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Flashback Propensity Of Gas Mixtures

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Dedication

This thesis is dedicated to my parents and son.

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by

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THESIS

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Abstract

In this study, experimental measurements of flashback propensity of hydrogen (H2)-carbon monoxide (CO) mixtures, which are the primary constituents of syngas fuels, are described. The effects of H_2 concentration, diluents and swirl on the flashback propensity of H_2-CO flames are discussed. For boundary layer type flashback, the critical velocity gradient (g_F) values of 5 to 95%, 15 to 85%, and 25 to 75% H_2-CO mixtures somewhat agree with the scaling relation ($g_F = c\frac{S_L^2}{\alpha}$) and yield an average c value of 0.038. At a lower S_L^2/α ratio, burner diameters have small effects on critical velocity gradient measurements; however, the effect is significant at higher S_L^2/α ratio. For a given U_{bulk}, the %F at which the combustion induced vortex breakdown (CIVB) flashback occurs decreases with the increase in H_2 concentration in fuel mixtures. The more swirl, the more stabilized the recirculation zone and flame. For a given U_{bulk}, the %F at which the CIVB flashback occurs increases with the increase of swirl number. The 6 vane swirler (swirl number S = 0.71) stabilized flame is more prone to CIVB flashback than the 12 vane swirler (swirl number S = 0.97) stabilized flame. The flashback of 25 % H_2 - 75% CO mixture with 12 vane swirler (swirl number S = 0.97) occurs at 14.4 to 15.2% fuel; on the other hand, the same composition with 6 vane swirler (swirl number S = 0.71) stabilized flame flashback occurs at the 11.2 to 12.8% fuel. The flashback map for actual syngas compositions derived from different source of coal is different due to the presence of diluents in the mixtures. Diluents play a vital role to map the flashback regimes for both the swirler stabilized flames. Lignite coal derived syngas compositions went up to 33 to 35% fuel at which the flashback occurs. The strong swirled flow produces a more stabilized reaction zone (OH concentration) just after the swirler. The 12 vane swirler (swirl number S = 0.97) produce a more OH concentration

(1 through 4 sequence images) after the flow separation as compared to the 6 vane swirler (swirl number S = 0.71).

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1.0 Introduction

Turbine combustors of advanced power systems have goals to achieve very low pollutants emissions (NOx < 2 ppm), fuel variability, and fuel flexibility [1]. Future generation gas turbine combustors should tolerate fuel compositions ranging from natural gas to a broad range of syngas without sacrificing operational advantages and low emission characteristics [1-2]. However, issues of fuel variability and NOx control through premixing also bring a number of concerns, especially combustor flashback and flame blowout.

Flashback is a combustion condition at which 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. In swirl stabilized lean premixed turbine combustors onset of flashback [3-4] may occur due to (i) boundary layer flame propagation (critical velocity gradient), (ii) turbulent flame propagation in core flow, (iii) combustion instabilities, and (iv) upstream flame propagation induced by combustion induced vortex breakdown (CIVB).

Flashback due to the first two foregoing mechanisms has been studied extensively for pure fuels [3]. Generally, analytical theories and experimental determinations of laminar and turbulent burning velocities model these mechanisms with sufficient precision for design usages. However, the effects of composition variations on flashback propensity of fuel blends, such as syngas, are largely unknown.

The presence of hydrogen in syngas significantly increases the potential for flashback. Due to high laminar burning velocity and low lean flammability limit, hydrogen tends to shift the combustor operating conditions towards flashback regime. Even a small amount of hydrogen in fuel mixtures triggers the onset of flashback by altering the kinetics and thermo physical

characteristics of the mixture. Furthermore, the swirling flow complicates the flashback processes in premixed combustors and the boundary layer flame propagation inadequately describes the flashback propensity of most practical combustors. Recent investigations suggest that the CIVB mechanism is an important flashback process in swirl stabilized burner [4-5].

1.1 Research Objectives

The major challenges for gas turbine combustors of advanced power systems are to achieve very low pollutants emissions (NOx < 2 ppm), fuel variability, and fuel flexibility. And also gas turbine combustors should tolerate fuel compositions ranging from natural gas to a broad range of syngas without sacrificing operational advantages. The primary objectives are:

1. To determine the effects of burner diameter and fuel compositions (H_2-CO mixtures) on boundary layer flashback process;
2. To develop a fundamental understanding of the effects of fuel (syngas) composition on CIVB flashback limits in swirl stabilized gas turbine combustors;
3. To determine the flow-field conditions experientially in order to establish design space for CIVB flashback safety;
4. To determine the reaction zone (OH concentration) during CIVB flashback process; and
5. To investigate how turbulence and chemistry intrigue each other during the CIVB flashback process.

1.2 Thesis Organization

Chapter 1 provides an outline of the future generation gas turbine combustors, which should tolerate fuel compositions ranging from natural gas to a broad range of syngas without sacrificing operational advantages and low emission characteristics and should have the ability to

achieve fuel variability and fuel flexibility. Further, this chapter discusses the objectives and scope of study.

Chapter 2 provides a summary of the technical background on hypothetical basis by which conclusions of the experimental data will be drawn.

Chapter 3 provides an outline of the detailed experimental setup in determining the sequences of boundary layer flashback and CIVB driven flashback. The instrument used to carry out the research includes flashback burner, swirl stabilized burner.

Chapter 4 presents the comparison and justification of the results for flashback of different syngas fuels with respect to varying fuel compositions.

Chapter 5 concludes the results and provides the scope for further research.

1.3 Practical Relevance

Flashback is a major design challenge for swirl stabilized low emission premixed combustors configured for fuel variability and flexibility. The high concentration of hydrogen in synthesized and alternative fuels (syngas) increases the flashback propensity of turbine combustors. The outcomes of the research will provide a critical insight for developing flashback control techniques for combustors fueled with syngas. Through systemic experimentations the research will investigate the effects of burner configurations and syngas fuel compositions on flashback propensity due to boundary layer. The research will also explore aerodynamic modifications of near burner flow structures to avoid CIVB flashback. The information gained from the research will improve the understanding of flashback and aid in the development of design tools for fuel flexible turbine combustors.

1.4 Center for Space Exploration Research Technology

The Center for the Space Exploration Technology Research (cSETR) (formerly the Combustion and Propulsion Research Lab) is located in Mechanical Engineering Department at The University of Texas at El Paso. The Center provides computational and experimental research related to the field of combustion, fluid mechanics and propulsion with a wide range of software and equipment. The primary focus of the research is in the development of micro-propulsion and micro-combustion technologies. The laboratory has state of the art burner and combustor systems, which includes flat flame, nozzle, twin flame counter flow, and swirl stabilized burners. The burner systems are modular and can be changed to various experimental configurations based on work. The burner systems are fitted with pressure sensors, heat flux sensors, fast thermocouples, and digital mass flow controllers, and data acquisition systems. The laboratory also has sophisticated flow excitation systems (signal processor, USB audio interface, amplifier, speakers, and probe microphones) required for combustion instability research. These systems are used to determine combustion characteristics (i.e. flame speed, flashback propensity and flame extinction limits). Apart from these, the Center also provides a collection of optical instrumentation; high speed cameras; an intensified charge-coupled device (CCD) camera; laser based measurement techniques, such as particle image velocimetry (PIV); and a vacuum chamber to replicate the space atmosphere, which completes the necessary equipment for propulsion systems development. Current fluid dynamics instrumentation includes a laser doppler velocimeter (LDV), a PIV, a stereo particle image velocimeter, a high speed particle image velocimeter (HPIV), a multi-channel hotwire (thermal) anemometry system, a spectroscopy system (imaging spectrograph; detectors; control and gating electronics), thermal

imaging systems, intensified high speed camera, various flow controllers, flow meters, and high speed data acquisition systems.

2.0 Background

2.1 Flashback Propensity in Boundary Layers

In their classical study Lewis and von Elbe [3] defined the term ‘boundary velocity gradient’ to explain the boundary layer flashback process. If the velocity profile at the flame is linear, the velocity gradient g can be defined as

$$\mathbf{g = \frac{u_b}{y}} \qquad \textbf{[1]}$$

where y is the distance from the stream boundary and u_b is the unburned gas velocity. Eq [1] is generally true for a large diameter burner tube. The velocity gradient (g) decreases with the decrease in unburned gas velocity, and the flame stabilizes at a position close to the burner leap. When the unburned gas velocity becomes smaller than the burning velocity (S) the flame propagates downstream against the unburned gas flow. This condition is referred to as the boundary layer flashback, and the critical value of ‘g’ at which the flashback condition is observed is denoted by g_F. From experimentally determined flow rates, Lewis and von Elbe [10] calculated g_F for natural gas-air mixture at room temperature and pressure for various cylindrical tube diameters.

The critical value, g_F, primarily depends on the laminar burning velocity (S_L) and can be expressed as

$$\mathbf{g_F = \frac{S_L}{d_p}} \qquad \textbf{[2]}$$

where d_p is the flame penetration distance which generally correlates with the quenching distance (dq) as follows

$$\mathbf{d_p = ad_q} \qquad \textbf{[3]}$$

where a is a burner constant. The quenching distance d_q again broadly depends on the laminar

burning velocity and the mixture thermal diffusivity

$$\mathbf{d_q = 2\sqrt{b}\,\frac{\alpha}{S_L}} \quad \textbf{[4]}$$

where b is a burner scaling constant. Combining equations 2 to 4 yields

$$\mathbf{g_F = c\frac{S_L^2}{\alpha}} \qquad \textbf{[5]}$$

where $\mathbf{c = \frac{1}{2a\sqrt{b}}}$

If S_L and 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.

Flashback due to combustion instabilities occurs in various combustor conditions even when flame propagation in the boundary layer is not possible [6-7]. Combustion instabilities are the product of complex non-linear interactions of pressure fluctuations, periodic heat release and flow hydrodynamics. Combustion instabilities can cause the flame to propagate upstream periodically during the pulsation cycles [8-10].

Turbulent flame propagation in the core flow occurs generally in highly swirling flow where local burning velocity [Turbulent flame speed $S_T \sim S_L + u'$] supersedes local flow velocity. A highly swirling flow (swirl number > 0.7) extends the flame surface and triggers the onset of flashback along the burner axis [11]. Although specific literature on the effects of syngas compositions on flashback due to turbulent flame propagation is limited, generally the topic of turbulence-kinetics interactions is well studied [12-14]. Additionally, recent literature addressed various issues of turbulent flame propagation flashback in premixed combustion [4-5, 15].

2.2 Flashback Due to Combustion Induced Vortex Breakdown (CIVB)

In their CFD analysis, T. sattelmayer defined the CIVB driven flashback of highly turbulent methane-air flames with hub less swirler. Based on this analysis, it is noticed that the highly swirling (center body swirler) flows of H_2-CO mixtures make more stabilized recirculation zone after flow separation. The relevant effects for the CIVB driven flashback of H_2-CO mixtures are described schematically in Figure 2.1.

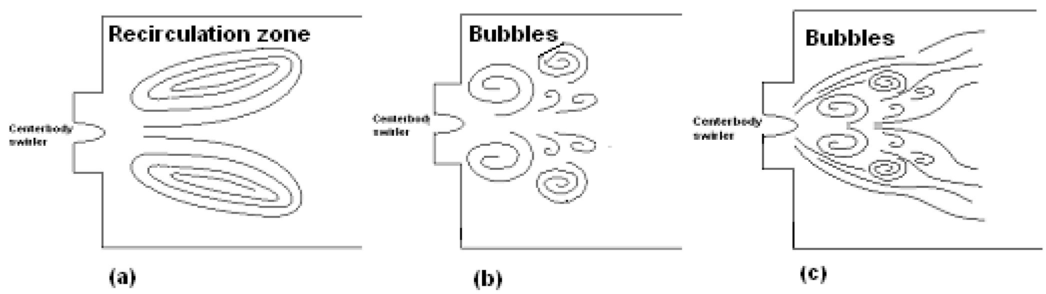

Figure 2.1 Sketches of the Effects of CIVB Driven Flashback

a) The highly swirling flows of H_2-CO mixtures make more stabilized recirculation zone right after the centerbody of the swirler in specific ranges of equivalence ratio. The swirler spinning the flow such a way that it turns around and tries to anchor the flow in front of the centerbody and tends to move upstream. In specific ranges of equivalence ratio the unburnt H_2-CO mixtures from upstream come to equilibrium position with the mixture of burnt and unburnt gases from downstream in front of the centerbody and eventually make a stabilized recirculation zone.

b) If the equivalence ratio is increased, hydrogen tries to diffuse faster than others to the downstream due to its high mass diffusivity. The swirler tries to anchor the flow in front of the centerbody; on the other hand, hydrogen diffuses quickly to the downstream and

changes the equilibrium position. It starts to breakdown stabilized recirculation zone and forms bubbles.

c) If the equivalence ratio is further increased, the recirculation zone is distorted completely, forms bubbles, and tends to move the flame to the upstream.

2.3 Methodology

A design of experiments has been generated to systematically investigate the effects of syngas compositions [%H_2, %CO, %CH_4 and %CO_2] on the flashback propensity of the laboratory combustors. Through experimental observations, the flashback conditions in terms of burner configurations [swirl number and swirler geometries: swirler with center body], mass-flow rate, and equivalence ratio is mapped. Based on the flashback regime mapping, the flow-fields that led to the CIVB flashback were analyzed.

3.0 Experimental Facilities

3.1 Boundary Layer Flashback Burner

The flashback burner system shown in Figure 3.1 has four primary components: (a) mixing manifold, (b) flow excitation hub (base, speaker and speaker housing), (c) flow conditioner (honeycomb, honeycomb housing and wire mesh), and (d) burner tube assembly (converging nozzle, glass tubes, glass tube adapters, adjustable supports, and c-clamps). The converging nozzle section seamlessly merges with the adapters to accommodate glass tubes of different diameters (10.6 mm, 7 mm and 6 mm). The fuel and air enter into the manifold through four alternate injection holes. The fuel-air mixture then passes through the flow conditioning section to eliminate injection induced flow irregularities and to ensure laminar flow through the burner tube. Since the burner system is also designed to analyze the flashback with external excitation, the bottom part of the injection manifold opens to a flow excitation hub section. The flow excitation segment consists of a thin copper membrane vibration source fed by a 100-W speaker.

Figure 3.1 Experimental Setup: Boundary Layer Flashback

In the forced flow configuration, various synthesized signals are fed to the speaker by an amplifier and a computer controlled audio signal synthesizer combination. The burner is located in a vertical combustion chamber, which has a window opening over one side for the ignition system. The top of the combustion chamber was open to atmosphere through an exhaust duct. The flame was ignited at a flow rate higher than the expected critical flow rate. During an experiment, the flow rate was reduced in small increments while keeping the composition constant until the flame propagated back into the tube. A high-speed direct video imaging system (FASTCAM Super 10K) was used to confirm the flashback condition. The critical boundary velocity gradient g_F for different compositions of hydrocarbon fuel blends and syngas were calculated using the following relation

$$g_F = \frac{4\mathbb{V}}{\pi d^3} \qquad [6]$$

where V is experimentally measured volumetric flow rate at flashback condition and d is the tube

diameter. 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.

3.2 Swirl Stabilized Burner

The swirl flow combustor rig [Figure 3.2] has three configurable modules: (i) inlet manifold with static mixture, (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 fuel and air enter into the inlet manifold through five alternate injection holes. The fuel-air mixture then passes through the static mixer to eliminate injection induced flow irregularities. The quartz glass mixing tube is needed for the high speed imaging of the flashback inside the premixer. The swirl burner module can accommodate both center body and hub less swirlers. Depending on the test conditions, the burner system can accommodate a rectangular or a circular combustion chamber. Digital images of the flame are captured with a high definition camcorder to see the sequences of flashback. High resolution direct imaging and high speed PIV systems with intensified camera systems will be employed to investigate combustor operability issues. Experimental uncertainties (bias + random errors) of present measurements are less than ±0.5% of the mean value. All H_2-CO mixture compositions reported in this article are volumetric percent.

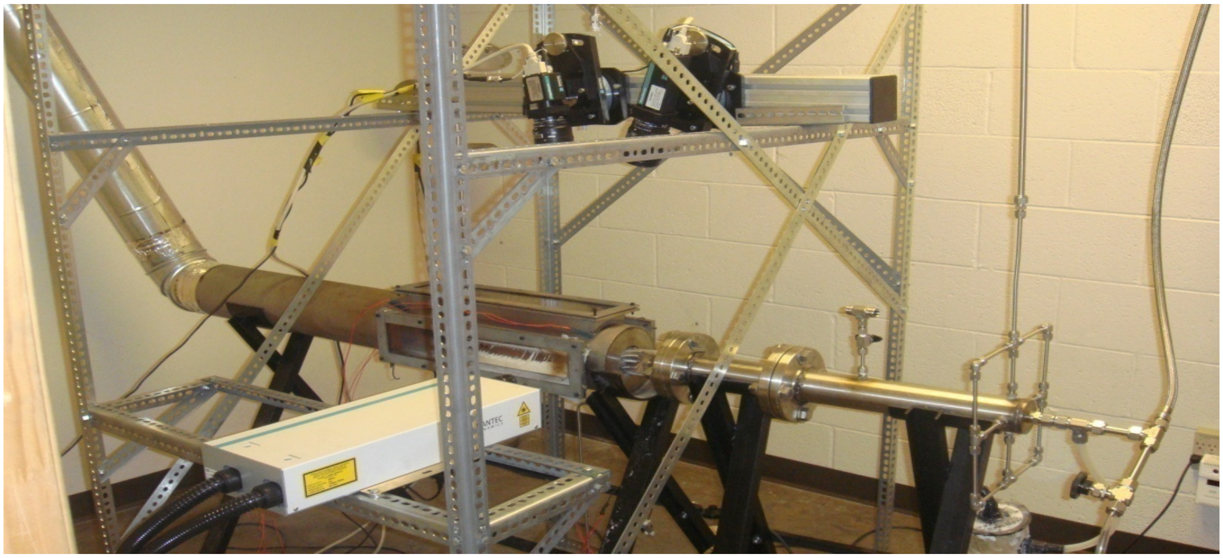

Figure 3.2 Experimental Setup: Swirl Combustor

All the gases (H_2, CO, CO_2, N_2, and Air) are stored separately in gas cylinders under 1600 psi pressure. The purity of these gases is 99%. Different flow meters are used in this experiment to maintain volumetric flow rate ranges from 0 to 500 LPM. Manual precision metering valves in conjunction with low-torque-quarter-turn plug valves are used to control and meter fuel and air flow rates. Prior to each experiment, mass flow meters are calibrated using a laser based mass flow meter calibrator.

3.3 Flow Measurement Devices and Data Acquisition

3.3.1 Flow Meter

Digital mass flow meters (Omega FMA 1700/1800 series in Figure 3.3 were used to measure the mass flow rate of air and fuel. The specifications of the mass flow meters are: temperatures ranging from 0°C to 50°C, pressures up to 500 psig, relative humidity of 70%, and accuracy ±1.5% of full scale. The mass flow meters used in the present study varied in full scale ranges 0 to 10 L/min, 0 to 10 L/min, and 0 to 500 L/min. Prior to each experiment, flow meters are calibrated by using Dry Cal Meter Calibrates as shown in Figure 3.4.

Figure 3.3 Digital Mass Flow Meter

Figure 3.4 Dry Cal Calibrator

3.3.2 Metering and Shutoff Valves

Manual precision metering valves (SS-SS4VH in Figure 3.5) in conjunction with low-torque-quarter-turn plug valves were used to control and meter fuel and air flow rates. The

Shutoff values (SS-4P4T4 in Figure 3.6) were used to shut off the fuel flow from the pressurized gas cylinders.

Figure 3.5 Swagelok SS-SS4VH Metering Value 1

Figure 3.6 Swagelok SS-4P4T4 Shutoff Value 1

4.0 Results and Discussion

4.1 Visual Observation and Qualification of the Test Apparatus

Flame images at a typical flashback condition are presented in Figure 4.1. The flame attaches to parts of the burner inner surface due to a slow locally unburned velocity near the wall. The partial flame inside the burner tube heats the tube wall and increases the temperature of the upstream fuel-air mixture. The flame then rapidly moves inside the burner to cause a flashback. Figure 4.2 shows the partially penetrated flame superimposed on flow stream lines [3]. 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 were measured to reproduce the data provided by the Lewis and von Elbe [3] work. Figure 4.3 shows the measured g_F values in the present study plotted with the Lewis and von Elbe's measurements. Present measurements agree fairly well with the previously reported data.

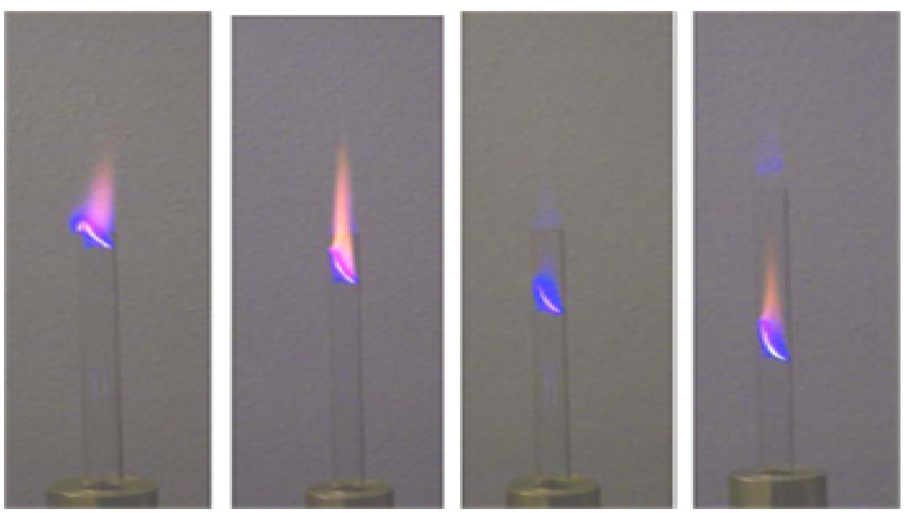

Figure 4.1 Boundary Layer Flashback Process

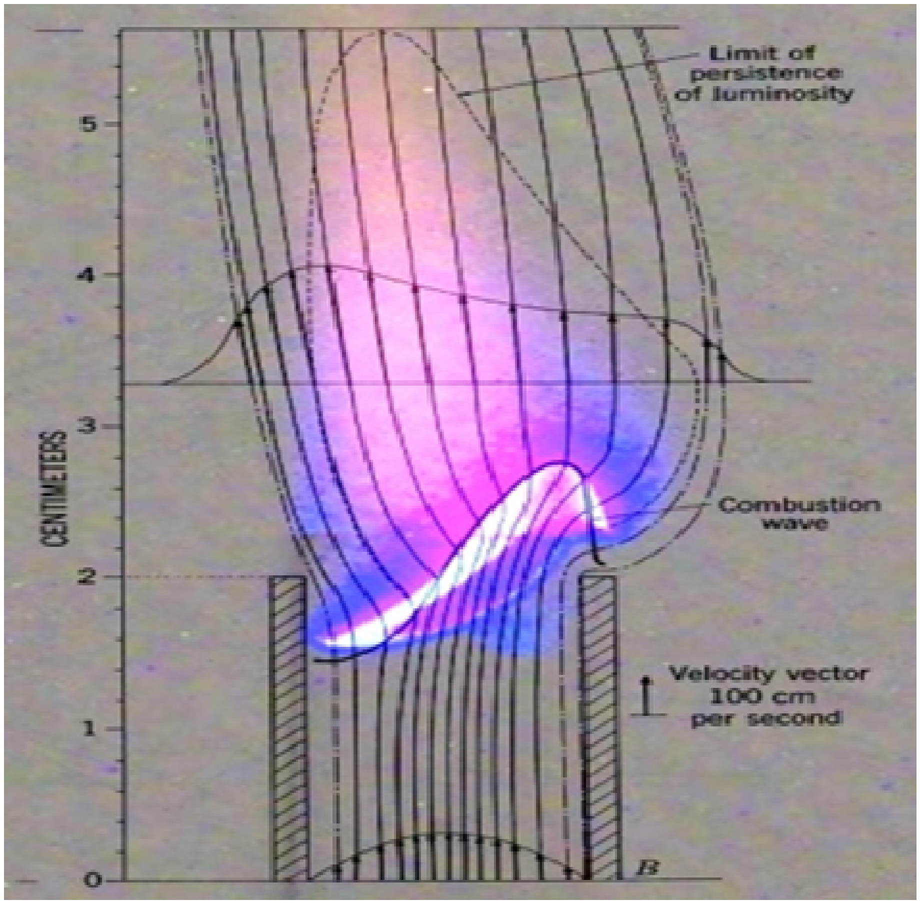

Figure 4.2 Streamlines of a Partial Flame Penetration

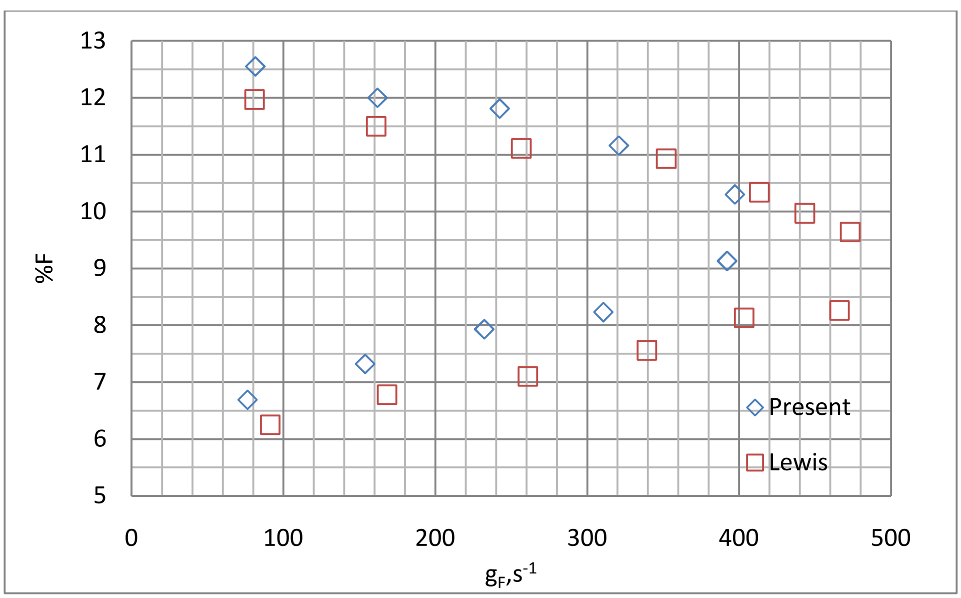

Figure 4.3 Comparisons of Present Measurements and Data [3]

Figure 4.4 shows the typical CIVB flashback sequence. In the first snap, flame was stabilized in front of the swirler. Next, the flame slowly moves upstream of the center body and then starts to oscillate. The oscillation frequency increases with the increase in equivalence ratio. With a further increase in equivalence ratio the flame stabilizes upstream of the center body.

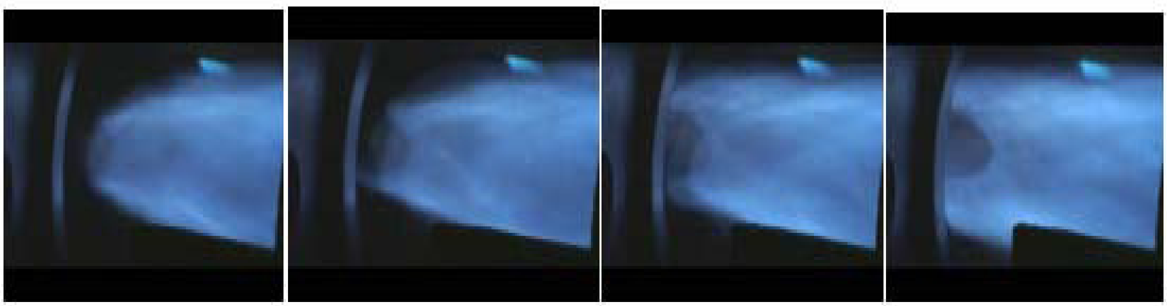

Figure 4.4 CIVB Driven Flashback Process

Figure 4.5 shows that the results obtained by the CFD analysis are the same as the actual flow field generated by the swirler. With the experimental setup ready to operate, experiments were performed to investigate the effects of syngas compositions [ranging from 5%H_2-95%CO to 25%H_2-75%CO] on the flashback propensity.

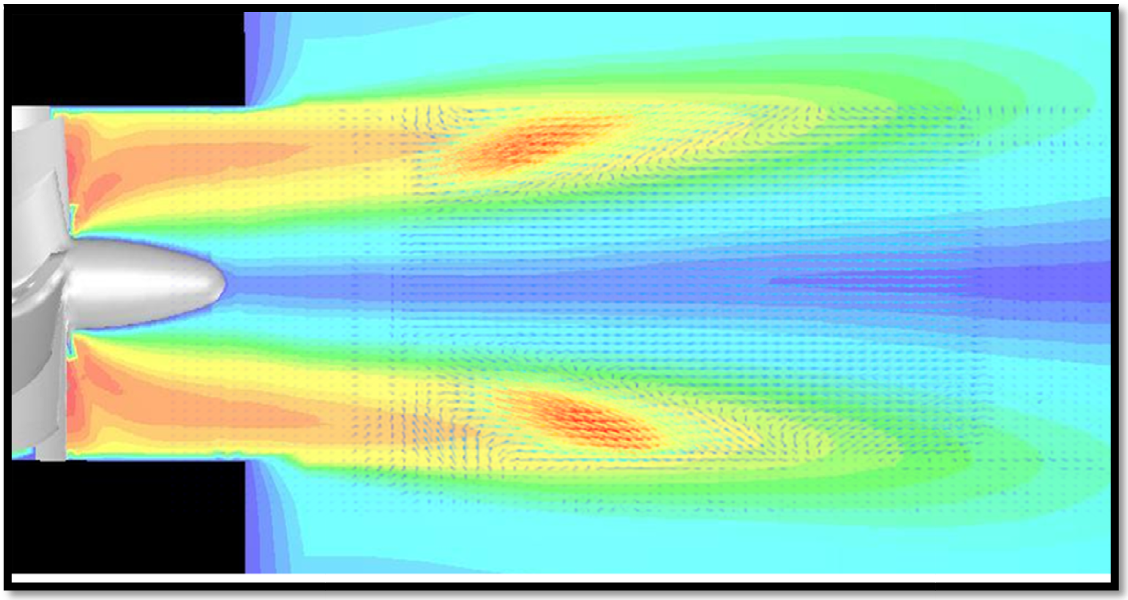

Fig. 4.5 Vector Flow Field obtained using the PIV Technique Superimposed with the CFD Contour Velocity

In addition to the flashback maps, experimental fluid mechanics techniques were used to delineate interactions between flame and flow field at various syngas compositions.

4.2 Scaling with the Laminar Burning Velocity

Equation 5 shows a generally accepted scaling relation between g_F, S_L and α. The scaling constant, c, in Equation 5 is related to the burner dimension and does not necessarily capture the effects of fuel compositions. During the initial formulation of Equation 5, it was assumed that the fuel effects were captured in the variation of S_L and α value. However, the measured values of g_F at different concentration of H_2 in H_2-CO mixtures clearly indicate that other transport processes, such as preferential diffusion, may also have significant effects on boundary layer flashback propensity. Thus, a higher order formulation may be necessary to capture both fuel and burner effects. Figure 4.6 shows the g_F values measured at a 7-mm diameter burner fitted in the scaling relation. The g_F values of 5%-95%, 15%-85%, and 25%-75% H_2-CO mixtures somewhat agree

with the scaling relation and yield an average c value of 0.038. The S_L and α value are computed with the CHEMKIN kinetic code using the GRI 3.0 mechanism.

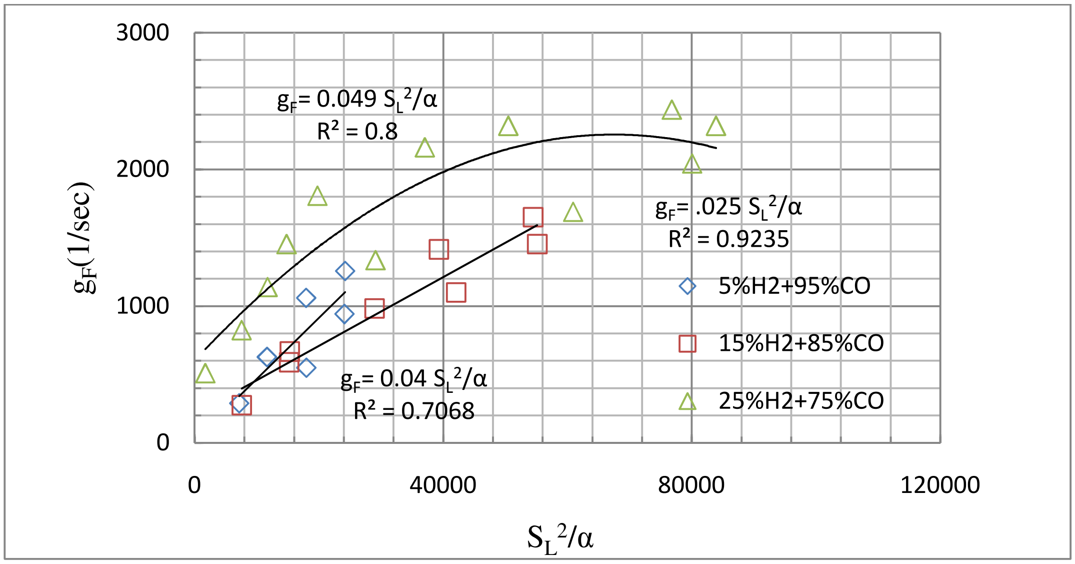

Figure 4.6 Scaling of g_F and S_L^2/α (7.0-mm Burner)

Figure 4.7 shows the g_F values of 25%-75% H_2-CO mixture measured at different burner diameters and plotted against the scaling ratio S_L^2/α. It appears that at a lower S_L^2/α ratio there are insignificant effects of burner diameters, however the data diverge at a higher S_L^2/α ratio.

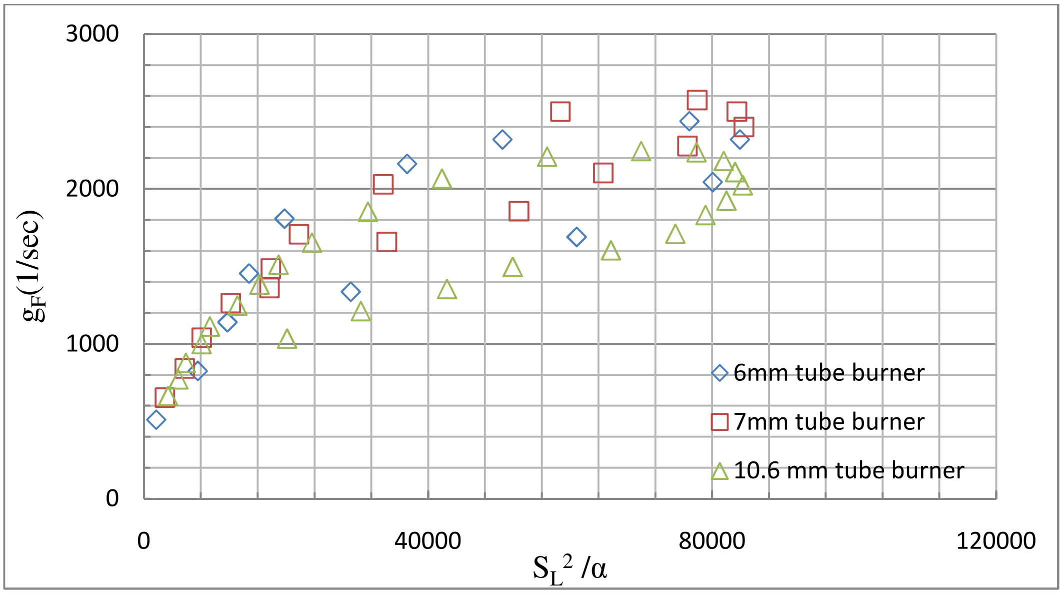

Figure 4.7 Scaling of g_F and S_L^2/α (25%-75% H_2-CO Mixture)

4.3 Effects of Fuel Composition on CIVB Flashback Map

Figure 4.8 shows the flashback limits (slow and oscillating; swirl number 0.71) of the combustor at different mixture compositions and equivalence ratios. The effect of hydrogen concentration on the CIVB flashback is clearly evident in Figure 4.8. For a given U_{bulk}, the %F at which the CIVB flashback occurs decreases with the increase in hydrogen concentration in fuel mixtures.

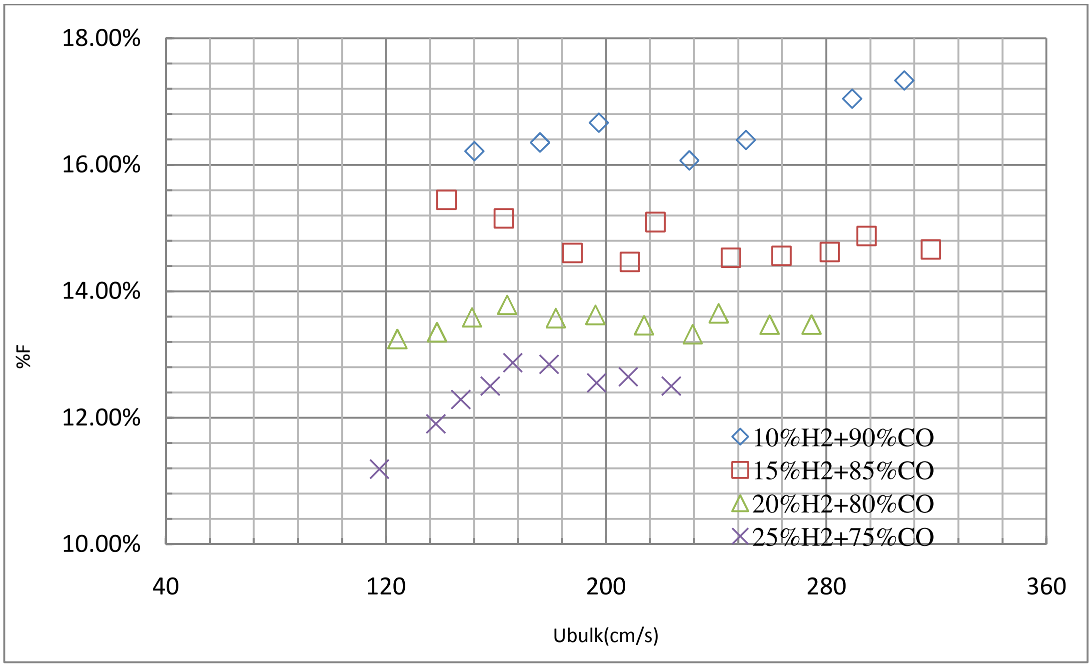

Figure 4.8 Flashback Map of the Swirl Combustor with 6 Vane Swirler (Swirl Number S = 0.71)

Similarly Figure 4.9 shows the flashback limits (slow and oscillating; swirl number 0.97) of the combustor at different mixture compositions and equivalence ratios. The effect of hydrogen concentration on the CIVB flashback is clearly evident in Figure 4.9. For a given U_{bulk}, the %F at which the CIVB flashback occurs decreases with the increase in hydrogen concentration in fuel mixtures.

Table 4.1: Compositions of Synthesized gases						
Gasification	Type of coal	CO (%)	H_2 (%)	CH_4 (%)	N_2 (%)	CO_2 (%)
Coal	Brown coal	16	25	5	40	14
	Bituminous	17.2	24.8	4.1	42.7	11
	Lignite	22	12	1	55	10
	Coke	29	15	3	50	3
Wood		21	21	1.83	43	12

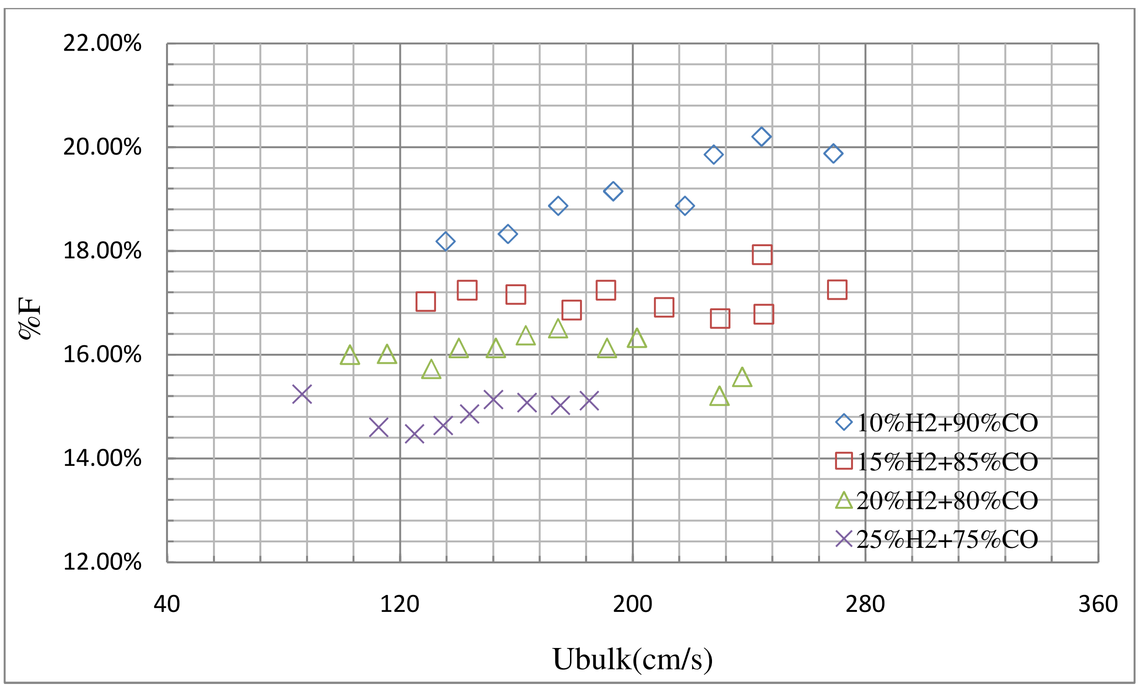

Figure 4.9 Flashback Map of the Swirl Combustor with 12 Vane Swirler (Swirl Number S=.97)

In Figure 4.10 the actual syngas compositions flashback map is shown; the presence of diluents is shown to play a vital role to map the flashback regimes. As previoulsy mentioned, for a given U_{bulk}, the %F at which the CIVB flashback occurs decreases with the increase in

hydrogen concentration in fuel mixtures. For a given U_{bulk} of brown and bituminous coal derived syngas compositions, the %F at which the CIVB flashback occurs is close to each other because of nearly similar compositions but differs from lignite and coke coal derived syngas compositions due to the presence of higher percentage of hydrogen and diluents (N_2, CO_2). For a given U_{bulk}, the %F at which the flashback occurs increases with the increase in diluents (N_2, CO_2) concentration in fuel mixtures.

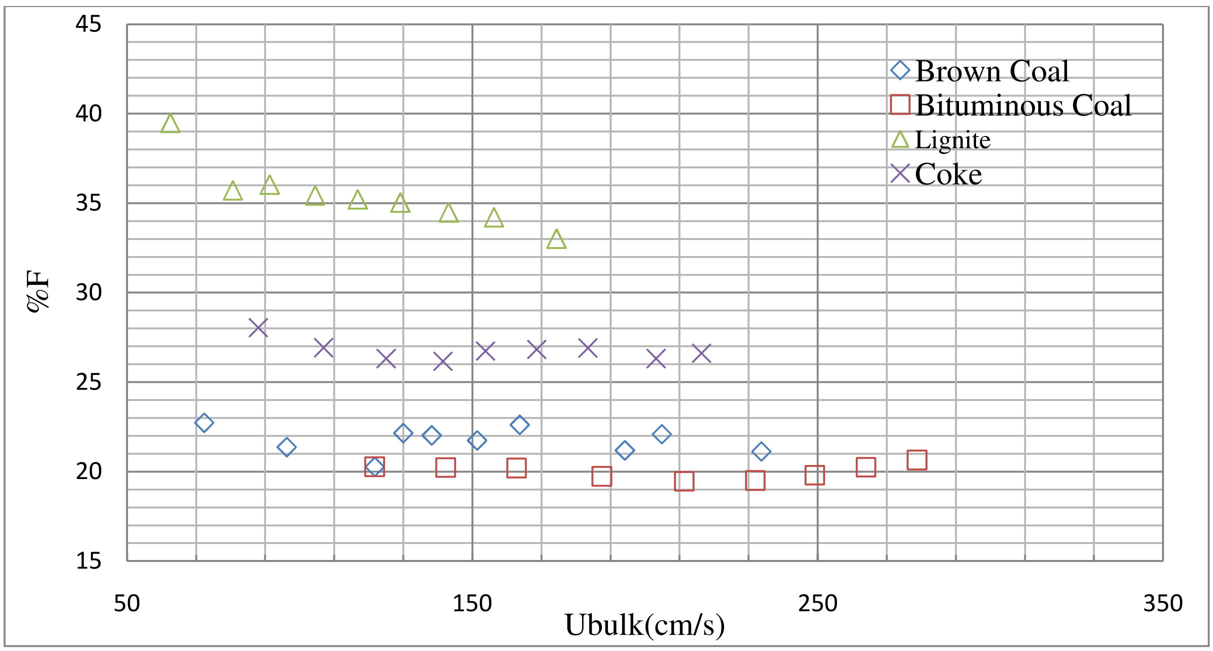

Figure 4.10 Flashback Map of the Swirl Combustor for Actual Syngas Compositions with 12 Vane Swirler (Swirl Number S=.97)

As mentioned earlier, the presence of diluents decrease the burning velocities of any mixture of fuel. Along with turbulence, burning velocity also dictates the flashback phenomenon.

4.4 Effects of Swirl on CIVB Flashback

Figure 4.11 shows the effect of swirl (based on swirl number) on the CIVB flashback. The 12 vane swirler (swirl number S = 0.97) makes a more stabilized recirculation zone and stabilized flame as compared to the 6 vane swirler (swirl number S = 0.71). Figure 4.11 clearly

indicates that the 6 vane swirler is more prone to CIVB flashback than 12 vane swirler. For a given U_{bulk}, the %F at which the CIVB flashback occurs increases with the increase of swirl number.

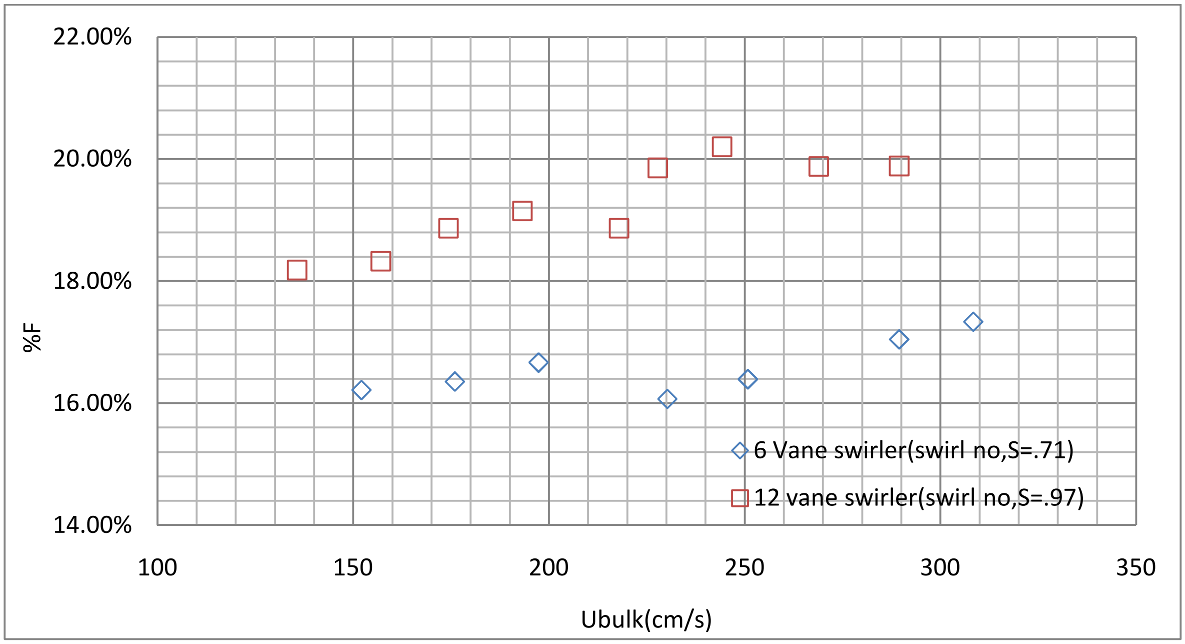

Figure 4.11 Comparison between 6 Vane (Swirl Number S=.71) and 12 Vane (Swirl Number S=.97) Swirler Strength for Flashback Map

4.5 Characterization of CIVB Driven Flashback

The intensifier system is available with a multialkali photocathode that has a wide range of spectral response ranges from ultra-violet (UV) through near infrared, and hence capable of identifying the OH* chemiluminescence from the flame region zone. It was employed to visualize the CIVB driven flame propagation to the upstream and also to characterize the reaction zones of the flame front during flashback. The recordings have been made at a frame rate of 1000 images per second.

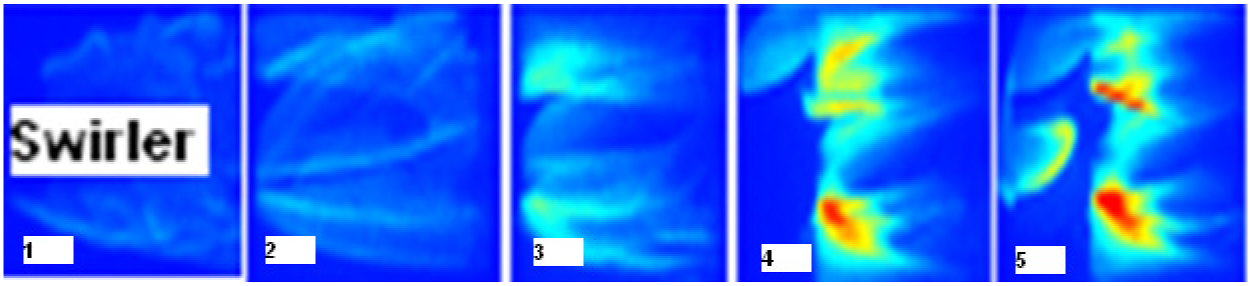

Figure 4.12 OH Concentration Distribution in the Flame Front during Flashback Sequences (1-5) [6 Vane Swirler with 10%H2+90%CO]

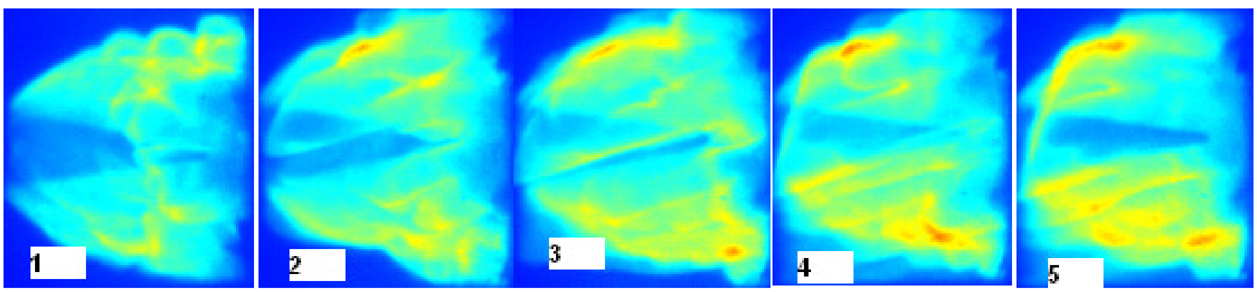

Figure 4.13 OH Concentration Distribution in the Flame Front during Flashback Sequences (1-5) [12 Vane Swirler with 10%H2+90%CO]

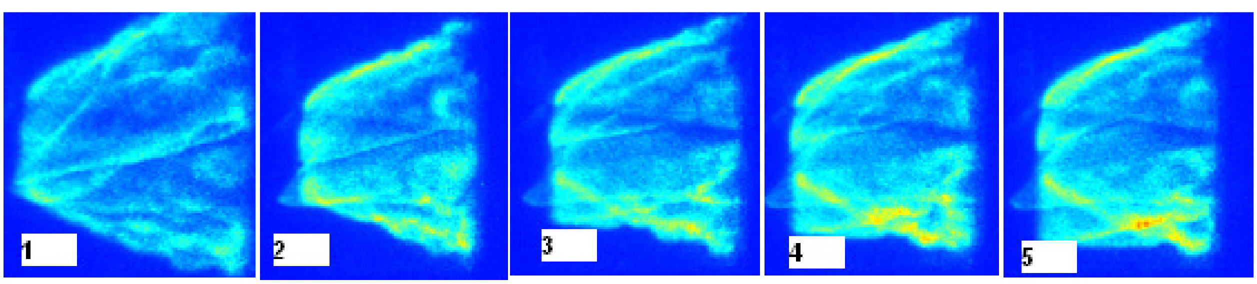

Figure 4.14 OH Concentration Distribution in the Flame Front during Flashback Sequences (1-5) [12 Vane Swirler with Bituminous Coal derived Syngas Compositions]

Figures 4.12 through 4.14 show the OH concentration zone of the flame front during flashback. The 12 vane swirler (swirl number S = 0.97) produces more OH concentration (1 through 5 sequence images) after the flow separation compare to the 6 vane swirler (swirl

number S = 0.71). The main purpose of the swirler is to maintain a stabilized recirculation zone for flame stabilization and to ensure proper mixing of the fuel and oxidizer for complete combustion.

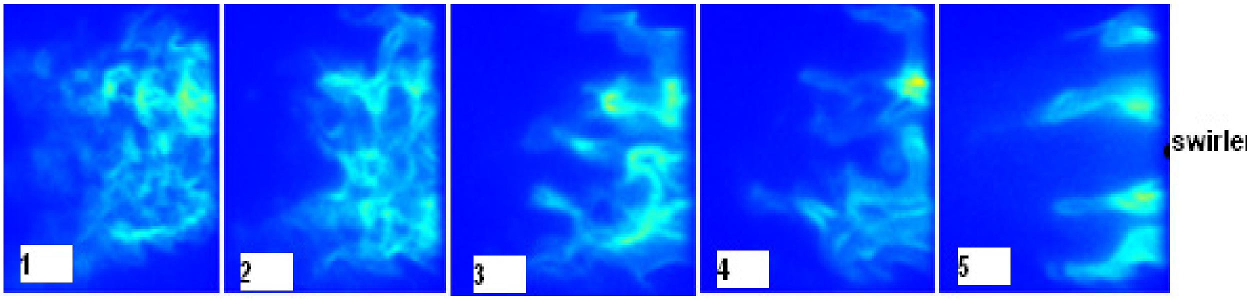

Figure 4.15 OH Concentration Distribution in the Flame Tail during Flashback Sequences (1-5) [6 Vane Swirler with 10%H2+90%CO]

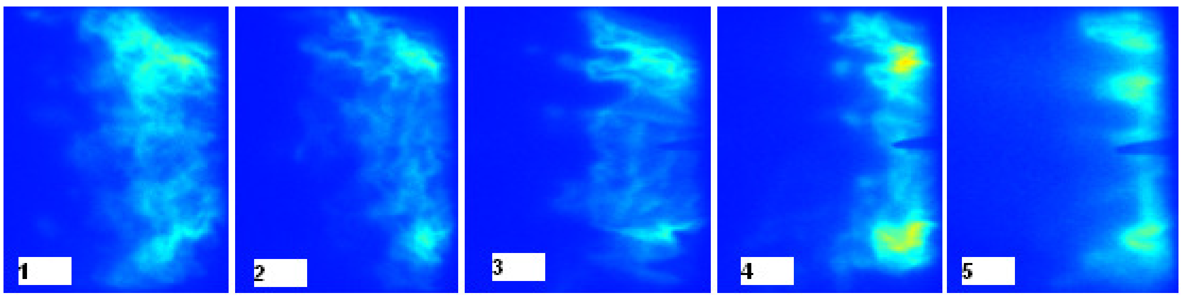

Figure 4.16 OH Concentration Distribution in the Flame Tail during Flashback Sequences (1-5) [12 Vane Swirler with 10%H2+90%CO]

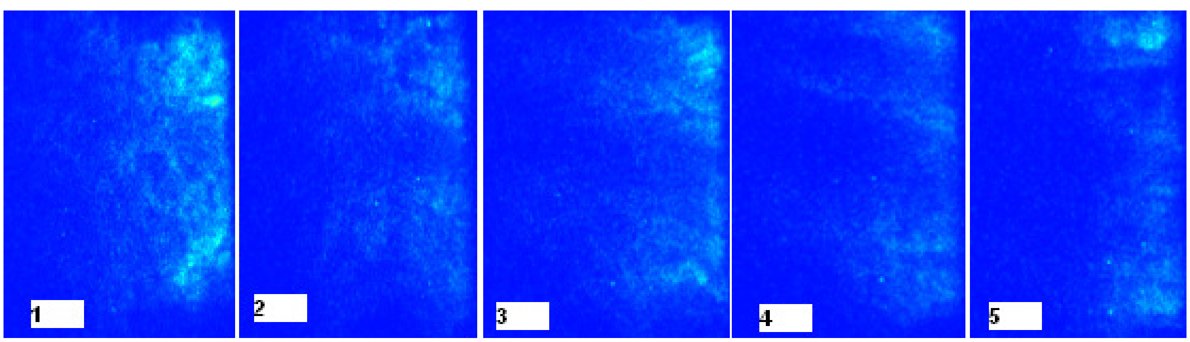

Figure 4.17 OH Concentration Distribution in the Flame Tail during Flashback Sequences (1-5) [12 Vane Swirler with Bituminous coal derived Syngas Compositions]

The strong swirled flow produces a more stabilized reaction zone (OH concentration) just after the swirler. Figure 4.14 shows less OH concentration because of the presence of diluents in the bituminous coal derived syngas compositions.

A high speed PIV system includes a high speed camera, Litron LDY 300 series laser (1 kHz), and scitek PS-10 Remote Operation Powder Seeder. This system was applied to track the flow field during the CIVB driven flashback sequences.

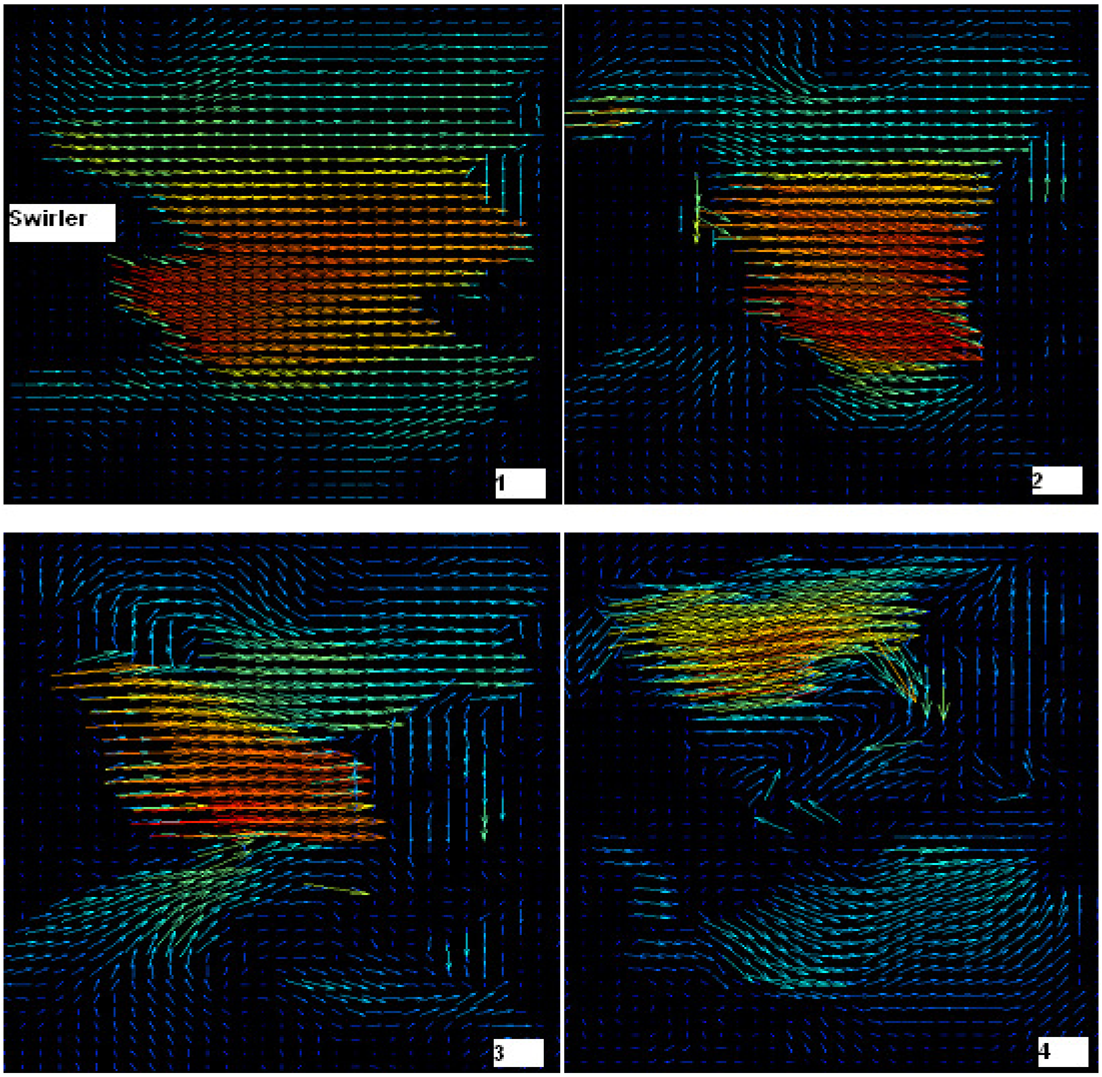

Figure 4.18 Vector Flow Field Sequences (1-4) During Flashback

[12 Vane Swirler with 10%H2+90%CO]

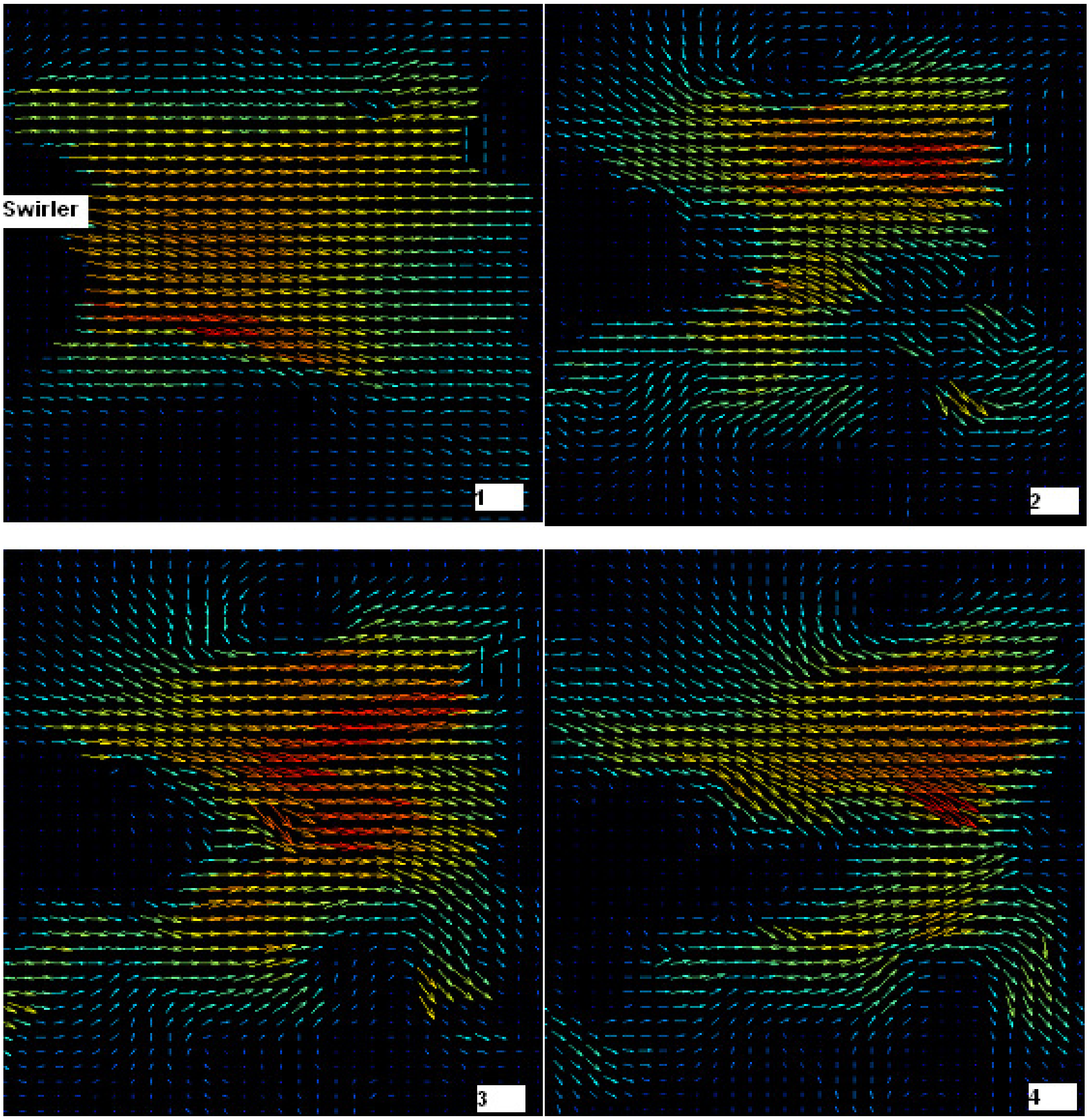

Figure 4.19 Vector Flow Field Sequences (1-4) During Flashback

[12 Vane Swirler with Brown Coal derived Syngas Compositions]

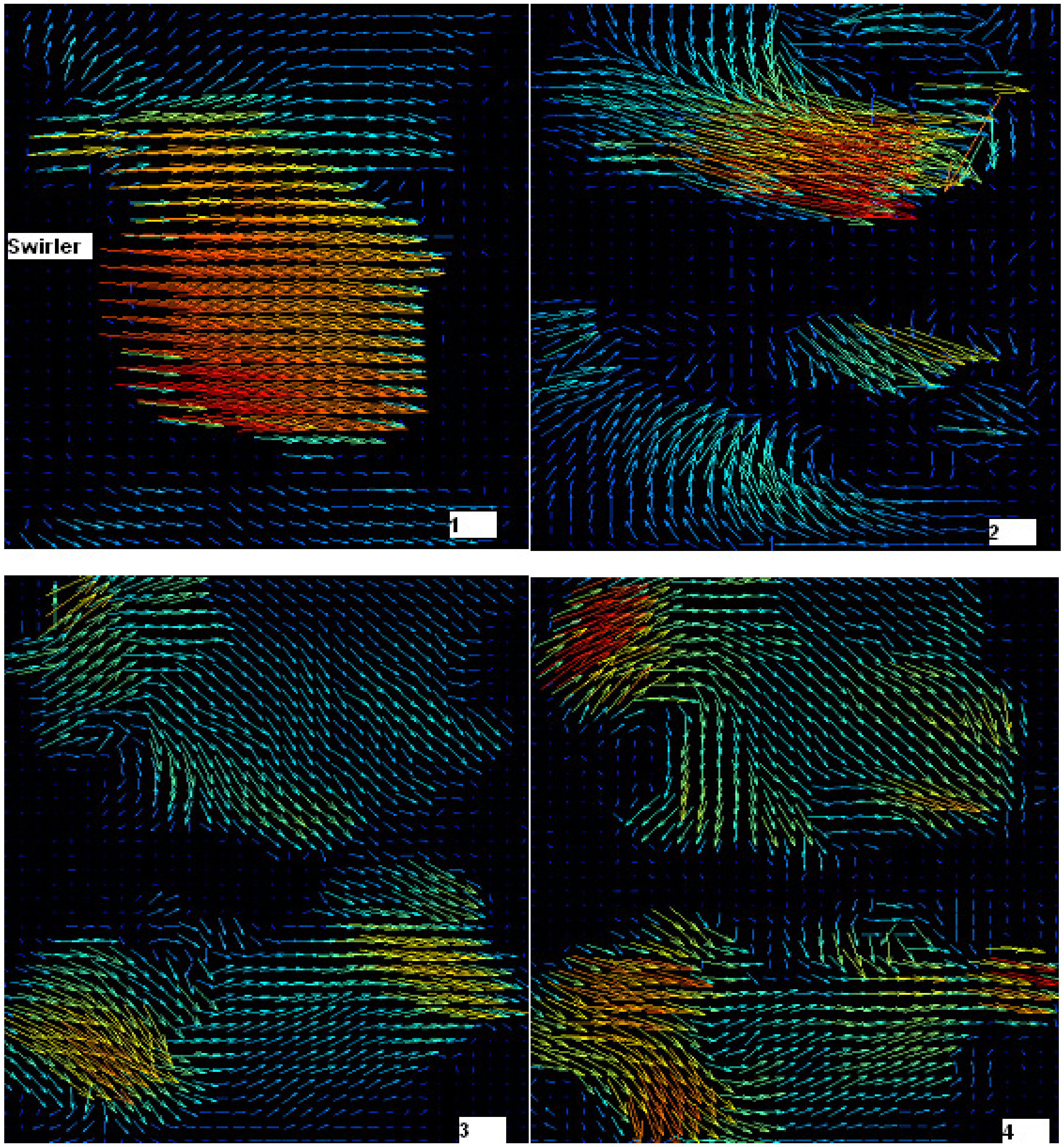

Figure 4.20 Vector Flow Field Sequences (1-4) During Flashback

[12 Vane Swirler with Coke Coal derived Syngas Compositions]

Figures 4.18 through 4.20 show the vector flow field during flashback with different operating conditions. The sequences for different conditions are almost same. In the first snap, the flame was stabilized in front of the swirler making stabilized recirculation zone. Next, the flame slowly starts to distort the flow field with the increase in equivalence ratio. With a further

increase in equivalence ratio, the flame completely distorted the stabilized recirculation zone and propagated upstream.

5.0 Conclusions

For a given U_{bulk}, the %F at which the CIVB flashback occurs decreases with the increase in hydrogen concentration in fuel mixtures.

For a given U_{bulk}, the %F at which the CIVB flashback occurs increases with the increase of swirl number.

For a given U_{bulk}, the %F at which the flashback occurs decreases with the decrease in diluents (N_2, CO_2) concentration in fuel mixtures.

Among actual syngas compositions derived from different coal source, for a given U_{bulk}, lignite coal derived syngas compositions have higher %F at which the flashback occurs.

The strong swirled flow produced a more stabilized reaction zone (OH concentration) just after the swirler, and the flame was stabilized in front of the swirler making a stabilized recirculation zone. With a further increase in equivalence ratio, the flame completely distorted the stabilized recirculation zone and propagated upstream.

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Curriculum Vita

Bidhan Kumar Dam was born on December 1, 1978 to Shymol Dam and Renuka Dam. He graduated with a Mathematics and Science Degree at the Cantonment College (Jessore, Bangladesh) in 1996. In 2004, he received his Bachelor's of Science Degree in Chemical Engineering and Polymer Science from Shahjalal University of Science and Technology, Bangladesh. He also received a Master's of Business Administration Degree from the University of Dhaka, Bangladesh. Ultimately, he completed his Masters of Science in Mechanical Engineering in 2009, focusing his research in the Center for Space Exploration Technology Research (formerly Combustion and Propulsion Research Lab) under the guidance of Dr. Ahsan Choudhuri, Ph.D.

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