

# Laboratory Investigations of a Low-swirl Injector with H<sub>2</sub> and CH<sub>4</sub> at Gas Turbine Conditions

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## Abstract

Laboratory experiments were conducted at gas turbine and atmospheric conditions ( $0.101 < P_0 < 0.810$  MPa,  $298 < T_0 < 580$ K,  $18 < U_0 < 60$  m/s) to characterize the overall behaviors and emissions of the turbulent premixed flames produced by a low-swirl injector (LSI) for gas turbines. The objective was to investigate the effects of hydrogen on the combustion processes for the adaptation to gas turbines in an IGCC power plant. The experiments at high pressures and temperatures showed that the LSI can operate with 100% H<sub>2</sub> at up to  $\phi = 0.5$  and has a slightly higher flashback tolerance than an idealized high-swirl design. With increasing H<sub>2</sub> fuel concentration, the lifted LSI flame begins to shift closer to the exit and eventually attaches to the nozzle rim and assumes a different shape at 100% H<sub>2</sub>. The STP experiments show the same phenomena. The analysis of velocity data from PIV shows that the stabilization mechanism of the LSI remains unchanged up to 60% H<sub>2</sub>. The change in the flame position with increasing H<sub>2</sub> concentration is attributed to the increase in the turbulent flame speed. The NO<sub>x</sub> emissions show a log linear dependency on the adiabatic flame temperature and the concentrations are similar to those obtained previously in a LSI prototype developed for natural gas. These results show that the LSI exhibits the same overall behaviors at STP and at gas turbine conditions. Such insight will be useful for scaling the LSI to operate at IGCC conditions.

## NOMENCLATURE

$a_x, a_r$	normalized axial and radial stretch rates (1/mm)
$\alpha$	reactants thermal diffusivity
$c_{\text{quench}}$	quenching factor $\alpha U_0 / S_L^2 d$
$d$	injector diameter (mm)
$K$	$S_T$ correlation parameter
$m = m_c / m_s$	ratio of the flows through the center-channel, $m_c$ , and the swirl passage, $m_s$
$M_r / M_0$	recirculation strength: $M_r$ mass flux of fluid with negative $U$ , $M_0$ mass flux of the reactants
$q'$	2D turbulent kinetic energy = $_{-}(u'^2 + v'^2)^{1/2}$
$R = R_c / R_i$	ratio of the center channel radius, $R_c$ to injector radius, $R_i$
$S$	swirl number
$S_L$	laminar flame speed
$S_T$	turbulent flame speed
$T_{\text{ad}}$	adiabatic flame temperature
$U_0$	bulk flow velocity
$x_f, x_x^*$	leading edge and mean flame brush positions
$x_0$	virtual origin of divergent flow

## 1. INTRODUCTION

Integrated Gasification Combined Cycle (IGCC) is an advanced concept to reduce the emissions of greenhouse gases from coal power plants. Its basic premise is to extract syngas from coal that consists of primarily  $H_2$ ,  $CO$  and other diluents for burning in a gas turbine to generate electricity. When  $CO$  is separated from the syngas and converted to  $CO_2$  for sequestration, the gas turbine operates on nearly 100%  $H_2$ . This is the goal of the FutureGen Alliance which is a U.S. public-private partnership to develop near-zero emissions coal power plants. One of FutureGen's key components is a cost-competitive hydrogen turbine with ultra low  $NO_x$  emission and high efficiency. The goal of our research is to adapt our lean premixed low-swirl injector (LSI) [1-4] to the  $H_2$  turbines.

For land-based power turbines, lean premixed combustion is a proven dry-low-NO<sub>x</sub> (DLN) method to control NO<sub>x</sub> < 10 ppm and CO < 15 ppm (both @ 15% O<sub>2</sub>) without requiring exhaust gas cleanup. The use of hydrogen addition has been proposed as a means to extend the lean blow off limits to reach the ultra-low emission target of < 5 ppm NO<sub>x</sub> [5]. Laboratory studies have shown that the addition of a modest amount of H<sub>2</sub> can change the global flame characteristics [6, 7]. Therefore, the combustor needs to be modified to operate effectively with hydrogen enriched fuels. Burning near 100% H<sub>2</sub> requires a substantial re-design of the combustor to address additional issues associated with the faster combustion chemistry of H<sub>2</sub> and its influences on processes such as flame anchoring, flame stability, flashback, and auto-ignition. Because of the high cost and risk involved in conducting H<sub>2</sub> experiment at gas turbine conditions and the propriety nature of the subject, there are very few basic studies on high pressure premixed turbulent H<sub>2</sub> flames in the scientific literature (e.g. [8]).

To start the development of LSI for H<sub>2</sub> we investigated diluted and undiluted H<sub>2</sub>, CH<sub>4</sub> and CH<sub>4</sub>/H<sub>2</sub> flames in open atmospheric condition [3, 9]. These flames showed that the H<sub>2</sub> influences on the flowfield and other flame features are less than those in a conventional high-swirl burner [6]. The purpose of this study is to extend the investigation to the operating conditions of typical gas turbines, i.e.  $0.4 < P_0 < 2.0$  MPa,  $450 < T_0 < 700$ K,  $30 < U_0 < 80$  m/s, and to gain an overview of the functional changes in the global characteristics of the LSI flames with H<sub>2</sub> concentration,  $\phi$ ,  $P_0$ ,  $T_0$  and  $U_0$ . To assist in the interpretation of the high pressure results, velocity measurements by PIV were made for representative flames at STP.

## 2. BACKGROUND

The LSI [1, 3] is based on a flame stabilization concept developed for basic studies that has been adapted to industrial heaters [10-14]. Recent tests of a 7 MW gas turbines with a set of LSI show it to be a promising method to attain  $< 5$  ppm  $\text{NO}_x$  for natural gas operation. The LSI has also been evaluated with fuels of a wide range of Wobbe indices and the results show it to be a fuel-flexible design [3].

The heart of the LSI is a swirler with an open center-channel that allows a portion of reactants to remain unswirled [15]. The nonswirling center flow inhibits vortex breakdown and promotes flow divergence that is the key aerodynamic feature for the low-swirl flame stabilization method. To control the mass ratio,  $m$ , between the un-swirled and swirled passages a perforated screen is placed at the entrance of the centerchannel (Fig. 1 bottom left). From Ref [1, 16]  $S$  is:

$$S = \frac{2}{3} \tan a \frac{1 - R^3}{1 - R^2 + m^2 \left( \frac{1}{R^2} - 1 \right)^2 R^2} \quad \text{Eq. 1}$$

Ref. [4] introduced an expression that explains why the LSI flame remains stationary regardless of  $U_0$ . It stems from a velocity balanced at the leading edge of the flame brush,  $x_f$ .

$$1 - \frac{dU}{dx} \frac{(x_f - x_o)}{U_o} = \frac{S_T}{U_0} = \frac{S_L}{U_0} + \frac{Ku'}{U_o} \quad \text{Eq. 2}$$

On the LHS,  $dU/dx/U_o$  is the normalized axial divergence rate  $a_x$  that has shown to be a constant because the nearfield of the LSI is self-similar. The far RHS is the normalized linear  $S_T$  correlation with an empirical constant,  $K$  based on previous measurements showing a non-bending linear  $S_T$  correlation for the detached flames low-swirl burners [17]. Of the two terms, the contribution from  $S_L/U_0$  becomes small for large  $U_0$  because  $S_L$  for ultra-lean flames

pertinent to gas turbines are typically  $< 1.0$  m/s. The  $Ku'/U_0$  term is dominant and is constant because  $u'/U_0$  is controlled by the center-channel plate. Consequently,  $x_f - x_0$  does not vary significantly for large  $U_0$ .

A practical application of Eq. 2 is to predict the flashback velocity [4]. It also describes the fuel effects. Recent correlation of  $S_T$  shows that  $H_2$  has a higher correlation constant  $K$  (3.17) than  $CH_4$  ( $1.73^1$ ) which implies an upstream shift in the  $H_2$  flame position [9]. This simple model can be the basis for scaling the LSI to different sizes and conditions if the flame shift and turbulent flame speed correlation can be verified at gas turbine conditions.

### **3. EXPERIMENTAL SYSTEM AND DIAGNOSTICS**

The high pressure experiments were performed in a facility called SimVal (Fig. 1) designed to provide data to support modeling and computational developments [5, 8]. SimVal consists of an optically-accessible idealized combustor capable of operating at  $T_0$  up to 810 K and  $P_0$  up to 2.31 MPa with maximum supplies of air at 1.23 kg/s, natural gas at 53.3 g/s and hydrogen at 2.3 g/s. The test section has four 10.2 cm wide by 30.5 cm windows with a central combustor liner that is a 31.8 cm long quartz tube of 18.0 cm I.D. This geometry is representative of a typical can-style combustor.

The LSI is similar to the one used previously [3]. It is sized to fit SimVal ( $d = 5.715$  cm diameter) with  $R = 0.66$ . The number of vanes (16) and the swirl blade angle ( $\alpha = 40^\circ$ ) are same as earlier versions and the swirler recess ( $l_x = 4.6$  cm) is shorter. To meet the SimVal start-up requirement, a small (0.32 mm) pilot is embedded at the center of the perforated screen that is mounted in the upstream end of the center-channel. The pilot fuel was not used during the

experiments. This LSI has a swirl number of 0.5 similar to the one used in Ref [3]. The approach flow to the LSI is fully premixed and spatially uniform. The pressurized flames were monitored by a video camera capturing the visible luminosity (350 – 475 nm) from the CH<sub>4</sub> combustion emissions. The images were used to characterize flame shift and other changes in the global flame characteristics. A high speed (900 fps) OH chemiluminescence video camera was also used to capture the flashback events.

The STP experiments were performed in a separate combustor to facilitate the collection of a large data set for the flowfield analysis. It has the same inflow plenum, quartz liner and exit restriction as SimVal but without the outer liner and with an exit plate with a center opening instead of a cylindrical resonant exit section. Flowfield information was obtained by the PIV system described in Ref. [1, 3]. Data analysis was performed on 224 image pairs (13 by 13 cm field of view) using software developed by Wernet [18]. Due to deposition of the PIV seeds on the inner wall of the quartz tube, repeated runs were required at some conditions to collect the 224 image pairs. Flame shift and flame shape changes were investigated in a series of experiment by using the PIV camera to capture the visible luminosity of the CH<sub>4</sub> combustion.

The experimental conditions are summarized in Fig. 2. The pressurized preheated experiments were initiated by generating a NG flame (96.0% CH<sub>4</sub>, 2.5% C<sub>2</sub>H<sub>6</sub>, 0.4% C<sub>3</sub>H<sub>8</sub>, and 0.7% N<sub>2</sub> and higher hydrocarbons) at a given temperature ( $500 < T_0 < 600$  K), pressure ( $0.101 < P_0 < .811$  MPa), velocity ( $20 < U_0 < 60$ ) m/s, and equivalence ratio ( $0.4 < \phi < 0.5$ ). After the flame reached a steady state and its emissions and flame position recorded, the H<sub>2</sub> concentration was gradually increased to 40%, then to 60%, 80%, and for some cases 100% while holding all other variables

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<sup>1</sup> The correlation constant for hydrocarbon reported in Ref. [3] is deduced from data measured in all low-swirl burners. The 1.73 value is deduced from data from the LSI.

constant. Data from 46 flames were collected with the majority at  $P_0 = 0.202, 0.405$  MPa and  $U_0 = 40, 60$  m/s. These conditions are representative of the operation of a gas turbine at idling and partial load. The flashback limits for the high  $H_2$  fuels were determined in separate runs in which  $\phi$  was increased while holding the %  $H_2$ ,  $U_0$ ,  $T_0$ , and  $P_0$  constant until flashback occurred. Due to the hazards and safety risks of flashback tests, these experiments were not repeated. But by using a slow rate of increase in  $\phi$  over 30 minutes the uncertainty at flashback was controlled to below 0.015. PIV measurements on six flames were conducted at  $U_0 = 18$  m/s with  $\phi = 0.59$  for  $CH_4$ ,  $\phi = 0.48$  for 40%  $H_2$ , and  $\phi = 0.4$  for the 40, 60, 80, and 100%  $H_2$ . The flow velocity at STP is at the low end of the high pressure experiments and the fuel and mixture conditions are compatible.

## 4. RESULTS

### 4.1. Global behavior of high pressure flames

The changes in the flame shape at high pressure and at STP with increasing  $H_2$  fuel concentration are shown in Fig. 3. These images illustrate for the first time that the general features of LSI flames at gas turbine conditions are the same as those at STP. At 40%  $H_2$ , both the STP and pressurized flames are lifted and have a bowl shape that is characteristic of the open LSI flames [3]. Increasing to 60%  $H_2$  results in the flames shifting closer to the nozzle exit but the general shape remains unchanged. More significant changes are shown at  $H_2 > 80\%$  where the flames are drawn to the exit and the flames attach to the rim of the LSI nozzle. This phenomenon also occurs in open  $H_2/CH_4$  flames [9] where the high diffusivity of  $H_2$  promotes burning in the outer shear layer and causes the flame to attach. At  $H_2 > 92\%$ , the STP and the high pressure flames become almost planar to suggest a change in the flame stabilization process.

Due to the high flame speeds of H<sub>2</sub> mixtures, addressing flashback is a major challenge for H<sub>2</sub> gas turbine. The  $\phi_{FB}$  for the LSI determined at six conditions are listed in Table I. Though the results are limited, they show a trend of  $\phi_{FB}$  increasing with  $U_0$  and decreasing with H<sub>2</sub>%. But the effect of pressure is still unclear. The changes in  $\phi_{FB}$  with  $U_0$  and % H<sub>2</sub> are consistent with the results obtained in SimVal from an idealized high-swirl configuration (SV-HSI) [19]. The values of  $\phi_{FB}$ , however, indicate that the LSI has a slightly higher flashback resistance.

To characterize the difference in their flashback behavior, the quenching factor,  $C_{quench}$ , of Fritz et al. [20] was used. These authors show that the Peclet number at  $\phi_{FB}$   $Pe_U = U_0 d / \alpha$  correlates with  $Pe_{S_L} = S_L d / \alpha$  based on  $S_L$ . When reformulated in term of a quenching factor,  $C_{quench} = \alpha U_0 / S_L^2 d$ ,  $C_{quench}$  is shown to be a function of the density ratio of unburnt to burnt gases  $\rho_u / \rho_b$ . Flashback resistance is associated with small values of  $C_{quench}$  that represents a short chemical time at flashback compared to the mean convective time. In Fig. 4, the  $C_{quench}$  values of LSI are generally lower than those from SV-HSI to show the LSI has a lesser propensity to flashback.

Fritz et al. attributed the physical process of flashback in a swirl burner to vortex bursting or baroclinic vorticity production by which a premixed flame can propagate through the core of a free vortex at speeds much higher than the laminar flame speed. This implies that vorticity production in the shear region of the flowfield is where flashback originates. This may explain the flashback resistance of the LSI because the shear stresses in its flowfield are less than that of a typical high-swirl burner [1].

#### 4.2. Observations in STP flames and flowfield analysis

Six STP flames were selected to investigate how the changes in the global flame characteristics affect the flowfield and the stabilization mechanism. As shown in Fig. 3, increasing the H<sub>2</sub> fuel concentration pulled the STP flame closer to the dump plane. Flame attachment occurred at H<sub>2</sub> > 40% and the flame was fully attached at 60%. The 80% H<sub>2</sub> flame exhibited fluctuating behavior due to intermittent burning in the outer recirculation zone that changed the flame brush from “M” shape to a planar shape. The 100% H<sub>2</sub> flame was compact in appearance and produced high-frequency audible broad-band flame noise that was louder than the quieter lower frequency broad band noises produced by the CH<sub>4</sub>/H<sub>2</sub> flames. The change in the sound signature was not associated with chamber acoustic because it was also found in the open flames. This phenomenon may be indicative of the differences in the fundamental processes of H<sub>2</sub> and hydrocarbon flames.

The influence of the outer recirculation zone on the high H<sub>2</sub> flames was also reported in the high-swirl burner studies of Schefer et al. [6] and Strakey et al. [5]. Schefer et al. observed burning in the outer recirculation zone at relatively low H<sub>2</sub> concentration of 29% and Strakey et al. found flame anchoring in the outer recirculation prior to lean blow-off. Therefore, the outer recirculation zone is a significant controlling process of the H<sub>2</sub> flames in a swirling combustion system.

The mean velocity vectors for three flames are compared in Fig. 5. These PIV data are contaminated by laser reflections from the quartz enclosure and by particle deposition on the inner wall. However, the affected regions are away from the centerline and the nearfield ( $x/D < 0.5$ ) where the analyses are performed. In Fig. 5(a), the nearfield features of the detached 40% H<sub>2</sub> flame such as the central divergent zone are the same as those reported previously for open H<sub>2</sub>/CH<sub>4</sub> flames [3]. The main difference is the formation of the outer recirculation zone shown by

the inward velocity vectors at the lower side boundaries. In the farfield, a broad central recirculation zone is shown. As reported in Ref. [21], the strength of the central recirculation ( $M_r/M_0 = 0.06$  at  $x/D = 2$ ) is affected by the enclosure size and the heat release rate, but it has no influence on the flame brush upstream. In Fig 5(b) the overall flowfield of the 60% H<sub>2</sub> flame remain unchanged. Therefore, burning in the shear layer and flame attachment do not seem to have a significant influence on the mean flowfield. In the farfield, reductions in the size and strength of the central recirculation zone are found ( $M_r/M_0 = 0.02$  at  $x/D = 2$ ). More significant changes are found in the flowfield of the 80% H<sub>2</sub> flame of Fig. 5(c). As discussed above, this flame was fully attached and the planar-shaped flame occupied most of the nearfield. Therefore, the PIV domain captured mostly the flow within the products region.

The centerline velocity profiles in Fig. 6 illustrate the similarity and differences of the six STP flames. In Fig. 6(a), the nearfield regions of the 0 % to 60% H<sub>2</sub> flames are consistent and show divergent regions with linear  $U/U_0$  decays. These profiles deviate at  $x > 30$  mm due to differences in the heat releases. The  $U/U_0$  profiles of the two flames with H<sub>2</sub>  $\geq$  80% have different features with lower nearfield decay rates and higher flow acceleration in the farfield. The  $q'/U_0$  profiles in Fig. 6 (b) show relatively flat regions up to  $x = 50$  mm. The increases in the scatter of the  $q'/U_0$  data in the farfield for the three flames with H<sub>2</sub>  $>$  60% are symptoms of data degradation because the particle deposition problem was exacerbated by burning in the outer recirculation zone. The relatively flat  $q'/U_0$  distributions shown by the three other flames are consistent with those observed in open flames.

As discussed previously [3, 4, 9], the centerline velocity profiles are used to deduce the four parameters in Eq. 2 that characterize the nearfield region. The virtual origin,  $x_0$ , and the normalized axial stretch rate,  $a_x = (dU/dx)/U_0$  are deduced by linear fit and extrapolation of the

$U/U_0$  profile in the nearfield divergent regions at  $x < 30$  mm. The turbulent flame speed  $S_T$ , is defined as the axial velocity at the leading edge flame positions,  $x_f$  according to the procedure described in Ref [4]. The  $x_0$ ,  $a_x$  and  $S_T$  results are shown in Fig. 7. The  $x_f$  results will be presented later. In Fig 7 (a) and (b),  $x_0$  and  $a_x$  remain unchanged up to  $H_2 = 60\%$ . Their values of  $x_0 = -15$  mm are slightly larger than those reported in Ref [3, 4, 9] because this LSI generated more lifted flames. The mean  $a_x$  value of  $-0.18 \text{ mm}^{-1}$ , however, is typical of those reported for open and enclosed flames burning pure or blended hydrocarbon and  $H_2$  fuels. The abrupt changes in  $x_0$  and  $a_x$  at 80%  $H_2$  are clearly the consequences of flame attachment.

The  $S_T$  for the flames with  $H_2 \leq 60\%$  are compared in Fig 7 (c) with those measured in the LSI for  $CH_4$ ,  $H_2$  and various fuel blends. This plot differs from previous version (e.g. [3, 4, 9]) in two ways. First, the normalization uses  $S_L$  data for  $CH_4$  by Jomaas et. al [22] and  $S_L$  for  $H_2$  and fuel blends computed by CHEMKIN-PREMIX using GRI 3.0. Second, only the  $S_T$  data from the LSI are shown. The use of updated  $S_L$  and a specific data set does not change the main conclusion that the  $S_T$  from LSI correlates linearly with  $u'$  and that  $H_2$  has a higher  $S_T$  correlation constant  $K$  than  $CH_4$ . The implication is that the  $S_T$  of the blended fuels should fall within the region bounded by the two linear correlations. The four data points from this study support this notion despite the fact that these are enclosed flames and have some of the largest values of  $S_T/S_L$  and  $u'/S_L$ .

Figure 8 shows radial profiles at  $x = 15$  mm for the STP flames. The  $U/U_0$  profiles in Fig 8(a) all collapse on to a consistent distribution that has a relatively flat region at the center flanked by two asymmetric peaks corresponding to the swirl annulus shear regions. Closer examination shows slight outward expansion of the shear regions with increasing  $H_2\%$  due to burning in the outer recirculation zones. In Fig 8(b), the  $v/U_0$  profiles for the four flames with  $H_2 < 80\%$  show a

linear central region with  $a_r$  of  $-0.009 \text{ mm}^{-1}$ . Therefore, these enclosed flames also exhibit a 2:1 ratio between  $a_x$  and  $a_r$  as in the open flames. At  $H_2 > 80\%$ ,  $a_r$  reduces slightly to  $-0.005 \text{ mm}^{-1}$  and is accompanied by higher radial outflow in the shear regions indicated by the larger minimum and maximum peaks. In Fig 8(c), the  $q'/U_0$  levels in the center region for all flames are consistent. But in the swirling shear region, significant increases in the turbulence levels are shown by the  $H_2 = 80\%$  and pure  $H_2$  flames. Again, this is a consequence of burning in the shear region.

The PIV results confirm that the nearfield self-similarity flow features are preserved up to 60%  $H_2$  despite the fact that the flame begins to attach to the rim at  $H_2 > 40\%$ . Therefore, flame propagation in the divergent central regions remains the dominant process. With  $H_2 \geq 80\%$ , burning in the outer recirculation and within the shear regions become dominant. In addition to altering the flowfield, the increase in turbulence level within the shear region may provide a flashback pathway.

#### 4.3. Flame shift and $\text{NO}_x$ emissions

To quantify flame shift,  $x_f^*$  were deduced from the flame luminosity images by the steepest gradient points on the centerline intensity profiles. In the absence of laser-based data at elevated  $T_0$  and  $P_0$ ,  $x_f^*$  is a sufficiently well-defined parameter to characterize flame position because it relates directly to  $x_f$ . The set of high pressure flame data was analyzed to examine their sensitivity to  $T_0$ ,  $P_0$ ,  $U_0$  and %  $H_2$ . The result (Fig. 9) shows that  $x_f^*$  for the pressurized flames is the same at  $x_f$  for the STP flames. Both  $x_f^*$  and  $x_f$  are sensitive to %  $H_2$ . Changing  $U_0$ , as illustrated by the three inserts does not have a strong effect on  $x_f^*$ . This shows that Eq. (2) describing the coupling between the divergent flowfield and turbulent flame speed should also apply to gas turbine conditions.

Eq. (2) also shows that the flame shift due to H<sub>2</sub> is associated with the higher value of  $K$ . To determine if this model is qualitatively correct,  $x_f$  for a lean CH<sub>4</sub> and a lean H<sub>2</sub> flame were computed using  $x_0 = -15$  mm,  $a_x = -0.018$ ,  $u'/U_0 = 0.1$ , and  $U_0 = 20$  m/s. A heavy broken line joining the two points is shown in Fig 9 with the underlying assumption that  $K$  is a monotonically increasing function with % H<sub>2</sub>. The slope of the model prediction is in general agreement with  $x_f^*$  but is less than that of the STP flames on which the two values of  $K$  were based. The difference is due to flame attachment at high % H<sub>2</sub> drawing the flame closer to the nozzle and changing the  $x_0$  and  $a_x$ .

The NO<sub>x</sub> emissions are shown Fig 10 and they are compared with the correlation from Leonard and Stegmaier [23] that is considered by the gas turbine community to be the reference for a well-designed premixed combustion system. Also shown are logarithmic fits of the emissions from natural gas LSI [1] and SV-HSI [8]. For the mixtures with up to 60% H<sub>2</sub> the NO<sub>x</sub> emissions from the LSI are close to the reference Leonard and Stegmaier correlation and to those reported previously. This supports the conclusion of Leonard and Stegmaier that the NO<sub>x</sub> emission from a well-designed natural-gas premixed combustion system is predominantly a function  $T_{ad}$  at  $T_{ad} < 1900$ K. There is however a slight increasing trend with  $H_2 \geq 80\%$  that is especially noticeable at  $T_{ad} < 1750$ K. A similar trend has also been observed in SV-HSI. As these NO<sub>x</sub> data are among the first to be reported for premixed H<sub>2</sub> flames at gas turbine conditions, much more needs to be done to determine the cause of this upward shift.

## 5. DISCUSSION

Our studies show that the basic LSI design is amenable to burning pure H<sub>2</sub> at gas turbine conditions. The flame shapes and the flame shifts at STP and gas turbine conditions are the same.

The main implication is that except for fuels with very high % H<sub>2</sub> the physical processes at high T<sub>0</sub> and P<sub>0</sub> can be explained by a simple model that describes the coupling between the self-similar nearfield flow divergence and linear turbulent flame speed correlation. This provides a foundation for future studies to verify this model at gas turbine conditions so that it can be used for scaling the LSI design to different sizes, fuels, and operating conditions. From an experimental perspective, the knowledge that the STP experiments provide relevant and useful information can reduce the reliance on costly and time-consuming high pressure runs.

Another significant observation is that the change in flame shape at high H<sub>2</sub>% is strongly affected by burning in the outer recirculation zone. The process pulled the flame close to the LSI exit where turbulence intensities are higher. Although it is difficult to quantify, close examination of the flashback high speed videos shows that flashback does not originate at the nozzle wall but in the region of high  $q'/U_0$  in Fig. 8(c). Therefore, changing the dump-plane geometry to eliminate the outer recirculation may improve the LSI flashback resistance and perhaps NO<sub>x</sub> performance for high H<sub>2</sub> fuels.

## 6. CONCLUSIONS

Laboratory experiments have been performed to investigate the operation of a low-swirl injector with natural gas and H<sub>2</sub> at atmospheric and gas turbine conditions of  $500 < T_0 < 600$  K,  $0.101 < P_0 < .811$  MPa, and  $20 < U_0 < 60$  m/s. The flashback limits show that the LSI has a slightly higher flashback resistance than an idealized high-swirl design. The primary effect of H<sub>2</sub> is to draw the flame closer to the dump plane. At H<sub>2</sub> > 80% the flame attaches to the rim and changes into disk shape due to burning in the outer recirculation zone. The STP flames exhibit similar behavior and analysis of their flowfields and turbulent flame speed showed that the flame

stabilization mechanism remains unchanged up to 60% H<sub>2</sub>. An analytical model shows that upstream shift in the flame position with increasing H<sub>2</sub> concentration is associated with the higher S<sub>T</sub> correlation constant for H<sub>2</sub>. The trend predicted by this model is consistent with the trends observed at gas turbine conditions. This implies that nearfield flow-similarity and linear S<sub>T</sub> correlation are relevant at gas turbine conditions. Further experimental studies are needed to verify this coupling. NO<sub>x</sub> emissions show log linear dependence on T<sub>ad</sub> and are consistent with those of a well-designed premixed combustion system. A slight upward shift in NO<sub>x</sub> for high H<sub>2</sub> flame is also observed and requires further study to identify the mechanism for the excess NO<sub>x</sub> production.

This study verified earlier conjecture that the LSI does not need to undergo significant alterations to operate with H<sub>2</sub>. But the LSI design for H<sub>2</sub> turbines needs to address the influence due to burning in the outer recirculation zone.

## 7. ACKNOWLEDGEMENT

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**Table I** Conditions at flashback

H <sub>2</sub> %	P <sub>0</sub> Mpa	T <sub>0</sub> K	U <sub>0</sub> m/s	ϕ <sub>FB</sub>
100	0.202	530	20	0.5
100	0.202	550	30	0.57
87	0.405	560	20	0.52
100	0.405	570	30	0.4
82	0.810	575	20	0.49
92	0.810	575	20	0.42

## FIGURE CAPTIONS

Fig. 1 Schematics of the SimVal combustor and the LSI

Fig. 2. Experimental conditions used for this study.

Figure 3. Visible luminosity of CH/H<sub>2</sub> LSI flames at 0.405 MPa, ϕ = 0.4 and U<sub>0</sub> = 40 m/s.

Figure 4. Comparison of the flashback criterion, C<sub>quench</sub>, of LSI and the baseline SV-HSI for 60% - 100% H<sub>2</sub> fuels at 0.101 < P<sub>0</sub> < 0.810 MPa, 500 < T<sub>0</sub> < 600K and 0.4 < ϕ < 0.7

Figure 5. Mean velocity vectors for three H<sub>2</sub>/CH<sub>4</sub> flames at STP, U<sub>0</sub> = 18 m/s, and ϕ = 0.4.

Figure 6. Centerline profiles of the STP LSI flames.

Figure 7. Virtual origin, x<sub>0</sub> (a), normalized axial divergence, a<sub>x</sub>, (b) of the STP flames and their turbulent flame speeds (c).

Figure 8. Radial profiles (at x = 15 mm) of the STP LSI flames. Symbol legend same as in Fig. 6.

Figure 9. Mean flame brush positions of the NG/H<sub>2</sub>.

Figure 10. NO<sub>x</sub> emissions of the LSI compared with the baseline HSI configuration.

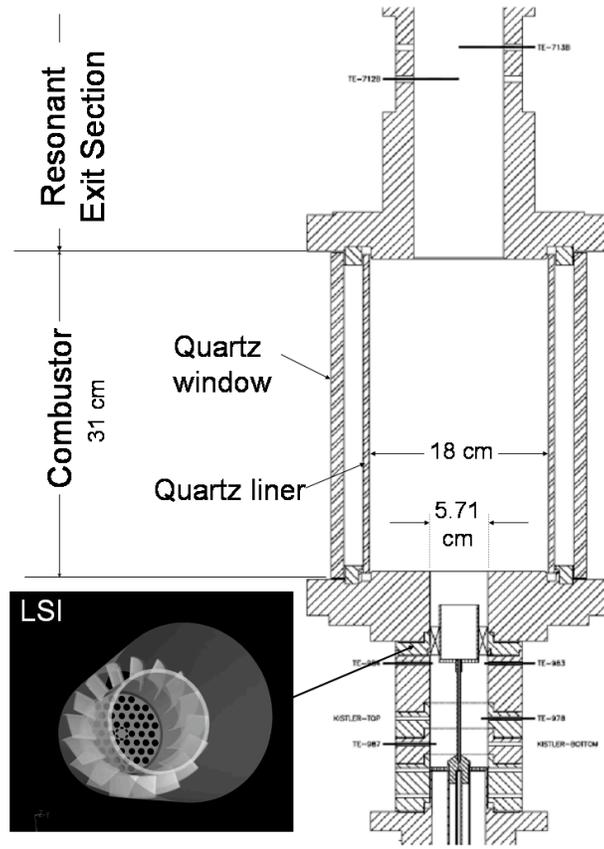


Figure 1 Schematics of SimVal and the low-swirl injector.

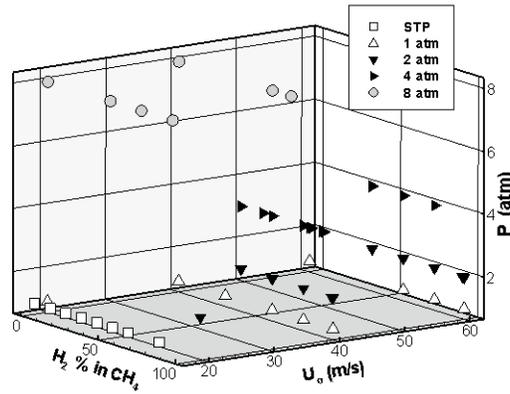


Figure 2 Experimental conditions for this study.

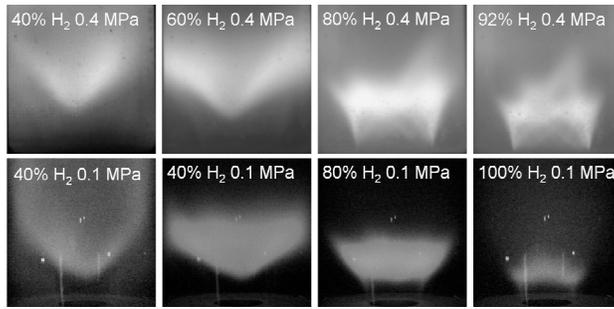


Figure 3 Visible luminosity of CH<sub>4</sub>/H<sub>2</sub> LSI flames: top row 0.405 MPa,  $\phi = 0.4$  and  $U_0 = 40$  m/s and bottom row 0.101 MPa,  $\phi = 0.4$  and  $U_0 = 18$  m/s.

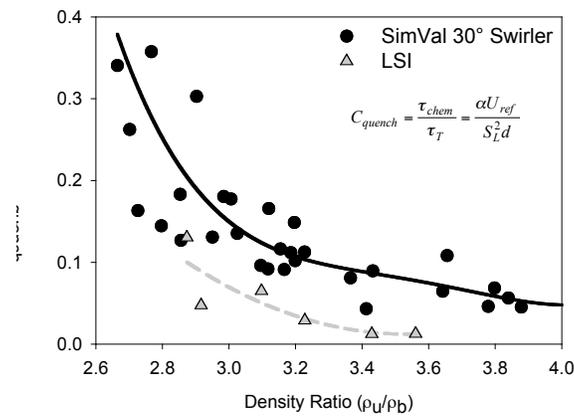


Figure 4  $C_{quench}$ , of LSI and the baseline SV-HSI for 60% - 100% H<sub>2</sub> fuels at  $0.101 < P_0 < 0.810$  MPa,  $500 < T_0 < 600$ K and  $0.4 < \phi < 0.7$ .

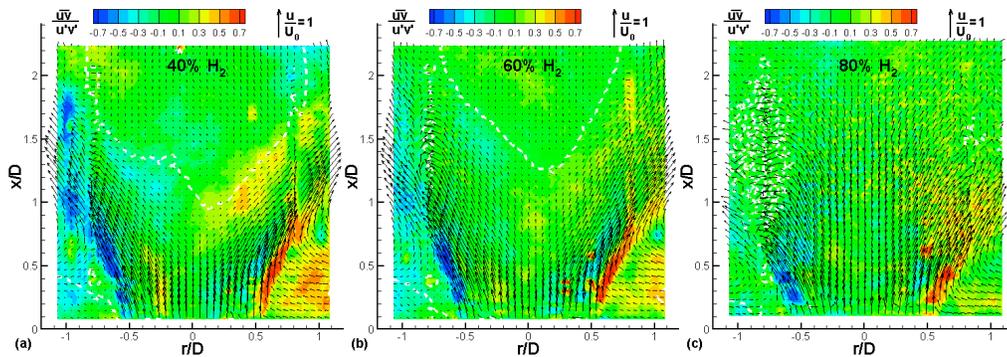


Figure 5 Mean velocity vectors for three H<sub>2</sub>/CH<sub>4</sub> flames at STP,  $U_0 = 18$  m/s, and  $\phi = 0.4$ . Color contours of the normalized shear stresses are show in the background.

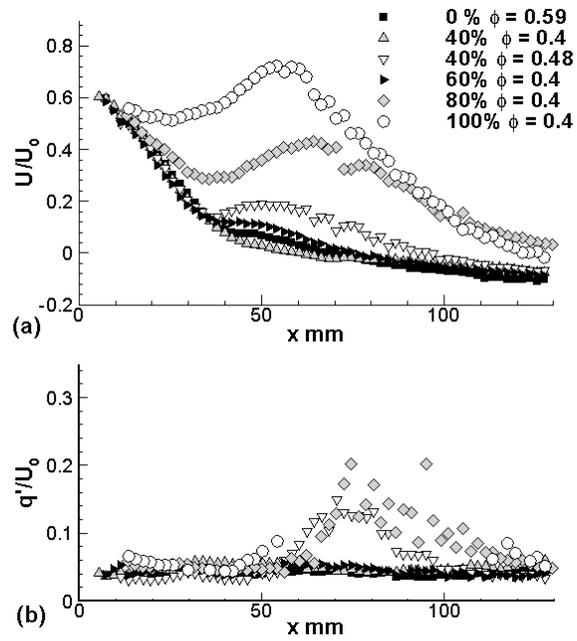


Figure 6 Centerline profiles of the STP LSI flames.

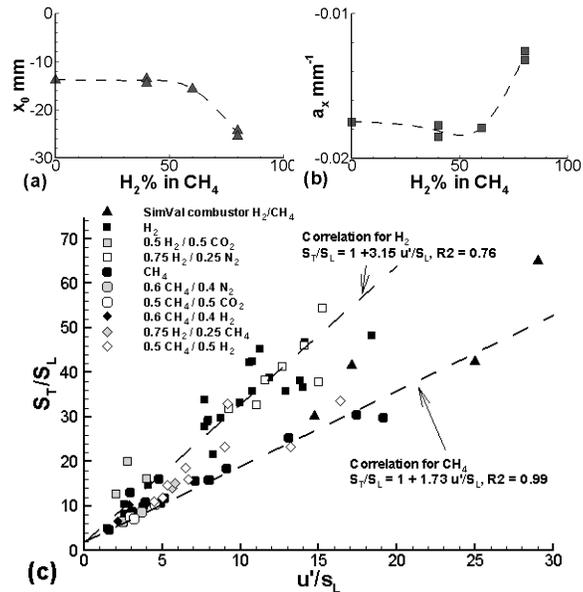


Figure 7  $x_0$  (a),  $a_x$  (b) of the STP flames and their  $S_T$  (c).

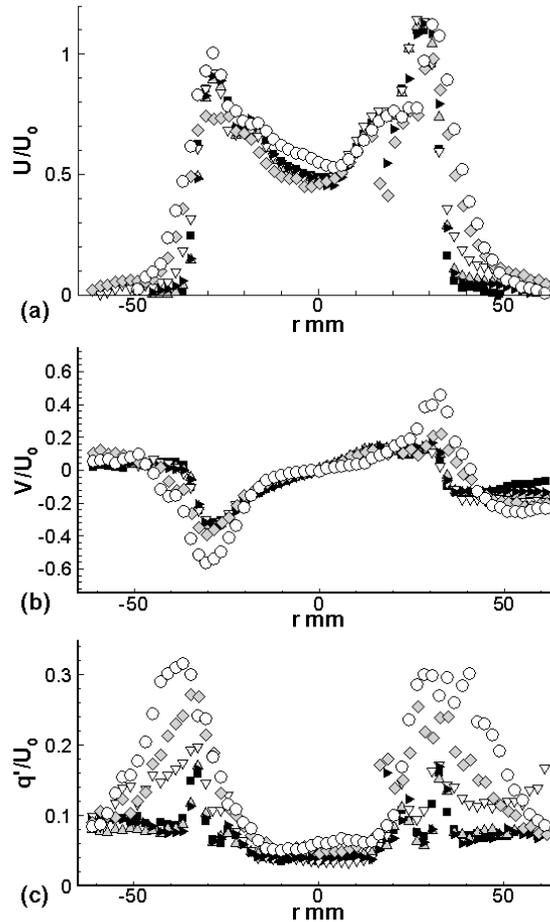


Figure 8 Radial profiles (at  $x = 15$  mm) of the STP LSI flames. Symbol legend same as in Fig. 6.

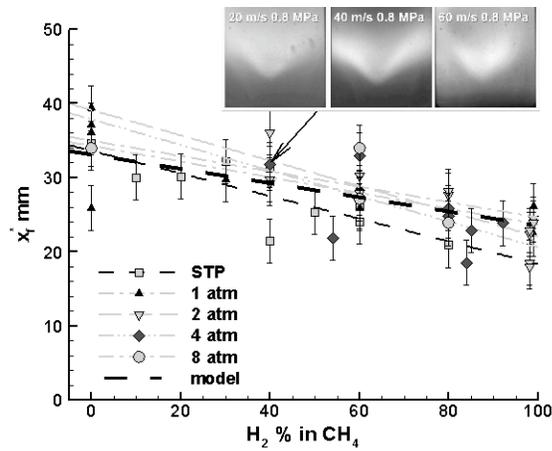


Figure 9 Mean flame brush positions of the NG/ $H_2$  flames

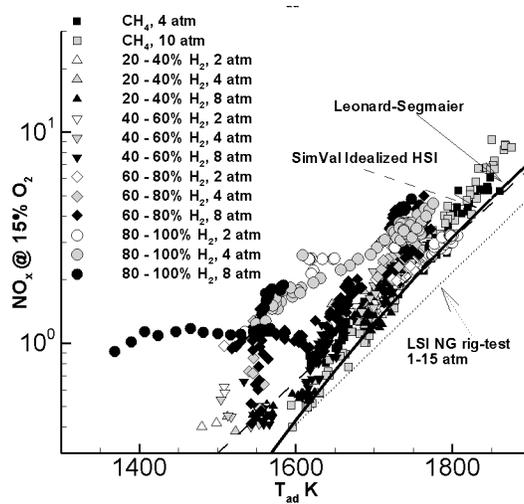


Figure 10 NO<sub>x</sub> emissions of the LSI compare with the baseline HSI configuration.