Final Report

Project Title: Investigation on Flame Characteristics and Burner Operability Issues of Oxy-Fuel Combustion

Grant No: DE-FE-0002402

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Project Period: 12/01/09 - 5/31/2013

Reporting Period: Final

Reporting Frequency: One Time

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Submission Date: 09/30/2013

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Abstract

Oxy-fuel combustion has been used previously in a wide range of industrial applications. Oxy-combustion is carried out by burning a hydrocarbon fuel with oxygen instead of air. Flames burning in this configuration achieve higher flame temperatures which present opportunities for significant efficiency improvements and direct capture of CO₂ from the exhaust stream. In an effort to better understand and characterize the fundamental flame characteristics of oxy-fuel combustion this research presents the experimental measurements of flame stability of various oxyfuel flames. Effects of H₂ concentration, fuel composition, exhaust gas recirculation ratio, firing inputs, and burner diameters on the flame stability of these fuels are discussed. Effects of exhaust gas recirculation i.e. CO₂ and H₂O (steam) acting as diluents on burner operability are also presented. The roles of firing input on flame stability are then analyzed. For this study it was observed that many oxy-flames did not stabilize without exhaust gas recirculation due to their higher burning velocities. In addition, the stability regime of all compositions was observed to decrease as the burner diameter increased. A flashback model is also presented, using the critical velocity gradient (g_F) values for CH₄-O₂-CO₂ flames. The scaling relation ($g_F = c \frac{S_L^2}{\alpha}$) for different burner diameters was obtained for various diameter burners. The report shows that results correlated linearly with a scaling value of $c = 0.0174$.

The second part of the study focuses on the experimental measurements of the flow field characteristics of premixed CH₄/21%O₂/79%N₂ and CH₄/38%O₂/72%CO₂ mixtures at constant firing input of 7.5 kW, constant, equivalence ratio of 0.8, constant swirl number of 0.92 and constant Reynolds Numbers. These measurements were taken in a swirl stabilized combustor at atmospheric pressure. The flow field visualization using Particle Imaging Velocimetry (PIV) technique is implemented to make a better understanding of the turbulence characteristics of CH₄/air and CH₄/38%O₂/72%CO₂ combustion. The velocity fluctuations, turbulence intensities and local propagation velocities along the combustion chamber have been determined. The turbulent intensities increase as we move away from the combustor axis. CH₄-38%O₂-72%CO₂ flames have low radial velocity and turbulent intensity distributions at different axial distances when compared with CH₄-Air flames.

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Project Information

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Preface

This is the final technical report on DOE Grant DE-FE-0002402 entitled “Investigation on Flame Characteristics and Burner Operability Issues of Oxy-Fuel Combustion”. Technical work supported by this grant described in parts in the doctoral and master’s thesis of Bidhan Dam and Martin De La Torre. The results presented in the report are also included in two publications titled: “*Flame Stability of Methane and Syngas Oxy-Fuel Steam Flames*,” *Energy and Fuels*, Vol. 27 (2013), pp. 523-529 and “*Investigation on Flame Characteristics of Oxy-Fuel Combustion*” *Energy Tech Magazine*, July 2012. The publications are coauthored by Ahsan Choudhuri, Norman Love, Bidhan Dam, and Rafiqul Islam.

Executive Summary

I. Overview

Oxy-fuel combustion is a promising post combustion CO₂ capture technique currently being considered by the U.S. Department of Energy's Innovations for Existing Plants Program to meet the goal of capturing 90 percent CO₂ capture without increasing the cost of electricity more than 35 percent (DOE, 2008). In an oxy-fuel combustion system nitrogen is removed from the combustion air to create an exhaust stream containing only CO₂ and H₂O for easy sequestration and storage. Recirculated CO₂ and H₂O are also added to the nitrogen-separated combustion air-stream to maintain the required flame temperature. Technologies for oxy-fuel combustion systems are being developed for both gas turbine power cycles and pulverized coal based generation units. The goal is to not only build new oxy-fuel based units but also retrofitting existing plants with oxy-fuel combustion capabilities. Although some technical components of oxy-fuel combustion technologies are commercially available, there are critical needs for combustion data and high fidelity modeling tools to optimize oxy-fuel plant performance (Huckaby, 2009; Tigges et al., 2008; Kobayashi and Hassel, 2005). The Energy System Dynamics research group at the National Energy Technology Laboratory has been developing plant level modeling tools to analyze, predict, and recommend performance improvement measures for new oxy-fuel designs and existing plant retrofits. The proposed project was aimed at complementing this effort by providing experimental data of oxy-fuel flame characteristics for model validations and verifications.

For both turbine cycles and pulverized coal fired plants, several combustor operability issues such as heat transfer characteristics and heat loading, flame stability, and flashback become important with the transition from air to oxygen based combustion (Anderson et al., 2008; Devanna, 2007). These operability issues are related to a shift in flame behavior due to the absence of N₂ and the presence of CO₂ and H₂O in the oxidizer stream. For instance, flame stability in gas turbine combustors with O₂ concentration similar to that found in air based systems is not achievable with O₂/CO₂ systems and requires at least 30% O₂ concentration in the oxidizer stream (Ditaranto and Hals, 2006). Similarly, in pulverized coal units, oxy-fuel systems with flue gas recirculation require an average of 35% O₂ concentration in the gas entering into the boiler to maintain the heat transfer characteristics similar to the air-fired system (DOE, 2008). Additional O₂ requirements can generate localized O₂ enrichment in the combustor flow-field and perturb the overall combustor equivalence ratio. The shift in local and global combustor equivalence ratio affect the flame temperature, local burning velocities, and heat release rate and ultimately lead to a change in combustor transient dynamics in terms of stability, flashback and heat loading [Andersson et al., 2008; Andersson and Johnsson, 2007].

Currently available and emerging modeling (fluid dynamics, heat transfer and combustion) tools can be effectively used to develop new oxy-fuel designs and analyze retrofits to meet the sequestration goals. However, computational tools are yet to be validated for oxy-fuel combustion systems and a suit of experimental data of fundamental flame characteristics relevant to oxy-fuel combustion is needed for this purpose. Motivated by this pressing need for experimental data the project was aimed at (i) measuring fundamental flame characteristics of oxy-fuel combustion and (ii) investigating their influence on combustor operability parameters. In the planned research, flat flame, nozzle, counter flow burners will be used to measure important oxy-fuel combustion characteristics such as flame radiation, radiative heat release factor, burning velocities,

flammability, flame shapes, flame lift-off and blowout. The project systematically investigated the effects of fundamental flame characteristics on operability issues (combustor blowout and flashback) of oxygen fired combustors as well. The burners and the combustor were developed previously through several DOE funded projects and extensive qualification experiments were already performed to confirm validity of their measurements (Choudhuri, 2006; 2005a; 2005b).

I. a Oxy-Fuel Combustion

Oxy-fuel combustion, as is described in this report, refers to the process of burning fuel with oxygen instead of air. When the fuel is burned in this oxygen environment products will be primarily CO₂ and water as steam. Water can be condensed from the exhaust stream and the CO₂ stored at some other location, typically underground. In some power generation plants using coal-derived synthesis gas fuels such as Integrated Gasification Combined Cycle (IGCC) power plants an integrated carbon capture and sequestration system could greatly lower GHG emissions. Before this type of technology can be widely implemented, however, a broad-based effort is necessary to characterize flame stability and radiative properties of synthetic gas – oxygen type combustion. This is necessary since few data exist on the prediction of flame stability of these types of fuels burning with oxygen and since radiative heat transfer from combustion products, CO₂ and H₂O, may have a significant impact on the overall flame temperature and emissivity. This report looks to contribute to the existing body of knowledge by experimentally investigating the combined effects of H₂ in fuel and CO₂ diluent concentrations and firing inputs on radiation on flame stability. This data is thought to help both industrial practitioners and combustion modeling experts in this area.

I. b Oxy-syngas Combustion

Many studies have investigated the burning of synthetic fuels in air under many different conditions. Few authors, however, have focused on experimental measurements of oxy-syngas combustion and its fundamental characteristics. Kobayashi et. al. investigated highly CO₂ diluted oxy-syngas turbulent flame characteristics in a high-pressure environment. The major results of this study include a report on an increase in the total radiation intensity due to the high concentrations of CO₂ used. Wang et al. investigated the laminar burning velocities and flame characteristics of oxy-syngas CO₂ diluted mixtures. Having CO₂ as a major component of the flue gases in oxy-syngas combustion it became relevant to study its effects on flame characteristics. Wang et al. major results include the behavior of laminar flame speed with a variation in the CO₂ content, radiation heat loss of oxy-syngas flames is determined to be much stronger than syngas-air and hydrocarbons-air due to the larger presence of CO₂ in the flame among other CO₂ related effects in the combustion.

II. Goals and Objectives for the Project

The overall project goal was to investigate oxy-fuel flame characteristics and assess their impact on operability of oxy-fuel combustion systems. Fundamental flame characteristics data and related burner operability parameters are essential for designing and developing oxy-fuel combustion systems for new power plants and retrofitting existing power generation units (DOE 2009; 2008). Oxy-fuel combustion data are critically needed to validate and improve the fidelity of modeling tools as well.

Objective 1: To measure fundamental flame characteristics of oxy-fuel combustion

Flat flame, counter-flow, and nozzle burners were used to measure fundamental flame characteristics (*flame radiation, radiative heat release factor, burning velocities, flame extinction/flammability limits, flame shapes, lift-off, and blow-out velocities*) of CH₄ (natural gas)/O₂ and H₂-CO (syngas)/O₂ combustion. The effects of CO₂ and H₂O additions on flame characteristics will be systematically investigated to delineate the influence of dry and wet flue gas recirculation on burner operations.

Objective 2: To investigate combustor operability issues of oxy-fuel combustion.

The fundamental flame characteristics stated in objective 1 critically influence two important combustor operability issues: *blowout and flashback*. Therefore, the tasks under objective 2 are aimed at determining flame blowout and flashback limits of CH₄/O₂ and H₂-CO/O₂ flames at different CO₂ and O₂ loadings and correlating them with the fundamental flame characteristics. A swirl combustor will be used for the planned study. Of special interest is the investigation of flame radiation effects on burner operability parameters.

III. Task 1- Project Management and Planning

I.A. Summary of Project Management Activities and Meeting of ARRA Requirements

While the details of the project tasks are presented in later sections, a summary for each year as stated by objective is as follows:

Year 1: Conduct Task 1: Flame Radiation Measurements and Task 2: Radiative Heat Release Rate, Flame Shapes, Lift-off, and Blow-out Measurements, while also attending meetings, and preparing technical, financial and management status reports within ARRA requirements.

Year 2: Conduct Task 3: To measure laminar and turbulent burning velocities, as well as Task 4: To measure flame extinction (flammability) limits, while also meeting ARRA requirements, e.g. attending meetings, preparing technical, financial and management status reports.

Year 3: Complete Task 5, Measurements of Combustor Blowout and Heat Flux Contour, and Task 6, Measurements of Combustor Flashback, while also attending meetings, and preparing technical and financial status and management reports to conform to ARRA requirements.

The progression of these efforts is depicted per contract year in the figure below then followed by a table of milestones, such as those reported in the quarterly reports previously submitted.

	Year 1	Year 2	Year 3
Objective 1: Fundamental Flame Measurements			
Task 1: flame radiatn.	■	■	■
Task 2: radiatv heat rl	■	■	■
Task 3: velocities	■	■	■
Task 4: limits	■	■	■
Objective 2: Combustor Operability Analysis			
Task 5: blowout	■	■	■
Task 6: flashback	■	■	■
Reporting			
Progress Report	■	■	■
Final Report	■	■	■

Yard-stone	Title	Description	Relation	Validation	Qtr	Date	Complete
Budget Period 1							
1.1.a	Oxy-fuel Flame Characteristics	Complete plans for Facility, Resources, Quality, Safety, Documentation Management, etc	Predecessor of all following tasks	Plan delivered to DOE PM	Q1	3/1/2010	1/22/10 (Plan) 1/26/10 (Presentation)

	2.1.a	Flame Radiation	Submit Steam System Design & Experimental Setup Plan	Predecessor for 2.2 tasks	Plan delivered to DOE PM	Q2	6/1/2010	6/1/10 (Boiler system design; draft test matrix)
	2.1.b	Flame Radiation	Set up Experimental Apparatus and Area for Flame Radiation	Predecessor for 2.2 tasks	Summarized in Quarterly Report	Q3	9/1/2010	8/28/10
	2.2.a	Radiative & Flame Factors	Produce Flame Radiation Characteristics Quantification Data Set	Data set for 1st Decision Point	Summarize results in Yearly Report	Q4	12/1/2010	11/30/10
Budget Period 2								
	2.2.b	Radiative & Flame Factors	Produce Radiative Characteristics Quantification Data Set	Data set for 1st Decision Point	Summarize results in Quarterly Report	Q5	3/1/2011	3/1/11
	2.3.a	Laminar and Turbulent Burning Velocities	Set up Experimental Apparatus and Research Area for Flow Modeling	Predecessor for 2.4 tasks	Summarized in Quarterly Report	Q6	6/1/2011	6/1/2011
	2.3.b	Laminar and Turbulent Burning Velocities	Produce Flow Modeling Data Set	Predecessor for 2.4 tasks	Summarize results in Quarterly Report	Q7	9/1/2011	9/1/2011
	2.4.a	Flame Extinction (flammability) Limits	Set up Experimental Apparatus and Area for Flame Ext Limits	Data set for 2nd Decision Point	Summarized in Yearly Report	Q8	12/1/2011	12/1/2011
Budget Period 3								
	2.4.b	Flame Extinction (flammability) Limits	Produce Flame Ext Limit Data Set	Data set for 2nd Decision Point	Summarize results in Quarterly Report	Q9	3/1/2012	3/30/2012
	3.1.a	Combustor Blowout	Set up Experimental Apparatus and Area for Combustor	Independent Data Set	Summarized in Quarterly Report	Q10	6/1/2012	4/30/2012
	3.1.b	Combustor Blowout	Produce Combustor Data Set: Blowback	Independent Data Set	Summarize results in Quarterly Report	Q11	9/1/2012	8/25/12
	3.2.a	Combustor Flashback	Produce Combustor Data Set: Flashback	Independent Data Set	Summarize results in Yearly Report	Q12	12/1/2012	4/25/2013

IV. Task 2- Measurement of Oxy-Fuel Flame Characteristics

IV. a Goals and Objectives

Objective 1: To measure fundamental flame characteristics of oxy-fuel combustion

Subtask 1: Flame Radiation Measurements: Systematic measurements of radiation from CH₄/O₂ and H₂-CO/O₂ were performed using the flat flame and tubular burners and radiometer. Three parameters were varied to study their effects on flame radiation: equivalence ratio (ϕ), recirculation ratios ($RR_{CO_2} = \frac{m_{CO_2}}{m_{O_2}+m_{CO_2}+m_{H_2O}}$ and $RR_{H_2O} = \frac{m_{H_2O}}{m_{O_2}+m_{CO_2}+m_{H_2O}}$), and firing rate or fuel energy input (q_{in}). The measured data supports the validation and extension of CFD radiation models.

Subtask 2: Radiative Heat Release Factor, Flame Shapes, Lift-off, Blow-out Measurements: For total flame radiation measurements, a wide-angle (150 °) pyroheliometer (Hy-Cal) and the nozzle (or tube) burner will be used. Four parameters will be varied to study their effects on flame radiation: equivalence ratio (ϕ), recirculation ratios, burner diameter, and firing rate or fuel energy input (q_{in}). A radiation heat release factor ($F = q_r/q_{in}$) was then calculated. Flame shapes, flame lift-off, and blow-out were also measured and their relations with the radiation heat release factor will be analyzed. The goal was to develop experimental correlation between radiation heat release factor, burner exit Reynolds number (Re_j), Froude Number (Fr_j). The correlations will not only benefit preliminary design estimation processes but also help setting up the initial and boundary conditions for CFD simulations.

Subtask 3: To measure laminar and turbulent burning velocities: Laminar and turbulent burning velocities are fundamental to combustion processes. Burning velocity measurements not only provide critical insight of the flame behavior but also allow understanding of the combustor dynamics. Burning velocity data relevant to oxy-fuel turbine cycles are not currently available in literature. In the conducted research burning velocity of CH₄/O₂ and H₂-CO/O₂ at relevant oxy-fuel combustion conditions were measured using the flat flame and nozzle burners. Heat Flux (flat flame burner), flame surface (nozzle burner), and turbulent flames were used in order to determine the flame propagation velocity. Three parameters (mentioned in Task 1) were varied to study their effects on burning velocities.

Subtask 4: To measure flame extinction (flammability) limits: The *flame extinction limit* of a fuel mixture is important to understand the basic combustion mechanisms and flame stability in practical systems. The *flame extinction limit* is a fundamental thermo-chemical characteristic and represents a limiting concentration of fuel in a mixture of fuel and oxidizer at which chemical reaction is not self-sustaining (i.e. flame propagation is not possible). A tubular burner was used to measure extinction limits of CH₄/O₂ and H₂-CO/O₂ flames. Three parameters (i.e. equivalence ratio, circulation ratios, and firing rate) were varied to study their effects on flame extinction limits.

IV. b Apparatus and Testing Methods

Development of Burner System

A burner facility was designed and developed in order to investigate the flame stability characteristics using different diameter burners. A laboratory scale burner was designed and fabricated based on capability of withstanding the higher oxy-fuel flame temperatures which were calculated to potentially reach as high as 3600K. A finite element analysis of the designed burner, under thermal stress, was carried out using NASTRAN 6.1. The purpose of this numerical analysis was to ensure that the burner could withstand the high thermal load. Figure 1 presents the final design of the tubular burner used for the experiments. The tubular burner system consists of three primary components: (a) platform, (b) mixing manifold, and (c) burner tube assembly. The tube assembly section merges with the adapters to accommodate tubes of different diameters.

Figure 1: Schematic drawing of the tubular burner

Steam Generation System

A steam generation system consisted of a laboratory scale electric boiler and a water reservoir. The boiler was synchronized with a pump connected to the reservoir to keep boiler exit steam pressure constant. The steam piping from boiler to burner facility was insulated to avoid steam condensation in the line. A steam pressure regulator valve was installed in the line, right before the burner entrance, in order to maintain constant steam pressure at the downstream of the line. This unit was designed to offer highly sensitive response to reduced pressure changes and ensure desired flow conditions without appreciable pressure drop.

Setup and Components

Figure 2 presents the complete experimental setup schematic used for oxy-fuel flame stability measurements. The fuels used for these experiments were methane and syngas (CO-H₂) which were burned with oxidants O₂ and recirculated CO₂ and H₂O. Research grade fuel and oxidant were delivered to the burners from pressurized tanks. Manual precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and oxidant flow rates. A bank of digital mass flow meters was used to measure mass flow rates of fuels and oxidant composition. Prior to each experiment mass flow meters were calibrated using a laser based mass flow meter calibrator.

Figure 2: Schematic diagram of experimental setup

In the burner system premixed fuel, oxidant, and recirculated gases entered into the manifold through four alternate injection holes. A laboratory scale boiler system and pump produced superheated steam. Steam was then premixed with fuel and oxygen and sent to the burner. In order to maintain superheated steam throughout the line up to the burner exit, heavy insulated high temperature heater tape along with fiberglass insulation was used for keeping lines continuously heated. A temperature controller was used to monitor and control the required temperature in the steam line up to the burner exit. The combination of these components allowed for the analysis of the effect of steam recirculation in the burner. After the premixing section the fuel and oxygen mixture was ignited with an external ignition source. A flame arrestor device was positioned in the line before the manifold for safety. The resulting flame was analyzed with the use of a high-resolution digital video camera.

Measurement of steam flow rate from the boiler was calibrated using a graduated cylinder. Steam was captured into a flask through a bypass numbered needle valve and allowed to condense in the cylinder. The subsequent weight of the condensate was measured using a high precision digital scale. This value was then used to determine the recirculation ratio. The actual experimental setup is presented in figure 3 on the following page.

A robust test matrix of oxy-fuel was developed for investigating the effect of recirculating CO_2 and H_2O on flame stability using different burner diameters. The equivalence ratio was set at a constant value of $\Phi=1$ for all the experiments without considering CO_2 in the oxidizer to draw a stability limit ($\Phi = \frac{F/\text{O}_2)_{\text{act}}}{F/\text{O}_2)_{\text{stoic}}}$). Furthermore, the recirculation ratio, which is presented in many figures in this report, was calculated using Eq (1). This ratio is used in this study to quickly gauge the amount of CO_2 from the exhaust stream that is premixed with the oxidizer.

$$\text{Recirculation Ratio} = \frac{\dot{m}_{\text{CO}_2}}{\dot{m}_{\text{CO}_2} + \dot{m}_{\text{O}_2} + \dot{m}_{\text{H}_2\text{O}}} \quad (1)$$

Figure 3: Experimental setup used for measurements

At the beginning of the experiment the flame was ignited at a stable condition. During an experiment, the firing input and equivalence ratio was kept constant while the amount of diluents (CO_2 , H_2O) was varied until the flame propagated back into the tube or experienced blowout. A high-speed direct video imaging system was used to confirm the flashback condition which was defined at the point when the flame entered the burner. For the flashback modeling portion of the work the critical boundary velocity gradient of different compositions of hydrocarbon fuel blends and syngas was calculated using Eq. (2).

$$g_F = \frac{4V}{\pi r^3} \quad (2)$$

Where V is experimentally measured volumetric flow rate at flashback condition and r is the tube radius. The volumetric flow rate for a particular tube diameter and mixture composition at which the flame propagates down the burner tube were defined as the critical flow rate V . In order to draw the flashback propensity map, critical volumetric flow rate for flashback at different mixture compositions in cylindrical tubes of various diameters were measured. The critical volumetric flow rate was defined in Eq. (3).

$$g_F = c \frac{S_L^2}{\alpha} \quad (3)$$

If laminar flame speed (S_L) and thermal diffusivity (α) are known it is possible to estimate the boundary layer flashback propensity of a fuel mixture, provided the value of c is available. However, boundary layer flashback data for fuel blends are scarce and the value of c is not readily available for various fuel mixtures. Therefore for this study c is experimentally determined by calculating S_L and α from the CHEMKIN kinetic code using the GRI 3.0 mechanism, this has been done previously to estimate this parameter.

After measurements the experimental uncertainties were calculated using a Student's t-distribution with 95% confidence interval. Random error associated with the measurements was very low and considered negligible for all measurements. Therefore, experimental uncertainties are based on the bias error associated with the instrumentation which were less than $\pm 1\%$ of the mean value. Global radiation measurements, wavelength range of .2 to 50 μm , were taken from a Mark IV non-contact temperature sensor & radiometer with a 150° view angle. The sensor is used in conjunction with a DAQ system to record the necessary readings at a rate of 1Hz. Voltage readings recorded would be later be manipulated using the manufacturer's provided calibration factor in order to acquire the desired measurements. For all experiments, experimental uncertainties were calculated using a Student's t-distribution with 95% confidence interval. Experimental uncertainties of present measurements are less than $\pm 1\%$ of the mean value thus error bars are not visible in the graphs presented.

Laminar and Turbulent Burning Velocity Measurements

The figure (4) below reflects the Flat Flame burner used in experiments. The Flat Flame Burner apparatus consists of a 6 cm diameter, sintered, stainless steel porous disk. The flame is shielded from the surrounding environment by flowing nitrogen through a concentric 0.5 cm wide porous metal strip. The burner cooling system extends throughout the porous disk system and varies the heat loss rate from the burner.

Figure 4: Flat Flame Burner

For turbulent burning velocities the burner used in the present investigation consisted of five primary components (Figure 5): (a) mixing manifold, (b) stem, (c) perforated plate, (d) connector, and (e) burner nozzle assembly. The burner nozzles were fabricated out of brass, selected for high heat resistance and thermal properties compared to aluminum. The exit diameter of the nozzle is about 8 mm. The perforated plate was fitted in between the connector and burner nozzle. Different levels of turbulence were generated by changing the blockage ratio of the perforated plate. Research grade fuels were delivered to the combustor from pressurized tanks. Precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and air flow rates. A bank of digital mass flow controller was used to measure mass flow rates of fuels and air.

Figure 5: Tubular Burner (Cross sectional)

A high resolution direct imaging system and a high speed PIV system operating at 15 Hz and output energy of 65 mJ were used to capture the flame fluctuation sequences and analyze the reacting and non-reacting particle velocity flow-fields, respectively. All the equipments were set to record using the appropriate data acquisition software. In PIV experiments, alumina particles were used as seeding elements. The image buffer size is about 63 images which was used to capture the images. The averages of these images were then taken and are representative of the time-averaged flame. However, during the experiments it was determined that the temporal resolution of the camera to be too low to track the time dependent characteristics of the flame thus it is recommended to use a larger amount of frames to capture turbulence characteristics of the flame in future studies. The term blockage ratio for a perforated plate is defined as the solid area of perforated plate (A_{Perf}) to the exposed area (A_{Exp}), as shown by Eq. (4). Increasing of the blockage ratio can be achieved either by decreasing the number of holes in the perforated plate or by decreasing the size of the holes of perforated plate.

$$BR = \frac{A_{Perf}}{A_{Exp}} = \frac{A_{Exp} - A_{Hole}}{A_{Exp}} = 1 - \frac{Nd_o^2}{D^2} \quad (4)$$

Where N is the total number of holes, d_o is the hole diameter and D is the overall disc diameter. Three different set of perforated plates (with blockage ratios of 73%, 83% and 93%) were used for the set of experimentation as shown in figure 6.

Figure 6: Perforated plate with blockage ratios of (a) 73% (b) 83% and (c) 93%

IV. c Results and Conclusions

Visual Observation and Qualification of Experimental Setup

Flame images at a typical blowout and flashback condition are presented in figure 7. For blowout, the flame initially attached to the tip of the burner followed by flame detachment from the tip of the burner before blowout. For a typical flashback sequence flashback was defined at the condition when the flame initially moved inside the burner. Initially a benchmarking test was performed for the critical velocity gradients (g_F) for a natural gas composition of 81.8% CH_4 , 17.7% C_2H_6 and 0.5% N_2 to reproduce the data provided by Lewis and von Elbe.

Figure 7: (Top) Typical blowout sequence and (Bottom) Flame flashback sequence of a $\text{CH}_4\text{-O}_2$ flame

Effect of Recirculation of CO_2 and H_2O

Figure 8 shows the stability map of $\text{CH}_4\text{-O}_2\text{-CO}_2$ flames with an initial condition of 0.5, 1.0 and 1.5 kW firing rate using different burner diameters. The filled and unfilled symbols represent the flashback and blowout condition for each burner diameter, respectively. The flashback and blowout behavior is significantly controlled by the percentage of diluents (CO_2 and H_2O) in the mixtures.

Figure 8: Stability limits including blowout (BO) and flashback (FB) of $\text{CH}_4\text{-O}_2\text{-CO}_2$ flames for different firing inputs and burner diameters

Figure 9: Stability limits of $\text{CH}_4\text{-O}_2\text{-CO}_2$ and $\text{CH}_4\text{-O}_2\text{-CO}_2\text{-H}_2\text{O}$ flames. The filled and empty symbols represent a firing input of 1.5 kW and 1.0 kW, respectively. Triangles represent CO_2 diluent flashback limits while diamonds represent extinction limits using CO_2 and H_2O .

It is interesting to note that $\text{CH}_4\text{-O}_2$ flames did not stabilize at this equivalence ratio without recirculated gases, even with lower firing input conditions due to a higher adiabatic flame temperature. The stability regime was also observed to be narrow as burner diameter increased since the unburned gas velocity in the upstream is decreased as the burner diameter increased. Figure 9 is on the following page and presents the effects of recirculated steam (H_2O) on the stability regime of $\text{CH}_4\text{-O}_2$ flames. Experiments were performed with an increase of steam at a fixed amount of CO_2 in the fuel mixture. An almost equal amount of steam could be recirculated potentially until the flame was extinguished. The effect of steam was primarily observed for lower burner diameters causing the flame to extinguish. Figure 9 demonstrates that at these conditions the large latent heat of water quenched the flames ceasing chemical reactions.

Effect of Fuel Composition

The stability limit of syngas ($\text{H}_2\text{-CO}$) mixtures diluted with CO_2 at different H_2 concentrations was also tested. It is interesting to note that the flames of 10% H_2 -90% CO mixture stabilized without CO_2 in the fuel mixture using the 3 mm diameter burner due to a lower adiabatic flame temperature compared to $\text{CH}_4\text{-O}_2$ flames. However, the presence of CO_2 is necessary for stabilizing flames at higher diameter (ranges from 6 to 20mm) burners. Initially blowout points of each fuel composition were different at smaller diameter burners but those points merged together at larger diameters. Furthermore, there is no significant difference between $\text{CH}_4\text{-O}_2\text{-CO}_2$ and $\text{H}_2/\text{CO-O}_2\text{-CO}_2$ flames on stability limit.

Effect of Firing Input

The effects of firing input on the flame stability limit was also investigated and plotted. Burner diameter is plotted against recirculation ratio of CO_2 in oxidizer by mass, figure 10. It is expected that there is a higher concentration of CO_2 in the fuel mixture in the case of smaller firing input conditions until blowout. This is due to the small bulk velocity in the low firing input condition. Experimental results show this behavior at smaller diameter burners (ranges 3-9mm).

Figure 10: Stability limit of 10% H_2 -90% CO mixture at different firing input conditions

However, at 13 mm diameter burner the firing input does not show a significant effect on flame stability. The required amount of CO₂ recirculated in the fuel mixtures for stabilizing flame is significant compared to the amount of fuel-oxidizer mixture as the burner diameter increases. A comparison between stability limits between CH₄-O₂-CO₂ and 10% H₂-90% CO-O₂-CO₂ flames at different firing input conditions showed that the 10% H₂-90% CO-O₂ flames have a wider stability regime than CH₄-O₂ flames at smaller diameter burners. This effect was due to the reheating caused by the presence of a partially entered flame front which increased the propensity of flashback.

Conclusions for Objective 1

Oxy-fuel flame stability of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames burning with steam have been analyzed and factors affecting their behaviors have been explored. A broad range of variables that potentially affect the flame stability have been investigated.

Effects of CO₂ and steam on the flame stability of CH₄-O₂ mixtures showed that the flashback and blowout points of the flame were controlled by the amount recirculated in the fuel mixture. It was observed that CH₄-O₂ flames did not stabilize without recirculated gases even with lower firing inputs due to the higher adiabatic flame temperature of the mixture. In addition, the stability regime of all compositions was observed to decrease as the burner diameter increased. Furthermore, it was found that more diluents in the fuel mixtures was necessary to stabilize the flame as the burner diameter increased in order to balance between flame speed and unburned gas velocity.

A comparison of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames showed that stability limits of syngas mixtures diluted with CO₂ at different H₂ concentrations did not stabilize at small burner diameters (3mm) without the presence of recirculated gases in the fuel mixture. For larger burner diameter burners (6-20mm) recirculated components were also necessary. Another important finding was that for 10% H₂-90% CO-O₂ flames, a wider stability regime exists compared to CH₄-O₂ flames due to the reheating caused by the presence of a partially entered flame front which increases the propensity of flashback.

V. Task 3 – Investigation on Oxy-Fuel Combustor Operability Issues

V. a Goals and Objectives

Objective 2: To investigate combustor operability issues of oxy-fuel combustion.

Subtask 1: Measurements of Combustor Blowout: Blowout refers to a condition when the flame lift-off from the anchoring point and ultimately blown out of the combustor. It is an important operability issues since the fuel oxidizer compositions critically affect the combustor blowout behavior. The blowout characteristics of the swirl combustor fired with CH₄/O₂ and H₂-CO/O₂ will be mapped. Four parameters (i.e. equivalence ratio, circulation ratios, swirl number and firing rate) will be varied to study their effects on the combustor blowout behavior. However, one of the primary scopes of this task was to systematically analyze the effects of fundamental flame characteristics (measured under Objective 1 Tasks) on the combustor blowout dynamics.

Subtask 2: Measurements of Combustor Flashback: Flashback is a combustion condition when the flame propagates upstream against the gas stream into the burner tube. Flashback is a critical issue for premixed combustor designs, because it not only causes serious hardware damages but also increases pollutant emissions. The flashback mechanism is also critically sensitive to fuel oxidizer compositions and flow conditions. Thus, this subtask was done to map the combustor flashback regimes. Experiments similar to the previous subtask was done and the effects of fundamental flame characteristics of oxy-fuel flames on combustor flashback analyzed.

V. b Apparatus and Testing Methods

Combustor System

The combustor rig used for these experiments had three configurable modules: (i) inlet manifold with static mixer, (ii) swirl burner with mixing tube, and (iii) optically accessible combustion chamber. The module integrates a pilot flame ring with a mixture of methane and air. The swirl burner module is fitted with a quartz mixing tube. The quartz glass tube is needed for the high speed imaging of flashback inside the premixer. The fuel and air enter the inlet manifold through five alternate injection holes. The fuel-air mixture then passes through the static mixture section (honeycomb) to eliminate injection induced flow irregularities and to ensure proper mixing of air and fuel. The burner module can accommodate both center body and hubless swirlers. In the present study, experiments were carried out using centerbody swirlers. During conducting experiments, a conical circular sleeve was fitted inside the inlet of the combustion chamber which allowed the air-fuel mixture to enter the combustion chamber through the passage between the sleeve and the centerbody of the swirler, and thus reduced the pressure drop that the mixture might experience due to the divergence at the inlet of the combustion chamber.

The combustion chamber is constructed in a rectangular-type cross-section whose side-walls are made up of quartz glass to provide optical access inside it. Air was supplied to the rig through a high pressure (maximum 900 cfm of air at 125 psi) rotary screw type compressor. Research grade fuels were delivered to the combustor from pressurized tanks. Precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and air flow rates. A bank of digital mass flow controller was used to measure mass flow rates of fuels and air.

A high resolution direct imaging system (Phantom v310 camera, with a resolution of 1280 x 800 at 3250 fps and a maximum frame rate of 500,000 fps) and a high speed PIV system (20 kHz) with intensified camera systems (Hamamatsu C10880, with maximum repetition frequency of 200 kHz) will be used to analyze the reacting particle velocity flow-fields of CH₄/Air and CH₄-O₂-CO₂ flames respectively. All the equipments were synchronized with Dantec Dynamics software. In PIV experiments, Aluminum particles were used as seeding elements. Figure 11 shows the combustor setup integrated with high speed PIV system.

Figure 11: Gas turbine combustor setup with mounted high speed PIV

V. c Results and Conclusions

Experimental measurements were carried out for methane (CH_4)-air mixtures and (CH_4)- O_2 - CO_2 mixtures maintaining a constant Reynolds number ($\text{Re} = 4500$) and a constant firing input of 7.5 kW. A swirl number ($S=0.92$) was used to stabilize the flame and velocity flow-field measurements were taken using PIV, which was used to compare turbulence intensities along the combustor exit radially as depicted in figure 12.

Reacting flow field analysis of CH_4 - O_2 - CO_2 combustion

Figure 12: (left) scalar map of turbulence intensity of CH_4 -38% O_2 -72% CO_2 flame at $\phi = 0.75$ (right) vector field of CH_4 -38% O_2 -72% CO_2 flame at $\phi = 0.75$

Figure 13 shows the vector flow field of CH_4 -38% O_2 -72% CO_2 flames with a firing input of 7.4 kW and $S = 0.97$. The high velocity regions which were located closer to the combustion chamber walls, provides enough space recirculation zones which helps the flame to stabilize right in front of the swirler. Figure 13 shows that turbulence intensity is highest at the shear regions in the combustor.

Comparison of Velocity and Turbulent intensities for CH_4 -air mixtures and CH_4 - O_2 - CO_2 mixtures

Figure 13: (Top) Velocity distribution of CH_4 -air flame at $\phi=0.75$ radially at different axial positions, (Bottom) Turbulent intensity distribution of CH_4 -air flame at $\phi=0.75$ radially at different axial positions

Figure 14 shows the velocity distributions at $X/D = 0.96$, from this figure methane air flames have high velocity peaks when compared to methane oxygen flames at constant firing input (1700) and constant Re (4500), due to the high heat capacity of CO_2 , increasing the third body reactions thereby reducing the reaction rate and lower propagation velocities. Similar trend have been observed at different axial distances.

Figure 14: (Top) Velocity distribution of CH_4 -air flame and CH_4 -38% O_2 -72% CO_2 at $X/D=0.19$, (Bottom) Velocity distribution of CH_4 -air flame and CH_4 -38% O_2 -72% CO_2 at $X/D=1.96$

Figure 15 shows the radial velocity distributions at different axial distances. The peaks at $X/D = 0.19$ are mainly due to the high velocity regions residing closer to the combustor walls and the dip is due to the recirculation zone. As we move farther away from the combustor axis the velocity distributions tend to be uniform due to the mass diffusion of mixtures. Figure 15 also shows the radial turbulent intensity distributions at different axial distances. The turbulent intensity tends to increase farther away from the combustor.

Figure 15: (Top) Turbulent intensity distribution of CH4-air flame and CH4-O2-CO2 at $X/D = 0.19$,
(Bottom) Turbulent intensity distribution of CH4-air flame and CH4-O2-CO2 at $X/D = 1.96$

Conclusions

The radial velocity and turbulent intensity distributions of both CH₄-Air flames and CH₄-38%O₂-72%CO₂ flames increased as we move away from the combustor axis. For a constant equivalence ratio of 0.85, constant firing input of 7.5kW and Re of 4500, radial velocity distributions of CH₄-Air flames were higher when compared with CH₄-38%O₂-72%CO₂ flames. The radial turbulent intensity fluctuations of CH₄-Air flames are higher when compared with CH₄-38%O₂-72%CO₂ flames.

VI. Conclusions

For the first part of the experimental testing Oxy-fuel flame stability of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames burning with steam have been analyzed and factors affecting their behaviors have been explored. A broad range of variables that potentially affect the flame stability have been investigated.

Effects of CO₂ and steam on the flame stability of CH₄-O₂ mixtures showed that the flashback and blowout points of the flame were controlled by the amount recirculated in the fuel mixture. It was observed that CH₄-O₂ flames did not stabilize without recirculated gases even with lower firing inputs due to the higher adiabatic flame temperature of the mixture. In addition, the stability regime of all compositions was observed to decrease as the burner diameter increased. Furthermore, it was found that more diluents in the fuel mixtures was necessary to stabilize the flame as the burner diameter increased in order to balance between flame speed and unburned gas velocity.

A comparison of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames was also presented. Stability limits of syngas mixtures diluted with CO₂ at different H₂ concentrations did not stabilize at small burner diameters (3mm) without the presence of recirculated gases in the fuel mixture. For larger burner diameter burners (6-20mm) recirculated components were also necessary. Another important finding was that for 10%H₂-90%CO-O₂ flames, a wider stability regime exists compared to CH₄-O₂ flames due to the reheating caused by the presence of a partially entered flame front which increases the propensity of flashback.

For the second part of the experimental investigation, the flashback and blowout limits were carried out for H₂-CO fuel blends and actual syngas fuel compositions in a swirl combustor. The effects of different constituent concentrations and Swirl number on flashback propensity were discussed. The radial velocity and turbulent intensity distributions of both CH₄-Air flames and CH₄-38%O₂-72%CO₂ flames increased as measurements moved away from the combustor axis. For a constant equivalence ratio of 0.85, constant firing input of 7.5kW and Re of 4500, radial velocity distributions of CH₄-Air flames were higher when compared with CH₄-38%O₂-72%CO₂ flames. The radial turbulent intensity fluctuations of CH₄-Air flames are higher when compared with CH₄-38%O₂-72%CO₂ flames.

Further details on other measurements conducted and experimental procedures can be found in the report body portion of the report.

Report Body

I. Introduction and Background

Oxy-fuel combustion is a promising post combustion CO₂ capture technique currently being considered by the U.S. Department of Energy's Innovations for Existing Plants Program to meet the goal of capturing 90 percent CO₂ capture without increasing the cost of electricity more than 35 percent (DOE, 2008). In an oxy-fuel combustion system nitrogen is removed from the combustion air to create an exhaust stream containing only CO₂ and H₂O for easy sequestration and storage. Recirculated CO₂ and H₂O are also added to the nitrogen-separated combustion air-stream to maintain the required flame temperature. Technologies for oxy-fuel combustion systems are being developed for both gas turbine power cycles and pulverized coal based generation units. The goal is to not only build new oxy-fuel based units but also retrofitting existing plants with oxy-fuel combustion capabilities. Although some technical components of oxy-fuel combustion technologies are commercially available, there are critical needs for combustion data and high fidelity modeling tools to optimize oxy-fuel plant performance (Huckaby, 2009; Tigges et al., 2008; Kobayashi and Hassel, 2005). The Energy System Dynamics research group at the National Energy Technology Laboratory has been developing plant level modeling tools to analyze, predict, and recommend performance improvement measures for new oxy-fuel designs and existing plant retrofits. The proposed project was aimed at complementing this effort by providing experimental data of oxy-fuel flame characteristics for model validations and verifications.

For both turbine cycles and pulverized coal fired plants, several combustor operability issues such as heat transfer characteristics and heat loading, flame stability, and flashback become important with the transition from air to oxygen based combustion (Anderson et al., 2008; Devanna, 2007). These operability issues are related to a shift in flame behavior due to the absence of N₂ and the presence of CO₂ and H₂O in the oxidizer stream. For instance, flame stability in gas turbine combustors with O₂ concentration similar to that found in air based systems is not achievable with O₂/CO₂ systems and requires at least 30% O₂ concentration in the oxidizer stream (Ditaranto and Hals, 2006). Similarly, in pulverized coal units, oxy-fuel systems with flue gas recirculation require an average of 35% O₂ concentration in the gas entering into the boiler to maintain the heat transfer characteristics similar to the air-fired system (DOE, 2008). Additional O₂ requirements can generate localized O₂ enrichment in the combustor flow-field and perturb the overall combustor equivalence ratio. The shift in local and global combustor equivalence ratio affect the flame temperature, local burning velocities, and heat release rate and ultimately lead to a change in combustor transient dynamics in terms of stability, flashback and heat loading [Andersson et al., 2008; Andersson and Johnsson, 2007].

Currently available and emerging modeling (fluid dynamics, heat transfer and combustion) tools can be effectively used to develop new oxy-fuel designs and analyze retrofits to meet the sequestration goals. However, computational tools are yet to be validated for oxy-fuel combustion systems and a suit of experimental data of fundamental flame characteristics relevant to oxy-fuel combustion is needed for this purpose. Motivated by this pressing need for experimental data the project was aimed at (i) measuring fundamental flame characteristics of oxy-fuel combustion and (ii) investigating their influence on combustor operability parameters. In the planned research, flat flame, nozzle, counter flow burners will be used to measure important oxy-fuel combustion characteristics such as flame radiation, radiative heat release factor, burning velocities, flammability, flame shapes, flame lift-off and blowout. The project systematically investigated the

effects of fundamental flame characteristics on operability issues (combustor blowout and flashback) of oxygen fired combustors as well. The burners and the combustor were developed previously through several DOE funded projects and extensive qualification experiments were already performed to confirm validity of their measurements (Choudhuri, 2006; 2005a; 2005b).

I. a Oxy-Fuel Combustion

Oxy-fuel combustion, as is described in this report, refers to the process of burning fuel with oxygen instead of air. When the fuel is burned in this oxygen environment products will be primarily CO₂ and water as steam. Water can be condensed from the exhaust stream and the CO₂ stored at some other location, typically underground. In some power generation plants using coal-derived synthesis gas fuels such as Integrated Gasification Combined Cycle (IGCC) power plants an integrated carbon capture and sequestration system could greatly lower GHG emissions. Before this type of technology can be widely implemented, however, a broad-based effort is necessary to characterize flame stability and radiative properties of synthetic gas – oxygen type combustion. This is necessary since few data exist on the prediction of flame stability of these types of fuels burning with oxygen and since radiative heat transfer from combustion products, CO₂ and H₂O, may have a significant impact on the overall flame temperature and emissivity. This report looks to contribute to the existing body of knowledge by experimentally investigating the combined effects of H₂ in fuel and CO₂ diluent concentrations and firing inputs on radiation on flame stability. This data is thought to help both industrial practitioners and combustion modeling experts in this area.

I. b Oxy-syngas Combustion

Many studies have investigated the burning of synthetic fuels in air under many different conditions. Few authors, however, have focused on experimental measurements of oxy-syngas combustion and its fundamental characteristics. Kobayashi et. al. investigated highly CO₂ diluted oxy-syngas turbulent flame characteristics in a high-pressure environment. The major results of this study include a report on an increase in the total radiation intensity due to the high concentrations of CO₂ used. Wang et al. investigated the laminar burning velocities and flame characteristics of oxy-syngas CO₂ diluted mixtures. Having CO₂ as a major component of the flue gases in oxy-syngas combustion it became relevant to study its effects on flame characteristics. Wang et al. major results include the behavior of laminar flame speed with a variation in the CO₂ content, radiation heat loss of oxy-syngas flames is determined to be much stronger than syngas-air and hydrocarbons-air due to the larger presence of CO₂ in the flame among other CO₂ related effects in the combustion.

II. Motivation and Objectives

The overall project goal was to investigate oxy-fuel flame characteristics and assess their impact on operability of oxy-fuel combustion systems. Fundamental flame characteristics data and related burner operability parameters are essential for designing and developing oxy-fuel combustion systems for new power plants and retrofitting existing power generation units (DOE 2009; 2008). Oxy-fuel combustion data are critically needed to validate and improve the fidelity of modeling tools as well.

Objective 1: To measure fundamental flame characteristics of oxy-fuel combustion

Flat flame, counter-flow, and nozzle burners were used to measure fundamental flame characteristics (*flame radiation, radiative heat release factor, burning velocities, flame extinction/flammability limits, flame shapes, lift-off, and blow-out velocities*) of CH₄ (natural gas)/O₂ and H₂-CO (syngas)/O₂ combustion. The effects of CO₂ and H₂O additions on flame characteristics were systematically investigated to delineate the influence of dry and wet flue gas recirculation on burner operations.

Objective 2: To investigate combustor operability issues of oxy-fuel combustion.

The fundamental flame characteristics stated in objective 1 critically influence two important combustor operability issues: *blowout and flashback*. Therefore, the tasks under objective 2 were aimed at determining flame blowout and flashback limits of CH₄/O₂ and H₂-CO/O₂ flames at different CO₂ and O₂ loadings and correlating them with the fundamental flame characteristics. A swirl combustor will be used for the planned study. Of special interest is the investigation of flame radiation effects on burner operability parameters.

III. Experimental Setup and Methodology

A burner facility was designed and developed in order to investigate the flame stability characteristics using different diameter burners. A laboratory scale burner was designed and fabricated based on capability of withstanding the higher oxy-fuel flame temperatures which were calculated to potentially reach as high as 3600K. A finite element analysis of the designed burner, under thermal stress, was carried out using NASTRAN 6.1. The purpose of this numerical analysis was to ensure that the burner could withstand the high thermal load. Figure 16 presents the final design of the tubular burner used for the experiments. The tubular burner system consists of three primary components: (a) platform, (b) mixing manifold, and (c) burner tube assembly. The tube assembly section merges with the adapters to accommodate tubes of different diameters as presented in figure 16.

Figure 16: Schematic drawing of the tubular burner

Steam Generation System

A steam generation system consisted of a laboratory scale electric boiler and a water reservoir. The boiler was synchronized with a pump connected to the reservoir to keep boiler exit steam pressure constant. The steam piping from boiler to burner facility was insulated to avoid steam condensation in the line. A steam pressure regulator valve was installed in the line, right before the burner entrance, in order to maintain constant steam pressure at the downstream of the line.

This unit was designed to offer highly sensitive response to reduced pressure changes and ensure desired flow conditions without appreciable pressure drop.

Setup and Components

Figure 17 shows the complete experimental setup schematic used for oxy-fuel flame stability measurements. The fuels used for these experiments were methane and syngas (CO-H₂) which were burned with oxidants O₂ and recirculated CO₂ and H₂O. Research grade fuel and oxidant were delivered to the burners from pressurized tanks. Manual precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and oxidant flow rates. A bank of digital mass flow meters was used to measure mass flow rates of fuels and oxidant composition. Prior to each experiment mass flow flow meters were calibrated using a laser based mass flow meter calibrator.

Figure 17: Schematic diagram of experimental setup

In the burner system premixed fuel, oxidant, and recirculated gases entered into the manifold through four alternate injection holes. A laboratory scale boiler system and pump produced superheated steam. Steam was then premixed with fuel and oxygen and sent to the burner. In order to maintain superheated steam throughout the line up to the burner exit, heavy insulated high temperature heater tape along with fiberglass insulation was used for keeping lines continuously heated. A temperature controller was used to monitor and control the required temperature in the steam line up to the burner exit. The combination of these components allowed for the analysis of the effect of steam recirculation in the burner. After the premixing section the fuel and oxygen mixture was ignited with an external ignition source. A flame arrestor device was positioned in the line before the manifold for safety. The resulting flame was analyzed with the use of a high-resolution digital video camera.

Measurement of steam flow rate from the boiler was calibrated using a graduated cylinder. Steam was captured into a flask through a bypass numbered needle valve and allowed to condense in the cylinder. The subsequent weight of the condensate was measured using a high precision digital

scale. This value was then used to determine the recirculation ratio. A robust test matrix of oxy-fuel was developed for investigating the effect of recirculating CO₂ and H₂O on flame stability using different burner diameters. The equivalence ratio was set at a constant value of $\Phi=1$ for all the experiments without considering CO₂ in the oxidizer to draw a stability limit ($\Phi = \frac{F/O_2)_{act}}{F/O_2)_{stoic}}$). Furthermore, the recirculation ratio, which is presented in many figures in this report, was calculated using Eq (5). This ratio is used in this study to quickly gauge the amount of CO₂ from the exhaust stream that is premixed with the oxidizer.

$$\text{Recirculation Ratio} = \frac{\dot{m}_{CO_2}}{\dot{m}_{CO_2} + \dot{m}_{O_2} + \dot{m}_{H_2O}} \quad (5)$$

At the beginning of the experiment the flame was ignited at a stable condition. During an experiment, the firing input and equivalence ratio was kept constant while the amount of diluents (CO₂, H₂O) was varied until the flame propagated back into the tube or experienced blowout. A high-speed direct video imaging system was used to confirm the flashback condition which was defined at the point when the flame entered the burner. The critical boundary velocity gradient of different compositions of hydrocarbon fuel blends and syngas was calculated using Eq. (6).

$$g_F = \frac{4V}{\pi r^3} \quad (6)$$

Where V is experimentally measured volumetric flow rate at flashback condition and r is the tube radius. The volumetric flow rate for a particular tube diameter and mixture composition at which the flame propagates down the burner tube were defined as the critical flow rate V. In order to draw the flashback propensity map, critical volumetric flow rate for flashback at different mixture compositions in cylindrical tubes of various diameters were measured. The critical volumetric flow rate was defined in Eq. (7).

$$g_F = c \frac{S_L^2}{\alpha} \quad (7)$$

If laminar flame speed (S_L) and thermal diffusivity (α) are known it is possible to estimate the boundary layer flashback propensity of a fuel mixture, provided the value of c is available. However, boundary layer flashback data for fuel blends are scarce and the value of c is not readily available for various fuel mixtures. Therefore for this study c is experimentally determined by calculating S_L and α from the CHEMKIN kinetic code using the GRI 3.0 mechanism. After measurements the experimental uncertainties were calculated using a student's t-distribution with 95% confidence interval. Random error associated with the measurements was very low and considered negligible for all measurements. Therefore, experimental uncertainties are based on the bias error associated with the instrumentation which are less than $\pm 1\%$ of the mean value. Global radiation measurements, wavelength range of .2 to 50 μm , were taken from a mark iv non-contact temperature sensor & radiometer with a 150° view angle. The sensor is used in conjunction with a DAQ system to record the necessary readings at a rate of 1hz. Voltage readings recorded would be later be manipulated using the manufacturer's provided calibration factor in order to acquire the desired measurements. For all experiments, experimental uncertainties were calculated using a student's t-distribution with 95% confidence interval. Experimental uncertainties of present measurements are less than $\pm 1\%$ of the mean value thus error bars are not visible in the graphs presented.

Laminar and Turbulent Burning Velocity Measurements

Figure 18 reflects the Flat Flame burner to be used in the experiments. The Flat Flame Burner apparatus consists of a 6 cm diameter, sintered, stainless steel porous disk. The flame is shielded from the surrounding environment by flowing nitrogen through a concentric 0.5 cm wide porous metal strip. The burner cooling system extends throughout the porous disk system and varies the heat loss rate from the burner.

Figure 18: Flat Flame Burner

For turbulent burning velocities the burner used in the present investigation consisted of five primary components: (a) mixing manifold, (b) stem, (c) perforated plate, (d) connector, and (e) burner nozzle assembly (figure 19). The burner nozzles were fabricated out of brass, selected for high heat resistance and thermal properties compared to aluminum. The exit diameter of the nozzle is about 8 mm. The perforated plate was fitted in between the connector and burner nozzle. Different levels of turbulence were generated by changing the blockage ratio of the perforated plate. Research grade fuels were delivered to the combustor from pressurized tanks. Precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and air flow rates.

Figure 19: Tubular Burner (Cross sectional view)

A high resolution direct imaging system and a high speed PIV system operating at 15 Hz and output energy of 65 mJ are used to capture the flame fluctuation sequences and analyze the reacting and non-reacting particle velocity flow-fields, respectively. All of the equipment was set to record using the appropriate data acquisition software. In PIV experiments, alumina particles were used as seeding elements. The image buffer size is about 63 images which was used to capture the images. The averages of these images were then taken and are representative of the time-averaged flame. However, during the experiments it was determined that the temporal resolution of the camera to be too low to track the time dependent characteristics of the flame thus it is recommended to use a larger amount of frames to capture turbulence characteristics of the flame in future studies.

The term blockage ratio for a perforated plate is defined as the solid area of perforated plate (A_{Perf}) to the exposed area (A_{Exp}), as shown by Eq. (8). Increasing of the blockage ratio can be achieved either by decreasing the number of holes in the perforated plate or by decreasing the size of the holes of perforated plate.

$$BR = \frac{A_{Perf}}{A_{Exp}} = \frac{A_{Exp} - A_{Hole}}{A_{Exp}} = 1 - \frac{Nd_o^2}{D^2} \quad (8)$$

Where N is the total number of holes, d_o is the hole diameter and D is the overall disc diameter.

Three different set of perforated plates (with blockage ratios of 73%, 83% and 93%) were used for the present set of experimentation as shown in the figure 20.

Figure 20: Perforated plate with blockage ratios of (a) 73% (b) 83% and (c) 93%

Combustor System

The combustor rig used for the oxy-fuel measurements has three configurable modules: (i) inlet manifold with static mixture, (ii) swirl burner with mixing tube, and (iii) optically accessible combustion chamber, see figure 21. The module integrates a pilot flame ring with a mixture of methane and air. The swirl burner module is fitted with a quartz mixing tube. The quartz glass tube is needed for the high speed imaging of flashback inside the premixer. The fuel and air enter the

inlet manifold through five alternate injection holes. The fuel-air mixture then passes through the static mixture section (honeycomb) to eliminate injection induced flow irregularities and to ensure proper mixing of air and fuel. The burner module can accommodate both center body and hubless swirlers. In the present study, experiments were carried out using centerbody swirlers. During conducting experiments, a conical circular sleeve was fitted inside the inlet of the combustion chamber which allowed the air-fuel mixture to enter the combustion chamber through the passage between the sleeve and the centerbody of the swirler, and thus reduced the pressure drop that the mixture might experience due to the divergence at the inlet of the combustion chamber.

Figure 21: Schematic of the combustor assembly

The combustion chamber is constructed in a rectangular-type cross-section whose side-walls are made up of quartz glass to provide optical access inside it. Air was supplied to the rig through a high pressure (maximum 900 cfm of air at 125 psi) rotary screw type compressor. Research grade fuels were delivered to the combustor from pressurized tanks. Precision metering valves in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and air flow rates. A bank of digital mass flow controller was used to measure mass flow rates of fuels and air.

A high resolution direct imaging system (Phantom v310 camera, with a resolution of 1280 x 800 at 3250 fps and a maximum frame rate of 500,000 fps) and a high speed PIV system (20 kHz) with intensified camera systems (Hamamatsu C10880, with maximum repetition frequency of 200 kHz) will be used to analyze the reacting particle velocity flow-fields of CH₄/Air and CH₄-O₂-CO₂ flames respectively. All the equipments were synchronized with Dantec Dynamics software. In PIV experiments, Aluminum particles were used as seeding elements. Figure 22 shows the combustor setup integrated with high speed PIV system.

Figure 22: Gas turbine combustor setup with mounted high speed PIV

Reynolds number

For the current set of experiments the Re is calculated using the equations below. Kinematic viscosities for the fuel and air mixture were also calculated using these equations.

$$\mu_{mixture} = \sum_{i=1}^n \frac{\chi_i \mu_i}{\sum_{j=1}^n \chi_j \Omega_{ij}} \quad \Omega_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{MW_i}{MW_j} \right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j} \right)^{-1/2} \left(\frac{MW_j}{MW_i} \right)^{1/4} \right]^2$$

$$\rho_{mixture} = \sum_i^n \chi_i \rho_i \quad v_{mixture} = \frac{\mu_{mixture}}{\rho_{mixture}}$$

$$Re = \frac{velocity_{burner\ exit} \cdot exit\ diameter}{v_{mixture}}$$

Where χ_i is mole fraction of the species i, n is total number of species in the mixture, μ_i is the viscosity of the species i, ρ_i is the density of the species i and MW_i is the molecular weight of species i.

IV. Results

Visual Observation and Qualification of Experimental Setup

Flame images at a typical blowout and flashback condition are presented in figure 23.

Figure 23: (Top) Typical blowout sequence and (Bottom) Flame flashback sequence of a CH₄-O₂ flame at $\Phi = 1$

For blowout, the flame initially attached to the tip of the burner followed by flame detachment from the tip of the burner before blowout. For a typical flashback sequence flashback was defined at the condition when the flame initially moved inside the burner. Initially a benchmarking test was performed for the critical velocity gradients (gF) for a natural gas composition of 81.8% CH₄, 17.7% C₂H₆ and 0.5% N₂ to reproduce the data provided by Lewis and von Elbe (9).

Effect of Recirculation of CO₂ and H₂O

Figure 24 shows the stability map of CH₄-O₂-CO₂ flames with an initial condition of 0.5, 1.0 and 1.5 kW firing rate using different burner diameters. The filled and unfilled symbols represent the flashback and blowout condition for each burner diameter, respectively. The flashback and blowout behavior is significantly controlled by the percentage of diluents (CO₂ and H₂O) in the mixtures. It is interesting to note that CH₄-O₂ flames did not stabilize at this equivalence ratio without recirculated gases, even with lower firing input conditions due to a higher adiabatic flame temperature. The stability regime was also observed to narrow as burner diameter increased since the unburned gas velocity in the upstream is decreased as the burner diameter increased.

Figure 24: Stability limits including blowout (BO) and flashback (FB) of CH₄-O₂-CO₂ flames for different firing inputs and burner diameters

Figure 25 presents the effects of recirculated steam (H₂O) on the stability regime of CH₄-O₂ flames. Experiments were performed with an increase of steam at a fixed amount of CO₂ in the fuel mixture. An almost equal amount of steam could be recirculated potentially until the flame was extinguished. The effect of steam was primarily observed for lower burner diameters causing the flame to extinguish. Figure 25 demonstrates that at these conditions the large latent heat of water quenched the flames ceasing chemical reactions.

Figure 25: Stability Limits of CH₄-O₂-CO₂ and CH₄-O₂-CO₂-H₂O flames

The flashback and blowout limits were also plotted against recirculation ratio of CO₂ with respect to theoretical amount of CO₂ production obtained from a thermodynamic calculation, figure 26. The purpose of this graph was to estimate the maximum allowable recirculation of CO₂ from the exhaust stream.

Figure 26: Stability limits of CH₄-O₂-CO₂ plotted as a ratio of CO₂ recirculated to the amount calculated using equilibrium chemistry

Effect of Fuel Composition

Figure 27 shows the stability limit of syngas (H₂-CO) mixtures diluted with CO₂ at different H₂ concentrations. It is interesting to note that the flames of 10%H₂-90%CO mixture stabilized without CO₂ in the fuel mixture using the 3 mm diameter burner due to a lower adiabatic flame temperature compared to CH₄-O₂ flames. However, the presence of CO₂ is necessary for stabilizing flames at higher diameter (ranges from 6 to 20mm) burners. Initially blowout points of each fuel composition were different at smaller diameter burners but those points merged together at larger diameters. A comparison of CH₄-O₂-CO₂ and H₂-CO-O₂-CO₂ flames on stability limit shows no significant difference between CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flame stability.

Figure 27: Stability limits of CH₄-O₂-CO₂ and CH₄-O₂-CO₂-H₂O flames. The filled and empty symbols represent a firing input of 1.5 kW and 1.0kW, respectively. Triangles represent CO₂ diluent flashback limits while diamonds represent extinction limits using CO₂

Effect of Firing Input

The effects of firing input on the flame stability limit was also investigated and plotted. Burner diameter is plotted against recirculation ratio of CO₂ in oxidizer by mass. It is expected that there is a higher concentration of CO₂ in the fuel mixture in the case of smaller firing input conditions until blowout. This is due to the small bulk velocity in the low firing input condition. Experimental results show this behavior at smaller diameter burners (ranges 3-9mm). However, at 13 mm diameter burner the firing input did not show a significant effect on flame stability. The required amount of CO₂ recirculated in the fuel mixtures for stabilizing flame is significant compared to the amount of fuel-oxidizer mixture as the burner diameter increases. A comparison between stability limits between CH₄-O₂-CO₂ and 10%H₂-90%CO-O₂-CO₂ flames at different firing input conditions shows that the 10%H₂-90%CO-O₂ flames have a wider stability regime than CH₄-O₂ flames at smaller diameter burners. This effect was due to the reheating caused by the presence of a partially entered flame front which increased the propensity of flashback (figure 28).

Figure 28: Stability limit of 10% H2-90%CO mixture at different firing input conditions

Flashback Modeling

The critical velocity gradients of CH₄-O₂-CO₂ mixtures at different burner diameters and mixture ratios (%F) were measured. The flashback behavior of CH₄-O₂-CO₂ changed linearly with the increase in %F in the mixture. The 20 mm burner had significantly lower g_F values compared to the 3 and 6 mm burner tubes. The cooling of a partially entered flame front due to extended surface area of large burner tube determined the propensity of flashback. Experimental results also show that the increased concentration of recirculated gas in the fuel mixture lowered the critical velocity gradients of CH₄-O₂-CO₂. The scaling constant c for CH₄-O₂-CO₂ mixtures measured at different burner diameters was found to be linear and correlate with a c value of 0.0174.

Quantitative Measurement of Turbulent Flame Speed of Oxy-Fuel Mixtures

There are two different approaches to determine the turbulent burning velocity, one of them is to calculate the flame area/flame angle or by using quantitative measurement approach. In flame area method, flame images obtained using the high speed intensifier are averaged over 1000 samples and then mean flame area is calculated using the equation below.

$$S_T = \frac{\dot{m}_r}{\rho_r A_c}$$

where $\dot{m}_r$, ρ_r , A_c denote reactant mass flow rate, reactant density and mean flame area which is related to some given variable named as $\langle c \rangle$ contour or progress variable. Thus, the value of S_T is itself a function of the progress variable surface used to define the mean flame front area. The present study uses this approach to determine the S_T as this method was used extensively by several authors. Calculated flame speeds were higher when compared to laminar flame speed due to the turbulence for same initial conditions. Flame speeds measured in a gas turbine combustor significantly increase due to the presence of turbulence.

The extent of turbulence influence on the flame speed is not fully resolved, however. Lefebvre and Ballal described the visualization of a turbulent flame and explained how the turbulence caused a wrinkling the flame front which increased its specific surface area thus increasing burning rate. The authors show the following equation which can be used to determine turbulent flame speed:

$$S_T = S_L + u'$$

Where S_T is the turbulent flame speed, S_L is the laminar burning velocity and u' is the RMS value of fluctuating velocity or the turbulent intensity which is obtained from the PIV vector averaged data.

Digital images of the flame were taken with a 12 bit intensified CCD (2048x2048 pixels). The built in first image intensifier is available with a multialkali photocathode having a wide range of spectral response range from UV through near infrared, and hence capable of identifying the OH* chemiluminescence from the flame region zone. The ICCD system operates with a minimum gate time of 10 nanoseconds and a maximum gate repetition frequency up to 200 KHZ. It allows multi-exposure. The system is integrated with a OH* filter.

Images obtained from the ICCD camera are averaged over thousand samples. The mean image is symmetric along the burner axis. The brightest pixels images were tracked using a flow visualization software (Dantech Dynamics) and the straight lines are drawn through those points to the flame anchoring points on the burner the resulting image looks like the image shown in the Figure 29 shows the two peaks which are basically the brightest pixels when measures along the burner radius at an axial distance of 5 mm from burner top.

Figure 29: (a) Time averaged Flame image showing a mean intensified image (b) Pixel intensity along the radial axis of burner at an axial distance of 5 mm from burner top

Figure 30 shows flow-field fluctuations for H₂-CO/Air combustion. The height of the premixed cone is increased as the hydrogen content reduced as shown in the figure (sequence from (a) to (c)), which clearly shows the effect of hydrogen on the effective flame surface area resulting in increase in the local propagation velocity for high hydrogen content fuels. For the Bunsen type and rod-stabilized flames, the turbulence decays as the flow approaches the flame. The velocity fluctuations were observed to be highest at the burner top gradually reducing and at the inner cone or reaction zone tip. The fluctuations tended to increase up to certain distance due to the expansion of gases and then gradually decreased further downstream of the burner. This effect is observed predominantly at higher blockage ratios since the fluctuations were larger.

Figure 30: (a) Flow Field of 20%H₂ 80% CO at RE=2000 and $\Phi=0.9$ at BR=.83 (b)) Flow Field of 15 %H₂ 75 % CO at RE=2000 and $\Phi=0.9$ at BR=.83 (c)) Flow Field of 20%H₂ 80% CO at RE=2000 and $\Phi=0.9$ at BR=.83

Figure 31 shows the plot of velocity fluctuations of H₂-CO/air at a constant Reynolds number of 2000 and constant equivalence ratio of 1 and at the two different blockage ratios of 83% and 73%. As we can see the velocity fluctuations increase with increase in the BR. From the Figure 31 the data shows that flame brush thickness increases with the increase in the BR. Figure 32 shows the velocity fluctuation at different syngas compositions at constant blockage ratio. The velocity fluctuations tend to remain same as hydrogen content increased. On the contrary Figure 33 shows the effect of turbulence on turbulent propagation speed at a constant equivalence ratio of 0.9 and a constant Reynolds number of 2000. The turbulent propagation speed increased not only with the increase in the hydrogen content in the syngas mixture but also with the increase in the blockage ratio. Velocity fluctuations tend to increase with increase in the blockage ratio resulting in increase in the effective flame area. The turbulent flame propagation velocities are obtained using the flame area method.

Figure 31: Turbulent intensity along the burner exit axially for 20% H₂-80% CO at $Re=2000$ and $\Phi=0.9$

Figure 32: Turbulent intensity along the burner exit axially for 20% H₂-80% CO at $Re=2000$ and $\Phi=0.9$

Figure 33: ST for different syngas compositions at constant RE=2000 and $\Phi=0.9$

Laminar burning velocities and adiabatic flame temperatures of oxy-fuel Flames

The adiabatic flame temperatures and laminar burning velocities of CH₄-O₂-Diluent flames are evaluated using the GRI mechanism. Figure 34 shows the laminar burning velocities of CH₄-O₂-Diluent flames. The diluents used in the present case are N₂, Ar and CO₂. From the Figure 34, the data clearly states that CO₂ in CH₄-O₂ mixtures has a more dominating role in reducing the S_L when compared with N₂, and Ar. The addition of more diluents to the mixtures, the recombination ($H+H+M \rightarrow H_2+M$) reaction is faster compare to the chain branching ($H+O_2 \rightarrow O+OH$) step.

Figure 34: Laminar burning velocities of CH₄-O₂-Diluent mixtures

Figure 35 shows the adiabatic flame temperatures of the CH₄-O₂-Diluent mixtures. Due to the higher heat capacity of CO₂, temperature is reduced thereby reducing the rate of energy release causing reduction in the adiabatic flame temperatures when compared with N₂ and Ar.

Figure 35: Adiabatic flame temperatures of CH₄-O₂-Diluent mixtures

Figure 36 shows the axial plot of velocity fluctuations of CH₄-O₂-CO₂ flames at a constant Re (1000), Firing input (1 KW) and constant stoichiometric ratio ($\Phi=1$). As we can see the velocity fluctuations increase with increase in the BR.

Figure 36: RMS fluctuating velocity profiles at $X/D = 0$ for CH₄-O₂-CO₂ flames

Figure 37 shows flow-field fluctuations for CH₄-O₂-CO₂ flames. The height of the premixed cone is increased as the turbulent intensity reduced as shown in the figure (sequence from (a) to (c)), which clearly shows the effect of blockage ratio on the effective flame surface area resulting in decrease in the local propagation velocity.

Figure 37: Scalar map of velocity for CH₄-O₂-CO₂ flames (a) 93% BR (b)83% BR (c)73% BR

Figure 38 shows the radial plot of velocity fluctuations at an axial distance of 5 mm above the burner at different turbulent intensities (93% BR, 83% BR and 73% BR).

Figure 38: RMS fluctuating velocity profiles at Y/D =0.53 for CH₄-O₂-CO₂ flames at different blockage ratios

The turbulent propagation speed increased with the increase in the blockage ratio. Velocity fluctuations tend to increase with increase in the blockage ratio resulting in increase in the effective flame area. Figure 39 and 40 show the plots of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at 93%, 83% and 73% blockage ratios.

Figure 39: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at 93% blockage ratio

Figure 40: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at 83% blockage ratio.

Three different firing inputs (1.5 kW, 1.7 kW and 1.9 kW) were chosen for the current study. Figure 41 shows flow-field fluctuations for CH₄-O₂-CO₂ combustion. The height of the premixed cone is decreased as the firing input reduced as shown in the figure (sequence from (a) to (c)), which clearly shows the effect of firing input on the effective flame surface area resulting in increase in the local propagation velocity at higher firing input while maintain the constant Re (2500), constant blockage ratio of 83% and constant stoichiometric ratio ($\phi=1$). At higher firing inputs the amount of heat released is higher, in addition to that by keeping the Reynolds number to be fixed at 2500 for all the three firing inputs, the recirculation ratio ($RR_{CO_2} = \frac{m_{CO_2}}{m_{O_2} + m_{CO_2}}$) at higher firing input is lower when compared to the lower firing inputs, thereby increase in the local propagation velocity and increase in the effective flame surface area.

(a) (b) (c)

Figure 41: Flow-Field for CH₄-O₂-CO₂ flames (a) 1700 KW (b) 1800 KW (c) 1900 KW

Figure 42 shows the scalar velocity maps of CH₄-O₂-CO₂ flames at different firing inputs (1.5 KW, 1.7 KW and 1.9 KW), constant Re (2500), constant blockage ratio of 83% and constant stoichiometric ratio($\phi=1$).

Figure 42: Scalar map of velocity for CH₄-O₂-CO₂ flames (a) 1500 W (b) 1700 W (c) 1900 W

Figure 43 shows the comparison of radial velocity fluctuations at different axial distances for different firing inputs while maintain the constant Re (2500), constant blockage ratio of 83% and constant stoichiometric ratio ($\phi=1$).

Initially at the distance $Y/D = .52$ the velocity fluctuations for all the three firing inputs remained the same. As the axial distance increase (i.e $Y/D=1.52$ to 2.63) velocity fluctuations were highest for higher firing input, as the heat released is high at higher firing inputs. Figure 44, 45 and 46 show Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at firing input of 1500, 1700 and 1900 W, respectively.

Figure 44: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at firing input of 1500 W.

Figure 45: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at firing input of 1700 W.

Figure 46: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at firing input of 1900 W.

Velocity fluctuations were recorded minimum at an axial distance $X/D=0.52$ and then increased as we moved away from the burner exit, due to the high heat release rates and abrupt change in densities of the unburnt and burnt gas mixtures. Figure 47 presents a scalar map of turbulent intensity for CH₄-O₂-CO₂ flames at firing inputs of 1500, 1700 and 1900 W. An increase in the turbulent intensity is noted as we move away from the burner exit due to the changes in density of the unburnt and burnt gas mixtures.

Figure 47: Scalar map of turbulent intensity for CH₄-O₂-CO₂ flames at (a) 1500 W (b) 1700 W (c) 1900 W.

Two different recirculation ratios ($RR_{CO_2} = 74\%$ and $RR_{CO_2} = 70\%$) were chosen for the current study. In case of mixture with RR_{CO_2} of 70 percent, equal amounts of argon was replaced with CO_2 (by mass) to maintain the Reynolds number to be 2500 for the mixture. Argon was chosen in this case, it is chemically inert and the density and viscosity of argon were close to CO_2 . Figure 48 shows flow-field fluctuations for $CH_4-O_2-CO_2$ and $CH_4-O_2-CO_2-Ar$ combustion. The height of the premixed cone is decreased as the recirculation ratio is reduced 74 percent to 70 percent as shown in the figure (sequence from (a) to (b)), which clearly shows the effect of recirculation ratio on the effective flame surface area resulting in increase in the local propagation velocity at lower recirculation ratio while maintaining constant Re (2500), constant blockage ratio of 83% and constant stoichiometric ratio ($\phi=1$). The result clearly states that CO_2 is chemically active and reduces the flame temperature thereby reducing the local propagation velocity and decrease in the effective flame surface area.

Figure 48: Flow-Field for $CH_4-O_2-CO_2/ CH_4-O_2-CO_2-Ar$ flames at (a) $RR_{CO_2} = 74\%$ (b) $RR_{CO_2} = 70\%$

Figure 49 shows the comparison of radial velocity fluctuations at different axial distances for different recirculation ratios while maintain the constant Re (2500), constant blockage ratio of 83% and constant stoichiometric ratio ($\phi=1$). Initially at the distance $Y/D = .52$ the velocity fluctuations for $RR_{CO_2} = 74\%$ and $RR_{CO_2} = 70\%$ remained the same. As the axial distance increase (i.e $Y/D = 1.35$ to 3.15) velocity fluctuations were highest for higher at $RR_{CO_2} = 70\%$, as the heat released is high for $CH_4-O_2-CO_2-Ar$ flames, as CO_2 is chemically active and reduces the flame temperature whereas Argon is chemically inert and does not participate in any reaction.

Figure 49: Flow-Field for CH₄-O₂-CO₂/ CH₄-O₂-CO₂-Ar flames at (a) $RR_{CO_2} = 74\%$ (b) $RR_{CO_2} = 70\%$

Figure 50 and 51 show the plots of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂/ CH₄-O₂-CO₂-Ar flames at recirculation ratios ($RR_{CO_2} = 74\%$ and $RR_{CO_2} = 70\%$) respectively. Velocity fluctuations were recorded minimum at an axial distance $X/D = .26$ and then increased as we moved away from the burner exit.

Figure 50: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at $RR_{CO_2} = 74\%$

Figure 51: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂-Ar flames at RRCO₂=70%.

Figure 52 presents the scalar map of turbulent intensities for CH₄-O₂-CO₂ flames at different CO₂ recirculation ratios. Argon was used to account for the needed flowrate to generate a constant Re of 2500.

Figure 52: Scalar map of turbulent intensity for CH₄-O₂-CO₂/ CH₄-O₂-CO₂-Ar flames at (a) RRCO₂=74% (b) RRCO₂ =70%

The effect of RR of CO₂ are noted since CO₂ is chemically active and decreases flame temperature thereby reducing the local propagation velocity and decreasing the effective flame surface area. Figure 53 presents a comparison of the velocity fluctuations acquired for all different conditions used.

Figure 53: Comparison of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at (a) RRCO₂= 74% (b) RRCO₂ =70%

Three different blockage ratios (78%, 83% and 93%) were chosen to vary the turbulent intensity level above the burner exit. Figure 54 shows flow-field fluctuations for CH₄-O₂-CO₂ flames. The height of the premixed cone is decreases as the turbulent intensity increases as shown in the figure (sequence from (a) to (c)), which clearly shows the effect of blockage ratio on the effective flame surface area resulting in increase in the effective flame surface area thereby resulting in increase in the local propagation velocity. At higher blockage ratio, the turbulent intensity is higher which greatly enhances the fuel mixing and heat transport from burnt to unburnt gases thereby increasing the local flame propagation velocity.

Figure 54: Flow-Field for CH₄-O₂-CO₂ flames at (a) BR of 73% (b) BR of 83% (c) BR of 93%

Figure 55 shows the scalar velocity maps of CH₄-O₂-CO₂ flames at different blockage ratios (78%, 83% and 93%), constant firing input (1700), constant Re (2500) and constant stoichiometric ratio($\phi=1$).

Figure 55: Scalar map of velocity for CH₄-O₂-CO₂ flames at (a) BR of 73% (b) BR of 83% (c) BR of 93%

Figure 56, 57 and 58 shows the plots of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at blockage ratios (73%, 83% and 93%) respectively. Velocity fluctuations were recorded minimum at an axial distance $X/D=0.05$ and then increased as we moved away from the burner exit while figure 55 presents the scalar map representation under these conditions.

Figure 56: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at 73% BR

Figure 57: Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at 83% BR

Figure 58: Radial RMS fluctuating velocity profiles at different axial distances for $\text{CH}_4\text{-O}_2\text{-CO}_2$ flames at 93% blockage ratio

Figure 59 presents an increase in turbulence intensity as the blockage ratio is increased from 73 to 93% under the same conditions.

Figure 59: Scalar map of turbulent intensity for $\text{CH}_4\text{-O}_2\text{-CO}_2$ flames at (a) BR of 73% (b) BR of 83% (c) BR of 93%

Figure 60 shows the axial plot of velocity fluctuations of CH₄-O₂-CO₂ flames at a constant Re (2500), Firing input (1.7 KW) and constant stoichiometric ratio ($\Phi=1$).

Figure 60: Comparison of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂ flames at (a) BR of 73% (b) BR of 83% (c) BR of 93%

The velocity fluctuations increase with increase in the BR, as the turbulent intensity is increased by varying the BR from 73% to 93%. The velocity fluctuations increased substantially at different axial distances (i.e $Y/D = .26$ and 1.57).

Figure 61 shows flow-field fluctuations for H₂-CO-O₂-CO₂ combustion. The height of the premixed cone is decreased as the hydrogen content increased as shown in the figure (sequence from (a) to (b)), which clearly shows the effect of hydrogen on the effective flame surface area resulting in increase in the local propagation velocity for high hydrogen content fuels.

Figure 61: Flow-Field for H₂-CO-O₂-CO₂ flames (a) 10%H₂-90%CO (b) 20% H₂-80%CO

Figure 62 shows the scalar velocity maps of CH₄-O₂-CO₂ flames at different blockage ratios (78%, 83% and 93%), constant firing input (1700), constant Re (2500) and $\phi=1$.

Figure 62: Flow-Field for H₂-CO-O₂-CO₂ flames (a) 10%H₂-90%CO (b) 20% H₂-80%CO

Figure 63 and 64 shows the plots of Radial RMS fluctuating velocity profiles at different axial distances for H₂-CO-O₂-CO₂ flames at 10% H₂-90% CO--O₂-CO₂ and 20% H₂-80% CO-O₂-CO₂ respectively. Velocity fluctuations were recorded minimum at an axial distance X/D=.26 and then increased as we moved away from the burner exit.

Figure 63: Radial RMS fluctuating velocity profiles at different axial distances for 10% H₂-90% CO--O₂-CO₂ flames

Figure 64: Radial RMS fluctuating velocity profiles at different axial distances for 20% H₂-80% CO--O₂-CO₂ flames

Figure 65 presents the turbulent intensity scalar maps for 10 and 20% H₂ content in the syngas mixture. Higher turbulence is noted near the burner exit due to the increase in H₂ content.

Figure 65: Scalar maps of turbulent intensity for H₂-CO-O₂-CO₂ flames (a) 10% H₂-90% CO (b) 20% H₂-80% CO

Figure 66 presents the comparison of the RMS fluctuating velocity profiles for the different conditions tested at different x/D values.

Figure 66: Comparison of radial RMS fluctuating velocity profiles at different axial distances (a) 10% H₂-90% CO (b) 20% H₂-80% CO

A recirculation ratio $RR_{H_2O} = \frac{m_{H_2O}}{m_{O_2} + m_{CO_2} + m_{H_2O}}$ ($RR_{H_2O} = 27\%$) were chosen for the current study.

The gaseous mixture is preheated to 115 degrees centigrade prior to the combustion. Figure 67 shows the flow field fluctuations of CH₄-O₂-CO₂-H₂O flames at constant Re (1500), constant Firing input (1700 W) and constant stoichiometric ratio. To observe the effect of steam on flame stability, it is removed from the preheated mixture and an equal amount of CO₂ (by mass) is added to maintain the Reynolds number constant. But, at the same Reynolds number the preheated CH₄-O₂-CO₂ flame has flashback indicating that CH₄-O₂-CO₂-H₂O mixture absorbs more heat from the combustible mixture when compared to CO₂. The result clearly states that steam is chemically active, as it has smaller diffusivity and enhances the backward reaction thereby reducing the flame temperature thereby reducing the local propagation velocity and decrease in the effective flame surface area.

Figure 67: Flow-Field for CH₄-O₂-CO₂-H₂O flames (b) scalar map of velocity for CH₄-O₂-CO₂-H₂O flames

Figure 68 shows the plots of Radial RMS fluctuating velocity profiles at different axial distances for CH₄-O₂-CO₂-H₂O flames. Velocity fluctuations were recorded minimum at an axial distance $X/D = 0.26$ and then increased as we moved away from the burner exit.

Figure 68: Radial RMS fluctuating velocity profiles at different axial distances for 20%H₂-80%CO--O₂-CO₂ flames

Figure 69 presents the scalar map of the turbulent intensity. As we move away from the burner exit the turbulent intensity increases as described by the profiles presented.

Figure 69: (a) Scalar of turbulent intensity for CH₄-O₂-CO₂-H₂O flames at constant Re (1500), constant Firing input (1700 W) and $\phi=1$

Comparison of burning velocity and local flow velocity profiles across the diameter of the combustion chamber were done at two positions $x=5\text{cm}$ and $x=10\text{cm}$ from the tip of the swirler. The profile for the local longitudinal flow velocity, fluctuating velocity was generated by averaging over 4000 samples using the instantaneous velocity data extracted from the PIV measurement. The turbulent burning velocity, S_T was computed using the equation proposed by Damkohler:

$$S_T = S_L + u'$$

where, S_L is the laminar burning velocity provided by the authors in a previous study and u' is the RMS value of the fluctuating velocity component also extracted from the PIV measurement. Figure 70 shows that turbulence intensity increases along the swirler axis up to certain distance and then decreases.

Figure 70: (a) scalar map of turbulence intensity of CH4-air flame at $\phi=1$

Figure 71, 72, 73, 74 shows the vector flow field of methane air flames with a bulk velocity of 1.9 m/sec and $S=0.97$ and the velocity profiles at different x/d values. The high velocity regions which were located closer to the combustion chamber walls, provides enough space recirculation zones which helps the flame to stabilize right in front of the swirler. In recirculation zone, hot exhaust gases travel upstream heating up the un burnt gas mixtures. Eddies and vortices are formed and destroyed rapidly in the recirculation zone. Figure 72 shows the velocity profile of

methane air flames at two different locations, $x=5$ and $x=10$ cm from the tip of the swirler. Figure 73 shows the turbulent intensity increases as we move farther away from the center of the combustor. Figure 74 shows the turbulent burning velocity increases as we move farther away from the center of the combustor for methane air flames.

Figure 71: vector field of CH₄- air flame at $\phi=1$

Figure 72: Local flow velocity profile at a distance $x=5$ cm and $x=10$ cm from the center of combustion chamber for methane air flame at $\Phi = 1$

Figure 73: Turbulent intensity profile at a distance $x=5$ cm and $x=10$ cm from the centre of combustion chamber for methane air flame at $\Phi = 1$

Figure 74: Turbulent burning velocity profile at a distance $x=5$ cm and $x=10$ cm from the centre of combustion chamber for methane air flame at $\Phi = 1$

The temperature measurements are done at an offset distance of 5 cm away from the combustor axis. Figure 75 shows the temperature profile for methane and various compositions of syngas oxy combustion at a constant firing input of 5.5 Kw and the $\Phi = 1$.

Figure 75 shows that the higher CO₂ concentrations are needed in the oxidizer mixture, to stabilize the flame as we move from methane to syngas fuels. The burning velocity of higher hydrogen fuels are higher when compared to low hydrogen content fuels, so higher amounts of CO₂ is needed in the mixture to reduce the flame temperature thereby reducing the flame speed. The temperatures across the combustor remained constant as the firing input was maintained constant for all the mixtures.

Figure 75: temperature distribution of methane and various compositions of syngas oxy combustion at a constant firing input of 5.5 Kw and the $\Phi = 1$.

Reacting flow field analysis of $\text{CH}_4\text{-O}_2\text{-CO}_2$ combustion

Figure 76 shows the vector flow field of $\text{CH}_4\text{-38\%O}_2\text{-72\%CO}_2$ flames with a firing input of 7.4 KW and $S = 0.97$. The high velocity regions which were located closer to the combustion chamber walls, provides enough space recirculation zones which helps the flame to stabilize right in front of the swirler. Figure 76 also shows that turbulence intensity is highest at the shear regions in the combustor

Figure 76: (a) scalar map of turbulence intensity of $\text{CH}_4\text{-38\%O}_2\text{-72\%CO}_2$ flame at $\phi=.75$ (b) vector field

Figure 77-1 and 77-2 show the radial velocity and turbulent intensity distributions at different axial distances. The peaks at $X/D = .19$ are mainly due to the high velocity regions residing closer to the combustor walls and the dip is due to the recirculation zone. As we farther way from the combustor axis the velocity distributions tend to be uniform due to the mass diffusion of mixtures. Figure 77 (b) shows the radial turbulent intensity distributions at different axial distances. The turbulent intensity tends to increase as we move farther away from the combustor.

Figure 77-1: (Left) Velocity distribution of CH₄-air flame at $\phi = .75$ radially at different axial positions (Right) Turbulent intensity distribution of CH₄-air flame at $\phi = .75$ radially at different axial positions

Comparison of Velocity and Turbulent intensities for CH₄-air mixtures and CH₄-O₂-CO₂ mixtures

Figure 78 shows the velocity distributions at $X/D = 1.96$ and it clearly states that methane air

Figure 77-2: (a) Turbulent intensity distribution of CH₄-air flame and CH₄-O₂-CO₂ at $X/D = .19$ (b) Turbulent intensity distribution of CH₄-air flame and CH₄-O₂-CO₂ at $X/D = 1.96$

flames have high velocity peaks when compared to methane oxygen flames at constant firing input (1700) and constant $Re(4500)$, due to the high heat capacity of CO₂ and it increases the third body reactions thereby reducing the reaction rate and lower propagation velocities⁶. Similar trend has been observed at different axial distances.

Figure 78 also shows the velocity distributions at $X/D=1.96$ and it clearly states that methane air flames have high velocity peaks when compared to methane oxygen flames at constant firing input (1700) and constant $Re(4500)$. Similar trend has been observed at different axial distances.

Figure 78: (left) Velocity distribution of CH₄-air flame and CH₄-38%O₂-72%CO₂ at $X/D=0.19$ (right) Velocity distribution of CH₄-air flame and CH₄-38%O₂-72%CO₂ at $X/D=1.96$

V. Conclusions

Oxy-fuel flame stability of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames burning with steam have been analyzed and factors affecting their behaviors have been explored. A broad range of variables that potentially affect the flame stability have been investigated.

Effects of CO₂ and steam on the flame stability of CH₄-O₂ mixtures showed that the flashback and blowout points of the flame were controlled by the amount recirculated in the fuel mixture. It was observed that CH₄-O₂ flames did not stabilize without recirculated gases even with lower firing inputs due to the higher adiabatic flame temperature of the mixture. In addition, the stability regime of all compositions was observed to decrease as the burner diameter increased. Furthermore, it was found that more diluents in the fuel mixtures was necessary to stabilize the flame as the burner diameter increased in order to balance between flame speed and unburned gas velocity.

A comparison of CH₄-O₂-CO₂ and H₂/CO-O₂-CO₂ flames was also presented. Stability limits of syngas mixtures diluted with CO₂ at different H₂ concentrations did not stabilize at small burner diameters (3mm) without the presence of recirculated gases in the fuel mixture. For larger burner diameter burners (6-20mm) recirculated components were also necessary. Another important finding was that for 10% H₂-90% CO-O₂ flames, a wider stability regime exists compared to CH₄-O₂ flames due to the reheating caused by the presence of a partially entered flame front which increases the propensity of flashback.

The second part of the study focuses on the experimental measurements of the flow field characteristics of premixed CH₄/21%O₂/79%N₂ and CH₄/38%O₂/72%CO₂ mixtures at constant firing input of 7.5 kW, constant, equivalence ratio of 0.8, constant swirl number of 0.92 and constant Reynolds Numbers. These measurements were taken in a swirl stabilized combustor at atmospheric pressure. The flow field visualization using Particle Imaging Velocimetry (PIV) technique is implemented to make a better understanding of the turbulence characteristics of

CH₄/air and CH₄/38% O₂/72% CO₂ combustion. The velocity fluctuations, turbulence intensities and local propagation velocities along the combustion chamber have been determined. The turbulent intensities increase as we move away from the combustor axis. CH₄-38% O₂-72% CO₂ flames have low radial velocity and turbulent intensity distributions at different axial distances when compared with CH₄-Air flames.

VI. References

Amato A, Hudak B, D'Souza P., D'Carlo P., Noble D., Scarbrough D., Seitzman J., Lieuwen T, "Measurements and analysis of CO and O₂ emissions in CH₄/CO₂/O₂ flames" Proceedings of Combustion Institute, Vol. 33. pp. 3399-3405, 2010.

Andersson K, Johansson R, Leckner B, "Radiation intensity of propane-fired oxy-fuel flames: implications for soot formation." Vol. 22, pp.1523-41, 2008.

Ashman P.J, Haymes B.S, "Rate coefficient of $H+O_2+M \Rightarrow HO_2+M$ ($M=Ar, N_2, CO_2$)". Twenty-Seventh Symposium (International) on Combustion/The Combustion Institute, Australia, pp. 185-191, 2006.

Brandl A, Tangemann E, Pfitzner M, "Validation of premixed combustion models using turbulent Bunsen flames at high pressure" 10th International Workshop on Premixed Turbulent Flames Mainz, Germany, 2006.

Candel S. M and Poinot T, "Flame stretch and the balance equation for the flame area." *Combust. Sci. Technol.*, 70:1-15, 1990.

Carbon sequestration Technologies Website, National Energy Technology Laboratory, Department of Energy, Web address: http://www.netl.doe.gov/technologies/carbon_seq/2007Roadmap; Accessed on 2007.

Damkohler G 1940, Der Einfluss der Turbulenz auf die Flammgeschwindigkeit in Gasgemischen, *Zs, Electrochemie* 6(11):601–626

Davis S.G, Joshi A.V, Wang H, and Egolfopoulos F, "An Optimized Kinetic Model of H₂/CO Combustion." Proceedings of Combustion Institute, Vol. 30. pp.1283.

Davison A, Thambiathu K, "Technologies for capture of carbon dioxide" Technical Review. Canada, 2005

Dardea A, Prabhakar R, Tranier J, Perrin N, "Air separation and flue gas compression and purification units for oxy-coal combustion systems," 2009

Dickens P.G., Linett J.W, "Efficiencies of third bodies in the reaction $H+O_2+M \Rightarrow HO_2+M$." Chemistry and Physics, Vol. 2. pp. 259.

Ditaranto M, Hals J, "Combustion instabilities in sudden expansion of oxy-fuel flames. Combustion and flame", Trondheim, Vol. 146, pp. 493-512, 2006.

- Durst F, Melling A & Whitelaw J. H: “Principles and practice of Laser Doppler Anemometry”, second edition, *Academic Press*, 1981.
- Driscoll J. F, Turbulent premixed combustion –“Flamelet structure and turbulent burning velocities”. *Prog. Energy Combust. Sci.*, 34:91-134, 2008.
- Eggenspieler G and Menon S “Combustion and emission modelling near lean blow-out in a gas turbine engine.” *Prog. Comput. Fluid. Dy.*, 5(6):281-297, 2005.
- Ganapathisubramani B, Lakshminarasimhan K, Clemens NT (2007) "Determination of complete velocity gradient tensor by using cinematographic stereoscopic PIV in a turbulent jet. *Exp Fluids* 42(6):923–939
- Glarborg P., Bentzen L.B.. “*Chemical effects of high CO₂ concentration in Oxy-fuel combustion of Methane*” *Energy and fuels*, Vol. 22. pp. 291-296, 2008
- Jarosinski, Jozef, and Bernard Veyssiere. *Combustion Phenomena: Selected Mechanisms of Flame Formation, Propagation and Extinction*. 1 ed. Boca Raton: CRC, 2009.
- Koboyashi H., Hagiwara H ,Kaneko, Ogami H,Y. “*Effects of CO₂ dilution on turbulent premixed flames at high pressure and temperature.*” *Proceedings of the Combustion Institute*, , Vol. 31. pp. 1451-1458, 2007
- Law C. K and Sung C. J “Structure, aerodynamics, and geometry of premixed Flamelets.” *Prog. Energy and Combustion. Science.*, 26:459-505, 2000.
- Lieuwen, Tim C., Vigor Yang, and Richard Yetter. *Synthesis Gas Combustion: Fundamentals and Applications*. 1 ed. Boca Raton: CRC, 2009.
- Liu F, Guo H, Smallwood G. J, and Gulder O. L, "The chemical effects of carbon dioxide as an additive in an ethylene diffusion flame: implications for soot and NO_x formation," *Combustion and Flame*, vol. 125, pp. 778, 2001
- Liu F., Guo H., Smallwood G.J. “*The chemical effect of CO₂ replacement of N₂ in air on the burning velocity of CH₄ and H₂ premixed flames*” *Combustion and flame*, vol. 133 pp.495-497, 2003.
- Lumley, J. L., and Tennekes H. "1." In *A First Course in Turbulence*. London: The Mit Press, 1972. 1.
- Mallard E and Le Chatelier H. L. *Annals of Mines*, 4:379-568, 1883
- Matalon M.” On flame stretch”. *Combustion. Science. Technology.*, 31(3):169-181, 1983
- Natarajan J, Lieuwen T, Seitzman J, 2005,”Laminar Flame Speeds of H₂/CO Mixtures: Effect of CO₂ Dilution, Preheat Temperature, and Pressure,” *Combustion and Flame*, **151**, pp. 104–19.
- Peters N. “*Turbulent Combustion*”. Cambridge University Press, Cambridge, UK, 2000.
- Pocheau A. “Front propagation in a turbulent medium”. *Europhys. Lett.*, 20:401-406, 1992

Poinsot T and Veynante D. “*Theoretical and Numerical Combustion*”. Edwards, Philadelphia, PA, 2 edition, 2005.

Prabhakar Venkateswaran, Andrew D. Marshall, David R. Noble, Jose Antezana, Jerry M. Seitzman and Tim C. Liewen, “Global Turbulent Consumption Speeds of H₂/CO Blends” Proceedings of ASME Turbo Expo 2009, GT2009-59685

Ruan J, Kobayashy H, Niioka T, “*Combined effects of nongray radiation and pressure on premixed CH₄/O₂/CO₂ Flames.*” Japan : s.n.

Upatnieks A, Driscoll JF, Ceccio SL, Rasmussen CC (2004) “Liftoff of turbulent jet flame assessment of edge flame and other concepts using cinema-PIV”. Combust Flame 138(3):259–272

Vishwanath Ardha, Bidhan Dam and Ahsan Choudhuri.”Laminar Burning Velocities of Syngas Fuels”. Journal of Energy Resource Technology, JERT-10-1047

Wall TF, “*Combustion processes for carbon capture.*” s.l. : Proceedings of Combustion Institute, 2007, Vol. 31. 31-47.

Westbrook C.K., Dryer F.L, “*Chemical kinetic modelling of hydrocarbon combustion.*” 1, s.l. : Progress in Energy and Combustion Science, Vol. 10, 1989

Zhang C, Atreya A, Lee K, “*Sooting structure of methane counterflow diffusion flames with preheated reactants and dilution by products of combustion.*” Combustion and Flame, pp.1049,1992