Flashback Characteristics of Syngas-Type Fuels Under Steady and Pulsating Conditions

Annual Report

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1. ABSTRACT

The objective of this project is to improve the state of the art in understanding and modeling of flashback, which is known to be a significant issue in low emissions combustors containing high levels of hydrogen. During this reporting period, extensive progress was made in several areas. Experimental studies were performed over a range of fuel compositions, flow velocities, reactant temperatures, and combustor pressures to study the factors leading to flashback. In addition, our experimental setup was redesigned to facilitate high speed flashback visualization. One of the key findings was that there exist multiple mechanisms which can lead to flashback, each with different underlying parametric dependencies. Specifically, two mechanisms of "flashback" were noted: rapid flashback into the premixer, presumably through the boundary layer, and movement of the static flame position upstream along the centerbody. The former and latter mechanisms were observed at high and low hydrogen concentrations. In the latter mechanism, flame temperature, not flame speed, appears to be the key parameter describing flashback tendencies. We suggest that this is due to an alteration of the vortex breakdown location by the adverse pressure gradient upstream of the flame, similar to the mechanism proposed by Sattelmayer and co-workers [1]. As such, a key conclusion here is that classical flashback scalings derived from, e.g., Bunsen flames, may not be relevant for some parameter regimes found in swirling flames. Moreover, with higher pressure tests, it was found that rapid flashback became dominant regardless of the %H_2. Finally, it was found that in cases of higher pressure/temperature, pure H_2 flames could not be stabilized, i.e., the flame would either flashback or blowout at ignition. This result could have significant implications on the development of future high hydrogen turbine systems.

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4. EXECUTIVE SUMMARY

Under the DOE/NETL program, Georgia Institute of Technology is investigating the flashback characteristics of SYNGAS fuels under steady and oscillatory conditions. This program consists of three main tasks. The first task is to perform a design of experiments such that all the independent parameters can be examined. The next task is investigating the flashback limits under steady combustor conditions. The final task is that of investigating flashback limits under oscillatory conditions. Currently, flashback is a major issue in low emissions combustors when fueled with high H_2 levels. The information gained from this project will lend a better insight into preventing flashback occurrences when using alternative fuels.

During this reporting period, extensive progress was made in several areas. Experimental studies were performed over a range of fuel compositions, flow velocities, reactant temperatures, and combustor pressures to study the factors leading to flashback. In addition, our experimental setup was redesigned to facilitate high speed flashback visualization. One of the key findings was that there exist multiple mechanisms which can lead to flashback, each with different underlying parametric dependencies. Specifically, two mechanisms of "flashback" were noted: rapid flashback into the premixer, presumably through the boundary layer, and movement of the static flame position upstream along the centerbody. The former and latter mechanisms were observed at high and low hydrogen concentrations. In the latter mechanism, flame temperature, not flame speed, appears to be the key parameter describing flashback tendencies. We suggest that this is due to an alteration of the vortex breakdown location by the adverse pressure gradient upstream of the flame, similar to the mechanism proposed by Sattelmayer and co-workers [1]. As such, a key conclusion here is that classical flashback scalings derived from, e.g., Bunsen flames, may not be relevant for some parameter regimes found in swirling flames. Moreover, with higher pressure tests, it was found that rapid flashback became dominant regardless of the %H_2. Finally, it was found that in cases of higher pressure/temperature, pure H_2 flames could not be stabilized, i.e., the flame would either flashback or blowout at ignition. This result could have significant implications on the development of future high hydrogen turbine systems.

5. PROJECT DESCRIPTION

Under the DOE/NETL program, Georgia Institute of Technology is investigating the flashback characteristics of SYNGAS fuels under steady and oscillatory conditions. The information gained will improve the understanding and modeling of flashback, which is known to be a significant issue in low emissions combustors containing high levels of hydrogen. Measurements and analysis shall be performed under steady and oscillatory flow conditions. While particular attention shall be given to coal-derived gaseous fuels, consideration shall also be given to other candidate fuels, such as process gas or other fuels containing hydrogen or higher hydrocarbons.

The project consists of three main thrusts. First, a systematic design of experiments that formed the test matrix for the experiments performed under this project. Because of the significant number of independent parameters that need to be examined (e.g., fuel composition, pressure, pre-mixer design), a systematic effort is needed so that the resulting parameter studies are of sufficient breadth and detail, yet still realistic in scope. The second and third research thrusts are to investigate the flashback characteristics of synthetic gas fueled combustors under steady and pulsating conditions, respectively. An extensive series of tests are performed which characterize the dependence of flashback characteristics upon fuel composition, pressure, inlet temperature, and pre-mixer configuration. Because flashback is often found to be strongly influenced by combustor oscillations, great effort shall be taken to characterize the effects of oscillations in the last third of the project. Work is performed under conditions where the combustor is as “quiet” as possible and where external oscillations of varying amplitude and frequency are imposed. Parallel efforts are focused on developing a computational methodology for correlating these results and predicting flashback behavior under steady and oscillatory conditions.

6. BACKGROUND

Flame stabilization involves competition between the rates of the chemical reactions and the rates of turbulent diffusion of species and energy. While a significant amount of fundamental understanding of flame propagation and stability characteristics of lean, premixed systems has been gained in conventionally fueled, natural gas-air systems [2], little is known about these issues for alternate gaseous fuels, such as syngas or low BTU fuel mixtures. Furthermore, the majority of the fundamental investigations of the combustion characteristics of these synthetic gases are for non-premixed flame configurations [3,4,5,6,7]. Limited studies have been initiated relatively recent to investigate the characteristics of premixed, hydrogen-enriched methane fuels [8,9,10]. Additional studies are needed, however, to broaden the scope of fuels of interest.

Flashback is used here to describe situations where the flame physically propagates upstream of the region where it is supposed to anchor and into premixing passages that are not designed for high temperatures. Flashback is an issue because of the widely varying flame speeds of candidate fuels. While this is a classical topic that has been extensively investigated [11,12,13], the complexity of the topic increases substantially in swirling flows. In particular, several potential modes of flashback occur in swirling flows, as discussed in a series of papers by Sattelmayer and co-workers [14,15,16]. They identify three mechanisms for flashback: flashback in the boundary layer, turbulent flame propagation in the core flow, and flashback due to combustion instabilities [17]. The first two mechanisms are captured partially by the laminar and/or turbulent flame propagation speed. A thorough investigation of boundary layer flashback in syngas fueled Bunsen flames has been detailed by Davu *et al.* [18]. When the local turbulent flame speed exceeds the local flow velocity, the flame can propagate upstream into the premixing section. This issue is complicated by the radial variation in flow velocity, quenching losses, and turbulent flame speed. In the experiments reported here for higher H_2 cases and all higher pressure cases, we get this “rapid” flashback. For other cases, the second mechanism that occurs is a phenomenon Sattelmayer and co-workers refer to as “combustion induced vortex breakdown”. The basic idea is that the flame contributes to vortex breakdown, and therefore a low or negative flow region ahead of it. The flame advances forward, causing the vortex breakdown region location to advance farther upstream. This process continues as the flame proceeds farther and farther upstream. In this scenario, flashback could occur even if S_T is everywhere less than the flow velocity. As will be discussed below, we believe that a similar phenomenon is occurring in many cases in the tests reported here. However, rather than the flame continuously propagating upstream, we have found that the static flame anchoring position can monotonically move upstream, in lower pressure cases, as the mixture fuel/air ratio increases, apparently due to a change in the location of vortex breakdown.

We believe that this "slow flashback" mechanism occurs due to the fact that the fuel nozzle in many combustors operates in a bi-stable regime of swirling flows. This is illustrated by the figures below, which plots the qualitative stability diagram for a swirling flow, following Rusak [19]. The left graph plots a qualitative vortex breakdown stability map, as a function of swirl number and vortex core size. As shown, at low swirl numbers, no vortex breakdown occurs. At very high swirl numbers, vortex breakdown occurs. However, at intermediate values which are typical of those used in practical systems (e.g., ~0.6-1.2) the system has two possible states – no vortex breakdown or vortex breakdown. This is illustrated more abstractly in the right figure which plots a functional proportional to the energy in the flow. The graph labeled $\omega<\omega_o$ corresponds to the no vortex breakdown state. The graph possesses a single minimum, which corresponds to the steady state flow solution, axial flow. The graph labeled ω_o corresponds to sitting on the line of the bistable region and the next graphs $\omega_o+\varepsilon$ move into the bistable region. Note that *two minima are present, corresponding to two possible flow solutions*. The graph labeled ω_1 corresponds to sitting on the line of the vortex breakdown region – at this swirl level the initial minima, corresponding to the no vortex breakdown solution is no longer present. Further increases in swirl lead to only one possible solution state, vortex breakdown.

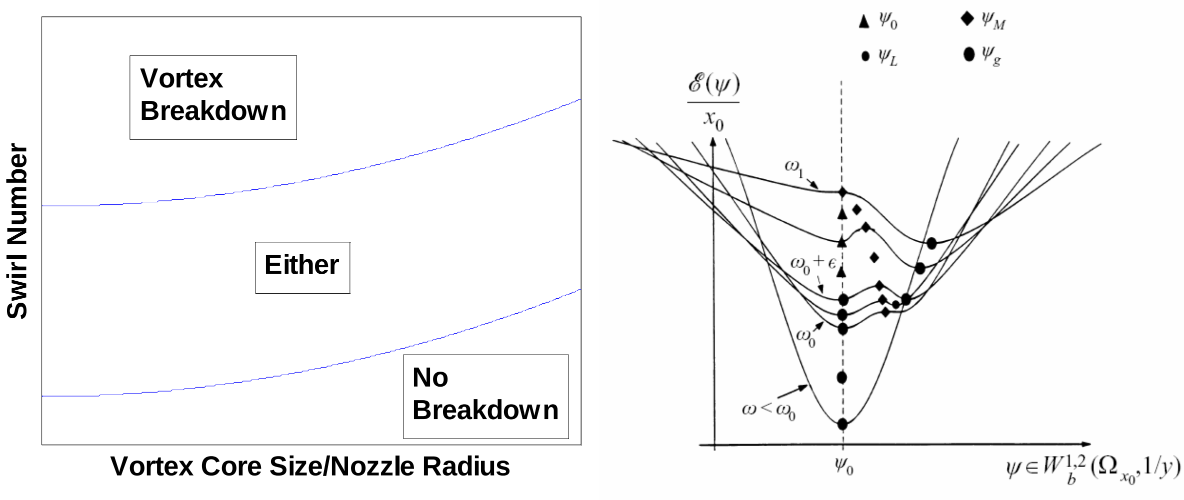


Figure 1: Ratio of Vortex Core Size to Nozzle Radius versus Swirl Number map showing vortex breakdown regions [19, 20].

Basically, we believe that this new flashback mechanism occurs in the bistable region. The flow is nominally axial, but can also, if appropriately perturbed jump over the barrier and find the other energy functional minima corresponding to vortex breakdown – *we hypothesize that the adverse pressure gradient in front of the flame is what provides this perturbation to the flow*. Moreover, the amplitude of the perturbation provided by the flame is proportional to two quantities – the relative angle of the flame and flow and the temperature ratio across the flame. The appendix reproduces an analysis presented in last years report demonstrating these two points. As such, this explains our experimental observation that the temperature ratio across the flame, and not the flame speed, is the key parameter controlling the regions of occurrence of the "slow flashback" mechanism.

The next sections describe the facility and measurements which present more detailed presentations of the results of the program.

7. INSTRUMENTATION AND FACILITY

Flashback measurements were obtained in a 7.6 cm (3") diameter quartz tube combustor housed in a pressure vessel, see Figure 2. The premixer was modified with additional instrumentation as needed for the flashback measurements. This premixer is fully modular as the centerbody and swirler can be easily removed and replaced; tests reported here were performed with a single 12 vane, 35° swirler. More details about the facility are in Ref. [21]. Although referred to here as a “premixer”, we actually mix the fuel and air far upstream to ensure a homogeneous mixture.

Fuels of arbitrary composition were generated with a blending facility consisting of six mass flow controllers, plumbed to bottles of H_2, CO, CH_4, CO_2, N_2, and/or any other arbitrary fuel.

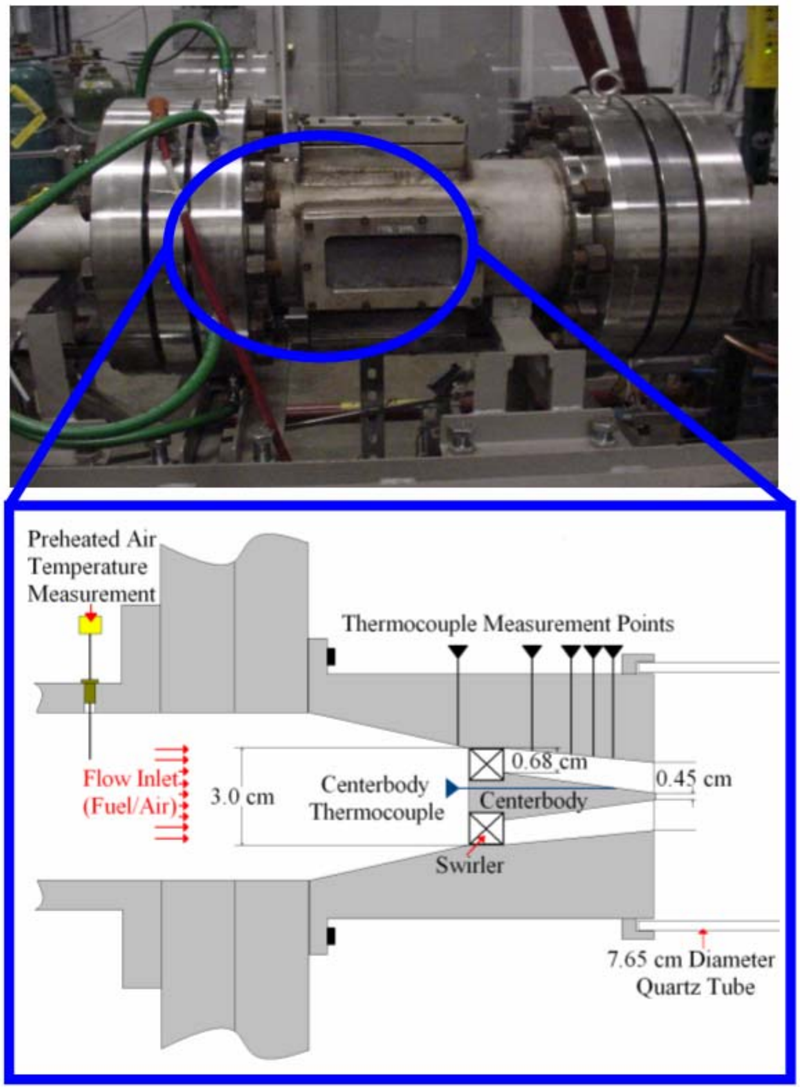


Figure 2: Photograph of high pressure combustor facility.

To detect flashback, a total of fifteen measurement points were arranged on the outer wall of the premixer, as shown below, five in a row at successive axial locations, with three locations at successive 120° azimuthal positions at each axial location. Also, a thermocouple was mounted on the surface of the centerbody, approximately 1.9 cm from the tip (see Figure 3). An additional thermocouple was located upstream of the premixer (see Figure 2).

Figure 3 shows the premixer with the three rows of five thermocouples. The first three thermocouples, along with the centerbody thermocouple, were used to determine flashback. The two end thermocouples were only used to determine the distance of flashback into the premixer. Once the flame moves upstream, it was sensed by the thermocouple, triggering a flashback alarm. The mixture was quickly leaned out, and the flashback procedure repeated. Note that target temperatures were chosen based upon prior tests and visual observations of the flame shape and behavior. In other words, in cases where the "slow flashback" mechanism was observed, defining the point of flashback is somewhat arbitrary as it is really a continuous process, as opposed to a discrete one. However, for the rapid flashback cases, such as observed with high hydrogen fuels or at higher pressure, the centerbody thermocouple was used to detect flashback by exhibiting a large jump in temperature (+150^{0}F or more).

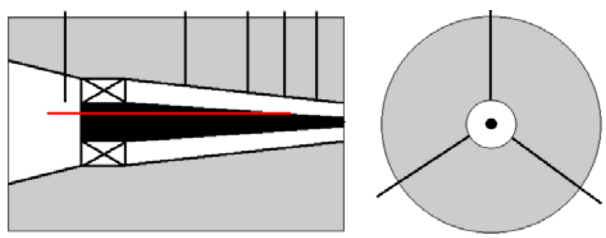


Figure 3: Premixer with swirler, centerbody, radial thermocouples, and centerbody thermocouple.

In order to facilitate presentation of results, we represented the mixture composition of H_2/CO/CH_4 by an assigned color. Primary colors at the three vertices were used to represent each fuel constituent, where red, yellow, and blue denote H_2, CO, and CH_4, respectively. This is illustrated in the figure below. Unfortunately, Figure 4 will be difficult to interpret if reproduced in grayscale.

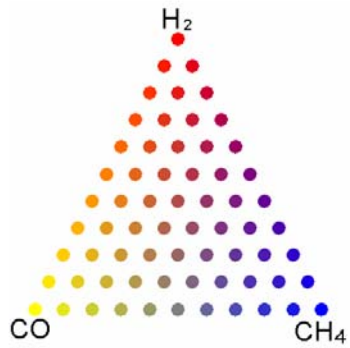


Figure 4: Primary color mixing scheme used to denote fuel blend composition.

The basic test sequence was to operate at uniformly spaced fuel compositions in H_2/CO/CH_4 space, such as is depicted in the figure above. At each fuel composition, the mixture equivalence ratio was adjusted at constant unburned velocity until the mixture flashed back. Obtaining this data was complicated by the need to keep the approach flow velocity, combustor pressure, and mixture temperature constant across the range of fuel compositions. As such, fixing the relative fuel compositions required simultaneously adjusting the air and three fuel flow rates in order to keep constant approach flow velocity. In addition, due to variations in mixture burned gas temperature, maintaining a constant combustor pressure required simultaneous adjustment of the back pressure valve. Finally, variations in molar volume of the fuel necessitated adjusting the air temperature in order to maintain a constant reactant temperature. For the data shown in the Results section, the approach flow velocity, pressure, and temperature remained constant to within 2%, 5%, and 20 K of their quoted values.

Combustor unburned flow velocities which are quoted here equal the mass flow rate divided by the unburned gas density and combustor area – this was the combustor velocity if there were no flame. It should be emphasized that this was purely a reference velocity, as the actual flow velocities may have been different. The burned gas velocity simply equaled this velocity multiplied by the theoretical temperature ratio across the flame. The velocity at the premixer exit, relevant for the flashback data, equaled the unburned flow velocity multiplied by 18.

It should be emphasized that applying a consistently uniform definition of flashback was complicated by the fact that the manner in which the flame flashed back varied with composition. Different flashback mechanisms were found for different fuel compositions. For low H_2 mixtures and lower combustor pressure, the flame anchoring location moved gradually upstream (along the centerbody) with increased equivalence ratio, see Figure 5. In other words, flashback was not a discontinuous phenomenon, where the flame actually propagated upstream into the premixer in a rapid manner. For these cases, flashback was defined here as the point where the thermocouple closest to the exit plane of the premixer reached 450K and 505K for the 300K and 460K reactant preheat cases, respectively.

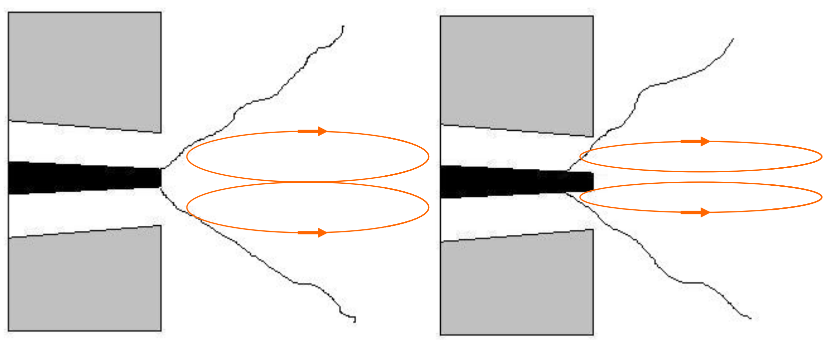


Figure 5: Flame front and postulated recirculation zone locations for normal flame (left) and with flame propagated upstream [”slow” flashback] (right).

However, for high H_2 mixtures and combustor pressure of 7.1 atm, flashback occurred very abruptly – triggered by only a slight change in mixture stoichiometry (~0.05 or less). The flame would very rapidly propagate upstream, sometimes all the way through the swirler where it triggered the thermocouple upstream of the premixer.

8. RESULTS AND DISCUSSION

For this year, the main focus of testing was on preheated, raised combustor testing. In continuing the flashback studies on $CO/H_2/CH_4$ mixtures with preheated reactants and raised combustor pressure, we decided that it would be beneficial to examine a set of data at 7.1 atm and 500K, as well as, a set where several fuel combinations were examined at a variety of combustor pressures with constant flow unburned velocity and preheat temperature. Thus, the conditions chosen were preheat temperature of 480K and nozzle velocity of 17.3 m/s with combustor pressures of 2, 3, and 4 atm. The fuel mixtures used were pure CO, pure CH_4, 95% H_2/5% CH_4, 50/50 CH_4/CO, 50/50 CH_4/H_2, and 50/50 H_2/CO.

We started by examining flashback data at preheated reactant temperatures and higher combustion pressures. As for completeness, all the data taken up to this point was included in this section. Figure 6-Figure 9 plot these results in terms of equivalence ratio, T_{ad}, and S_L at which flashback occurs. Note that for some cases, S_L data is not shown because Chemkin would not converge on many all the cases because the equivalence ratio was quite low. Figure 10 uses an estimate of S_L for the 7.1atm/500K case using $S_L^2 \propto \alpha/\tau_{chem}$, where the chemical time and thermal diffusivity were scaled using residence times at blowoff using *AURORA*.

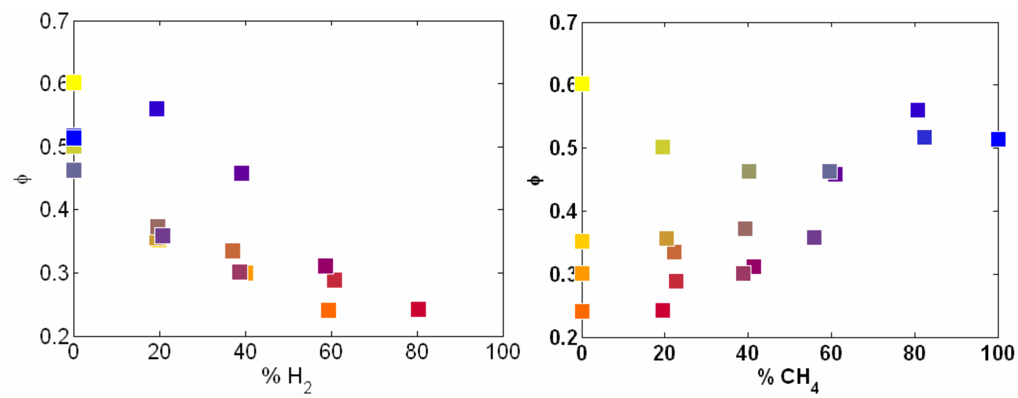
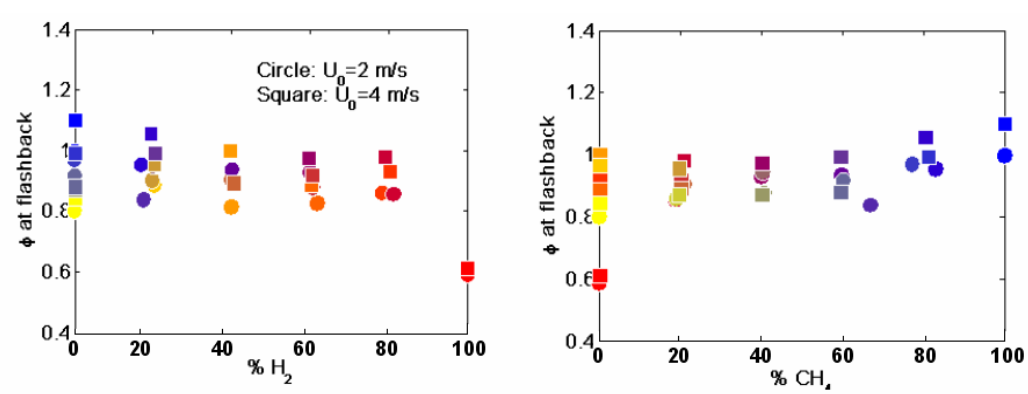
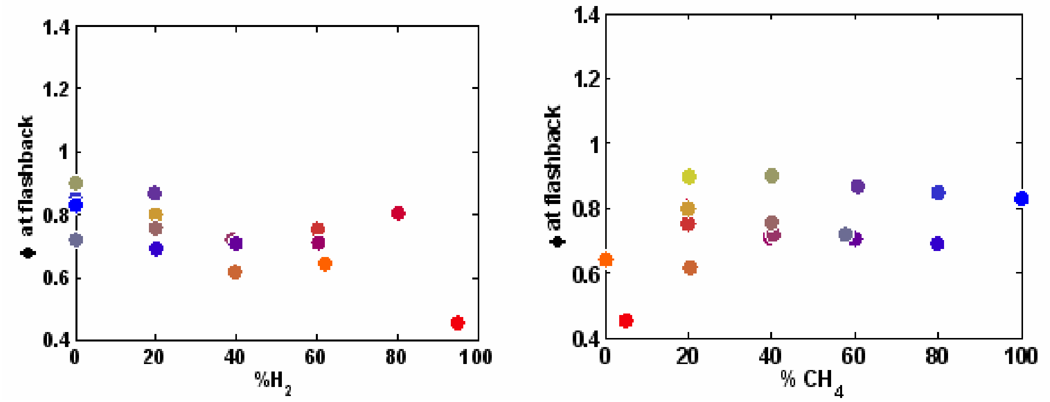


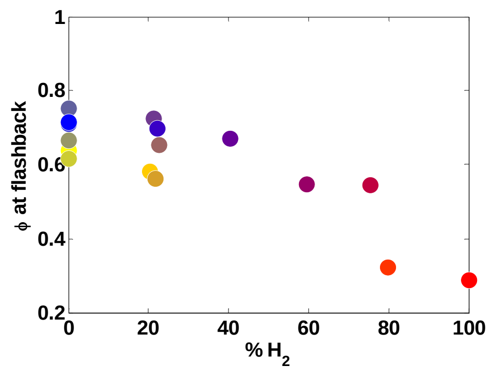
Figure 6: ϕ at Flashback versus %H_2 and % CH_4: U_0=1.2m/s, T_0=500K, and P=7.1 atm.



(a)

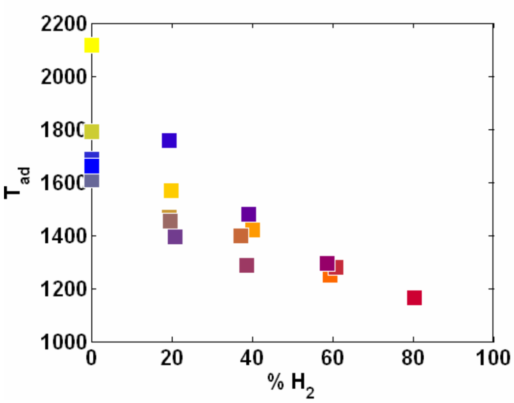


(b)

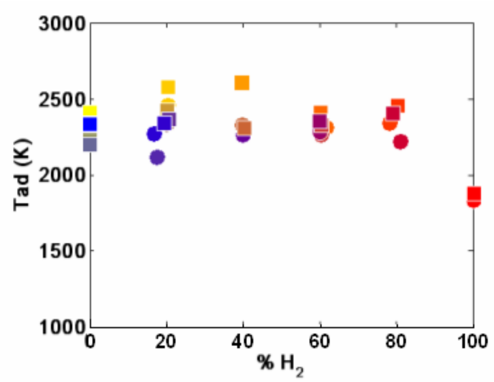


(c)

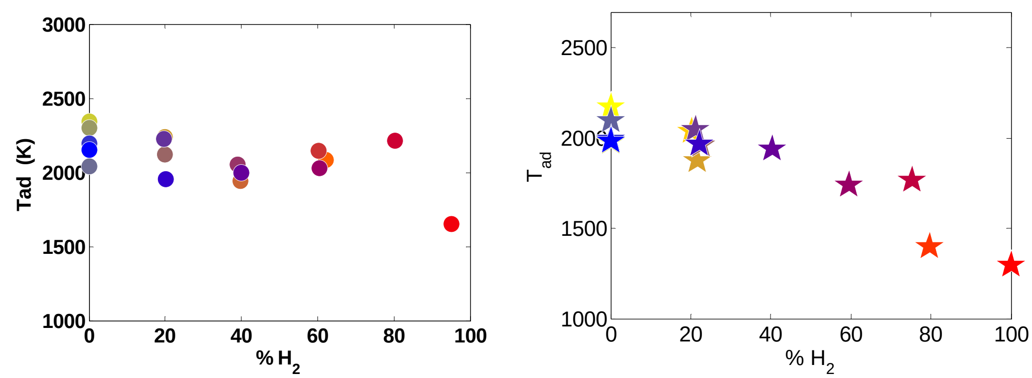
Figure 7: ϕ at Flashback versus %H_2 and % CH_4: (a) T_0=300K and P=1.7 atm [Circle: U_o=2m/s & Square: U_o=4m/s], (b) U_0= 5.4 m/s, T_0=458K and P=4.4 atm and ϕ at Flashback versus %H_2, and (c) U_0=4 m/s, T_0=458K and P=4.4 atm.



(a)



(b)



(c) (d)

Figure 8: Dependence of Adiabatic Flame Temperature on %H_2: (a) U_0= 1.2 m/s, T_0=500K and P=7.1 atm, (b) T_0=300K and P=1.7 atm [Circle: U_o=2m/s & Square: U_o=4m/s], (c) U_0= 5.4 m/s, T_0=458K and P=1.7 atm, and (d) U_0= 4 m/s, T_0=458K and P=4.4 atm.

From the previous three figure sets (Figure 6-Figure 8), the dependence on equivalence ratio and T_{ad} diminished as the pressure and temperature increased. It was not as prevalent with the 4.4 atm/458 K case, but with the new 7.1 atm/500 K set, it was very clear during testing that the mode of flashback changed to favoring the rapid mode and the determination of the flashback point changed from a T_{ad} dependence to now, an unknown dependence. Note that the rapid flashback was very clear in the new case data. The centerbody thermocouple was utilized for determining the exact point of flashback. A temperature change of 150 to +600^{0}F was noted for all cases for an equivalence ratio change of 0.05 or less.

Moreover, the new set of data did not include pure H_2 because a stable flame could not be found. No matter the flow speed or equivalence ratio, the flame would flashback or blow off as soon as pressure was increased from ignition (~2 atm) to 7.1 atm. The occurrence was even worse (flashback wise) if ignition was attempted at 7.1 atm. This is a significant observation that could have important ramifications in the design of future high hydrogen combustion systems.

For the laminar flame speed correlation of the data (Figure 9 and Figure 10), all data showed that S_L was not the proper way of correlating flame flashback over the range of fuel compositions. Moreover, in the latter figure, the flame speed was estimated and not the actual numbers from Chemkin. Clearly the better parameter for correlating these data is the turbulent flame speed, S_T, but very little of these data exist. We have initiated a new project at Georgia Tech that will be obtaining measurements of S_T, thus the data from this experiment will build a data base so that we can properly determine if a correlation exists or not, specifically at the higher pressure/temperature cases.

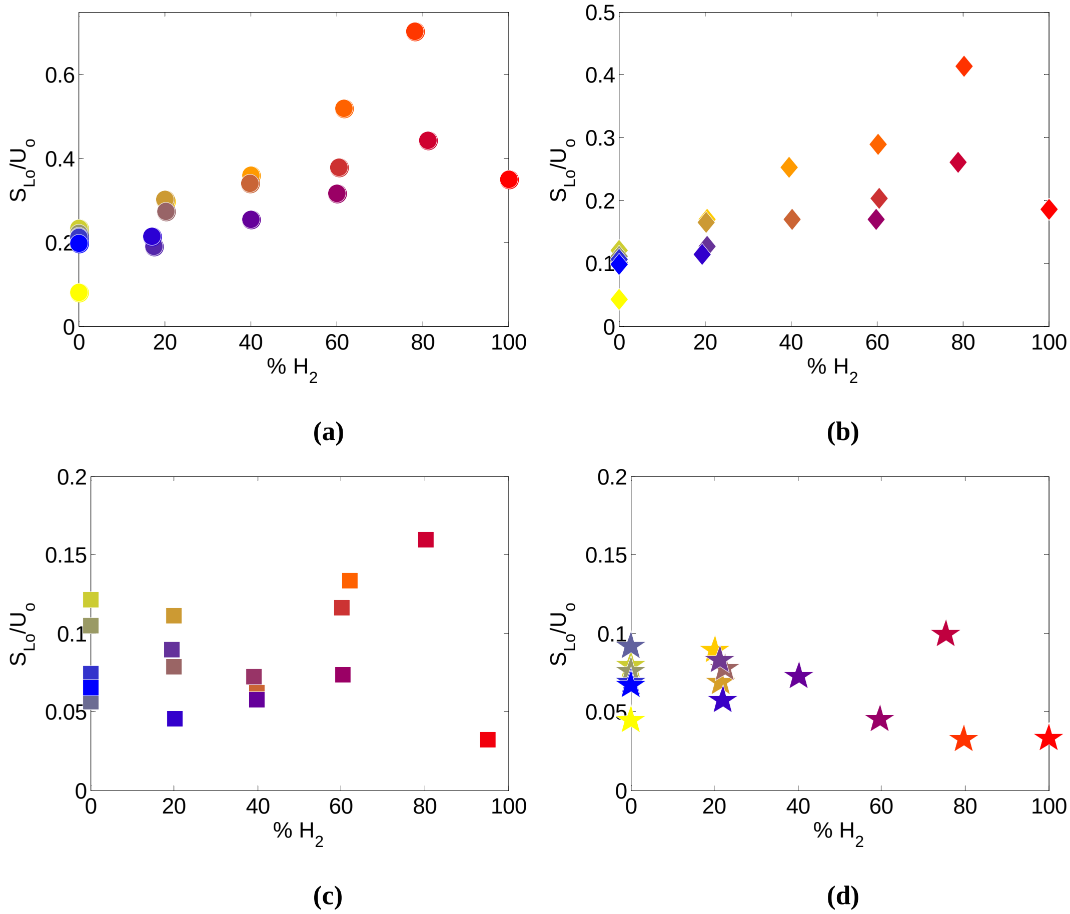


Figure 9: Dependence of Laminar Flame Speed on %H_2: (a) U_0= 2m/s, T_0=300K and P=1.7 atm, (b) U_o=4m/s, T_0=300K and P=1.7 atm, (c) U_0= 5.4 m/s, T_0=458K and P=1.7 atm, and (d) U_0= 4 m/s, T_0=458K and P=4.4 atm.

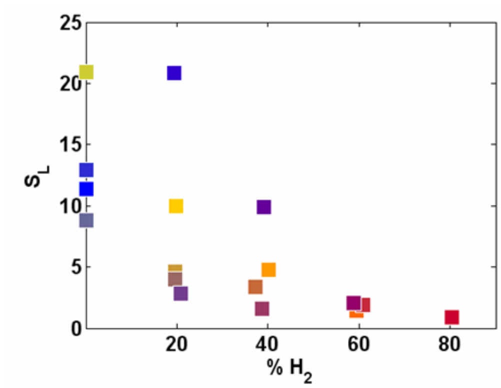
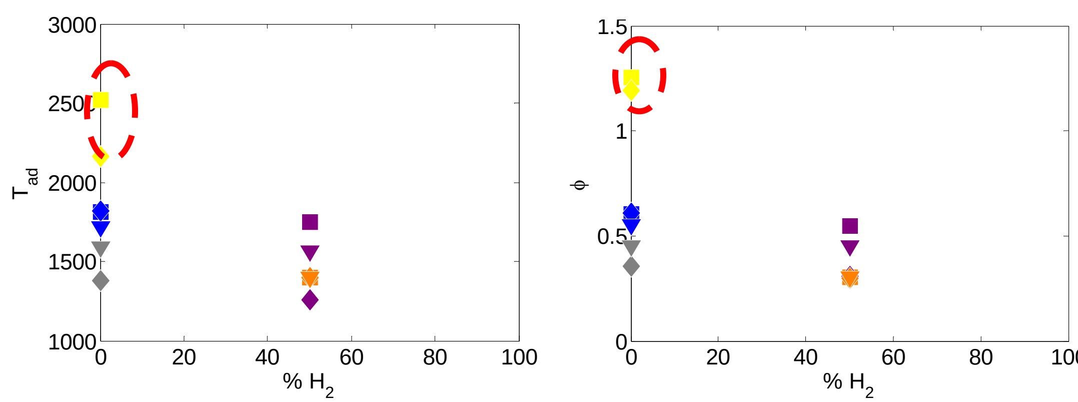


Figure 10: Dependence of Estimated Laminar Flame Speed on %H_2: U_0=1.2m/s, T_0=500K, and P=7.1 atm.

In order to better understand pressure/Reynolds number effects (note that the Reynolds number scales with the pressure if the flow velocity and temperature are kept constant), pressure sweep data were obtained at constant velocity and preheat temperature. Figure 11 plots the adiabatic flame temperature and equivalence ratio for this case. Note that we were not able to stabilize pure H_2 flames to examine flashback, corresponding to the same problem that was previously described where the flame would flashback or blow off. Also, the pure CO cases were not clearly defined as flashback as per our temperature requirements; however, the flame visually was inside the nozzle (see Figure 12). As before, these cases at lower pressures, even with the much lower velocities, flashed back with a slower mode. As the pressure went up to 4 atm, the flashback mode transitioned to the more rapid flashback. Figure 13 shows that as the pressure is increased, the flashback flame temperature does not change greatly, excluding the CO points; however, again we did notice visually that the mode of flashback changed. This is counter to the 7.1 atm data that showed T_{ad} dependency decreased as pressure increased. This may suggest that the dependency change occurs at combustor pressures between 4 and 7.1 atm.



(a) **(b)**

Figure 11: Pressure Sweep Data at U_o=0.96 m/s (Nozzle U=17.3 m/s) and T_{in}=480K: (a) T_{ad} [K] versus %H_2 and (b) ϕ versus %H_2 [Square=2 atm, Diamond=3 atm, and Triangle=4 atm] {Circled points indicate that flashback was not well defined}. Stable pure hydrogen flames could not be stabilized at these conditions.

Figure 12: CO Flame Anchored in nozzle.

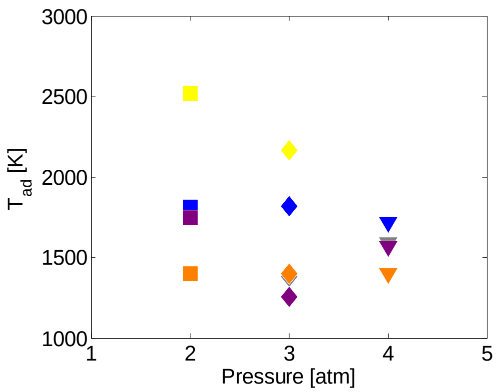


Figure 13: Pressure sweep data: Tad vs. combustor pressure, same conditions as Figure 11.

9. OPTICALLY ACCESSIBLE NOZZLE/PREMIXER

For the imaging of the dynamic flashback process, the optically accessible premixer was fabricated with a new torch igniter and 3 inch long quartz tube upstream of the nozzle dump plane. Figure 14 illustrates the new nozzle for these tests. Essentially, the same setup as before was used, except there no longer is a converging section with a centerbody. We will increase the flow rate to correspond with similar flow velocities in the premixer as before. We can capture flashback images with or without a laser sheet using a Redlake high speed, black and white camera. These images can be colorized using Matlab and a code previously written here at Georgia Tech. These tests will continue for part of the 2007 calendar year as per the project milestones.

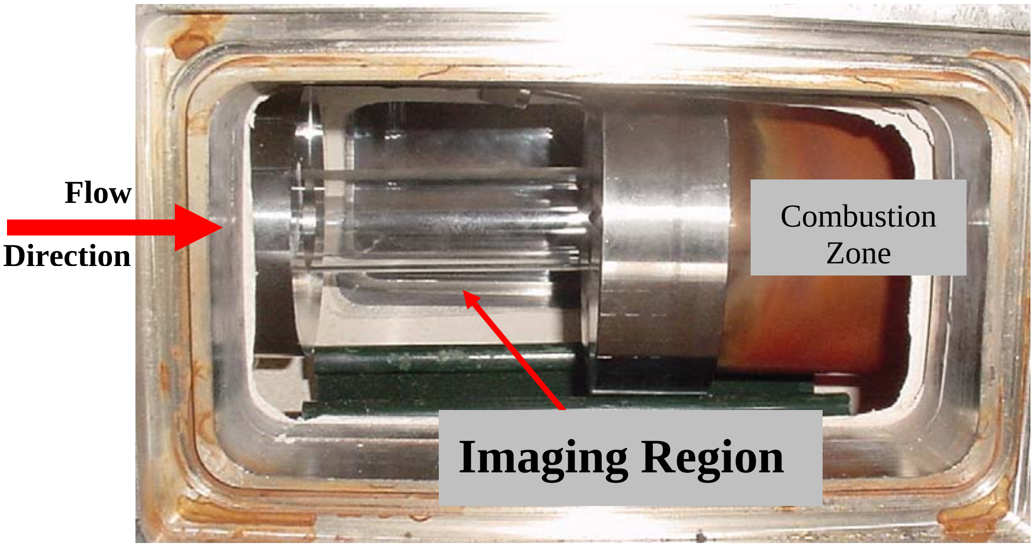


Figure 14: New Nozzle for Flashback Imaging.

10. ONGOING WORK

1. Experimental studies of flashback characteristics: As informed from the monthly updates, the imaging testing has been slightly delayed, but ready for testing due to building high pressure air issues. We are going to continue the flashback imaging for the atmospheric cases, as well as move to testing under pressurized conditions. We will also change the geometry of the system with various swirlers. Lastly, we will pulsate the system for the last quarter of the project.

2. Data Correlation: We are still looking at correlating the data for the higher pressure cases. We plan on using S_T data from another project to aid in correlating. Using ways of estimating/calculating the turbulent flame speed is very arbitrary and previously with blowout data we found that changing the conditions slightly, great changes the turbulent flame speed value.

11. APPENDIX

This appendix details a perturbation solution extracted from the Darrieus-Landau flame stability analysis[1] [[22]] for a flame with small sinusoidal wrinkles of spatial wavenumber *k* and amplitude *D* (see Figure 15), with flame temperature ratio $\Re = T_b/T_u$. This is included as a reminder of the combustion induced vortex breakdown

[1] Note that this stability theory shows that such a perturbation is unstable. However, the corresponding pressure profiles are correct for the flame front whose instantaneous perturbation amplitude is *D*.

mechanism from the previous yearly report. The pressure upstream of the flame equals its nominal value, plus a small perturbation due to the wrinkle, $P(x) = \overline{P} + P^{'}(x)$. The acceleration of the gases through the flame causes the nominal burned gas pressure to drop, as given by the following expression:

$$\overline{P_b} = \overline{P_u} - (\Re - 1)\overline{\rho_u}\,\overline{U_u}^2 \qquad (1)$$

The alteration of the upstream pressure field by the flame wrinkle along the indicated line in the figure below is given by:

$$\frac{P_u^{'}(x)}{(\frac{1}{2}\overline{\rho_u}\,\overline{U_u}^2)(kD)} = \frac{-(\Re - 1)(\sigma - \Re)e^{kx}}{2\left(\Re\frac{(\sigma - 1)}{(\sigma + \Re)}[1 + \sigma] + \left(1 - \frac{\sigma}{\Re}\right)\right)} \qquad (2)$$

where

$$\sigma = \frac{-\Re}{1 + \Re}\left[\sqrt{1 + \Re + \frac{1}{\Re}} - 1\right] \qquad (3)$$

The spatial dependence of the pressure through the flame along the dashed line in Figure 15 is plotted in Figure 17.

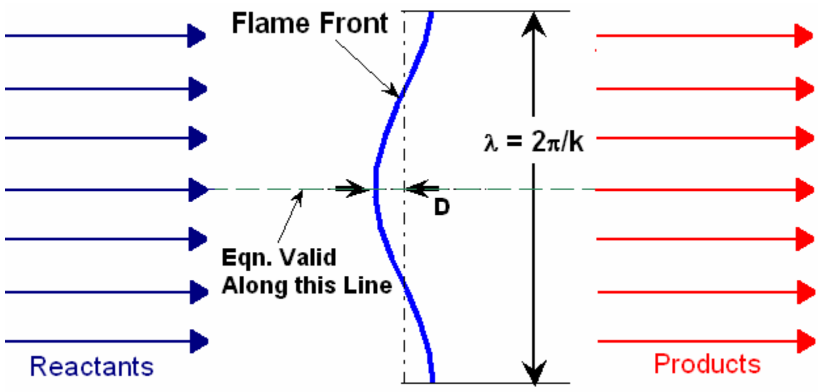


Figure 15: Schematic of flame front with small perturbation (Dashed line: x axis, Dot-dashed line: y axis).

The magnitude of the pressure rise upstream of the flame, indicated in Figure 17, is given by the expression:

$$\frac{\Delta P'}{\left(\frac{1}{2}\overline{\rho_u}\,\overline{U_u}^{\,2}\right)(kD)} = \frac{-(\Re - 1)(\sigma - \Re)}{2\left(\Re\frac{(\sigma-1)}{(\sigma+\Re)}[1+\sigma] + \left(1 - \frac{\sigma}{\Re}\right)\right)} \quad (4)$$

The dependence of this pressure rise upon the temperature ratio across the flame is plotted in Figure 16:

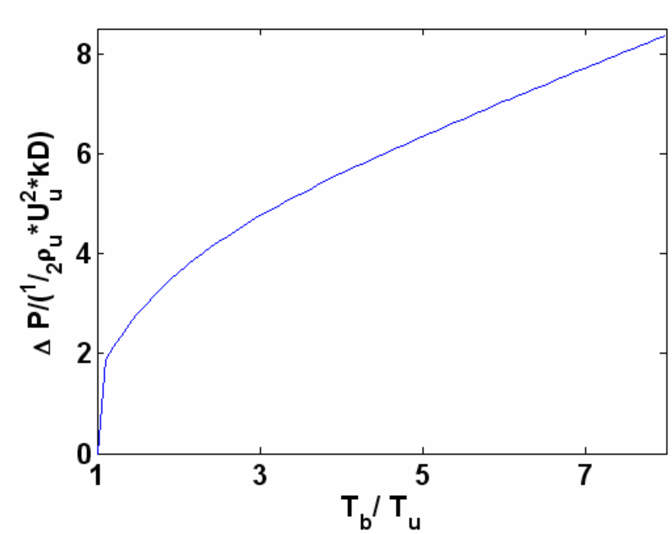


Figure 16: Dependence of pressure rise upstream of the flame upon flame temperature ratio.

This result shows that the adverse pressure gradient ahead of the flame grows monotonically with temperature ratio across the flame, as well as the relative inclination angle of the flame with respect to the flow, related to kD.

A result from this analysis showing the spatial variation of the pressure through the flame is plotted in Figure 17. The key point to note from this figure is that convex flame orientation to the flow causes the pressure to actually rise upstream of the flame, followed by the pressure drop across the flame. Note that if the flame were perfectly normal to the flow, there is no pressure rise upstream of the flame.

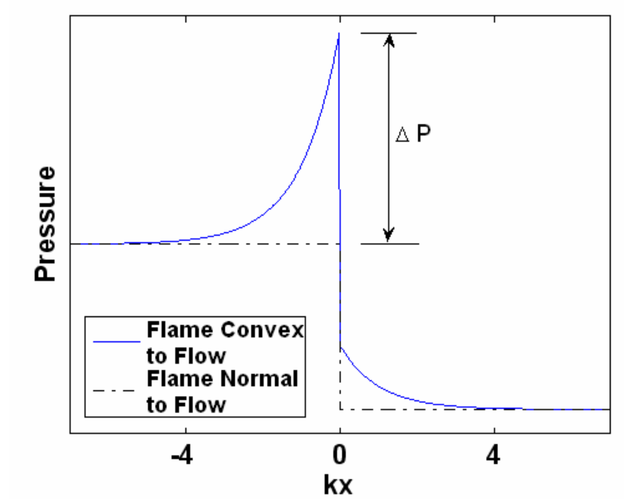


Figure 17: Total pressure (mean plus fluctuation) across the flame front.

Our argument regarding this slow flashback mechanism can be better understood with reference to Figure 18, which shows the hypothesized streamlines in the vicinity of the flame and recirculation bubble in more detail.

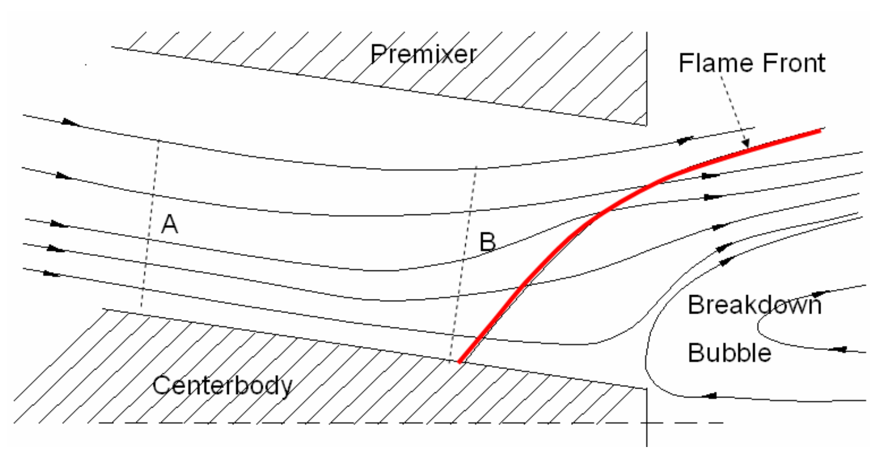


Figure 18: Hypothesized flow streamlines in the vicinity of the flame and recirculation bubble.

The conditions under which the recirculation bubble begins to move backward into the premixer, so that there is actually reverse flow in the premixer, can be understood by reference to the pressure drop in the premixer, P_A-P_B, where the locations "*A*" and "*B*" are illustrated in the figure above.

$$\frac{P_A - P_B}{P} = \frac{U_u^2}{RT_u}\left[C_D(\mathrm{Re}, S) - \left(\frac{A_A}{A_B}\right)^2 - f\left(\frac{T_b}{T_u} - 1\right)\right] \qquad (5)$$

where C_D and (A_A/A_B) denote the contribution to the pressure drop due to viscous losses and the cross-section area change, respectively. As indicated, C_D is a function of Reynolds, *Re*, and swirl number, *S*. The burned and unburned gas properties are represented by *u* and *b*. Presumably, flow instability and vortex breakdown tendencies are enhanced as P_A-P_B decreases, which becomes more likely as T_b/T_u increases.

12. REFERENCES

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