31.1150	0.000	0.00000
32.3850	0.0000	76.2000	32.3850	0.000	0.00000
33.6550	0.0000	76.2000	33.6550	0.000	0.00000
34.9250	0.0000	76.2000	34.9250	0.000	0.00000
36.1950	0.0000	76.2000	36.1950	0.000	0.00000

Plane: 152.4 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-36.8300	0.0000	152.4000	36.8300	0.000	0.00000
-35.5600	0.0000	152.4000	35.5600	0.000	0.00000
-34.2900	0.0000	152.4000	34.2900	0.000	0.00000
-33.0200	0.0000	152.4000	33.0200	0.000	0.00000
-31.7500	0.0000	152.4000	31.7500	0.000	0.00000
-30.4800	0.0000	152.4000	30.4800	0.000	0.00000
-29.2100	0.0000	152.4000	29.2100	0.000	0.00000
-27.9400	0.0000	152.4000	27.9400	0.000	0.00000
-26.6700	0.0000	152.4000	26.6700	0.000	0.00000
-25.4000	0.0000	152.4000	25.4000	0.000	0.00000
-24.1300	0.0000	152.4000	24.1300	0.000	0.00000
-22.8600	0.0000	152.4000	22.8600	0.000	0.00000
-21.5900	0.0000	152.4000	21.5900	0.000	0.00000
-20.3200	0.0000	152.4000	20.3200	0.000	0.00000
-19.0500	0.0000	152.4000	19.0500	0.025	0.00025
-17.7800	0.0000	152.4000	17.7800	0.045	0.00045
-16.5100	0.0000	152.4000	16.5100	0.075	0.00075
-15.2400	0.0000	152.4000	15.2400	0.115	0.00115
-13.9700	0.0000	152.4000	13.9700	0.180	0.00180
-12.7000	0.0000	152.4000	12.7000	0.306	0.00306
-11.4300	0.0000	152.4000	11.4300	0.642	0.00642
-10.1600	0.0000	152.4000	10.1600	1.531	0.01531
-8.8900	0.0000	152.4000	8.8900	2.786	0.02786
-7.6200	0.0000	152.4000	7.6200	3.708	0.03708
-6.3500	0.0000	152.4000	6.3500	4.093	0.04093
-5.0800	0.0000	152.4000	5.0800	4.175	0.04175
-3.8100	0.0000	152.4000	3.8100	4.234	0.04234
-2.5400	0.0000	152.4000	2.5400	4.262	0.04262
-1.2700	0.0000	152.4000	1.2700	4.244	0.04244
0.0000	0.0000	152.4000	0.0000	4.323	0.04323
1.2700	0.0000	152.4000	1.2700	4.393	0.04393
2.5400	0.0000	152.4000	2.5400	4.422	0.04422
3.8100	0.0000	152.4000	3.8100	4.263	0.04263
5.0800	0.0000	152.4000	5.0800	4.262	0.04262
6.3500	0.0000	152.4000	6.3500	4.203	0.04203
7.6200	0.0000	152.4000	7.6200	4.058	0.04058
8.8900	0.0000	152.4000	8.8900	3.816	0.03816
10.1600	0.0000	152.4000	10.1600	3.489	0.03489
11.4300	0.0000	152.4000	11.4300	2.725	0.02725
12.7000	0.0000	152.4000	12.7000	1.530	0.01530
13.9700	0.0000	152.4000	13.9700	0.655	0.00655
15.2400	0.0000	152.4000	15.2400	0.363	0.00363
16.5100	0.0000	152.4000	16.5100	0.243	0.00243
17.7800	0.0000	152.4000	17.7800	0.163	0.00163
19.0500	0.0000	152.4000	19.0500	0.094	0.00094
20.3200	0.0000	152.4000	20.3200	0.045	0.00045
21.5900	0.0000	152.4000	21.5900	0.000	0.00000
22.8600	0.0000	152.4000	22.8600	0.000	0.00000
24.1300	0.0000	152.4000	24.1300	0.000	0.00000

25.4000	0.0000	152.4000	25.4000	0.000	0.00000
26.6700	0.0000	152.4000	26.6700	0.000	0.00000
27.9400	0.0000	152.4000	27.9400	0.000	0.00000
29.2100	0.0000	152.4000	29.2100	0.000	0.00000
30.4800	0.0000	152.4000	30.4800	0.000	0.00000
31.7500	0.0000	152.4000	31.7500	0.000	0.00000
33.0200	0.0000	152.4000	33.0200	0.000	0.00000
34.2900	0.0000	152.4000	34.2900	0.000	0.00000
35.5600	0.0000	152.4000	35.5600	0.000	0.00000
36.8300	0.0000	152.4000	36.8300	0.000	0.00000

Table B-18: Velocity field data. Case 6

Hardware Configuration: C				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.000369 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.1855	0.0000	25.4853	39.1855	0.0316	-0.0920
-38.3525	0.0000	25.4853	38.3525	0.0293	0.0021
-37.5194	0.0000	25.4853	37.5194	-0.0843	0.0209
-36.6864	0.0000	25.4853	36.6864	-0.1552	-0.0323
-35.8533	0.0000	25.4853	35.8533	-0.0164	-0.0787
-35.0203	0.0000	25.4853	35.0203	0.0123	-0.0960
-34.1872	0.0000	25.4853	34.1872	-0.0618	-0.0603
-33.3542	0.0000	25.4853	33.3542	-0.1053	0.0311
-32.5212	0.0000	25.4853	32.5212	-0.1565	0.2827
-31.6881	0.0000	25.4853	31.6881	-0.2473	0.8101
-30.8551	0.0000	25.4853	30.8551	-0.4407	1.7789
-30.0220	0.0000	25.4853	30.0220	-0.7860	3.4789
-29.1890	0.0000	25.4853	29.1890	-1.1643	5.5382
-28.3559	0.0000	25.4853	28.3559	-1.3184	6.4887
-27.5229	0.0000	25.4853	27.5229	-1.3244	6.0806
-26.6898	0.0000	25.4853	26.6898	-1.3671	5.2293
-25.8568	0.0000	25.4853	25.8568	-1.2947	4.3406
-25.0237	0.0000	25.4853	25.0237	-1.1742	3.4154
-24.1907	0.0000	25.4853	24.1907	-1.0370	2.4692
-23.3576	0.0000	25.4853	23.3576	-0.9157	1.6129
-22.5246	0.0000	25.4853	22.5246	-0.8416	0.9303
-21.6915	0.0000	25.4853	21.6915	-0.8014	0.3900
-20.8585	0.0000	25.4853	20.8585	-0.7673	-0.0277
-20.0254	0.0000	25.4853	20.0254	-0.7482	-0.2999
-19.1924	0.0000	25.4853	19.1924	-0.6966	-0.3667
-18.3594	0.0000	25.4853	18.3594	-0.5126	-0.3155
-17.5263	0.0000	25.4853	17.5263	-0.3364	-0.2206
-16.6933	0.0000	25.4853	16.6933	-0.3011	-0.0773
-15.8602	0.0000	25.4853	15.8602	-0.3814	0.1244
-15.0272	0.0000	25.4853	15.0272	-0.4311	0.4405
-14.1941	0.0000	25.4853	14.1941	-0.3662	0.9219
-13.3611	0.0000	25.4853	13.3611	-0.2473	1.5168
-12.5280	0.0000	25.4853	12.5280	-0.1262	1.9514
-11.6950	0.0000	25.4853	11.6950	0.0369	2.4040
-10.8619	0.0000	25.4853	10.8619	0.1967	3.2851
-10.0289	0.0000	25.4853	10.0289	0.3664	4.7011
-9.1958	0.0000	25.4853	9.1958	0.5458	6.2832
-8.3628	0.0000	25.4853	8.3628	0.7300	7.6385
-7.5297	0.0000	25.4853	7.5297	0.9344	8.6721
-6.6967	0.0000	25.4853	6.6967	1.2748	9.3696
-5.8637	0.0000	25.4853	5.8637	1.7536	9.2774
-5.0306	0.0000	25.4853	5.0306	2.3161	7.7286
-4.1976	0.0000	25.4853	4.1976	2.8702	4.9972
-3.3645	0.0000	25.4853	3.3645	3.3877	2.2766
-2.5315	0.0000	25.4853	2.5315	3.8874	0.5513
-1.6984	0.0000	25.4853	1.6984	4.3387	-0.0059
-0.8654	0.0000	25.4853	0.8654	4.6093	0.1595
-0.0323	0.0000	25.4853	0.0323	4.6364	0.6542
0.8007	0.0000	25.4853	0.8007	4.4934	1.6891
1.6338	0.0000	25.4853	1.6338	4.2836	3.8120
2.4668	0.0000	25.4853	2.4668	4.0847	6.6432
3.2999	0.0000	25.4853	3.2999	3.8381	9.1872
4.1329	0.0000	25.4853	4.1329	3.4140	10.5196
4.9660	0.0000	25.4853	4.9660	2.7554	10.5421
5.7990	0.0000	25.4853	5.7990	1.9767	9.7903
6.6320	0.0000	25.4853	6.6320	1.2748	8.7700
7.4651	0.0000	25.4853	7.4651	0.7851	7.6461
8.2981	0.0000	25.4853	8.2981	0.4138	6.3641
9.1312	0.0000	25.4853	9.1312	0.1218	4.6972

9.9642	0.0000	25.4853	9.9642	-0.0774	2.7303
10.7973	0.0000	25.4853	10.7973	-0.2036	1.4844
11.6303	0.0000	25.4853	11.6303	-0.2680	1.4094
12.4634	0.0000	25.4853	12.4634	-0.2917	1.7103
13.2964	0.0000	25.4853	13.2964	-0.3216	1.5811
14.1295	0.0000	25.4853	14.1295	-0.3207	1.1996
14.9625	0.0000	25.4853	14.9625	-0.2343	0.5819
15.7956	0.0000	25.4853	15.7956	-0.1414	0.3098
16.6286	0.0000	25.4853	16.6286	-0.1493	0.3822
17.4617	0.0000	25.4853	17.4617	-0.2567	0.7430
18.2947	0.0000	25.4853	18.2947	-0.3622	1.2084
19.1277	0.0000	25.4853	19.1277	-0.4405	1.6992
19.9608	0.0000	25.4853	19.9608	-0.5196	2.2199
20.7938	0.0000	25.4853	20.7938	-0.5831	2.7223
21.6269	0.0000	25.4853	21.6269	-0.6183	3.1698
22.4599	0.0000	25.4853	22.4599	-0.6194	3.5885
23.2930	0.0000	25.4853	23.2930	-0.6332	4.1391
24.1260	0.0000	25.4853	24.1260	-0.7228	4.8432
24.9591	0.0000	25.4853	24.9591	-0.8407	5.6576
25.7921	0.0000	25.4853	25.7921	-0.9424	6.4840
26.6252	0.0000	25.4853	26.6252	-1.0270	7.1950
27.4582	0.0000	25.4853	27.4582	-1.1131	7.7049
28.2913	0.0000	25.4853	28.2913	-1.2640	8.0864
29.1243	0.0000	25.4853	29.1243	-1.2552	7.6229
29.9574	0.0000	25.4853	29.9574	-0.9462	4.8416
30.7904	0.0000	25.4853	30.7904	-0.5930	2.3145
31.6234	0.0000	25.4853	31.6234	-0.3878	0.8383
32.4565	0.0000	25.4853	32.4565	-0.1980	0.2227
33.2895	0.0000	25.4853	33.2895	-0.0740	-0.0898
34.1226	0.0000	25.4853	34.1226	-0.1388	-0.2512
34.9556	0.0000	25.4853	34.9556	-0.2836	-0.2364
35.7887	0.0000	25.4853	35.7887	-0.2657	-0.1773
36.6217	0.0000	25.4853	36.6217	-0.0651	-0.0948
37.4548	0.0000	25.4853	37.4548	-0.0994	-0.0767
38.2878	0.0000	25.4853	38.2878	-0.2833	-0.2036
39.1209	0.0000	25.4853	39.1209	-0.3215	-0.2100
39.9539	0.0000	25.4853	39.9539	-0.2205	-0.0711
Plane: 76.2 mm downstream of injection					
-39.7766	0.0000	76.3197	39.7766	-0.0183	0.0729
-38.9537	0.0000	76.3197	38.9537	0.0224	0.1730
-38.1308	0.0000	76.3197	38.1308	-0.0245	0.1697
-37.3080	0.0000	76.3197	37.3080	-0.2488	0.2195
-36.4851	0.0000	76.3197	36.4851	-0.3429	0.6771
-35.6623	0.0000	76.3197	35.6623	-0.2884	1.3413
-34.8394	0.0000	76.3197	34.8394	-0.3983	1.8870
-34.0166	0.0000	76.3197	34.0166	-0.9495	2.2307
-33.1937	0.0000	76.3197	33.1937	-1.2258	2.4838
-32.3708	0.0000	76.3197	32.3708	-1.3205	2.6425
-31.5480	0.0000	76.3197	31.5480	-1.5222	2.7164
-30.7251	0.0000	76.3197	30.7251	-1.5912	2.5894
-29.9023	0.0000	76.3197	29.9023	-1.6266	2.3218
-29.0794	0.0000	76.3197	29.0794	-1.6859	2.0046
-28.2566	0.0000	76.3197	28.2566	-1.7394	1.6995
-27.4337	0.0000	76.3197	27.4337	-1.7498	1.4263
-26.6108	0.0000	76.3197	26.6108	-1.7426	1.1912
-25.7880	0.0000	76.3197	25.7880	-1.7299	0.9598
-24.9651	0.0000	76.3197	24.9651	-1.7698	0.7449
-24.1423	0.0000	76.3197	24.1423	-1.8287	0.5778
-23.3194	0.0000	76.3197	23.3194	-1.8991	0.4808
-22.4966	0.0000	76.3197	22.4966	-1.9786	0.4419
-21.6737	0.0000	76.3197	21.6737	-2.0517	0.4477
-20.8509	0.0000	76.3197	20.8509	-2.0894	0.5390
-20.0280	0.0000	76.3197	20.0280	-2.1086	0.7561
-19.2051	0.0000	76.3197	19.2051	-2.1390	1.0749
-18.3823	0.0000	76.3197	18.3823	-2.1587	1.5067
-17.5594	0.0000	76.3197	17.5594	-2.1621	2.0100
-16.7366	0.0000	76.3197	16.7366	-2.1721	2.5509
-15.9137	0.0000	76.3197	15.9137	-2.1962	3.1149
-15.0909	0.0000	76.3197	15.0909	-2.2186	3.7067
-14.2680	0.0000	76.3197	14.2680	-2.2417	4.3358
-13.4451	0.0000	76.3197	13.4451	-2.2728	5.0161
-12.6223	0.0000	76.3197	12.6223	-2.2826	5.7527
-11.7994	0.0000	76.3197	11.7994	-2.2957	6.5527
-10.9766	0.0000	76.3197	10.9766	-2.3058	7.4110
-10.1537	0.0000	76.3197	10.1537	-2.3286	8.2987
-9.3309	0.0000	76.3197	9.3309	-2.3761	9.1938
-8.5080	0.0000	76.3197	8.5080	-2.4355	10.0880
-7.6851	0.0000	76.3197	7.6851	-2.4704	10.9090
-6.8623	0.0000	76.3197	6.8623	-2.5381	11.3368
-6.0394	0.0000	76.3197	6.0394	-2.6427	11.0313

-5.2166	0.0000	76.3197	5.2166	-2.7181	9.7714
-4.3937	0.0000	76.3197	4.3937	-2.7719	7.6456
-3.5709	0.0000	76.3197	3.5709	-2.8168	5.0993
-2.7480	0.0000	76.3197	2.7480	-2.8848	2.7299
-1.9252	0.0000	76.3197	1.9252	-3.0546	0.9558
-1.1023	0.0000	76.3197	1.1023	-3.3269	-0.1391
-0.2794	0.0000	76.3197	0.2794	-3.3957	-0.3916
0.5434	0.0000	76.3197	0.5434	-3.1661	-0.2944
1.3663	0.0000	76.3197	1.3663	-2.7208	0.2152
2.1891	0.0000	76.3197	2.1891	-2.3281	1.2620
3.0120	0.0000	76.3197	3.0120	-2.0750	2.9503
3.8348	0.0000	76.3197	3.8348	-1.8494	5.2480
4.6577	0.0000	76.3197	4.6577	-1.6450	7.8655
5.4806	0.0000	76.3197	5.4806	-1.5341	9.9965
6.3034	0.0000	76.3197	6.3034	-1.5255	11.0888
7.1263	0.0000	76.3197	7.1263	-1.5665	11.2578
7.9491	0.0000	76.3197	7.9491	-1.6020	10.7328
8.7720	0.0000	76.3197	8.7720	-1.6314	9.8183
9.5948	0.0000	76.3197	9.5948	-1.6752	8.7614
10.4177	0.0000	76.3197	10.4177	-1.7421	7.6975
11.2406	0.0000	76.3197	11.2406	-1.8082	6.7067
12.0634	0.0000	76.3197	12.0634	-1.8350	5.8175
12.8863	0.0000	76.3197	12.8863	-1.8478	5.0255
13.7091	0.0000	76.3197	13.7091	-1.8471	4.3341
14.5320	0.0000	76.3197	14.5320	-1.8416	3.7052
15.3548	0.0000	76.3197	15.3548	-1.8394	3.0993
16.1777	0.0000	76.3197	16.1777	-1.8417	2.4971
17.0005	0.0000	76.3197	17.0005	-1.8405	1.9199
17.8234	0.0000	76.3197	17.8234	-1.8262	1.4086
18.6463	0.0000	76.3197	18.6463	-1.8021	1.0060
19.4691	0.0000	76.3197	19.4691	-1.7819	0.7185
20.2920	0.0000	76.3197	20.2920	-1.7574	0.5745
21.1148	0.0000	76.3197	21.1148	-1.7528	0.5480
21.9377	0.0000	76.3197	21.9377	-1.7728	0.5971
22.7605	0.0000	76.3197	22.7605	-1.7985	0.7040
23.5834	0.0000	76.3197	23.5834	-1.8200	0.8789
24.4063	0.0000	76.3197	24.4063	-1.8342	1.0976
25.2291	0.0000	76.3197	25.2291	-1.8358	1.3226
26.0520	0.0000	76.3197	26.0520	-1.8610	1.5585
26.8748	0.0000	76.3197	26.8748	-1.9205	1.8004
27.6977	0.0000	76.3197	27.6977	-2.0035	2.0472
28.5205	0.0000	76.3197	28.5205	-2.0897	2.2988
29.3434	0.0000	76.3197	29.3434	-2.1655	2.5618
30.1663	0.0000	76.3197	30.1663	-2.2338	2.8512
30.9891	0.0000	76.3197	30.9891	-2.2792	3.2144
31.8120	0.0000	76.3197	31.8120	-2.3272	3.5610
32.6348	0.0000	76.3197	32.6348	-2.3512	3.8972
33.4577	0.0000	76.3197	33.4577	-2.2749	4.2276
34.2805	0.0000	76.3197	34.2805	-1.9542	4.4470
35.1034	0.0000	76.3197	35.1034	-1.3627	4.2508
35.9262	0.0000	76.3197	35.9262	-0.6959	3.2636
36.7491	0.0000	76.3197	36.7491	-0.2113	1.4113
37.5720	0.0000	76.3197	37.5720	-0.0347	0.3804
38.3948	0.0000	76.3197	38.3948	-0.0190	0.1921
39.2177	0.0000	76.3197	39.2177	-0.0285	0.1096
40.0405	0.0000	76.3197	40.0405	-0.0060	0.0395
Plane: 152.4mm downstream of injection					
-39.2008	0.0000	152.3093	39.2008	-0.0894	0.2432
-38.3754	0.0000	152.3093	38.3754	-0.0973	-0.1747
-37.5500	0.0000	152.3093	37.5500	-0.0449	-0.2899
-36.7246	0.0000	152.3093	36.7246	-0.0399	0.4563
-35.8992	0.0000	152.3093	35.8992	-0.1289	1.4803
-35.0738	0.0000	152.3093	35.0738	-0.8897	2.4434
-34.2484	0.0000	152.3093	34.2484	-1.2289	2.7420
-33.4230	0.0000	152.3093	33.4230	-1.3076	3.1580
-32.5976	0.0000	152.3093	32.5976	-1.3159	3.1270
-31.7722	0.0000	152.3093	31.7722	-1.4128	2.9444
-30.9468	0.0000	152.3093	30.9468	-1.4875	2.7998
-30.1214	0.0000	152.3093	30.1214	-1.4599	2.6742
-29.2960	0.0000	152.3093	29.2960	-1.4877	2.5295
-28.4706	0.0000	152.3093	28.4706	-1.5551	2.3900
-27.6452	0.0000	152.3093	27.6452	-1.5570	2.2235
-26.8197	0.0000	152.3093	26.8197	-1.5355	2.0663
-25.9943	0.0000	152.3093	25.9943	-1.5500	1.8961
-25.1689	0.0000	152.3093	25.1689	-1.5935	1.7465
-24.3435	0.0000	152.3093	24.3435	-1.6464	1.6307
-23.5181	0.0000	152.3093	23.5181	-1.7022	1.5435
-22.6927	0.0000	152.3093	22.6927	-1.7709	1.4888
-21.8673	0.0000	152.3093	21.8673	-1.8578	1.4684
-21.0419	0.0000	152.3093	21.0419	-1.9404	1.5220

-20.2165	0.0000	152.3093	20.2165	-2.0215	1.6572
-19.3911	0.0000	152.3093	19.3911	-2.1301	1.8709
-18.5657	0.0000	152.3093	18.5657	-2.2547	2.1782
-17.7403	0.0000	152.3093	17.7403	-2.3746	2.6021
-16.9149	0.0000	152.3093	16.9149	-2.4988	3.1535
-16.0895	0.0000	152.3093	16.0895	-2.6641	3.8282
-15.2641	0.0000	152.3093	15.2641	-2.8017	4.6707
-14.4387	0.0000	152.3093	14.4387	-2.8452	5.7445
-13.6133	0.0000	152.3093	13.6133	-2.8988	6.9159
-12.7879	0.0000	152.3093	12.7879	-3.0071	8.0561
-11.9625	0.0000	152.3093	11.9625	-3.1879	9.1292
-11.1371	0.0000	152.3093	11.1371	-3.4357	10.2123
-10.3117	0.0000	152.3093	10.3117	-3.7065	11.3676
-9.4863	0.0000	152.3093	9.4863	-3.9156	12.5024
-8.6609	0.0000	152.3093	8.6609	-4.0254	13.5099
-7.8355	0.0000	152.3093	7.8355	-4.2602	13.9417
-7.0101	0.0000	152.3093	7.0101	-4.6093	13.2586
-6.1846	0.0000	152.3093	6.1846	-4.8865	11.3656
-5.3592	0.0000	152.3093	5.3592	-4.9088	8.5768
-4.5338	0.0000	152.3093	4.5338	-4.5319	5.4963
-3.7084	0.0000	152.3093	3.7084	-3.6894	2.7874
-2.8830	0.0000	152.3093	2.8830	-2.4828	0.9119
-2.0576	0.0000	152.3093	2.0576	-1.5397	0.0937
-1.2322	0.0000	152.3093	1.2322	-0.9968	-0.1499
-0.4068	0.0000	152.3093	0.4068	-0.7746	-0.1810
0.4186	0.0000	152.3093	0.4186	-0.8272	-0.1446
1.2440	0.0000	152.3093	1.2440	-1.1570	-0.0001
2.0694	0.0000	152.3093	2.0694	-1.7121	0.4428
2.8948	0.0000	152.3093	2.8948	-2.3826	1.4283
3.7202	0.0000	152.3093	3.7202	-3.0853	3.1567
4.5456	0.0000	152.3093	4.5456	-3.6767	5.9935
5.3710	0.0000	152.3093	5.3710	-3.8871	9.1675
6.1964	0.0000	152.3093	6.1964	-3.7638	11.3248
7.0218	0.0000	152.3093	7.0218	-3.6027	12.0890
7.8472	0.0000	152.3093	7.8472	-3.4541	11.7643
8.6726	0.0000	152.3093	8.6726	-3.2800	10.8921
9.4980	0.0000	152.3093	9.4980	-3.0924	9.8802
10.3234	0.0000	152.3093	10.3234	-2.9306	8.8443
11.1488	0.0000	152.3093	11.1488	-2.8006	7.6940
11.9742	0.0000	152.3093	11.9742	-2.7164	6.4309
12.7996	0.0000	152.3093	12.7996	-2.6299	5.1924
13.6251	0.0000	152.3093	13.6251	-2.4933	4.0662
14.4505	0.0000	152.3093	14.4505	-2.3144	3.1013
15.2759	0.0000	152.3093	15.2759	-2.1411	2.3057
16.1013	0.0000	152.3093	16.1013	-2.0198	1.6593
16.9267	0.0000	152.3093	16.9267	-1.9496	1.1449
17.7521	0.0000	152.3093	17.7521	-1.8495	0.7632
18.5775	0.0000	152.3093	18.5775	-1.8019	0.5273
19.4029	0.0000	152.3093	19.4029	-1.7817	0.4008
20.2283	0.0000	152.3093	20.2283	-1.7414	0.3466
21.0537	0.0000	152.3093	21.0537	-1.7065	0.3412
21.8791	0.0000	152.3093	21.8791	-1.7051	0.3735
22.7045	0.0000	152.3093	22.7045	-1.7137	0.4440
23.5299	0.0000	152.3093	23.5299	-1.7089	0.5739
24.3553	0.0000	152.3093	24.3553	-1.6961	0.7311
25.1807	0.0000	152.3093	25.1807	-1.7314	0.8908
26.0061	0.0000	152.3093	26.0061	-1.7610	1.0676
26.8315	0.0000	152.3093	26.8315	-1.7689	1.2665
27.6569	0.0000	152.3093	27.6569	-1.7747	1.4911
28.4823	0.0000	152.3093	28.4823	-1.7927	1.7410
29.3077	0.0000	152.3093	29.3077	-1.8083	2.0100
30.1331	0.0000	152.3093	30.1331	-1.8091	2.2938
30.9585	0.0000	152.3093	30.9585	-1.8309	2.6127
31.7839	0.0000	152.3093	31.7839	-1.8184	2.9353
32.6093	0.0000	152.3093	32.6093	-1.7407	3.2386
33.4348	0.0000	152.3093	33.4348	-1.5759	3.5586
34.2602	0.0000	152.3093	34.2602	-1.2204	3.5806
35.0856	0.0000	152.3093	35.0856	-0.7004	2.7692
35.9110	0.0000	152.3093	35.9110	-0.2620	1.0373
36.7364	0.0000	152.3093	36.7364	0.0856	0.0493
37.5618	0.0000	152.3093	37.5618	0.1807	-0.1036
38.3872	0.0000	152.3093	38.3872	0.0693	-0.0067
39.2126	0.0000	152.3093	39.2126	-0.0135	0.0252
40.0380	0.0000	152.3093	40.0380	-0.0024	-0.0061

B.13.8 Case 7: Swirling Axial Injection of Methane-Hydrogen Blend

Table B-19: Spatial fuel concentration data. Case 7

Hardware Configuration: C				Measurement Technique: Gas Chromatography			
Bulk Flow Type: Air				Fuel Type: Methane-Hydrogen			
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: Methane-0.000742 kg/min Hydrogen-0.0000867 kg/min			
Plane: 25.4 mm downstream of injection							
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-36.1950	0.0000	25.4000	36.1950	0.000	0.000	0.00000	0.00000
-34.9250	0.0000	25.4000	34.9250	0.000	0.000	0.00000	0.00000
-33.6550	0.0000	25.4000	33.6550	0.000	0.000	0.00000	0.00000
-32.3850	0.0000	25.4000	32.3850	0.000	0.000	0.00000	0.00000
-31.1150	0.0000	25.4000	31.1150	0.000	0.000	0.00000	0.00000
-29.8450	0.0000	25.4000	29.8450	0.000	0.000	0.00000	0.00000
-28.5750	0.0000	25.4000	28.5750	0.000	0.000	0.00000	0.00000
-27.3050	0.0000	25.4000	27.3050	0.000	0.000	0.00000	0.00000
-26.0350	0.0000	25.4000	26.0350	0.000	0.000	0.00000	0.00000
-24.7650	0.0000	25.4000	24.7650	0.000	0.000	0.00000	0.00000
-23.4950	0.0000	25.4000	23.4950	0.000	0.008	0.00000	0.00008
-22.2250	0.0000	25.4000	22.2250	0.008	0.009	0.00008	0.00009
-20.9550	0.0000	25.4000	20.9550	0.010	0.011	0.00010	0.00011
-19.6850	0.0000	25.4000	19.6850	0.011	0.012	0.00011	0.00012
-18.4150	0.0000	25.4000	18.4150	0.013	0.014	0.00013	0.00014
-17.1450	0.0000	25.4000	17.1450	0.014	0.015	0.00014	0.00015
-15.8750	0.0000	25.4000	15.8750	0.015	0.015	0.00015	0.00015
-14.6050	0.0000	25.4000	14.6050	0.015	0.015	0.00015	0.00015
-13.3350	0.0000	25.4000	13.3350	0.016	0.016	0.00016	0.00016
-12.0650	0.0000	25.4000	12.0650	0.027	0.025	0.00027	0.00025
-10.7950	0.0000	25.4000	10.7950	0.080	0.071	0.00080	0.00071
-9.5250	0.0000	25.4000	9.5250	0.311	0.306	0.00311	0.00306
-8.2550	0.0000	25.4000	8.2550	0.735	0.794	0.00735	0.00794
-6.9850	0.0000	25.4000	6.9850	1.337	1.573	0.01337	0.01573
-5.7150	0.0000	25.4000	5.7150	1.907	2.385	0.01907	0.02385
-4.4450	0.0000	25.4000	4.4450	2.317	3.049	0.02317	0.03049
-3.1750	0.0000	25.4000	3.1750	2.553	3.414	0.02553	0.03414
-1.9050	0.0000	25.4000	1.9050	2.837	3.877	0.02837	0.03877
-0.6350	0.0000	25.4000	0.6350	3.081	4.270	0.03081	0.04270
0.6350	0.0000	25.4000	0.6350	3.122	4.352	0.03122	0.04352
1.9050	0.0000	25.4000	1.9050	2.864	3.931	0.02864	0.03931
3.1750	0.0000	25.4000	3.1750	2.593	3.467	0.02593	0.03467
4.4450	0.0000	25.4000	4.4450	2.339	3.100	0.02339	0.03100
5.7150	0.0000	25.4000	5.7150	1.983	2.563	0.01983	0.02563
6.9850	0.0000	25.4000	6.9850	1.336	1.618	0.01336	0.01618
8.2550	0.0000	25.4000	8.2550	0.551	0.545	0.00551	0.00545
9.5250	0.0000	25.4000	9.5250	0.239	0.224	0.00239	0.00224
10.7950	0.0000	25.4000	10.7950	0.125	0.118	0.00125	0.00118
12.0650	0.0000	25.4000	12.0650	0.067	0.065	0.00067	0.00065
13.3350	0.0000	25.4000	13.3350	0.041	0.040	0.00041	0.00040
14.6050	0.0000	25.4000	14.6050	0.032	0.033	0.00032	0.00033
15.8750	0.0000	25.4000	15.8750	0.029	0.029	0.00029	0.00029
17.1450	0.0000	25.4000	17.1450	0.025	0.026	0.00025	0.00026
18.4150	0.0000	25.4000	18.4150	0.020	0.021	0.00020	0.00021
19.6850	0.0000	25.4000	19.6850	0.016	0.017	0.00016	0.00017
20.9550	0.0000	25.4000	20.9550	0.012	0.013	0.00012	0.00013
22.2250	0.0000	25.4000	22.2250	0.009	0.009	0.00009	0.00009
23.4950	0.0000	25.4000	23.4950	0.000	0.006	0.00000	0.00006
24.7650	0.0000	25.4000	24.7650	0.000	0.000	0.00000	0.00000
26.0350	0.0000	25.4000	26.0350	0.000	0.000	0.00000	0.00000
27.3050	0.0000	25.4000	27.3050	0.000	0.000	0.00000	0.00000
28.5750	0.0000	25.4000	28.5750	0.000	0.000	0.00000	0.00000
29.8450	0.0000	25.4000	29.8450	0.000	0.000	0.00000	0.00000
31.1150	0.0000	25.4000	31.1150	0.000	0.000	0.00000	0.00000
32.3850	0.0000	25.4000	32.3850	0.000	0.000	0.00000	0.00000
33.6550	0.0000	25.4000	33.6550	0.000	0.000	0.00000	0.00000
34.9250	0.0000	25.4000	34.9250	0.000	0.000	0.00000	0.00000
36.1950	0.0000	25.4000	36.1950	0.000	0.000	0.00000	0.00000
Plane: 76.2 mm downstream of injection							
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-36.1950	0.0000	76.2000	36.1950	0.000	0.000	0.00000	0.00000
-34.9250	0.0000	76.2000	34.9250	0.000	0.000	0.00000	0.00000
-33.6550	0.0000	76.2000	33.6550	0.000	0.000	0.00000	0.00000
-32.3850	0.0000	76.2000	32.3850	0.000	0.000	0.00000	0.00000
-31.1150	0.0000	76.2000	31.1150	0.000	0.000	0.00000	0.00000
-29.8450	0.0000	76.2000	29.8450	0.000	0.000	0.00000	0.00000
-28.5750	0.0000	76.2000	28.5750	0.000	0.000	0.00000	0.00000
-27.3050	0.0000	76.2000	27.3050	0.000	0.000	0.00000	0.00000
-26.0350	0.0000	76.2000	26.0350	0.000	0.005	0.00000	0.00005
-23.4950	0.0000	76.2000	23.4950	0.000	0.006	0.00000	0.00006
-20.9550	0.0000	76.2000	20.9550	0.000	0.006	0.00000	0.00006
-19.6850	0.0000	76.2000	19.6850	0.008	0.007	0.00008	0.00007
-18.4150	0.0000	76.2000	18.4150	0.009	0.007	0.00009	0.00007

-17.1450	0.0000	76.2000	17.1450	0.013	0.010	0.00013	0.00010
-15.8750	0.0000	76.2000	15.8750	0.020	0.017	0.00020	0.00017
-14.6050	0.0000	76.2000	14.6050	0.037	0.031	0.00037	0.00031
-13.3350	0.0000	76.2000	13.3350	0.067	0.055	0.00067	0.00055
-12.0650	0.0000	76.2000	12.0650	0.141	0.105	0.00141	0.00105
-10.7950	0.0000	76.2000	10.7950	0.316	0.236	0.00316	0.00236
-9.5250	0.0000	76.2000	9.5250	0.581	0.504	0.00581	0.00504
-8.2550	0.0000	76.2000	8.2550	0.850	0.860	0.00850	0.00860
-6.9850	0.0000	76.2000	6.9850	1.105	1.361	0.01105	0.01361
-5.7150	0.0000	76.2000	5.7150	1.248	1.687	0.01248	0.01687
-4.4450	0.0000	76.2000	4.4450	1.305	1.787	0.01305	0.01787
-3.1750	0.0000	76.2000	3.1750	1.364	1.890	0.01364	0.01890
-1.9050	0.0000	76.2000	1.9050	1.491	2.128	0.01491	0.02128
-0.6350	0.0000	76.2000	0.6350	1.624	2.421	0.01624	0.02421
0.6350	0.0000	76.2000	0.6350	1.645	2.419	0.01645	0.02419
1.9050	0.0000	76.2000	1.9050	1.507	2.146	0.01507	0.02146
3.1750	0.0000	76.2000	3.1750	1.367	1.891	0.01367	0.01891
4.4450	0.0000	76.2000	4.4450	1.240	1.675	0.01240	0.01675
5.7150	0.0000	76.2000	5.7150	1.103	1.444	0.01103	0.01444
6.9850	0.0000	76.2000	6.9850	0.939	1.172	0.00939	0.01172
8.2550	0.0000	76.2000	8.2550	0.730	0.854	0.00730	0.00854
9.5250	0.0000	76.2000	9.5250	0.482	0.515	0.00482	0.00515
10.7950	0.0000	76.2000	10.7950	0.282	0.271	0.00282	0.00271
12.0650	0.0000	76.2000	12.0650	0.149	0.132	0.00149	0.00132
13.3350	0.0000	76.2000	13.3350	0.084	0.071	0.00084	0.00071
14.6050	0.0000	76.2000	14.6050	0.050	0.042	0.00050	0.00042
15.8750	0.0000	76.2000	15.8750	0.033	0.028	0.00033	0.00028
17.1450	0.0000	76.2000	17.1450	0.024	0.021	0.00024	0.00021
18.4150	0.0000	76.2000	18.4150	0.018	0.016	0.00018	0.00016
19.6850	0.0000	76.2000	19.6850	0.014	0.013	0.00014	0.00013
20.9550	0.0000	76.2000	20.9550	0.011	0.011	0.00011	0.00011
22.2250	0.0000	76.2000	22.2250	0.010	0.009	0.00010	0.00009
23.4950	0.0000	76.2000	23.4950	0.009	0.008	0.00009	0.00008
24.7650	0.0000	76.2000	24.7650	0.000	0.007	0.00000	0.00007
26.0350	0.0000	76.2000	26.0350	0.000	0.006	0.00000	0.00006
27.3050	0.0000	76.2000	27.3050	0.000	0.006	0.00000	0.00006
28.5750	0.0000	76.2000	28.5750	0.000	0.006	0.00000	0.00006
29.8450	0.0000	76.2000	29.8450	0.000	0.005	0.00000	0.00005
31.1150	0.0000	76.2000	31.1150	0.000	0.005	0.00000	0.00005
32.3850	0.0000	76.2000	32.3850	0.000	0.004	0.00000	0.00004
33.6550	0.0000	76.2000	33.6550	0.000	0.000	0.00000	0.00000
34.9250	0.0000	76.2000	34.9250	0.000	0.000	0.00000	0.00000
36.1950	0.0000	76.2000	36.1950	0.000	0.000	0.00000	0.00000
Plane: 152.4 mm downstream of injection							
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-36.8300	0.0000	152.4000	36.8300	0.000	0.000	0.00000	0.00000
-35.5600	0.0000	152.4000	35.5600	0.000	0.000	0.00000	0.00000
-34.2900	0.0000	152.4000	34.2900	0.000	0.000	0.00000	0.00000
-33.0200	0.0000	152.4000	33.0200	0.000	0.000	0.00000	0.00000
-31.7500	0.0000	152.4000	31.7500	0.000	0.000	0.00000	0.00000
-30.4800	0.0000	152.4000	30.4800	0.000	0.000	0.00000	0.00000
-29.2100	0.0000	152.4000	29.2100	0.000	0.000	0.00000	0.00000
-27.9400	0.0000	152.4000	27.9400	0.000	0.000	0.00000	0.00000
-26.6700	0.0000	152.4000	26.6700	0.000	0.000	0.00000	0.00000
-25.4000	0.0000	152.4000	25.4000	0.000	0.000	0.00000	0.00000
-24.1300	0.0000	152.4000	24.1300	0.000	0.000	0.00000	0.00000
-22.8600	0.0000	152.4000	22.8600	0.000	0.000	0.00000	0.00000
-21.5900	0.0000	152.4000	21.5900	0.000	0.006	0.00000	0.00006
-20.3200	0.0000	152.4000	20.3200	0.000	0.007	0.00000	0.00007
-19.0500	0.0000	152.4000	19.0500	0.013	0.011	0.00013	0.00011
-17.7800	0.0000	152.4000	17.7800	0.021	0.018	0.00021	0.00018
-16.5100	0.0000	152.4000	16.5100	0.033	0.027	0.00033	0.00027
-15.2400	0.0000	152.4000	15.2400	0.047	0.036	0.00047	0.00036
-13.9700	0.0000	152.4000	13.9700	0.071	0.052	0.00071	0.00052
-12.7000	0.0000	152.4000	12.7000	0.119	0.088	0.00119	0.00088
-11.4300	0.0000	152.4000	11.4300	0.238	0.205	0.00238	0.00205
-10.1600	0.0000	152.4000	10.1600	0.445	0.482	0.00445	0.00482
-8.8900	0.0000	152.4000	8.8900	0.655	0.788	0.00655	0.00788
-7.6200	0.0000	152.4000	7.6200	0.767	0.958	0.00767	0.00958
-6.3500	0.0000	152.4000	6.3500	0.819	1.028	0.00819	0.01028
-5.0800	0.0000	152.4000	5.0800	0.823	1.033	0.00823	0.01033
-3.8100	0.0000	152.4000	3.8100	0.826	1.037	0.00826	0.01037
-2.5400	0.0000	152.4000	2.5400	0.819	1.028	0.00819	0.01028
-1.2700	0.0000	152.4000	1.2700	0.822	1.021	0.00822	0.01021
0.0000	0.0000	152.4000	0.0000	0.818	1.022	0.00818	0.01022
1.2700	0.0000	152.4000	1.2700	0.831	1.040	0.00831	0.01040
2.5400	0.0000	152.4000	2.5400	0.836	1.052	0.00836	0.01052
3.8100	0.0000	152.4000	3.8100	0.811	1.023	0.00811	0.01023
5.0800	0.0000	152.4000	5.0800	0.815	1.030	0.00815	0.01030

6.3500	0.0000	152.4000	6.3500	0.797	1.004	0.00797	0.01004
7.6200	0.0000	152.4000	7.6200	0.768	0.965	0.00768	0.00965
8.8900	0.0000	152.4000	8.8900	0.721	0.898	0.00721	0.00898
10.1600	0.0000	152.4000	10.1600	0.627	0.762	0.00627	0.00762
11.4300	0.0000	152.4000	11.4300	0.448	0.502	0.00448	0.00502
12.7000	0.0000	152.4000	12.7000	0.255	0.242	0.00255	0.00242
13.9700	0.0000	152.4000	13.9700	0.140	0.116	0.00140	0.00116
15.2400	0.0000	152.4000	15.2400	0.092	0.076	0.00092	0.00076
16.5100	0.0000	152.4000	16.5100	0.069	0.058	0.00069	0.00058
17.7800	0.0000	152.4000	17.7800	0.047	0.039	0.00047	0.00039
19.0500	0.0000	152.4000	19.0500	0.026	0.021	0.00026	0.00021
20.3200	0.0000	152.4000	20.3200	0.014	0.011	0.00014	0.00011
21.5900	0.0000	152.4000	21.5900	0.009	0.007	0.00009	0.00007
22.8600	0.0000	152.4000	22.8600	0.000	0.006	0.00000	0.00006
24.1300	0.0000	152.4000	24.1300	0.000	0.006	0.00000	0.00006
25.4000	0.0000	152.4000	25.4000	0.000	0.006	0.00000	0.00006
26.6700	0.0000	152.4000	26.6700	0.000	0.006	0.00000	0.00006
27.9400	0.0000	152.4000	27.9400	0.000	0.005	0.00000	0.00005
29.2100	0.0000	152.4000	29.2100	0.000	0.006	0.00000	0.00006
30.4800	0.0000	152.4000	30.4800	0.000	0.005	0.00000	0.00005
31.7500	0.0000	152.4000	31.7500	0.000	0.005	0.00000	0.00005
33.0200	0.0000	152.4000	33.0200	0.000	0.004	0.00000	0.00004
34.2900	0.0000	152.4000	34.2900	0.000	0.004	0.00000	0.00004

Table B-20: Velocity field data. Case 7

Hardware Configuration: C				Measurement Technique: Particle Image Velocimetry	
Bulk Flow Type: Air				Fuel Type: Methane-Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: Methane-0.000742 kg/min Hydrogen-0.0000867 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.5218	0.0000	25.4853	39.5218	-0.0184	-0.3155
-38.6964	0.0000	25.4853	38.6964	-0.0277	-0.2330
-37.8710	0.0000	25.4853	37.8710	0.0783	-0.3363
-37.0456	0.0000	25.4853	37.0456	0.1136	-0.4498
-36.2202	0.0000	25.4853	36.2202	0.0359	-0.3094
-35.3948	0.0000	25.4853	35.3948	0.0657	-0.1927
-34.5694	0.0000	25.4853	34.5694	0.1196	-0.1459
-33.7440	0.0000	25.4853	33.7440	0.1580	-0.1293
-32.9186	0.0000	25.4853	32.9186	0.1474	-0.0564
-32.0932	0.0000	25.4853	32.0932	0.0291	0.2593
-31.2678	0.0000	25.4853	31.2678	-0.1539	1.1452
-30.4424	0.0000	25.4853	30.4424	-0.4414	2.7152
-29.6170	0.0000	25.4853	29.6170	-0.6451	3.8817
-28.7915	0.0000	25.4853	28.7915	-0.8233	4.2381
-27.9661	0.0000	25.4853	27.9661	-0.8649	3.9606
-27.1407	0.0000	25.4853	27.1407	-0.8427	3.4811
-26.3153	0.0000	25.4853	26.3153	-0.8107	2.9708
-25.4899	0.0000	25.4853	25.4899	-0.8001	2.4399
-24.6645	0.0000	25.4853	24.6645	-0.7875	1.9543
-23.8391	0.0000	25.4853	23.8391	-0.7326	1.4665
-23.0137	0.0000	25.4853	23.0137	-0.7293	1.0016
-22.1883	0.0000	25.4853	22.1883	-0.7660	0.6502
-21.3629	0.0000	25.4853	21.3629	-0.8033	0.3658
-20.5375	0.0000	25.4853	20.5375	-0.8113	0.1235
-19.7121	0.0000	25.4853	19.7121	-0.7958	-0.0504
-18.8867	0.0000	25.4853	18.8867	-0.7419	-0.1259
-18.0613	0.0000	25.4853	18.0613	-0.6375	-0.1021
-17.2359	0.0000	25.4853	17.2359	-0.5177	-0.0145
-16.4105	0.0000	25.4853	16.4105	-0.4200	0.1389
-15.5851	0.0000	25.4853	15.5851	-0.3521	0.3985
-14.7597	0.0000	25.4853	14.7597	-0.2988	0.7843
-13.9343	0.0000	25.4853	13.9343	-0.2292	1.3008
-13.1089	0.0000	25.4853	13.1089	-0.1343	1.9053
-12.2835	0.0000	25.4853	12.2835	-0.0197	2.5223
-11.4581	0.0000	25.4853	11.4581	0.0661	3.1735
-10.6327	0.0000	25.4853	10.6327	0.1989	4.0850
-9.8073	0.0000	25.4853	9.8073	0.3443	5.2335
-8.9818	0.0000	25.4853	8.9818	0.5023	6.3856
-8.1564	0.0000	25.4853	8.1564	0.6513	7.3938
-7.3310	0.0000	25.4853	7.3310	0.8774	8.1387
-6.5056	0.0000	25.4853	6.5056	1.2634	8.4565
-5.6802	0.0000	25.4853	5.6802	1.7407	8.1318
-4.8548	0.0000	25.4853	4.8548	2.1735	6.9571
-4.0294	0.0000	25.4853	4.0294	2.4742	4.8076
-3.2040	0.0000	25.4853	3.2040	2.9004	2.5249
-2.3786	0.0000	25.4853	2.3786	3.2235	0.8656

-1.5532	0.0000	25.4853	1.5532	3.4292	0.1422
-0.7278	0.0000	25.4853	0.7278	3.4732	0.3805
0.0976	0.0000	25.4853	0.0976	3.3244	1.4497
0.9230	0.0000	25.4853	0.9230	3.1103	3.2236
1.7484	0.0000	25.4853	1.7484	2.9453	5.3716
2.5738	0.0000	25.4853	2.5738	2.7645	7.1846
3.3992	0.0000	25.4853	3.3992	2.5343	8.1392
4.2246	0.0000	25.4853	4.2246	2.0500	8.1805
5.0500	0.0000	25.4853	5.0500	1.4551	7.5569
5.8754	0.0000	25.4853	5.8754	0.9115	6.7217
6.7008	0.0000	25.4853	6.7008	0.4887	5.9739
7.5262	0.0000	25.4853	7.5262	0.1676	5.3358
8.3516	0.0000	25.4853	8.3516	-0.0909	4.5023
9.1770	0.0000	25.4853	9.1770	-0.3623	3.5763
10.0024	0.0000	25.4853	10.0024	-0.4176	2.5351
10.8278	0.0000	25.4853	10.8278	-0.4117	1.8388
11.6533	0.0000	25.4853	11.6533	-0.4268	1.6460
12.4787	0.0000	25.4853	12.4787	-0.4357	1.6359
13.3041	0.0000	25.4853	13.3041	-0.3906	1.4521
14.1295	0.0000	25.4853	14.1295	-0.3182	1.0900
14.9549	0.0000	25.4853	14.9549	-0.3231	0.7104
15.7803	0.0000	25.4853	15.7803	-0.2520	0.4600
16.6057	0.0000	25.4853	16.6057	-0.1935	0.4221
17.4311	0.0000	25.4853	17.4311	-0.1629	0.6072
18.2565	0.0000	25.4853	18.2565	-0.1282	0.9678
19.0819	0.0000	25.4853	19.0819	-0.1044	1.3334
19.9073	0.0000	25.4853	19.9073	-0.1474	1.5895
20.7327	0.0000	25.4853	20.7327	-0.1513	1.7649
21.5581	0.0000	25.4853	21.5581	-0.2172	1.8944
22.3835	0.0000	25.4853	22.3835	-0.2809	1.9840
23.2089	0.0000	25.4853	23.2089	-0.2606	2.1105
24.0343	0.0000	25.4853	24.0343	-0.3516	2.2822
24.8597	0.0000	25.4853	24.8597	-0.4800	2.4978
25.6851	0.0000	25.4853	25.6851	-0.6437	2.7307
26.5105	0.0000	25.4853	26.5105	-0.8993	2.9025
27.3359	0.0000	25.4853	27.3359	-0.9839	3.0527
28.1613	0.0000	25.4853	28.1613	-1.0581	3.1557
28.9867	0.0000	25.4853	28.9867	-1.2518	3.0041
29.8121	0.0000	25.4853	29.8121	-1.2322	2.4254
30.6375	0.0000	25.4853	30.6375	-1.2108	1.4300
31.4630	0.0000	25.4853	31.4630	-1.2273	0.5713
32.2884	0.0000	25.4853	32.2884	-1.1716	0.1677
33.1138	0.0000	25.4853	33.1138	-0.9273	0.0492
33.9392	0.0000	25.4853	33.9392	-0.7115	0.0391
34.7646	0.0000	25.4853	34.7646	-0.6599	0.0985
35.5900	0.0000	25.4853	35.5900	-0.5126	0.0681
36.4154	0.0000	25.4853	36.4154	-0.4132	-0.0166
37.2408	0.0000	25.4853	37.2408	-0.2971	-0.0516
38.0662	0.0000	25.4853	38.0662	-0.2036	-0.0130
38.8916	0.0000	25.4853	38.8916	-0.1606	0.0612
39.7170	0.0000	25.4853	39.7170	-0.1548	0.1080
Plane:76.2 mm downstream of injection					
-39.5193	0.0000	76.3197	39.5193	-0.1145	-0.2190
-38.6913	0.0000	76.3197	38.6913	-0.1763	-0.1521
-37.8633	0.0000	76.3197	37.8633	-0.2218	-0.0640
-37.0354	0.0000	76.3197	37.0354	-0.0787	0.2819
-36.2074	0.0000	76.3197	36.2074	-0.1537	0.8415
-35.3795	0.0000	76.3197	35.3795	-0.4987	0.9210
-34.5515	0.0000	76.3197	34.5515	-0.6980	1.5617
-33.7236	0.0000	76.3197	33.7236	-0.8820	2.4744
-32.8956	0.0000	76.3197	32.8956	-1.1848	2.9532
-32.0677	0.0000	76.3197	32.0677	-1.4696	2.8346
-31.2397	0.0000	76.3197	31.2397	-1.5603	2.5820
-30.4118	0.0000	76.3197	30.4118	-1.4957	2.3635
-29.5838	0.0000	76.3197	29.5838	-1.5062	2.1143
-28.7559	0.0000	76.3197	28.7559	-1.5411	1.8249
-27.9279	0.0000	76.3197	27.9279	-1.5710	1.4902
-27.1000	0.0000	76.3197	27.1000	-1.5996	1.1771
-26.2720	0.0000	76.3197	26.2720	-1.6370	0.9213
-25.4441	0.0000	76.3197	25.4441	-1.6872	0.7070
-24.6161	0.0000	76.3197	24.6161	-1.7500	0.5156
-23.7882	0.0000	76.3197	23.7882	-1.7917	0.3751
-22.9602	0.0000	76.3197	22.9602	-1.8482	0.2761
-22.1323	0.0000	76.3197	22.1323	-1.9130	0.2729
-21.3043	0.0000	76.3197	21.3043	-1.9759	0.3403
-20.4764	0.0000	76.3197	20.4764	-2.0337	0.4895
-19.6484	0.0000	76.3197	19.6484	-2.0851	0.7489
-18.8205	0.0000	76.3197	18.8205	-2.1302	1.1200
-17.9925	0.0000	76.3197	17.9925	-2.1658	1.5646
-17.1646	0.0000	76.3197	17.1646	-2.1551	2.0912

-16.3366	0.0000	76.3197	16.3366	-2.1451	2.6792
-15.5087	0.0000	76.3197	15.5087	-2.1301	3.3054
-14.6807	0.0000	76.3197	14.6807	-2.1405	3.9790
-13.8528	0.0000	76.3197	13.8528	-2.1725	4.6672
-13.0248	0.0000	76.3197	13.0248	-2.1912	5.3806
-12.1968	0.0000	76.3197	12.1968	-2.1731	6.1642
-11.3689	0.0000	76.3197	11.3689	-2.1550	7.0389
-10.5409	0.0000	76.3197	10.5409	-2.1592	7.9686
-9.7130	0.0000	76.3197	9.7130	-2.1732	8.8494
-8.8850	0.0000	76.3197	8.8850	-2.1691	9.7530
-8.0571	0.0000	76.3197	8.0571	-2.1455	10.7066
-7.2291	0.0000	76.3197	7.2291	-2.1304	11.5916
-6.4012	0.0000	76.3197	6.4012	-2.1161	12.1164
-5.5732	0.0000	76.3197	5.5732	-2.0608	11.9130
-4.7453	0.0000	76.3197	4.7453	-1.9372	10.7353
-3.9173	0.0000	76.3197	3.9173	-1.8190	8.7067
-3.0894	0.0000	76.3197	3.0894	-1.7089	6.2445
-2.2614	0.0000	76.3197	2.2614	-1.6225	3.9271
-1.4335	0.0000	76.3197	1.4335	-1.5804	2.0386
-0.6055	0.0000	76.3197	0.6055	-1.4424	0.7259
0.2224	0.0000	76.3197	0.2224	-1.2223	0.2528
1.0504	0.0000	76.3197	1.0504	-1.0210	0.7303
1.8783	0.0000	76.3197	1.8783	-0.8363	1.8808
2.7063	0.0000	76.3197	2.7063	-0.7765	3.7903
3.5342	0.0000	76.3197	3.5342	-0.7133	6.2232
4.3622	0.0000	76.3197	4.3622	-0.6831	8.6290
5.1901	0.0000	76.3197	5.1901	-0.7338	10.4659
6.0181	0.0000	76.3197	6.0181	-0.8557	11.5044
6.8460	0.0000	76.3197	6.8460	-0.9879	11.7318
7.6740	0.0000	76.3197	7.6740	-1.0903	11.2790
8.5019	0.0000	76.3197	8.5019	-1.1934	10.3559
9.3299	0.0000	76.3197	9.3299	-1.3351	9.2553
10.1578	0.0000	76.3197	10.1578	-1.4597	8.2015
10.9858	0.0000	76.3197	10.9858	-1.5520	7.1921
11.8137	0.0000	76.3197	11.8137	-1.6214	6.2003
12.6417	0.0000	76.3197	12.6417	-1.6780	5.3021
13.4697	0.0000	76.3197	13.4697	-1.7109	4.5310
14.2976	0.0000	76.3197	14.2976	-1.7098	3.8566
15.1256	0.0000	76.3197	15.1256	-1.6967	3.2259
15.9535	0.0000	76.3197	15.9535	-1.6813	2.6161
16.7815	0.0000	76.3197	16.7815	-1.6907	2.0389
17.6094	0.0000	76.3197	17.6094	-1.7063	1.5100
18.4374	0.0000	76.3197	18.4374	-1.7097	1.0772
19.2653	0.0000	76.3197	19.2653	-1.7155	0.7701
20.0933	0.0000	76.3197	20.0933	-1.7210	0.6102
20.9212	0.0000	76.3197	20.9212	-1.7229	0.5833
21.7492	0.0000	76.3197	21.7492	-1.7263	0.6321
22.5771	0.0000	76.3197	22.5771	-1.7086	0.7141
23.4051	0.0000	76.3197	23.4051	-1.7016	0.8741
24.2330	0.0000	76.3197	24.2330	-1.7388	1.0812
25.0610	0.0000	76.3197	25.0610	-1.7821	1.3014
25.8889	0.0000	76.3197	25.8889	-1.8449	1.5270
26.7169	0.0000	76.3197	26.7169	-1.9387	1.7502
27.5448	0.0000	76.3197	27.5448	-2.0402	1.9691
28.3728	0.0000	76.3197	28.3728	-2.1069	2.1972
29.2007	0.0000	76.3197	29.2007	-2.1594	2.4513
30.0287	0.0000	76.3197	30.0287	-2.2039	2.7148
30.8566	0.0000	76.3197	30.8566	-2.2484	2.9712
31.6846	0.0000	76.3197	31.6846	-2.2920	3.2389
32.5125	0.0000	76.3197	32.5125	-2.3010	3.5493
33.3405	0.0000	76.3197	33.3405	-2.2477	3.8962
34.1684	0.0000	76.3197	34.1684	-2.0272	4.2022
34.9964	0.0000	76.3197	34.9964	-1.5098	4.2596
35.8243	0.0000	76.3197	35.8243	-0.8397	3.6590
36.6523	0.0000	76.3197	36.6523	-0.3052	1.6592
37.4803	0.0000	76.3197	37.4803	-0.0565	0.4844
38.3082	0.0000	76.3197	38.3082	0.0075	0.1747
39.1362	0.0000	76.3197	39.1362	0.0191	0.0933
39.9641	0.0000	76.3197	39.9641	0.0306	0.0194
Plane: 152.4 mm downstream of injection					
-39.7715	0.0000	152.3093	39.7715	0.0297	-0.2622
-38.9435	0.0000	152.3093	38.9435	0.0847	0.2644
-38.1156	0.0000	152.3093	38.1156	0.0419	0.4794
-37.2876	0.0000	152.3093	37.2876	0.0920	0.7133
-36.4597	0.0000	152.3093	36.4597	0.0070	2.0985
-35.6317	0.0000	152.3093	35.6317	-0.2130	3.0383
-34.8037	0.0000	152.3093	34.8037	-0.5864	2.9626
-33.9758	0.0000	152.3093	33.9758	-1.0802	3.1923
-33.1478	0.0000	152.3093	33.1478	-1.1643	3.1499
-32.3199	0.0000	152.3093	32.3199	-1.3409	2.8308

-31.4919	0.0000	152.3093	31.4919	-1.4440	2.7904
-30.6640	0.0000	152.3093	30.6640	-1.5159	2.8165
-29.8360	0.0000	152.3093	29.8360	-1.5702	2.7789
-29.0081	0.0000	152.3093	29.0081	-1.6282	2.6314
-28.1801	0.0000	152.3093	28.1801	-1.6622	2.4163
-27.3522	0.0000	152.3093	27.3522	-1.6354	2.2099
-26.5242	0.0000	152.3093	26.5242	-1.6211	2.0345
-25.6963	0.0000	152.3093	25.6963	-1.6853	1.8642
-24.8683	0.0000	152.3093	24.8683	-1.7507	1.7228
-24.0404	0.0000	152.3093	24.0404	-1.8190	1.6167
-23.2124	0.0000	152.3093	23.2124	-1.8797	1.5405
-22.3845	0.0000	152.3093	22.3845	-1.9402	1.5015
-21.5565	0.0000	152.3093	21.5565	-2.0128	1.5179
-20.7286	0.0000	152.3093	20.7286	-2.0959	1.6042
-19.9006	0.0000	152.3093	19.9006	-2.1692	1.7550
-19.0727	0.0000	152.3093	19.0727	-2.2706	1.9730
-18.2447	0.0000	152.3093	18.2447	-2.4021	2.2992
-17.4168	0.0000	152.3093	17.4168	-2.5236	2.7627
-16.5888	0.0000	152.3093	16.5888	-2.6728	3.3774
-15.7609	0.0000	152.3093	15.7609	-2.8255	4.1377
-14.9329	0.0000	152.3093	14.9329	-2.9312	5.0431
-14.1050	0.0000	152.3093	14.1050	-2.9742	6.0907
-13.2770	0.0000	152.3093	13.2770	-3.0150	7.2395
-12.4491	0.0000	152.3093	12.4491	-3.1248	8.3549
-11.6211	0.0000	152.3093	11.6211	-3.3273	9.4492
-10.7932	0.0000	152.3093	10.7932	-3.5925	10.6061
-9.9652	0.0000	152.3093	9.9652	-3.8182	11.7812
-9.1372	0.0000	152.3093	9.1372	-3.9715	12.9140
-8.3093	0.0000	152.3093	8.3093	-4.1228	13.8201
-7.4813	0.0000	152.3093	7.4813	-4.3625	14.1490
-6.6534	0.0000	152.3093	6.6534	-4.6686	13.4634
-5.8254	0.0000	152.3093	5.8254	-4.8777	11.4461
-4.9975	0.0000	152.3093	4.9975	-4.9871	8.8081
-4.1695	0.0000	152.3093	4.1695	-4.9915	6.0960
-3.3416	0.0000	152.3093	3.3416	-4.6464	3.5552
-2.5136	0.0000	152.3093	2.5136	-3.8590	1.6149
-1.6857	0.0000	152.3093	1.6857	-2.8846	0.4766
-0.8577	0.0000	152.3093	0.8577	-2.1793	0.0057
-0.0298	0.0000	152.3093	0.0298	-2.0376	-0.0638
0.7982	0.0000	152.3093	0.7982	-2.3073	0.1719
1.6261	0.0000	152.3093	1.6261	-2.9767	1.0064
2.4541	0.0000	152.3093	2.4541	-3.6392	2.5206
3.2820	0.0000	152.3093	3.2820	-3.9879	4.7454
4.1100	0.0000	152.3093	4.1100	-4.0460	7.3956
4.9379	0.0000	152.3093	4.9379	-3.9450	9.9952
5.7659	0.0000	152.3093	5.7659	-3.7991	11.9729
6.5938	0.0000	152.3093	6.5938	-3.6708	12.8106
7.4218	0.0000	152.3093	7.4218	-3.5036	12.4625
8.2497	0.0000	152.3093	8.2497	-3.3388	11.5430
9.0777	0.0000	152.3093	9.0777	-3.1641	10.5149
9.9056	0.0000	152.3093	9.9056	-2.9874	9.4327
10.7336	0.0000	152.3093	10.7336	-2.8800	8.3002
11.5615	0.0000	152.3093	11.5615	-2.8412	7.0855
12.3895	0.0000	152.3093	12.3895	-2.8020	5.8027
13.2174	0.0000	152.3093	13.2174	-2.7082	4.5734
14.0454	0.0000	152.3093	14.0454	-2.5767	3.5316
14.8733	0.0000	152.3093	14.8733	-2.4384	2.7322
15.7013	0.0000	152.3093	15.7013	-2.3083	2.0425
16.5293	0.0000	152.3093	16.5293	-2.1921	1.4622
17.3572	0.0000	152.3093	17.3572	-2.0928	1.0046
18.1852	0.0000	152.3093	18.1852	-2.0295	0.6708
19.0131	0.0000	152.3093	19.0131	-2.0098	0.4487
19.8411	0.0000	152.3093	19.8411	-2.0027	0.3233
20.6690	0.0000	152.3093	20.6690	-1.9693	0.2836
21.4970	0.0000	152.3093	21.4970	-1.9485	0.3336
22.3249	0.0000	152.3093	22.3249	-1.9237	0.4287
23.1529	0.0000	152.3093	23.1529	-1.9008	0.5631
23.9808	0.0000	152.3093	23.9808	-1.8903	0.7313
24.8088	0.0000	152.3093	24.8088	-1.9036	0.9117
25.6367	0.0000	152.3093	25.6367	-1.9327	1.0892
26.4647	0.0000	152.3093	26.4647	-1.9478	1.2784
27.2926	0.0000	152.3093	27.2926	-1.9395	1.5069
28.1206	0.0000	152.3093	28.1206	-1.9472	1.7518
28.9485	0.0000	152.3093	28.9485	-1.9380	1.9873
29.7765	0.0000	152.3093	29.7765	-1.9223	2.2288
30.6044	0.0000	152.3093	30.6044	-1.9280	2.4964
31.4324	0.0000	152.3093	31.4324	-1.9276	2.7802
32.2603	0.0000	152.3093	32.2603	-1.8819	3.0687
33.0883	0.0000	152.3093	33.0883	-1.7797	3.3805
33.9162	0.0000	152.3093	33.9162	-1.5710	3.7438

34.7442	0.0000	152.3093	34.7442	-1.0060	3.4796
35.5721	0.0000	152.3093	35.5721	-0.4724	1.7416
36.4001	0.0000	152.3093	36.4001	-0.0702	0.5337
37.2280	0.0000	152.3093	37.2280	0.1248	0.0701
38.0560	0.0000	152.3093	38.0560	0.1228	0.0301
38.8839	0.0000	152.3093	38.8839	0.0353	0.0714
39.7119	0.0000	152.3093	39.7119	0.0036	0.0141

B.13.9 Case 8: Swirling Radial Injection of Methane

Table B-21: Spatial fuel concentration data. Case 8

Hardware Configuration: D				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Methane	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.00864 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
-29.2100	0.0000	25.4000	29.2100	0.103	0.00103
-27.9400	0.0000	25.4000	27.9400	0.188	0.00188
-26.6700	0.0000	25.4000	26.6700	0.325	0.00325
-25.4000	0.0000	25.4000	25.4000	0.512	0.00512
-24.1300	0.0000	25.4000	24.1300	0.759	0.00759
-22.8600	0.0000	25.4000	22.8600	1.020	0.01020
-21.5900	0.0000	25.4000	21.5900	1.330	0.01330
-20.3200	0.0000	25.4000	20.3200	1.624	0.01624
-19.0500	0.0000	25.4000	19.0500	1.950	0.01950
-17.7800	0.0000	25.4000	17.7800	2.340	0.02340
-16.5100	0.0000	25.4000	16.5100	2.785	0.02785
-15.2400	0.0000	25.4000	15.2400	3.515	0.03515
-13.9700	0.0000	25.4000	13.9700	4.626	0.04626
-12.7000	0.0000	25.4000	12.7000	6.135	0.06135
12.7000	0.0000	25.4000	12.7000	5.950	0.05950
13.9700	0.0000	25.4000	13.9700	4.500	0.04500
15.2400	0.0000	25.4000	15.2400	3.354	0.03354
16.5100	0.0000	25.4000	16.5100	2.665	0.02665
17.7800	0.0000	25.4000	17.7800	2.244	0.02244
19.0500	0.0000	25.4000	19.0500	1.986	0.01986
20.3200	0.0000	25.4000	20.3200	1.727	0.01727
21.5900	0.0000	25.4000	21.5900	1.443	0.01443
22.8600	0.0000	25.4000	22.8600	1.071	0.01071
24.1300	0.0000	25.4000	24.1300	0.810	0.00810
25.4000	0.0000	25.4000	25.4000	0.562	0.00562
26.6700	0.0000	25.4000	26.6700	0.346	0.00346
27.9400	0.0000	25.4000	27.9400	0.215	0.00215
29.2100	0.0000	25.4000	29.2100	0.125	0.00125
-26.9865	11.1782	25.4000	29.2100	0.080	0.00080
-25.8132	10.6922	25.4000	27.9400	0.148	0.00148
-24.6399	10.2062	25.4000	26.6700	0.264	0.00264
-23.4665	9.7202	25.4000	25.4000	0.437	0.00437
-22.2932	9.2342	25.4000	24.1300	0.668	0.00668
-21.1199	8.7481	25.4000	22.8600	0.923	0.00923
-19.9466	8.2621	25.4000	21.5900	1.272	0.01272
-18.7732	7.7761	25.4000	20.3200	1.582	0.01582
-17.5999	7.2901	25.4000	19.0500	1.973	0.01973
-16.4266	6.8041	25.4000	17.7800	2.377	0.02377
-15.2533	6.3181	25.4000	16.5100	2.940	0.02940
-14.0799	5.8321	25.4000	15.2400	3.820	0.03820
-12.9066	5.3461	25.4000	13.9700	5.282	0.05282
-11.7333	4.8601	25.4000	12.7000	6.589	0.06589
11.7333	-4.8601	25.4000	12.7000	6.427	0.06427
12.9066	-5.3461	25.4000	13.9700	5.172	0.05172
14.0799	-5.8321	25.4000	15.2400	3.653	0.03653
15.2533	-6.3181	25.4000	16.5100	2.804	0.02804
16.4266	-6.8041	25.4000	17.7800	2.347	0.02347
17.5999	-7.2901	25.4000	19.0500	2.118	0.02118
18.7732	-7.7761	25.4000	20.3200	1.779	0.01779
19.9466	-8.2621	25.4000	21.5900	1.384	0.01384
21.1199	-8.7481	25.4000	22.8600	1.122	0.01122
22.2932	-9.2342	25.4000	24.1300	0.761	0.00761
23.4665	-9.7202	25.4000	25.4000	0.519	0.00519
24.6399	-10.2062	25.4000	26.6700	0.352	0.00352
25.8132	-10.6922	25.4000	27.9400	0.205	0.00205
26.9865	-11.1782	25.4000	29.2100	0.107	0.00107
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH4 Avg [%]	Mole Fraction
-35.5600	0.0000	76.2000	35.5600	0.626	0.00626
-33.0200	0.0000	76.2000	33.0200	0.876	0.00876

-30.4800	0.0000	76.2000	30.4800	1.040	0.01040
-27.9400	0.0000	76.2000	27.9400	1.093	0.01093
-25.4000	0.0000	76.2000	25.4000	1.137	0.01137
-22.8600	0.0000	76.2000	22.8600	1.189	0.01189
-20.3200	0.0000	76.2000	20.3200	1.236	0.01236
-19.0500	0.0000	76.2000	19.0500	1.270	0.01270
-17.7800	0.0000	76.2000	17.7800	1.383	0.01383
-16.5100	0.0000	76.2000	16.5100	1.486	0.01486
-15.2400	0.0000	76.2000	15.2400	1.686	0.01686
-13.9700	0.0000	76.2000	13.9700	2.074	0.02074
-12.7000	0.0000	76.2000	12.7000	2.804	0.02804
-11.4300	0.0000	76.2000	11.4300	3.874	0.03874
-10.1600	0.0000	76.2000	10.1600	4.751	0.04751
-8.8900	0.0000	76.2000	8.8900	5.152	0.05152
-7.6200	0.0000	76.2000	7.6200	5.437	0.05437
-6.3500	0.0000	76.2000	6.3500	5.771	0.05771
-5.0800	0.0000	76.2000	5.0800	5.821	0.05821
-3.8100	0.0000	76.2000	3.8100	5.838	0.05838
-2.5400	0.0000	76.2000	2.5400	5.851	0.05851
-1.2700	0.0000	76.2000	1.2700	5.813	0.05813
0.0000	0.0000	76.2000	0.0000	5.837	0.05837
1.2700	0.0000	76.2000	1.2700	5.878	0.05878
2.5400	0.0000	76.2000	2.5400	5.784	0.05784
3.8100	0.0000	76.2000	3.8100	5.786	0.05786
5.0800	0.0000	76.2000	5.0800	5.678	0.05678
6.3500	0.0000	76.2000	6.3500	5.524	0.05524
7.6200	0.0000	76.2000	7.6200	5.306	0.05306
8.8900	0.0000	76.2000	8.8900	4.926	0.04926
10.1600	0.0000	76.2000	10.1600	4.221	0.04221
11.4300	0.0000	76.2000	11.4300	3.228	0.03228
12.7000	0.0000	76.2000	12.7000	2.346	0.02346
13.9700	0.0000	76.2000	13.9700	1.833	0.01833
15.2400	0.0000	76.2000	15.2400	1.588	0.01588
16.5100	0.0000	76.2000	16.5100	1.456	0.01456
17.7800	0.0000	76.2000	17.7800	1.394	0.01394
19.0500	0.0000	76.2000	19.0500	1.359	0.01359
20.3200	0.0000	76.2000	20.3200	1.343	0.01343
22.8600	0.0000	76.2000	22.8600	1.313	0.01313
25.4000	0.0000	76.2000	25.4000	1.302	0.01302
27.9400	0.0000	76.2000	27.9400	1.298	0.01298
30.4800	0.0000	76.2000	30.4800	1.223	0.01223
33.0200	0.0000	76.2000	33.0200	1.017	0.01017
35.5600	0.0000	76.2000	35.5600	0.765	0.00765
36.8300	0.0000	76.2000	36.8300	0.668	0.00668
-32.8532	13.6082	76.2000	35.5600	0.677	0.00677
-30.5065	12.6362	76.2000	33.0200	0.909	0.00909
-28.1598	11.6642	76.2000	30.4800	1.068	0.01068
-25.8132	10.6922	76.2000	27.9400	1.154	0.01154
-23.4665	9.7202	76.2000	25.4000	1.206	0.01206
-21.1199	8.7481	76.2000	22.8600	1.243	0.01243
-18.7732	7.7761	76.2000	20.3200	1.288	0.01288
-16.4266	6.8041	76.2000	17.7800	1.399	0.01399
-15.2533	6.3181	76.2000	16.5100	1.520	0.01520
-14.0799	5.8321	76.2000	15.2400	1.750	0.01750
-12.9066	5.3461	76.2000	13.9700	2.242	0.02242
-11.7333	4.8601	76.2000	12.7000	3.050	0.03050
-10.5599	4.3741	76.2000	11.4300	3.993	0.03993
-9.3866	3.8881	76.2000	10.1600	4.685	0.04685
-8.2133	3.4021	76.2000	8.8900	5.141	0.05141
-7.0400	2.9160	76.2000	7.6200	5.577	0.05577
-5.8666	2.4300	76.2000	6.3500	5.795	0.05795
-4.6933	1.9440	76.2000	5.0800	5.804	0.05804
-3.5200	1.4580	76.2000	3.8100	5.858	0.05858
-2.3467	0.9720	76.2000	2.5400	5.875	0.05875
-1.1733	0.4860	76.2000	1.2700	5.859	0.05859
0.0000	0.0000	76.2000	0.0000	5.857	0.05857
1.1733	-0.4860	76.2000	1.2700	5.840	0.05840
2.3467	-0.9720	76.2000	2.5400	5.831	0.05831
3.5200	-1.4580	76.2000	3.8100	5.777	0.05777
4.6933	-1.9440	76.2000	5.0800	5.673	0.05673
5.8666	-2.4300	76.2000	6.3500	5.490	0.05490
7.0400	-2.9160	76.2000	7.6200	5.259	0.05259
8.2133	-3.4021	76.2000	8.8900	4.940	0.04940
9.3866	-3.8881	76.2000	10.1600	4.112	0.04112
10.5599	-4.3741	76.2000	11.4300	3.123	0.03123
11.7333	-4.8601	76.2000	12.7000	2.309	0.02309
12.9066	-5.3461	76.2000	13.9700	1.788	0.01788
14.0799	-5.8321	76.2000	15.2400	1.603	0.01603
15.2533	-6.3181	76.2000	16.5100	1.490	0.01490
16.4266	-6.8041	76.2000	17.7800	1.411	0.01411

18.7732	-7.7761	76.2000	20.3200	1.372	0.01372
21.1199	-8.7481	76.2000	22.8600	1.324	0.01324
23.4665	-9.7202	76.2000	25.4000	1.310	0.01310
25.8132	-10.6922	76.2000	27.9400	1.291	0.01291
28.1598	-11.6642	76.2000	30.4800	1.230	0.01230
30.5065	-12.6362	76.2000	33.0200	1.002	0.01002
32.8532	-13.6082	76.2000	35.5600	0.775	0.00775
34.0265	-14.0942	76.2000	36.8300	0.673	0.00673
Plane: 152.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume CH ₄ Avg [%]	Mole Fraction
-32.8532	13.6082	152.4000	35.5600	0.657	0.00657
-30.5065	12.6362	152.4000	33.0200	0.689	0.00689
-28.1598	11.6642	152.4000	30.4800	0.730	0.00730
-25.8132	10.6922	152.4000	27.9400	0.764	0.00764
-23.4665	9.7202	152.4000	25.4000	0.795	0.00795
-21.1199	8.7481	152.4000	22.8600	0.828	0.00828
-18.7732	7.7761	152.4000	20.3200	0.881	0.00881
-16.4266	6.8041	152.4000	17.7800	1.068	0.01068
-15.2533	6.3181	152.4000	16.5100	1.247	0.01247
-14.0799	5.8321	152.4000	15.2400	1.429	0.01429
-12.9066	5.3461	152.4000	13.9700	1.633	0.01633
-11.7333	4.8601	152.4000	12.7000	2.021	0.02021
-10.5599	4.3741	152.4000	11.4300	2.633	0.02633
-9.3866	3.8881	152.4000	10.1600	3.374	0.03374
-8.2133	3.4021	152.4000	8.8900	4.187	0.04187
-7.0400	2.9160	152.4000	7.6200	4.621	0.04621
-5.8666	2.4300	152.4000	6.3500	4.901	0.04901
-4.6933	1.9440	152.4000	5.0800	4.925	0.04925
-3.5200	1.4580	152.4000	3.8100	5.043	0.05043
-2.3467	0.9720	152.4000	2.5400	5.077	0.05077
-1.1733	0.4860	152.4000	1.2700	5.130	0.05130
0.0000	0.0000	152.4000	0.0000	5.187	0.05187
1.1733	-0.4860	152.4000	1.2700	5.139	0.05139
2.3467	-0.9720	152.4000	2.5400	5.115	0.05115
3.5200	-1.4580	152.4000	3.8100	5.072	0.05072
4.6933	-1.9440	152.4000	5.0800	4.996	0.04996
5.8666	-2.4300	152.4000	6.3500	4.908	0.04908
7.0400	-2.9160	152.4000	7.6200	4.752	0.04752
8.2133	-3.4021	152.4000	8.8900	4.289	0.04289
9.3866	-3.8881	152.4000	10.1600	3.462	0.03462
10.5599	-4.3741	152.4000	11.4300	2.877	0.02877
11.7333	-4.8601	152.4000	12.7000	2.167	0.02167
12.9066	-5.3461	152.4000	13.9700	1.752	0.01752
14.0799	-5.8321	152.4000	15.2400	1.552	0.01552
15.2533	-6.3181	152.4000	16.5100	1.340	0.01340
16.4266	-6.8041	152.4000	17.7800	1.120	0.01120
18.7732	-7.7761	152.4000	20.3200	0.933	0.00933
21.1199	-8.7481	152.4000	22.8600	0.867	0.00867
23.4665	-9.7202	152.4000	25.4000	0.816	0.00816
25.8132	-10.6922	152.4000	27.9400	0.785	0.00785
28.1598	-11.6642	152.4000	30.4800	0.753	0.00753
30.5065	-12.6362	152.4000	33.0200	0.715	0.00715
32.8532	-13.6082	152.4000	35.5600	0.710	0.00710
34.0265	-14.0942	152.4000	36.8300	0.690	0.00690

Table B-22: Velocity field data. Case 8

Hardware Configuration: D
Bulk Flow Type: Air
Bulk Flow Rate: 1.116 kg/min

Measurement Technique: Particle Image Velocimetry
Fuel Type: Methane
Fuel Flow Rate: 0.00864 kg/min

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.5243	0.0000	76.3025	39.5243	-0.0497	-0.1988
-38.7015	0.0000	76.3025	38.7015	0.0092	-0.3690
-37.8786	0.0000	76.3025	37.8786	0.0482	0.1282
-37.0558	0.0000	76.3025	37.0558	-0.1641	1.3202
-36.2329	0.0000	76.3025	36.2329	-0.7513	2.6632
-35.4101	0.0000	76.3025	35.4101	-1.8377	4.2930
-34.5872	0.0000	76.3025	34.5872	-2.5327	5.2177
-33.7644	0.0000	76.3025	33.7644	-2.6719	5.3640
-32.9415	0.0000	76.3025	32.9415	-2.5629	5.0483
-32.1186	0.0000	76.3025	32.1186	-2.4326	4.4675
-31.2958	0.0000	76.3025	31.2958	-2.0750	3.6580
-30.4729	0.0000	76.3025	30.4729	-1.6577	2.7876
-29.6501	0.0000	76.3025	29.6501	-1.3005	1.9050
-28.8272	0.0000	76.3025	28.8272	-1.0028	1.0806

-28.0044	0.0000	76.3025	28.0044	-0.7818	0.3552
-27.1815	0.0000	76.3025	27.1815	-0.6280	-0.2287
-26.3586	0.0000	76.3025	26.3586	-0.5142	-0.6538
-25.5358	0.0000	76.3025	25.5358	-0.4222	-0.9435
-24.7129	0.0000	76.3025	24.7129	-0.3709	-1.1161
-23.8901	0.0000	76.3025	23.8901	-0.3480	-1.1548
-23.0672	0.0000	76.3025	23.0672	-0.3336	-1.1140
-22.2444	0.0000	76.3025	22.2444	-0.3229	-0.9982
-21.4215	0.0000	76.3025	21.4215	-0.3144	-0.7938
-20.5986	0.0000	76.3025	20.5986	-0.3065	-0.4907
-19.7758	0.0000	76.3025	19.7758	-0.3077	-0.0918
-18.9529	0.0000	76.3025	18.9529	-0.3310	0.3761
-18.1301	0.0000	76.3025	18.1301	-0.3617	0.8676
-17.3072	0.0000	76.3025	17.3072	-0.3781	1.3914
-16.4844	0.0000	76.3025	16.4844	-0.3844	1.9132
-15.6615	0.0000	76.3025	15.6615	-0.3913	2.4414
-14.8387	0.0000	76.3025	14.8387	-0.3983	2.9907
-14.0158	0.0000	76.3025	14.0158	-0.4078	3.5804
-13.1929	0.0000	76.3025	13.1929	-0.4326	4.2504
-12.3701	0.0000	76.3025	12.3701	-0.4526	5.0681
-11.5472	0.0000	76.3025	11.5472	-0.4282	6.0627
-10.7244	0.0000	76.3025	10.7244	-0.4113	7.2270
-9.9015	0.0000	76.3025	9.9015	-0.4222	8.4556
-9.0787	0.0000	76.3025	9.0787	-0.4495	9.7098
-8.2558	0.0000	76.3025	8.2558	-0.4786	10.8868
-7.4329	0.0000	76.3025	7.4329	-0.5175	11.7399
-6.6101	0.0000	76.3025	6.6101	-0.5986	11.8460
-5.7872	0.0000	76.3025	5.7872	-0.7025	10.6586
-4.9644	0.0000	76.3025	4.9644	-0.8182	8.3759
-4.1415	0.0000	76.3025	4.1415	-1.0106	5.9491
-3.3187	0.0000	76.3025	3.3187	-1.2682	3.6273
-2.4958	0.0000	76.3025	2.4958	-1.5535	1.5157
-1.6729	0.0000	76.3025	1.6729	-1.8539	-0.2940
-0.8501	0.0000	76.3025	0.8501	-2.1056	-1.5777
-0.0272	0.0000	76.3025	0.0272	-2.1338	-1.9814
0.7956	0.0000	76.3025	0.7956	-1.6484	-1.2947
1.6185	0.0000	76.3025	1.6185	-1.2327	0.2672
2.4413	0.0000	76.3025	2.4413	-0.8789	2.3216
3.2642	0.0000	76.3025	3.2642	-0.5380	4.5492
4.0870	0.0000	76.3025	4.0870	-0.1900	6.9239
4.9099	0.0000	76.3025	4.9099	0.1570	9.2913
5.7328	0.0000	76.3025	5.7328	0.4523	11.1817
6.5556	0.0000	76.3025	6.5556	0.6514	11.9782
7.3785	0.0000	76.3025	7.3785	0.7232	11.6151
8.2013	0.0000	76.3025	8.2013	0.7246	10.7633
9.0242	0.0000	76.3025	9.0242	0.7039	9.7364
9.8470	0.0000	76.3025	9.8470	0.6362	8.6104
10.6699	0.0000	76.3025	10.6699	0.5085	7.4823
11.4928	0.0000	76.3025	11.4928	0.3593	6.4247
12.3156	0.0000	76.3025	12.3156	0.2331	5.4491
13.1385	0.0000	76.3025	13.1385	0.1038	4.5646
13.9613	0.0000	76.3025	13.9613	-0.0193	3.7741
14.7842	0.0000	76.3025	14.7842	-0.1443	3.0738
15.6070	0.0000	76.3025	15.6070	-0.2880	2.4396
16.4299	0.0000	76.3025	16.4299	-0.4325	1.8390
17.2528	0.0000	76.3025	17.2528	-0.5696	1.2590
18.0756	0.0000	76.3025	18.0756	-0.6913	0.7202
18.8985	0.0000	76.3025	18.8985	-0.7831	0.2594
19.7213	0.0000	76.3025	19.7213	-0.8589	-0.1249
20.5442	0.0000	76.3025	20.5442	-0.9503	-0.4195
21.3670	0.0000	76.3025	21.3670	-1.0117	-0.5993
22.1899	0.0000	76.3025	22.1899	-1.0309	-0.6336
23.0128	0.0000	76.3025	23.0128	-1.0359	-0.5267
23.8356	0.0000	76.3025	23.8356	-1.0308	-0.2976
24.6585	0.0000	76.3025	24.6585	-1.0094	0.0425
25.4813	0.0000	76.3025	25.4813	-0.9876	0.4951
26.3042	0.0000	76.3025	26.3042	-0.9886	1.0615
27.1270	0.0000	76.3025	27.1270	-0.9700	1.7192
27.9499	0.0000	76.3025	27.9499	-0.9282	2.4726
28.7727	0.0000	76.3025	28.7727	-0.8731	3.3091
29.5956	0.0000	76.3025	29.5956	-0.8035	4.1793
30.4185	0.0000	76.3025	30.4185	-0.7118	5.0376
31.2413	0.0000	76.3025	31.2413	-0.5850	5.8563
32.0642	0.0000	76.3025	32.0642	-0.4337	6.6036
32.8870	0.0000	76.3025	32.8870	-0.2765	7.1421
33.7099	0.0000	76.3025	33.7099	-0.1665	7.2507
34.5327	0.0000	76.3025	34.5327	-0.1377	7.0574
35.3556	0.0000	76.3025	35.3556	-0.1480	6.3648
36.1785	0.0000	76.3025	36.1785	-0.1336	4.6423
37.0013	0.0000	76.3025	37.0013	-0.0812	2.3007

37.8242	0.0000	76.3025	37.8242	-0.0392	0.6850
38.6470	0.0000	76.3025	38.6470	-0.0184	-0.0415
39.4699	0.0000	76.3025	39.4699	0.0043	-0.1801
40.2927	0.0000	76.3025	40.2927	-0.1538	-0.1475
Plane: 152.4 mm downstream of injection					
-39.5218	0.0000	152.2921	39.5218	-0.0467	1.5226
-38.6964	0.0000	152.2921	38.6964	-0.0692	1.6543
-37.8710	0.0000	152.2921	37.8710	-0.0015	1.2607
-37.0456	0.0000	152.2921	37.0456	-0.3682	2.0587
-36.2202	0.0000	152.2921	36.2202	-0.9716	3.5633
-35.3948	0.0000	152.2921	35.3948	-1.2829	4.0825
-34.5694	0.0000	152.2921	34.5694	-1.5058	4.0153
-33.7440	0.0000	152.2921	33.7440	-1.5860	3.7607
-32.9186	0.0000	152.2921	32.9186	-1.5280	3.5669
-32.0932	0.0000	152.2921	32.0932	-1.4687	3.3964
-31.2678	0.0000	152.2921	31.2678	-1.4553	3.2074
-30.4424	0.0000	152.2921	30.4424	-1.4307	2.9805
-29.6170	0.0000	152.2921	29.6170	-1.4301	2.7849
-28.7915	0.0000	152.2921	28.7915	-1.4257	2.6028
-27.9661	0.0000	152.2921	27.9661	-1.4240	2.4145
-27.1407	0.0000	152.2921	27.1407	-1.4345	2.2189
-26.3153	0.0000	152.2921	26.3153	-1.4533	2.0222
-25.4899	0.0000	152.2921	25.4899	-1.4770	1.8370
-24.6645	0.0000	152.2921	24.6645	-1.5323	1.6671
-23.8391	0.0000	152.2921	23.8391	-1.6045	1.5039
-23.0137	0.0000	152.2921	23.0137	-1.6543	1.3681
-22.1883	0.0000	152.2921	22.1883	-1.7243	1.2608
-21.3629	0.0000	152.2921	21.3629	-1.8224	1.1979
-20.5375	0.0000	152.2921	20.5375	-1.9404	1.2086
-19.7121	0.0000	152.2921	19.7121	-2.0700	1.3161
-18.8867	0.0000	152.2921	18.8867	-2.2150	1.5410
-18.0613	0.0000	152.2921	18.0613	-2.3669	1.8534
-17.2359	0.0000	152.2921	17.2359	-2.5258	2.3005
-16.4105	0.0000	152.2921	16.4105	-2.6739	2.8674
-15.5851	0.0000	152.2921	15.5851	-2.8153	3.5182
-14.7597	0.0000	152.2921	14.7597	-2.9735	4.3074
-13.9343	0.0000	152.2921	13.9343	-3.1424	5.2200
-13.1089	0.0000	152.2921	13.1089	-3.3052	6.1907
-12.2835	0.0000	152.2921	12.2835	-3.4746	7.1556
-11.4581	0.0000	152.2921	11.4581	-3.6942	8.1193
-10.6327	0.0000	152.2921	10.6327	-3.9917	9.0769
-9.8073	0.0000	152.2921	9.8073	-4.3202	10.0793
-8.9818	0.0000	152.2921	8.9818	-4.6803	11.1706
-8.1564	0.0000	152.2921	8.1564	-5.1262	12.2481
-7.3310	0.0000	152.2921	7.3310	-5.6706	13.1137
-6.5056	0.0000	152.2921	6.5056	-6.3078	13.4465
-5.6802	0.0000	152.2921	5.6802	-7.0466	12.8656
-4.8548	0.0000	152.2921	4.8548	-7.9106	11.1868
-4.0294	0.0000	152.2921	4.0294	-8.8684	8.8984
-3.2040	0.0000	152.2921	3.2040	-10.1532	6.4248
-2.3786	0.0000	152.2921	2.3786	-11.7065	3.9442
-1.5532	0.0000	152.2921	1.5532	-13.4563	1.7475
-0.7278	0.0000	152.2921	0.7278	-15.0464	0.1165
0.0976	0.0000	152.2921	0.0976	-15.8308	-0.6977
0.9230	0.0000	152.2921	0.9230	-15.2276	-0.5525
1.7484	0.0000	152.2921	1.7484	-13.6826	0.4630
2.5738	0.0000	152.2921	2.5738	-11.8546	2.2187
3.3992	0.0000	152.2921	3.3992	-10.2119	4.3540
4.2246	0.0000	152.2921	4.2246	-8.8088	6.6826
5.0500	0.0000	152.2921	5.0500	-7.6466	8.9497
5.8754	0.0000	152.2921	5.8754	-6.7146	10.7862
6.7008	0.0000	152.2921	6.7008	-5.9728	11.8054
7.5262	0.0000	152.2921	7.5262	-5.3377	11.8243
8.3516	0.0000	152.2921	8.3516	-4.8120	11.1039
9.1770	0.0000	152.2921	9.1770	-4.3278	10.1479
10.0024	0.0000	152.2921	10.0024	-3.9169	9.1657
10.8278	0.0000	152.2921	10.8278	-3.6199	8.1692
11.6533	0.0000	152.2921	11.6533	-3.3892	7.1250
12.4787	0.0000	152.2921	12.4787	-3.1782	6.0587
13.3041	0.0000	152.2921	13.3041	-2.9795	5.0477
14.1295	0.0000	152.2921	14.1295	-2.7969	4.1627
14.9549	0.0000	152.2921	14.9549	-2.5906	3.4135
15.7803	0.0000	152.2921	15.7803	-2.4012	2.6982
16.6057	0.0000	152.2921	16.6057	-2.2693	2.0041
17.4311	0.0000	152.2921	17.4311	-2.1675	1.3946
18.2565	0.0000	152.2921	18.2565	-2.0649	0.9070
19.0819	0.0000	152.2921	19.0819	-1.9554	0.5554
19.9073	0.0000	152.2921	19.9073	-1.8576	0.3444
20.7327	0.0000	152.2921	20.7327	-1.7787	0.2623
21.5581	0.0000	152.2921	21.5581	-1.6973	0.2940

22.3835	0.0000	152.2921	22.3835	-1.6270	0.4193
23.2089	0.0000	152.2921	23.2089	-1.5620	0.6164
24.0343	0.0000	152.2921	24.0343	-1.5134	0.8488
24.8597	0.0000	152.2921	24.8597	-1.4567	1.1049
25.6851	0.0000	152.2921	25.6851	-1.3919	1.3839
26.5105	0.0000	152.2921	26.5105	-1.3501	1.6793
27.3359	0.0000	152.2921	27.3359	-1.3425	1.9634
28.1613	0.0000	152.2921	28.1613	-1.3400	2.2081
28.9867	0.0000	152.2921	28.9867	-1.3349	2.4400
29.8121	0.0000	152.2921	29.8121	-1.3556	2.6559
30.6375	0.0000	152.2921	30.6375	-1.4072	2.8472
31.4630	0.0000	152.2921	31.4630	-1.4811	3.0153
32.2884	0.0000	152.2921	32.2884	-1.5559	3.1682
33.1138	0.0000	152.2921	33.1138	-1.6120	3.3113
33.9392	0.0000	152.2921	33.9392	-1.6883	3.4211
34.7646	0.0000	152.2921	34.7646	-1.6530	3.5023
35.5900	0.0000	152.2921	35.5900	-1.3301	3.3534
36.4154	0.0000	152.2921	36.4154	-0.8035	2.3985
37.2408	0.0000	152.2921	37.2408	-0.3216	1.0737
38.0662	0.0000	152.2921	38.0662	-0.0438	0.1198
38.8916	0.0000	152.2921	38.8916	0.0123	-0.1433
39.7170	0.0000	152.2921	39.7170	-0.0316	-0.0446

B.13.10 Case 9: Swirling Radial Injection of Hydrogen

Table B-23: Spatial fuel concentration data. Case 9

Hardware Configuration: D				Measurement Technique: Gas Chromatography	
Bulk Flow Type: Air				Fuel Type: Hydrogen	
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: 0.002952 kg/min	
Plane: 25.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-29.2100	0.0000	25.4000	29.2100	0.206	0.00206
-27.9400	0.0000	25.4000	27.9400	0.373	0.00373
-26.6700	0.0000	25.4000	26.6700	0.621	0.00621
-25.4000	0.0000	25.4000	25.4000	0.957	0.00957
-24.1300	0.0000	25.4000	24.1300	1.522	0.01522
-22.8600	0.0000	25.4000	22.8600	2.228	0.02228
-21.5900	0.0000	25.4000	21.5900	2.990	0.02990
-20.3200	0.0000	25.4000	20.3200	3.786	0.03786
-19.0500	0.0000	25.4000	19.0500	4.597	0.04597
-17.7800	0.0000	25.4000	17.7800	5.489	0.05489
-16.5100	0.0000	25.4000	16.5100	6.752	0.06752
-15.2400	0.0000	25.4000	15.2400	8.936	0.08936
-13.9700	0.0000	25.4000	13.9700	13.683	0.13683
-12.7000	0.0000	25.4000	12.7000	23.650	0.23650
12.7000	0.0000	25.4000	12.7000	21.979	0.21979
13.9700	0.0000	25.4000	13.9700	12.838	0.12838
15.2400	0.0000	25.4000	15.2400	8.705	0.08705
16.5100	0.0000	25.4000	16.5100	6.395	0.06395
17.7800	0.0000	25.4000	17.7800	5.257	0.05257
19.0500	0.0000	25.4000	19.0500	4.557	0.04557
20.3200	0.0000	25.4000	20.3200	3.957	0.03957
21.5900	0.0000	25.4000	21.5900	3.007	0.03007
22.8600	0.0000	25.4000	22.8600	2.387	0.02387
24.1300	0.0000	25.4000	24.1300	1.645	0.01645
25.4000	0.0000	25.4000	25.4000	1.056	0.01056
26.6700	0.0000	25.4000	26.6700	0.680	0.00680
27.9400	0.0000	25.4000	27.9400	0.440	0.00440
29.2100	0.0000	25.4000	29.2100	0.356	0.00356
-26.9865	11.1782	25.4000	29.2100	0.141	0.00141
-25.8132	10.6922	25.4000	27.9400	0.239	0.00239
-24.6399	10.2062	25.4000	26.6700	0.385	0.00385
-23.4665	9.7202	25.4000	25.4000	0.603	0.00603
-22.2932	9.2342	25.4000	24.1300	0.890	0.00890
-21.1199	8.7481	25.4000	22.8600	1.409	0.01409
-19.9466	8.2621	25.4000	21.5900	2.348	0.02348
-18.7732	7.7761	25.4000	20.3200	3.304	0.03304
-17.5999	7.2901	25.4000	19.0500	4.386	0.04386
-16.4266	6.8041	25.4000	17.7800	5.536	0.05536
-15.2533	6.3181	25.4000	16.5100	7.040	0.07040
-14.0799	5.8321	25.4000	15.2400	10.024	0.10024
-12.9066	5.3461	25.4000	13.9700	16.200	0.16200
-11.7333	4.8601	25.4000	12.7000	21.487	0.21487
11.7333	-4.8601	25.4000	12.7000	19.984	0.19984
12.9066	-5.3461	25.4000	13.9700	15.524	0.15524
14.0799	-5.8321	25.4000	15.2400	9.296	0.09296

15.2533	-6.3181	25.4000	16.5100	6.657	0.06657
16.4266	-6.8041	25.4000	17.7800	5.147	0.05147
17.5999	-7.2901	25.4000	19.0500	4.127	0.04127
18.7732	-7.7761	25.4000	20.3200	3.158	0.03158
19.9466	-8.2621	25.4000	21.5900	2.395	0.02395
21.1199	-8.7481	25.4000	22.8600	1.530	0.01530
22.2932	-9.2342	25.4000	24.1300	1.070	0.01070
23.4665	-9.7202	25.4000	25.4000	0.714	0.00714
24.6399	-10.2062	25.4000	26.6700	0.515	0.00515
25.8132	-10.6922	25.4000	27.9400	0.271	0.00271
26.9865	-11.1782	25.4000	29.2100	0.180	0.00180
Plane: 76.2 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-35.5600	0.0000	76.2000	35.5600	1.478	0.01478
-33.0200	0.0000	76.2000	33.0200	2.296	0.02296
-30.4800	0.0000	76.2000	30.4800	2.796	0.02796
-27.9400	0.0000	76.2000	27.9400	2.991	0.02991
-25.4000	0.0000	76.2000	25.4000	3.055	0.03055
-22.8600	0.0000	76.2000	22.8600	3.217	0.03217
-20.3200	0.0000	76.2000	20.3200	3.517	0.03517
-19.0500	0.0000	76.2000	19.0500	3.681	0.03681
-17.7800	0.0000	76.2000	17.7800	3.879	0.03879
-16.5100	0.0000	76.2000	16.5100	4.201	0.04201
-15.2400	0.0000	76.2000	15.2400	4.704	0.04704
-13.9700	0.0000	76.2000	13.9700	5.730	0.05730
-12.7000	0.0000	76.2000	12.7000	8.054	0.08054
-11.4300	0.0000	76.2000	11.4300	11.244	0.11244
-10.1600	0.0000	76.2000	10.1600	13.950	0.13950
-8.8900	0.0000	76.2000	8.8900	15.680	0.15680
-7.6200	0.0000	76.2000	7.6200	16.937	0.16937
-6.3500	0.0000	76.2000	6.3500	18.161	0.18161
-5.0800	0.0000	76.2000	5.0800	18.576	0.18576
-3.8100	0.0000	76.2000	3.8100	18.359	0.18359
-2.5400	0.0000	76.2000	2.5400	18.432	0.18432
-1.2700	0.0000	76.2000	1.2700	18.343	0.18343
0.0000	0.0000	76.2000	0.0000	18.318	0.18318
1.2700	0.0000	76.2000	1.2700	18.231	0.18231
2.5400	0.0000	76.2000	2.5400	18.121	0.18121
3.8100	0.0000	76.2000	3.8100	18.087	0.18087
5.0800	0.0000	76.2000	5.0800	18.008	0.18008
6.3500	0.0000	76.2000	6.3500	17.756	0.17756
7.6200	0.0000	76.2000	7.6200	17.175	0.17175
8.8900	0.0000	76.2000	8.8900	15.583	0.15583
10.1600	0.0000	76.2000	10.1600	12.718	0.12718
11.4300	0.0000	76.2000	11.4300	8.913	0.08913
12.7000	0.0000	76.2000	12.7000	6.164	0.06164
13.9700	0.0000	76.2000	13.9700	4.802	0.04802
15.2400	0.0000	76.2000	15.2400	4.311	0.04311
16.5100	0.0000	76.2000	16.5100	4.049	0.04049
17.7800	0.0000	76.2000	17.7800	3.896	0.03896
19.0500	0.0000	76.2000	19.0500	3.797	0.03797
20.3200	0.0000	76.2000	20.3200	3.731	0.03731
22.8600	0.0000	76.2000	22.8600	3.621	0.03621
25.4000	0.0000	76.2000	25.4000	3.586	0.03586
27.9400	0.0000	76.2000	27.9400	3.602	0.03602
30.4800	0.0000	76.2000	30.4800	3.439	0.03439
33.0200	0.0000	76.2000	33.0200	2.830	0.02830
35.5600	0.0000	76.2000	35.5600	1.866	0.01866
36.8300	0.0000	76.2000	36.8300	1.457	0.01457
-32.8532	13.6082	76.2000	35.5600	1.732	0.01732
-30.5065	12.6362	76.2000	33.0200	2.546	0.02546
-28.1598	11.6642	76.2000	30.4800	2.948	0.02948
-25.8132	10.6922	76.2000	27.9400	3.048	0.03048
-23.4665	9.7202	76.2000	25.4000	3.117	0.03117
-21.1199	8.7481	76.2000	22.8600	3.317	0.03317
-18.7732	7.7761	76.2000	20.3200	3.611	0.03611
-16.4266	6.8041	76.2000	17.7800	4.105	0.04105
-15.2533	6.3181	76.2000	16.5100	4.375	0.04375
-14.0799	5.8321	76.2000	15.2400	5.008	0.05008
-12.9066	5.3461	76.2000	13.9700	6.461	0.06461
-11.7333	4.8601	76.2000	12.7000	8.696	0.08696
-10.5599	4.3741	76.2000	11.4300	11.319	0.11319
-9.3866	3.8881	76.2000	10.1600	13.845	0.13845
-8.2133	3.4021	76.2000	8.8900	15.801	0.15801
-7.0400	2.9160	76.2000	7.6200	17.687	0.17687
-5.8666	2.4300	76.2000	6.3500	18.371	0.18371
-4.6933	1.9440	76.2000	5.0800	18.479	0.18479
-3.5200	1.4580	76.2000	3.8100	18.347	0.18347
-2.3467	0.9720	76.2000	2.5400	18.409	0.18409
-1.1733	0.4860	76.2000	1.2700	18.343	0.18343

0.0000	0.0000	76.2000	0.0000	18.309	0.18309
1.1733	-0.4860	76.2000	1.2700	18.162	0.18162
2.3467	-0.9720	76.2000	2.5400	18.090	0.18090
3.5200	-1.4580	76.2000	3.8100	18.099	0.18099
4.6933	-1.9440	76.2000	5.0800	17.980	0.17980
5.8666	-2.4300	76.2000	6.3500	17.747	0.17747
7.0400	-2.9160	76.2000	7.6200	17.093	0.17093
8.2133	-3.4021	76.2000	8.8900	15.427	0.15427
9.3866	-3.8881	76.2000	10.1600	12.552	0.12552
10.5599	-4.3741	76.2000	11.4300	8.611	0.08611
11.7333	-4.8601	76.2000	12.7000	5.877	0.05877
12.9066	-5.3461	76.2000	13.9700	4.656	0.04656
14.0799	-5.8321	76.2000	15.2400	4.218	0.04218
15.2533	-6.3181	76.2000	16.5100	3.961	0.03961
16.4266	-6.8041	76.2000	17.7800	3.843	0.03843
18.7732	-7.7761	76.2000	20.3200	3.685	0.03685
21.1199	-8.7481	76.2000	22.8600	3.571	0.03571
23.4665	-9.7202	76.2000	25.4000	3.559	0.03559
25.8132	-10.6922	76.2000	27.9400	3.579	0.03579
28.1598	-11.6642	76.2000	30.4800	3.393	0.03393
30.5065	-12.6362	76.2000	33.0200	2.704	0.02704
32.8532	-13.6082	76.2000	35.5600	1.666	0.01666
34.0265	-14.0942	76.2000	36.8300	1.408	0.01408
Plane: 152.4 mm downstream of injection					
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Mole Fraction
-32.8532	13.6082	152.4000	35.5600	1.606	0.01606
-30.5065	12.6362	152.4000	33.0200	1.695	0.01695
-28.1598	11.6642	152.4000	30.4800	1.841	0.01841
-25.8132	10.6922	152.4000	27.9400	1.940	0.01940
-23.4665	9.7202	152.4000	25.4000	2.042	0.02042
-21.1199	8.7481	152.4000	22.8600	2.146	0.02146
-18.7732	7.7761	152.4000	20.3200	2.391	0.02391
-16.4266	6.8041	152.4000	17.7800	3.021	0.03021
-15.2533	6.3181	152.4000	16.5100	3.590	0.03590
-14.0799	5.8321	152.4000	15.2400	4.133	0.04133
-12.9066	5.3461	152.4000	13.9700	4.816	0.04816
-11.7333	4.8601	152.4000	12.7000	5.768	0.05768
-10.5599	4.3741	152.4000	11.4300	7.409	0.07409
-9.3866	3.8881	152.4000	10.1600	9.686	0.09686
-8.2133	3.4021	152.4000	8.8900	12.360	0.12360
-7.0400	2.9160	152.4000	7.6200	14.334	0.14334
-5.8666	2.4300	152.4000	6.3500	15.318	0.15318
-4.6933	1.9440	152.4000	5.0800	15.658	0.15658
-3.5200	1.4580	152.4000	3.8100	15.778	0.15778
-2.3467	0.9720	152.4000	2.5400	15.944	0.15944
-1.1733	0.4860	152.4000	1.2700	16.113	0.16113
0.0000	0.0000	152.4000	0.0000	16.307	0.16307
1.1733	-0.4860	152.4000	1.2700	16.226	0.16226
2.3467	-0.9720	152.4000	2.5400	16.099	0.16099
3.5200	-1.4580	152.4000	3.8100	15.887	0.15887
4.6933	-1.9440	152.4000	5.0800	15.729	0.15729
5.8666	-2.4300	152.4000	6.3500	15.391	0.15391
7.0400	-2.9160	152.4000	7.6200	14.474	0.14474
8.2133	-3.4021	152.4000	8.8900	12.676	0.12676
9.3866	-3.8881	152.4000	10.1600	10.315	0.10315
10.5599	-4.3741	152.4000	11.4300	7.839	0.07839
11.7333	-4.8601	152.4000	12.7000	6.009	0.06009
12.9066	-5.3461	152.4000	13.9700	5.033	0.05033
14.0799	-5.8321	152.4000	15.2400	4.389	0.04389
15.2533	-6.3181	152.4000	16.5100	3.856	0.03856
16.4266	-6.8041	152.4000	17.7800	3.146	0.03146
18.7732	-7.7761	152.4000	20.3200	2.509	0.02509
21.1199	-8.7481	152.4000	22.8600	2.223	0.02223
23.4665	-9.7202	152.4000	25.4000	2.118	0.02118
25.8132	-10.6922	152.4000	27.9400	2.069	0.02069
28.1598	-11.6642	152.4000	30.4800	1.919	0.01919
30.5065	-12.6362	152.4000	33.0200	1.837	0.01837
32.8532	-13.6082	152.4000	35.5600	1.709	0.01709
34.0265	-14.0942	152.4000	36.8300	1.652	0.01652

Table B-24: Velocity field data. Case 9

Hardware Configuration: D
Bulk Flow Type: Air
Bulk Flow Rate: 1.116 kg/min
Plane: 76.2 mm downstream of injection

Measurement Technique: Particle Image
Velocimetry
Fuel Type: Hydrogen
Fuel Flow Rate: 0.002952 kg/min

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.7689	0.0000	76.3025	39.7689	-0.0909	-0.3199
-38.9384	0.0000	76.3025	38.9384	0.0298	0.0579
-38.1079	0.0000	76.3025	38.1079	-0.0949	0.9905
-37.2774	0.0000	76.3025	37.2774	-0.2439	2.3915
-36.4469	0.0000	76.3025	36.4469	-0.7067	3.6960
-35.6164	0.0000	76.3025	35.6164	-1.6936	4.6578
-34.7859	0.0000	76.3025	34.7859	-2.6172	5.2403
-33.9554	0.0000	76.3025	33.9554	-2.7401	5.4853
-33.1249	0.0000	76.3025	33.1249	-2.4698	5.2098
-32.2944	0.0000	76.3025	32.2944	-2.3633	4.6255
-31.4639	0.0000	76.3025	31.4639	-2.0084	3.8281
-30.6334	0.0000	76.3025	30.6334	-1.6134	2.8788
-29.8029	0.0000	76.3025	29.8029	-1.2588	1.9259
-28.9724	0.0000	76.3025	28.9724	-0.9761	1.0634
-28.1419	0.0000	76.3025	28.1419	-0.7529	0.3386
-27.3114	0.0000	76.3025	27.3114	-0.5653	-0.2331
-26.4809	0.0000	76.3025	26.4809	-0.4177	-0.6621
-25.6504	0.0000	76.3025	25.6504	-0.3014	-0.9815
-24.8199	0.0000	76.3025	24.8199	-0.2084	-1.1691
-23.9894	0.0000	76.3025	23.9894	-0.1583	-1.2370
-23.1589	0.0000	76.3025	23.1589	-0.1126	-1.1768
-22.3284	0.0000	76.3025	22.3284	-0.0867	-0.9939
-21.4979	0.0000	76.3025	21.4979	-0.0816	-0.7226
-20.6674	0.0000	76.3025	20.6674	-0.0914	-0.3987
-19.8369	0.0000	76.3025	19.8369	-0.1076	-0.0264
-19.0064	0.0000	76.3025	19.0064	-0.0957	0.4340
-18.1759	0.0000	76.3025	18.1759	-0.0763	0.9295
-17.3454	0.0000	76.3025	17.3454	-0.0697	1.4337
-16.5149	0.0000	76.3025	16.5149	-0.0551	1.9888
-15.6844	0.0000	76.3025	15.6844	-0.0484	2.5698
-14.8539	0.0000	76.3025	14.8539	-0.0526	3.1730
-14.0234	0.0000	76.3025	14.0234	-0.0541	3.8206
-13.1929	0.0000	76.3025	13.1929	-0.0360	4.5523
-12.3624	0.0000	76.3025	12.3624	0.0167	5.4172
-11.5319	0.0000	76.3025	11.5319	0.1074	6.4591
-10.7014	0.0000	76.3025	10.7014	0.2135	7.6276
-9.8709	0.0000	76.3025	9.8709	0.2914	8.9362
-9.0404	0.0000	76.3025	9.0404	0.3847	10.3546
-8.2099	0.0000	76.3025	8.2099	0.4883	11.8044
-7.3794	0.0000	76.3025	7.3794	0.5835	13.0422
-6.5489	0.0000	76.3025	6.5489	0.6627	13.5869
-5.7184	0.0000	76.3025	5.7184	0.7683	12.7701
-4.8879	0.0000	76.3025	4.8879	0.9113	10.3315
-4.0574	0.0000	76.3025	4.0574	0.9678	7.3370
-3.2269	0.0000	76.3025	3.2269	0.9848	4.4985
-2.3964	0.0000	76.3025	2.3964	1.0988	1.9335
-1.5659	0.0000	76.3025	1.5659	1.3502	-0.2558
-0.7355	0.0000	76.3025	0.7355	1.7423	-1.6882
0.0950	0.0000	76.3025	0.0950	2.1349	-1.8703
0.9255	0.0000	76.3025	0.9255	2.1575	-0.6666
1.7560	0.0000	76.3025	1.7560	2.1352	1.3643
2.5865	0.0000	76.3025	2.5865	2.0082	3.7832
3.4170	0.0000	76.3025	3.4170	1.9367	6.4652
4.2475	0.0000	76.3025	4.2475	1.9807	9.3631
5.0780	0.0000	76.3025	5.0780	2.0936	11.8411
5.9085	0.0000	76.3025	5.9085	2.1588	13.2813
6.7390	0.0000	76.3025	6.7390	2.0993	13.4603
7.5695	0.0000	76.3025	7.5695	1.9292	12.6897
8.4000	0.0000	76.3025	8.4000	1.7020	11.4938
9.2305	0.0000	76.3025	9.2305	1.5308	10.2740
10.0610	0.0000	76.3025	10.0610	1.3594	8.9424
10.8915	0.0000	76.3025	10.8915	1.1567	7.5987
11.7220	0.0000	76.3025	11.7220	0.9430	6.3225
12.5525	0.0000	76.3025	12.5525	0.7304	5.2233
13.3830	0.0000	76.3025	13.3830	0.5262	4.3362
14.2135	0.0000	76.3025	14.2135	0.3518	3.5840
15.0440	0.0000	76.3025	15.0440	0.1649	2.8791
15.8745	0.0000	76.3025	15.8745	-0.0367	2.2319
16.7050	0.0000	76.3025	16.7050	-0.2246	1.6071
17.5355	0.0000	76.3025	17.5355	-0.3786	0.9759
18.3660	0.0000	76.3025	18.3660	-0.5237	0.3803
19.1965	0.0000	76.3025	19.1965	-0.6596	-0.1141
20.0270	0.0000	76.3025	20.0270	-0.7742	-0.4783
20.8575	0.0000	76.3025	20.8575	-0.8592	-0.7317
21.6880	0.0000	76.3025	21.6880	-0.9289	-0.8829
22.5185	0.0000	76.3025	22.5185	-0.9568	-0.8763
23.3490	0.0000	76.3025	23.3490	-0.9668	-0.7327
24.1795	0.0000	76.3025	24.1795	-0.9983	-0.4230

25.0100	0.0000	76.3025	25.0100	-1.0296	0.0076
25.8405	0.0000	76.3025	25.8405	-1.0372	0.5341
26.6710	0.0000	76.3025	26.6710	-1.0077	1.1633
27.5015	0.0000	76.3025	27.5015	-0.9408	1.9089
28.3320	0.0000	76.3025	28.3320	-0.8591	2.7454
29.1625	0.0000	76.3025	29.1625	-0.7360	3.6540
29.9930	0.0000	76.3025	29.9930	-0.5568	4.5883
30.8235	0.0000	76.3025	30.8235	-0.3745	5.5114
31.6540	0.0000	76.3025	31.6540	-0.2066	6.3531
32.4845	0.0000	76.3025	32.4845	-0.0580	7.0314
33.3150	0.0000	76.3025	33.3150	0.0601	7.4249
34.1455	0.0000	76.3025	34.1455	0.1369	7.4784
34.9760	0.0000	76.3025	34.9760	0.1551	7.1279
35.8065	0.0000	76.3025	35.8065	0.0976	5.9273
36.6370	0.0000	76.3025	36.6370	0.0223	2.7390
37.4675	0.0000	76.3025	37.4675	0.0137	0.6994
38.2980	0.0000	76.3025	38.2980	0.1235	-0.0544
39.1285	0.0000	76.3025	39.1285	0.1498	-0.1409
39.9590	0.0000	76.3025	39.9590	0.1313	-0.0738
Plane: 152.4mm downstream of injection					
-39.5243	0.0000	152.2921	39.5243	-0.0468	0.8456
-38.7015	0.0000	152.2921	38.7015	-0.2041	2.0647
-37.8786	0.0000	152.2921	37.8786	-0.3439	2.5495
-37.0558	0.0000	152.2921	37.0558	-0.6011	2.6957
-36.2329	0.0000	152.2921	36.2329	-1.2382	4.4588
-35.4101	0.0000	152.2921	35.4101	-1.5605	4.4467
-34.5872	0.0000	152.2921	34.5872	-1.5783	3.9787
-33.7644	0.0000	152.2921	33.7644	-1.4810	3.7614
-32.9415	0.0000	152.2921	32.9415	-1.4239	3.6215
-32.1186	0.0000	152.2921	32.1186	-1.4300	3.4019
-31.2958	0.0000	152.2921	31.2958	-1.3686	3.2083
-30.4729	0.0000	152.2921	30.4729	-1.3401	3.0297
-29.6501	0.0000	152.2921	29.6501	-1.2916	2.8244
-28.8272	0.0000	152.2921	28.8272	-1.2549	2.6206
-28.0044	0.0000	152.2921	28.0044	-1.2455	2.4335
-27.1815	0.0000	152.2921	27.1815	-1.2586	2.2600
-26.3586	0.0000	152.2921	26.3586	-1.2779	2.0819
-25.5358	0.0000	152.2921	25.5358	-1.2928	1.9014
-24.7129	0.0000	152.2921	24.7129	-1.3544	1.7179
-23.8901	0.0000	152.2921	23.8901	-1.4520	1.5114
-23.0672	0.0000	152.2921	23.0672	-1.5343	1.3277
-22.2444	0.0000	152.2921	22.2444	-1.6093	1.1940
-21.4215	0.0000	152.2921	21.4215	-1.6801	1.1411
-20.5986	0.0000	152.2921	20.5986	-1.7594	1.1798
-19.7758	0.0000	152.2921	19.7758	-1.8673	1.3021
-18.9529	0.0000	152.2921	18.9529	-2.0105	1.5045
-18.1301	0.0000	152.2921	18.1301	-2.1640	1.8314
-17.3072	0.0000	152.2921	17.3072	-2.3150	2.2919
-16.4844	0.0000	152.2921	16.4844	-2.4494	2.8587
-15.6615	0.0000	152.2921	15.6615	-2.5892	3.5703
-14.8387	0.0000	152.2921	14.8387	-2.7407	4.4436
-14.0158	0.0000	152.2921	14.0158	-2.8924	5.4252
-13.1929	0.0000	152.2921	13.1929	-3.0437	6.4150
-12.3701	0.0000	152.2921	12.3701	-3.2319	7.3912
-11.5472	0.0000	152.2921	11.5472	-3.4525	8.3850
-10.7244	0.0000	152.2921	10.7244	-3.7037	9.3696
-9.9015	0.0000	152.2921	9.9015	-4.0235	10.4455
-9.0787	0.0000	152.2921	9.0787	-4.3693	11.7063
-8.2558	0.0000	152.2921	8.2558	-4.7592	13.0789
-7.4329	0.0000	152.2921	7.4329	-5.2549	14.3563
-6.6101	0.0000	152.2921	6.6101	-5.9230	15.2042
-5.7872	0.0000	152.2921	5.7872	-6.7779	15.0345
-4.9644	0.0000	152.2921	4.9644	-7.7439	13.1276
-4.1415	0.0000	152.2921	4.1415	-8.7639	10.5211
-3.3187	0.0000	152.2921	3.3187	-9.9862	7.7223
-2.4958	0.0000	152.2921	2.4958	-11.5309	5.0359
-1.6729	0.0000	152.2921	1.6729	-13.4101	2.6514
-0.8501	0.0000	152.2921	0.8501	-15.3109	0.7759
-0.0272	0.0000	152.2921	0.0272	-16.4586	-0.3291
0.7956	0.0000	152.2921	0.7956	-15.7632	-0.2596
1.6185	0.0000	152.2921	1.6185	-13.8267	0.6895
2.4413	0.0000	152.2921	2.4413	-11.8424	2.5170
3.2642	0.0000	152.2921	3.2642	-10.0696	4.9837
4.0870	0.0000	152.2921	4.0870	-8.5600	7.6702
4.9099	0.0000	152.2921	4.9099	-7.3043	10.2433
5.7328	0.0000	152.2921	5.7328	-6.2726	12.3571
6.5556	0.0000	152.2921	6.5556	-5.4355	13.4401
7.3785	0.0000	152.2921	7.3785	-4.8156	13.1505
8.2013	0.0000	152.2921	8.2013	-4.3738	12.1098
9.0242	0.0000	152.2921	9.0242	-3.9668	10.8985

9.8470	0.0000	152.2921	9.8470	-3.6018	9.7196
10.6699	0.0000	152.2921	10.6699	-3.3250	8.6070
11.4928	0.0000	152.2921	11.4928	-3.1134	7.5221
12.3156	0.0000	152.2921	12.3156	-2.9023	6.4185
13.1385	0.0000	152.2921	13.1385	-2.7001	5.3405
13.9613	0.0000	152.2921	13.9613	-2.5491	4.3764
14.7842	0.0000	152.2921	14.7842	-2.3938	3.5324
15.6070	0.0000	152.2921	15.6070	-2.2280	2.7533
16.4299	0.0000	152.2921	16.4299	-2.0768	2.0243
17.2528	0.0000	152.2921	17.2528	-1.9656	1.3944
18.0756	0.0000	152.2921	18.0756	-1.8892	0.9106
18.8985	0.0000	152.2921	18.8985	-1.8085	0.5688
19.7213	0.0000	152.2921	19.7213	-1.7163	0.3605
20.5442	0.0000	152.2921	20.5442	-1.6317	0.3069
21.3670	0.0000	152.2921	21.3670	-1.5504	0.3456
22.1899	0.0000	152.2921	22.1899	-1.4778	0.4458
23.0128	0.0000	152.2921	23.0128	-1.4192	0.6131
23.8356	0.0000	152.2921	23.8356	-1.3674	0.8380
24.6585	0.0000	152.2921	24.6585	-1.3083	1.0889
25.4813	0.0000	152.2921	25.4813	-1.2524	1.3299
26.3042	0.0000	152.2921	26.3042	-1.2309	1.5576
27.1270	0.0000	152.2921	27.1270	-1.2099	1.8131
27.9499	0.0000	152.2921	27.9499	-1.2111	2.0733
28.7727	0.0000	152.2921	28.7727	-1.2281	2.3125
29.5956	0.0000	152.2921	29.5956	-1.2517	2.5436
30.4185	0.0000	152.2921	30.4185	-1.2824	2.7725
31.2413	0.0000	152.2921	31.2413	-1.3329	2.9720
32.0642	0.0000	152.2921	32.0642	-1.4274	3.1140
32.8870	0.0000	152.2921	32.8870	-1.4995	3.2501
33.7099	0.0000	152.2921	33.7099	-1.5511	3.3456
34.5327	0.0000	152.2921	34.5327	-1.4818	3.4421
35.3556	0.0000	152.2921	35.3556	-1.1611	3.2840
36.1785	0.0000	152.2921	36.1785	-0.6122	2.2567
37.0013	0.0000	152.2921	37.0013	-0.0656	0.6911
37.8242	0.0000	152.2921	37.8242	0.1782	-0.1084
38.6470	0.0000	152.2921	38.6470	0.1034	-0.1625
39.4699	0.0000	152.2921	39.4699	-0.1299	-0.0565
40.2927	0.0000	152.2921	40.2927	-0.2771	-0.0030

B.13.11 Case 10: Swirling Radial Injection of Methane-Hydrogen Blend

Table B-25: Spatial fuel concentration data. Case 10

Hardware Configuration: D				Measurement Technique: Gas Chromatography			
Bulk Flow Type: Air				Fuel Type: Methane-Hydrogen			
Bulk Flow Rate: 1.116 kg/min				Fuel Flow Rate: Methane-0.00593 kg/min Hydrogen-0.000693 kg/min			
Plane: 25.4 mm downstream of injection							
X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-29.2100	0.0000	25.4000	29.2100	0.050	0.053	0.00050	0.00053
-27.9400	0.0000	25.4000	27.9400	0.102	0.104	0.00102	0.00104
-26.6700	0.0000	25.4000	26.6700	0.185	0.191	0.00185	0.00191
-25.4000	0.0000	25.4000	25.4000	0.290	0.301	0.00290	0.00301
-24.1300	0.0000	25.4000	24.1300	0.433	0.456	0.00433	0.00456
-22.8600	0.0000	25.4000	22.8600	0.609	0.648	0.00609	0.00648
-21.5900	0.0000	25.4000	21.5900	0.802	0.855	0.00802	0.00855
-20.3200	0.0000	25.4000	20.3200	0.975	1.047	0.00975	0.01047
-19.0500	0.0000	25.4000	19.0500	1.233	1.332	0.01233	0.01332
-17.7800	0.0000	25.4000	17.7800	1.536	1.623	0.01536	0.01623
-16.5100	0.0000	25.4000	16.5100	1.949	2.030	0.01949	0.02030
-15.2400	0.0000	25.4000	15.2400	2.557	2.650	0.02557	0.02650
-13.9700	0.0000	25.4000	13.9700	3.521	3.673	0.03521	0.03673
-12.7000	0.0000	25.4000	12.7000	4.531	4.945	0.04531	0.04945
12.7000	0.0000	25.4000	12.7000	4.391	4.743	0.04391	0.04743
13.9700	0.0000	25.4000	13.9700	3.376	3.586	0.03376	0.03586
15.2400	0.0000	25.4000	15.2400	2.423	2.542	0.02423	0.02542
16.5100	0.0000	25.4000	16.5100	1.885	1.965	0.01885	0.01965
17.7800	0.0000	25.4000	17.7800	1.521	1.614	0.01521	0.01614
19.0500	0.0000	25.4000	19.0500	1.236	1.343	0.01236	0.01343
20.3200	0.0000	25.4000	20.3200	1.054	1.110	0.01054	0.01110
21.5900	0.0000	25.4000	21.5900	0.854	0.954	0.00854	0.00954
22.8600	0.0000	25.4000	22.8600	0.656	0.725	0.00656	0.00725
24.1300	0.0000	25.4000	24.1300	0.466	0.509	0.00466	0.00509
25.4000	0.0000	25.4000	25.4000	0.334	0.368	0.00334	0.00368
26.6700	0.0000	25.4000	26.6700	0.209	0.226	0.00209	0.00226
27.9400	0.0000	25.4000	27.9400	0.117	0.127	0.00117	0.00127
29.2100	0.0000	25.4000	29.2100	0.071	0.076	0.00071	0.00076

-26.9865	11.1782	25.4000	29.2100	0.034	0.054	0.00034	0.00054
-25.8132	10.6922	25.4000	27.9400	0.066	0.104	0.00066	0.00104
-24.6399	10.2062	25.4000	26.6700	0.120	0.191	0.00120	0.00191
-23.4665	9.7202	25.4000	25.4000	0.191	0.311	0.00191	0.00311
-22.2932	9.2342	25.4000	24.1300	0.281	0.462	0.00281	0.00462
-21.1199	8.7481	25.4000	22.8600	0.400	0.650	0.00400	0.00650
-19.9466	8.2621	25.4000	21.5900	0.520	0.863	0.00520	0.00863
-18.7732	7.7761	25.4000	20.3200	0.647	1.086	0.00647	0.01086
-17.5999	7.2901	25.4000	19.0500	0.777	1.348	0.00777	0.01348
-16.4266	6.8041	25.4000	17.7800	0.947	1.695	0.00947	0.01695
-15.2533	6.3181	25.4000	16.5100	1.314	2.172	0.01314	0.02172
-14.0799	5.8321	25.4000	15.2400	2.247	2.957	0.02247	0.02957
-12.9066	5.3461	25.4000	13.9700	3.633	4.190	0.03633	0.04190
-11.7333	4.8601	25.4000	12.7000	4.783	5.381	0.04783	0.05381
11.7333	-4.8601	25.4000	12.7000	4.336	5.096	0.04336	0.05096
12.9066	-5.3461	25.4000	13.9700	3.204	3.946	0.03204	0.03946
14.0799	-5.8321	25.4000	15.2400	2.063	2.857	0.02063	0.02857
15.2533	-6.3181	25.4000	16.5100	1.148	2.004	0.01148	0.02004
16.4266	-6.8041	25.4000	17.7800	0.917	1.618	0.00917	0.01618
17.5999	-7.2901	25.4000	19.0500	0.839	1.463	0.00839	0.01463
18.7732	-7.7761	25.4000	20.3200	0.730	1.243	0.00730	0.01243
19.9466	-8.2621	25.4000	21.5900	0.602	0.962	0.00602	0.00962
21.1199	-8.7481	25.4000	22.8600	0.476	0.784	0.00476	0.00784
22.2932	-9.2342	25.4000	24.1300	0.317	0.545	0.00317	0.00545
23.4665	-9.7202	25.4000	25.4000	0.220	0.394	0.00220	0.00394
24.6399	-10.2062	25.4000	26.6700	0.112	0.239	0.00112	0.00239
25.8132	-10.6922	25.4000	27.9400	0.073	0.147	0.00073	0.00147
26.9865	-11.1782	25.4000	29.2100	0.047	0.075	0.00047	0.00075

Plane: 76.2 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-35.5600	0.0000	76.2000	35.5600	0.555	0.501	0.00555	0.00501
-33.0200	0.0000	76.2000	33.0200	0.751	0.684	0.00751	0.00684
-30.4800	0.0000	76.2000	30.4800	0.844	0.776	0.00844	0.00776
-27.9400	0.0000	76.2000	27.9400	0.861	0.791	0.00861	0.00791
-25.4000	0.0000	76.2000	25.4000	0.869	0.803	0.00869	0.00803
-22.8600	0.0000	76.2000	22.8600	0.911	0.839	0.00911	0.00839
-20.3200	0.0000	76.2000	20.3200	0.977	0.900	0.00977	0.00900
-17.7800	0.0000	76.2000	17.7800	1.060	0.975	0.01060	0.00975
-16.5100	0.0000	76.2000	16.5100	1.170	1.052	0.01170	0.01052
-15.2400	0.0000	76.2000	15.2400	1.381	1.212	0.01381	0.01212
-13.9700	0.0000	76.2000	13.9700	1.818	1.564	0.01818	0.01564
-12.7000	0.0000	76.2000	12.7000	2.599	2.264	0.02599	0.02264
-11.4300	0.0000	76.2000	11.4300	3.412	3.050	0.03412	0.03050
-10.1600	0.0000	76.2000	10.1600	3.945	3.566	0.03945	0.03566
-8.8900	0.0000	76.2000	8.8900	4.195	3.839	0.04195	0.03839
-7.6200	0.0000	76.2000	7.6200	4.514	4.167	0.04514	0.04167
-6.3500	0.0000	76.2000	6.3500	4.682	4.299	0.04682	0.04299
-5.0800	0.0000	76.2000	5.0800	4.709	4.325	0.04709	0.04325
-3.8100	0.0000	76.2000	3.8100	4.680	4.324	0.04680	0.04324
-2.5400	0.0000	76.2000	2.5400	4.701	4.305	0.04701	0.04305
-1.2700	0.0000	76.2000	1.2700	4.655	4.275	0.04655	0.04275
0.0000	0.0000	76.2000	0.0000	4.691	4.297	0.04691	0.04297
1.2700	0.0000	76.2000	1.2700	4.671	4.296	0.04671	0.04296
2.5400	0.0000	76.2000	2.5400	4.605	4.270	0.04605	0.04270
3.8100	0.0000	76.2000	3.8100	4.547	4.237	0.04547	0.04237
5.0800	0.0000	76.2000	5.0800	4.453	4.109	0.04453	0.04109
6.3500	0.0000	76.2000	6.3500	4.321	4.041	0.04321	0.04041
7.6200	0.0000	76.2000	7.6200	4.078	3.777	0.04078	0.03777
8.8900	0.0000	76.2000	8.8900	3.682	3.353	0.03682	0.03353
10.1600	0.0000	76.2000	10.1600	2.978	2.670	0.02978	0.02670
11.4300	0.0000	76.2000	11.4300	2.090	1.835	0.02090	0.01835
12.7000	0.0000	76.2000	12.7000	1.553	1.364	0.01553	0.01364
13.9700	0.0000	76.2000	13.9700	1.262	1.156	0.01262	0.01156
15.2400	0.0000	76.2000	15.2400	1.123	1.035	0.01123	0.01035
16.5100	0.0000	76.2000	16.5100	1.042	0.970	0.01042	0.00970
17.7800	0.0000	76.2000	17.7800	1.003	0.933	0.01003	0.00933
20.3200	0.0000	76.2000	20.3200	0.963	0.903	0.00963	0.00903
22.8600	0.0000	76.2000	22.8600	0.939	0.880	0.00939	0.00880
25.4000	0.0000	76.2000	25.4000	0.929	0.870	0.00929	0.00870
27.9400	0.0000	76.2000	27.9400	0.924	0.864	0.00924	0.00864
30.4800	0.0000	76.2000	30.4800	0.867	0.807	0.00867	0.00807
33.0200	0.0000	76.2000	33.0200	0.707	0.654	0.00707	0.00654
35.5600	0.0000	76.2000	35.5600	0.507	0.464	0.00507	0.00464
36.8300	0.0000	76.2000	36.8300	0.465	0.424	0.00465	0.00424
-32.8532	13.6082	76.2000	35.5600	0.567	0.506	0.00567	0.00506
-30.5065	12.6362	76.2000	33.0200	0.762	0.695	0.00762	0.00695
-28.1598	11.6642	76.2000	30.4800	0.860	0.785	0.00860	0.00785
-25.8132	10.6922	76.2000	27.9400	0.870	0.793	0.00870	0.00793
-23.4665	9.7202	76.2000	25.4000	0.875	0.808	0.00875	0.00808

-21.1199	8.7481	76.2000	22.8600	0.927	0.850	0.00927	0.00850
-18.7732	7.7761	76.2000	20.3200	1.001	0.992	0.01001	0.00992
-16.4266	6.8041	76.2000	17.7800	1.082	0.989	0.01082	0.00989
-15.2533	6.3181	76.2000	16.5100	1.249	1.069	0.01249	0.01069
-14.0799	5.8321	76.2000	15.2400	1.419	1.254	0.01419	0.01254
-12.9066	5.3461	76.2000	13.9700	1.894	1.599	0.01894	0.01599
-11.7333	4.8601	76.2000	12.7000	2.651	2.303	0.02651	0.02303
-10.5599	4.3741	76.2000	11.4300	3.433	3.072	0.03433	0.03072
-9.3866	3.8881	76.2000	10.1600	3.981	3.604	0.03981	0.03604
-8.2133	3.4021	76.2000	8.8900	4.255	3.856	0.04255	0.03856
-7.0400	2.9160	76.2000	7.6200	4.537	4.175	0.04537	0.04175
-5.8666	2.4300	76.2000	6.3500	4.686	4.303	0.04686	0.04303
-4.6933	1.9440	76.2000	5.0800	4.708	4.318	0.04708	0.04318
-3.5200	1.4580	76.2000	3.8100	4.718	4.334	0.04718	0.04334
-2.3467	0.9720	76.2000	2.5400	4.722	4.305	0.04722	0.04305
-1.1733	0.4860	76.2000	1.2700	4.716	4.300	0.04716	0.04300
0.0000	0.0000	76.2000	0.0000	4.704	4.301	0.04704	0.04301
1.1733	-0.4860	76.2000	1.2700	4.678	4.262	0.04678	0.04262
2.3467	-0.9720	76.2000	2.5400	4.593	4.253	0.04593	0.04253
3.5200	-1.4580	76.2000	3.8100	4.534	4.224	0.04534	0.04224
4.6933	-1.9440	76.2000	5.0800	4.444	4.101	0.04444	0.04101
5.8666	-2.4300	76.2000	6.3500	4.312	4.035	0.04312	0.04035
7.0400	-2.9160	76.2000	7.6200	4.087	3.784	0.04087	0.03784
8.2133	-3.4021	76.2000	8.8900	3.683	3.396	0.03683	0.03396
9.3866	-3.8881	76.2000	10.1600	2.977	2.651	0.02977	0.02651
10.5599	-4.3741	76.2000	11.4300	2.084	1.821	0.02084	0.01821
11.7333	-4.8601	76.2000	12.7000	1.568	1.377	0.01568	0.01377
12.9066	-5.3461	76.2000	13.9700	1.279	1.168	0.01279	0.01168
14.0799	-5.8321	76.2000	15.2400	1.130	1.042	0.01130	0.01042
15.2533	-6.3181	76.2000	16.5100	1.060	0.986	0.01060	0.00986
16.4266	-6.8041	76.2000	17.7800	1.012	0.944	0.01012	0.00944
18.7732	-7.7761	76.2000	20.3200	0.966	0.910	0.00966	0.00910
21.1199	-8.7481	76.2000	22.8600	0.938	0.876	0.00938	0.00876
23.4665	-9.7202	76.2000	25.4000	0.923	0.861	0.00923	0.00861
25.8132	-10.6922	76.2000	27.9400	0.913	0.859	0.00913	0.00859
28.1598	-11.6642	76.2000	30.4800	0.860	0.800	0.00860	0.00800
30.5065	-12.6362	76.2000	33.0200	0.695	0.639	0.00695	0.00639
32.8532	-13.6082	76.2000	35.5600	0.504	0.459	0.00504	0.00459
34.0265	-14.0942	76.2000	36.8300	0.477	0.436	0.00477	0.00436

Plane: 152.4 mm downstream of injection

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Volume H2 Avg [%]	Volume CH4 Avg [%]	H2 Mole Fraction	CH4 Mole Fraction
-32.8532	13.6082	152.4000	35.5600	0.422	0.444	0.00422	0.00444
-30.5065	12.6362	152.4000	33.0200	0.450	0.471	0.00450	0.00471
-28.1598	11.6642	152.4000	30.4800	0.475	0.499	0.00475	0.00499
-25.8132	10.6922	152.4000	27.9400	0.496	0.520	0.00496	0.00520
-23.4665	9.7202	152.4000	25.4000	0.517	0.544	0.00517	0.00544
-21.1199	8.7481	152.4000	22.8600	0.537	0.568	0.00537	0.00568
-18.7732	7.7761	152.4000	20.3200	0.580	0.608	0.00580	0.00608
-16.4266	6.8041	152.4000	17.7800	0.703	0.740	0.00703	0.00740
-15.2533	6.3181	152.4000	16.5100	0.826	0.858	0.00826	0.00858
-14.0799	5.8321	152.4000	15.2400	0.943	0.979	0.00943	0.00979
-12.9066	5.3461	152.4000	13.9700	1.135	1.150	0.01135	0.01150
-11.7333	4.8601	152.4000	12.7000	1.402	1.417	0.01402	0.01417
-10.5599	4.3741	152.4000	11.4300	1.739	1.805	0.01739	0.01805
-9.3866	3.8881	152.4000	10.1600	2.261	2.450	0.02261	0.02450
-8.2133	3.4021	152.4000	8.8900	2.725	3.024	0.02725	0.03024
-7.0400	2.9160	152.4000	7.6200	3.024	3.353	0.03024	0.03353
-5.8666	2.4300	152.4000	6.3500	3.179	3.545	0.03179	0.03545
-4.6933	1.9440	152.4000	5.0800	3.201	3.583	0.03201	0.03583
-3.5200	1.4580	152.4000	3.8100	3.262	3.628	0.03262	0.03628
-2.3467	0.9720	152.4000	2.5400	3.307	3.686	0.03307	0.03686
-1.1733	0.4860	152.4000	1.2700	3.330	3.721	0.03330	0.03721
0.0000	0.0000	152.4000	0.0000	3.428	3.824	0.03428	0.03824
1.1733	-0.4860	152.4000	1.2700	3.479	3.659	0.03479	0.03659
2.3467	-0.9720	152.4000	2.5400	3.343	3.731	0.03343	0.03731
3.5200	-1.4580	152.4000	3.8100	3.280	3.692	0.03280	0.03692
4.6933	-1.9440	152.4000	5.0800	3.217	3.599	0.03217	0.03599
5.8666	-2.4300	152.4000	6.3500	3.194	3.601	0.03194	0.03601
7.0400	-2.9160	152.4000	7.6200	3.072	3.410	0.03072	0.03410
8.2133	-3.4021	152.4000	8.8900	2.901	3.200	0.02901	0.03200
9.3866	-3.8881	152.4000	10.1600	2.382	2.663	0.02382	0.02663
10.5599	-4.3741	152.4000	11.4300	1.992	2.068	0.01992	0.02068
11.7333	-4.8601	152.4000	12.7000	1.536	1.547	0.01536	0.01547
12.9066	-5.3461	152.4000	13.9700	1.207	1.240	0.01207	0.01240
14.0799	-5.8321	152.4000	15.2400	0.998	1.111	0.00998	0.01111
15.2533	-6.3181	152.4000	16.5100	0.849	0.919	0.00849	0.00919
16.4266	-6.8041	152.4000	17.7800	0.728	0.775	0.00728	0.00775
18.7732	-7.7761	152.4000	20.3200	0.605	0.638	0.00605	0.00638
21.1199	-8.7481	152.4000	22.8600	0.608	0.591	0.00608	0.00591

23.4665	-9.7202	152.4000	25.4000	0.535	0.563	0.00535	0.00563
25.8132	-10.6922	152.4000	27.9400	0.522	0.548	0.00522	0.00548
28.1598	-11.6642	152.4000	30.4800	0.502	0.524	0.00502	0.00524
30.5065	-12.6362	152.4000	33.0200	0.479	0.501	0.00479	0.00501
32.8532	-13.6082	152.4000	35.5600	0.449	0.472	0.00449	0.00472
34.0265	-14.0942	152.4000	36.8300	0.440	0.458	0.00440	0.00458

Table B-26: Velocity field data. Case 10

Hardware Configuration: D
Bulk Flow Type: Air
Bulk Flow Rate: 1.116 kg/min
Plane: 76.2 mm downstream of injection

Measurement Technique: Particle Image Velocimetry
Fuel Type: Methane-Hydrogen
Fuel Flow Rate: Methane-0.00593 kg/min Hydrogen-0.000693 kg/min

X [mm]	Y [mm]	Z [mm]	Radius [mm]	Tangential Velocity [m/s]	Axial Velocity [m/s]
-39.7715	0.0000	76.3025	39.7715	-0.1719	-0.3784
-38.9435	0.0000	76.3025	38.9435	-0.0526	-0.3569
-38.1156	0.0000	76.3025	38.1156	-0.3117	-0.1301
-37.2876	0.0000	76.3025	37.2876	-0.6024	0.5211
-36.4597	0.0000	76.3025	36.4597	-1.0477	2.3509
-35.6317	0.0000	76.3025	35.6317	-1.7583	4.3553
-34.8037	0.0000	76.3025	34.8037	-2.3640	5.4201
-33.9758	0.0000	76.3025	33.9758	-2.3639	5.4437
-33.1478	0.0000	76.3025	33.1478	-2.1139	4.9268
-32.3199	0.0000	76.3025	32.3199	-2.0720	4.1423
-31.4919	0.0000	76.3025	31.4919	-1.8482	3.2550
-30.6640	0.0000	76.3025	30.6640	-1.5343	2.3982
-29.8360	0.0000	76.3025	29.8360	-1.2315	1.5911
-29.0081	0.0000	76.3025	29.0081	-0.9905	0.8463
-28.1801	0.0000	76.3025	28.1801	-0.8282	0.1839
-27.3522	0.0000	76.3025	27.3522	-0.7321	-0.3687
-26.5242	0.0000	76.3025	26.5242	-0.6719	-0.7989
-25.6963	0.0000	76.3025	25.6963	-0.6427	-1.0843
-24.8683	0.0000	76.3025	24.8683	-0.6409	-1.2089
-24.0404	0.0000	76.3025	24.0404	-0.6335	-1.2129
-23.2124	0.0000	76.3025	23.2124	-0.6226	-1.1423
-22.3845	0.0000	76.3025	22.3845	-0.6060	-0.9827
-21.5565	0.0000	76.3025	21.5565	-0.5822	-0.7170
-20.7286	0.0000	76.3025	20.7286	-0.5610	-0.3585
-19.9006	0.0000	76.3025	19.9006	-0.5636	0.0369
-19.0727	0.0000	76.3025	19.0727	-0.5876	0.4482
-18.2447	0.0000	76.3025	18.2447	-0.5795	0.8975
-17.4168	0.0000	76.3025	17.4168	-0.5488	1.3881
-16.5888	0.0000	76.3025	16.5888	-0.5314	1.9291
-15.7609	0.0000	76.3025	15.7609	-0.5183	2.4848
-14.9329	0.0000	76.3025	14.9329	-0.5079	3.0402
-14.1050	0.0000	76.3025	14.1050	-0.5103	3.6277
-13.2770	0.0000	76.3025	13.2770	-0.5036	4.3205
-12.4491	0.0000	76.3025	12.4491	-0.4780	5.1605
-11.6211	0.0000	76.3025	11.6211	-0.4773	6.1710
-10.7932	0.0000	76.3025	10.7932	-0.4575	7.3043
-9.9652	0.0000	76.3025	9.9652	-0.4336	8.5297
-9.1372	0.0000	76.3025	9.1372	-0.3995	9.8162
-8.3093	0.0000	76.3025	8.3093	-0.3654	11.0733
-7.4813	0.0000	76.3025	7.4813	-0.3507	12.0847
-6.6534	0.0000	76.3025	6.6534	-0.3776	12.4627
-5.8254	0.0000	76.3025	5.8254	-0.4017	11.5358
-4.9975	0.0000	76.3025	4.9975	-0.4169	9.3631
-4.1695	0.0000	76.3025	4.1695	-0.5560	6.8855
-3.3416	0.0000	76.3025	3.3416	-0.7850	4.4641
-2.5136	0.0000	76.3025	2.5136	-1.0631	2.1873
-1.6857	0.0000	76.3025	1.6857	-1.3319	0.1585
-0.8577	0.0000	76.3025	0.8577	-1.4967	-1.2842
-0.0298	0.0000	76.3025	0.0298	-1.4319	-1.5801
0.7982	0.0000	76.3025	0.7982	-1.0805	-0.6234
1.6261	0.0000	76.3025	1.6261	-0.7223	1.2267
2.4541	0.0000	76.3025	2.4541	-0.4517	3.4418
3.2820	0.0000	76.3025	3.2820	-0.2205	5.8355
4.1100	0.0000	76.3025	4.1100	0.0634	8.3410
4.9379	0.0000	76.3025	4.9379	0.4073	10.6571
5.7659	0.0000	76.3025	5.7659	0.7134	12.2337
6.5938	0.0000	76.3025	6.5938	0.8505	12.6459
7.4218	0.0000	76.3025	7.4218	0.8936	12.1270
8.2497	0.0000	76.3025	8.2497	0.8951	11.1508
9.0777	0.0000	76.3025	9.0777	0.8600	10.0306
9.9056	0.0000	76.3025	9.9056	0.7671	8.8268
10.7336	0.0000	76.3025	10.7336	0.6168	7.6262
11.5615	0.0000	76.3025	11.5615	0.4380	6.4919

12.3895	0.0000	76.3025	12.3895	0.2655	5.4463
13.2174	0.0000	76.3025	13.2174	0.1178	4.5078
14.0454	0.0000	76.3025	14.0454	0.0169	3.7131
14.8733	0.0000	76.3025	14.8733	-0.1020	3.0384
15.7013	0.0000	76.3025	15.7013	-0.2501	2.4074
16.5293	0.0000	76.3025	16.5293	-0.3526	1.7940
17.3572	0.0000	76.3025	17.3572	-0.4496	1.1979
18.1852	0.0000	76.3025	18.1852	-0.5717	0.6363
19.0131	0.0000	76.3025	19.0131	-0.7065	0.1263
19.8411	0.0000	76.3025	19.8411	-0.8234	-0.3143
20.6690	0.0000	76.3025	20.6690	-0.9241	-0.6662
21.4970	0.0000	76.3025	21.4970	-1.0027	-0.8804
22.3249	0.0000	76.3025	22.3249	-1.0631	-0.9445
23.1529	0.0000	76.3025	23.1529	-1.1065	-0.8988
23.9808	0.0000	76.3025	23.9808	-1.1260	-0.7524
24.8088	0.0000	76.3025	24.8088	-1.1327	-0.4805
25.6367	0.0000	76.3025	25.6367	-1.1429	-0.0573
26.4647	0.0000	76.3025	26.4647	-1.1607	0.5015
27.2926	0.0000	76.3025	27.2926	-1.1559	1.1818
28.1206	0.0000	76.3025	28.1206	-1.1050	2.0000
28.9485	0.0000	76.3025	28.9485	-1.0260	2.8794
29.7765	0.0000	76.3025	29.7765	-0.9197	3.7991
30.6044	0.0000	76.3025	30.6044	-0.7994	4.7441
31.4324	0.0000	76.3025	31.4324	-0.6598	5.6502
32.2603	0.0000	76.3025	32.2603	-0.4948	6.4372
33.0883	0.0000	76.3025	33.0883	-0.3320	7.0203
33.9162	0.0000	76.3025	33.9162	-0.2386	7.2312
34.7442	0.0000	76.3025	34.7442	-0.2332	7.0800
35.5721	0.0000	76.3025	35.5721	-0.2254	6.1622
36.4001	0.0000	76.3025	36.4001	-0.2044	3.6019
37.2280	0.0000	76.3025	37.2280	-0.1536	1.2379
38.0560	0.0000	76.3025	38.0560	-0.0339	0.0806
38.8839	0.0000	76.3025	38.8839	0.0914	-0.1542
39.7119	0.0000	76.3025	39.7119	0.0617	-0.1533
Plane: 152.4 mm downstream of injection					
-39.5243	0.0000	152.2921	39.5243	0.0081	0.7627
-38.7015	0.0000	152.2921	38.7015	-0.0855	1.5971
-37.8786	0.0000	152.2921	37.8786	-0.0567	2.8328
-37.0558	0.0000	152.2921	37.0558	-0.3718	3.3183
-36.2329	0.0000	152.2921	36.2329	-1.0234	3.4924
-35.4101	0.0000	152.2921	35.4101	-1.4774	3.7387
-34.5872	0.0000	152.2921	34.5872	-1.5942	3.7701
-33.7644	0.0000	152.2921	33.7644	-1.5420	3.6125
-32.9415	0.0000	152.2921	32.9415	-1.5101	3.4677
-32.1186	0.0000	152.2921	32.1186	-1.5309	3.3351
-31.2958	0.0000	152.2921	31.2958	-1.5038	3.2186
-30.4729	0.0000	152.2921	30.4729	-1.4629	3.0382
-29.6501	0.0000	152.2921	29.6501	-1.4260	2.8643
-28.8272	0.0000	152.2921	28.8272	-1.4058	2.6947
-28.0044	0.0000	152.2921	28.0044	-1.3995	2.5111
-27.1815	0.0000	152.2921	27.1815	-1.4140	2.3036
-26.3586	0.0000	152.2921	26.3586	-1.4448	2.0809
-25.5358	0.0000	152.2921	25.5358	-1.4786	1.8738
-24.7129	0.0000	152.2921	24.7129	-1.5281	1.7146
-23.8901	0.0000	152.2921	23.8901	-1.5966	1.5491
-23.0672	0.0000	152.2921	23.0672	-1.6564	1.3974
-22.2444	0.0000	152.2921	22.2444	-1.7284	1.2747
-21.4215	0.0000	152.2921	21.4215	-1.8117	1.2009
-20.5986	0.0000	152.2921	20.5986	-1.9087	1.2039
-19.7758	0.0000	152.2921	19.7758	-2.0267	1.3096
-18.9529	0.0000	152.2921	18.9529	-2.1616	1.5314
-18.1301	0.0000	152.2921	18.1301	-2.2862	1.8724
-17.3072	0.0000	152.2921	17.3072	-2.4274	2.3321
-16.4844	0.0000	152.2921	16.4844	-2.5685	2.8976
-15.6615	0.0000	152.2921	15.6615	-2.6859	3.5826
-14.8387	0.0000	152.2921	14.8387	-2.8154	4.4006
-14.0158	0.0000	152.2921	14.0158	-2.9777	5.3222
-13.1929	0.0000	152.2921	13.1929	-3.1584	6.2871
-12.3701	0.0000	152.2921	12.3701	-3.3222	7.2513
-11.5472	0.0000	152.2921	11.5472	-3.4894	8.2168
-10.7244	0.0000	152.2921	10.7244	-3.7278	9.1828
-9.9015	0.0000	152.2921	9.9015	-4.0298	10.1827
-9.0787	0.0000	152.2921	9.0787	-4.3547	11.2737
-8.2558	0.0000	152.2921	8.2558	-4.7346	12.4180
-7.4329	0.0000	152.2921	7.4329	-5.2120	13.4679
-6.6101	0.0000	152.2921	6.6101	-5.8001	14.1697
-5.7872	0.0000	152.2921	5.7872	-6.5307	14.0800
-4.9644	0.0000	152.2921	4.9644	-7.3989	12.5666
-4.1415	0.0000	152.2921	4.1415	-8.3034	10.3021
-3.3187	0.0000	152.2921	3.3187	-9.4205	7.7194

-2.4958	0.0000	152.2921	2.4958	-10.8153	5.1068
-1.6729	0.0000	152.2921	1.6729	-12.4771	2.7018
-0.8501	0.0000	152.2921	0.8501	-14.1923	0.7507
-0.0272	0.0000	152.2921	0.0272	-15.3744	-0.4812
0.7956	0.0000	152.2921	0.7956	-15.0690	-0.6325
1.6185	0.0000	152.2921	1.6185	-13.5052	0.3118
2.4413	0.0000	152.2921	2.4413	-11.7389	2.0427
3.2642	0.0000	152.2921	3.2642	-10.0678	4.3025
4.0870	0.0000	152.2921	4.0870	-8.6065	6.7807
4.9099	0.0000	152.2921	4.9099	-7.4035	9.1717
5.7328	0.0000	152.2921	5.7328	-6.4475	11.1139
6.5556	0.0000	152.2921	6.5556	-5.6816	12.2017
7.3785	0.0000	152.2921	7.3785	-5.0676	12.1747
8.2013	0.0000	152.2921	8.2013	-4.5606	11.4436
9.0242	0.0000	152.2921	9.0242	-4.1004	10.4687
9.8470	0.0000	152.2921	9.8470	-3.7264	9.4419
10.6699	0.0000	152.2921	10.6699	-3.4629	8.4009
11.4928	0.0000	152.2921	11.4928	-3.2625	7.3222
12.3156	0.0000	152.2921	12.3156	-3.0442	6.2157
13.1385	0.0000	152.2921	13.1385	-2.8165	5.1805
13.9613	0.0000	152.2921	13.9613	-2.6557	4.2943
14.7842	0.0000	152.2921	14.7842	-2.5007	3.5154
15.6070	0.0000	152.2921	15.6070	-2.3441	2.7788
16.4299	0.0000	152.2921	16.4299	-2.2060	2.0907
17.2528	0.0000	152.2921	17.2528	-2.0979	1.4887
18.0756	0.0000	152.2921	18.0756	-2.0079	1.0043
18.8985	0.0000	152.2921	18.8985	-1.9157	0.6495
19.7213	0.0000	152.2921	19.7213	-1.7981	0.4222
20.5442	0.0000	152.2921	20.5442	-1.7239	0.3251
21.3670	0.0000	152.2921	21.3670	-1.6556	0.3380
22.1899	0.0000	152.2921	22.1899	-1.5811	0.4457
23.0128	0.0000	152.2921	23.0128	-1.5062	0.6276
23.8356	0.0000	152.2921	23.8356	-1.4436	0.8649
24.6585	0.0000	152.2921	24.6585	-1.4002	1.1374
25.4813	0.0000	152.2921	25.4813	-1.3772	1.4162
26.3042	0.0000	152.2921	26.3042	-1.3707	1.6816
27.1270	0.0000	152.2921	27.1270	-1.3676	1.9336
27.9499	0.0000	152.2921	27.9499	-1.3542	2.1700
28.7727	0.0000	152.2921	28.7727	-1.3557	2.3895
29.5956	0.0000	152.2921	29.5956	-1.3826	2.6014
30.4185	0.0000	152.2921	30.4185	-1.4307	2.8037
31.2413	0.0000	152.2921	31.2413	-1.4877	2.9784
32.0642	0.0000	152.2921	32.0642	-1.5511	3.1200
32.8870	0.0000	152.2921	32.8870	-1.6054	3.2539
33.7099	0.0000	152.2921	33.7099	-1.6602	3.3536
34.5327	0.0000	152.2921	34.5327	-1.5960	3.4328
35.3556	0.0000	152.2921	35.3556	-1.2926	3.2557
36.1785	0.0000	152.2921	36.1785	-0.7772	2.3585
37.0013	0.0000	152.2921	37.0013	-0.2548	1.0105
37.8242	0.0000	152.2921	37.8242	0.0076	0.1879
38.6470	0.0000	152.2921	38.6470	-0.0406	-0.0159
39.4699	0.0000	152.2921	39.4699	-0.1163	-0.0260
40.2927	0.0000	152.2921	40.2927	-0.1474	-0.0162

B.13.12 PLIF Images

B.13.12.1 PLIF Images for Hardware Configuration A

Appendix B-13: PLIF image for hardware configuration A, non-swirling axial injection, of a methane-acetone blend at the plane 25.4 mm downstream of injection

Appendix B-14: PLIF image for hardware configuration A, non-swirling axial injection, of a methane-acetone blend at the plane 76.2 mm downstream of injection

Appendix B-15: PLIF image for hardware configuration A, non-swirling axial injection, of a methane-acetone blend at the plane 76.2 mm downstream of injection

B.13.12.2 PLIF Images for Hardware Configuration B

Appendix B-16: PLIF image for hardware configuration B, non-swirling radial injection, of a methane-acetone blend at the plane 50.8 mm downstream of injection

Appendix B-17: PLIF image for hardware configuration B, non-swirling radial injection, of a methane-acetone blend at the plane 76.2 mm downstream of injection

Appendix B-18: PLIF image for hardware configuration B, non-swirling radial injection, of a methane-acetone blend at the plane 152.4 mm downstream of injection

B.13.13 PIV Images

Appendix B-19: Velocity field for case 1. Non-swirling axial injection of methane

Appendix B-20: Velocity field for case 2. Non-swirling axial injection of hydrogen

Appendix B-21: Velocity field for case 3. Non-swirling radial injection of methane

Appendix B-22: Velocity field for case 4. Non-swirling radial injection of hydrogen

Appendix B-23: Velocity field for case 5. Swirling axial injection of methane

Appendix B-24: Velocity field for case 6. Swirling axial injection of hydrogen

Appendix B-25: Velocity field for case 7. Swirling axial injection of a methane-hydrogen blend

Appendix B-26: Velocity field for case 8. Swirling radial injection of methane

Appendix B-27: Velocity field for case 9. Swirling radial injection of hydrogen

Appendix B-28: Velocity field for case 10. Swirling radial injection of a methane-hydrogen blend