Correlating Induced Flashback with Air-Fuel Mixing Profiles for SoLoNOx Biomass Injector

Ryan Ehlig

University of California, Irvine

Mentor: Raj Patel

Supervisor: Ram Srinivasan

Department Manager: Andy Luts

University Turbine Systems Research

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Abstract

Flashback, the phenomenon in which the flame front propagates upstream into the reactant mixture, was induced at extreme conditions for two prototype, lean premix injectors. These injectors were operated with low Wobbe, hydrogen blend fuels in a high pressure combustion rig. The first prototype injector included multiple air-holes, which injected high velocity air around the centerbody region. Injector prototype 2 was designed without air-holes to study the effect of this airflow on flashback. Flashback was induced at two extreme cases: at Lean Blow Out (LBO) conditions, in which combustion instabilities caused the flame to flashback, and at extreme flame temperatures (T_{flame}) in which high flame speeds and low flow velocities in the boundary layer near the outer injector wall resulted in flashback.

In this project, work was done to establish air-fuel mixing profiles at the injector exit to correlate these profiles with flashback observations from the high pressure combustion rig. These profiles provide information regarding the fuel concentration (% vol. CH_4) distribution at the injector exit. Mixing profiles were subsequently plotted for each of the extreme cases. For the flashback case at the high T_{flame} condition, the mixing profile for injector prototype #1 indicated a fuel-rich region around the outer injector walls, confirming the idea that high flame speeds near the low velocity boundary layer at the outer wall led to flashback. For the flashback case at LBO, the mixing profile for injector prototype #2 indicated a fuel-rich region around the centerbody walls, which was the result of having no air holes. This rich region in combination with oscillations at LBO made this injector configuration more susceptible to flashback.

Background

Within the past decade, the focus toward renewable sources of power has intensified with the passing of California's aggressive Renewable Portfolio Standards (RPS). Under Senate Bill 350 (SB 350) signed by Governor Jerry Brown, this requires "retail sellers and publically owned utilities to procure 50% of their electricity from eligible renewable sources by 2030" [1]. One such renewable fuel source is gasified Biomass (Syngas). It is derived from feedstock waste via partial oxidation [2] . Syngas is composed of hydrogen, carbon monoxide, and other diluents such as carbon monoxide and nitrogen, and can vary in heating content depending upon the volumetric percentage of its fuel components [3].

The Combustion Technology group at Solar Turbines, located in San Diego, California, is developing an injector capable of operating the SoLoNOx Gas Turbine on syngas fuels. Syngas contains highly reactive hydrogen with flame speeds significantly higher than natural gas. Fuel injectors operating with hydrogen blends are susceptible to flashback, which is the phenomenon in which the flame propagates upstream into the reactant mixture.

There are four mechanisms by which flashback can occur [4]:

1. Boundary Layer Flashback – Due to the no-slip condition, flow velocities near the wall decrease. Once a critical velocity gradient is reached, where the flame speed exceeds the flow velocity in this region, the flame will propagate upstream.
2. Bulk Flow Flashback – Occurs when the local flame speed exceeds the bulk flow velocity.

3. Combustion Instabilities – Fluctuations of the flow as well as acoustic modes and heat release fluctuations lead to flashback.
4. Combustion Induced Vortex Breakdown – This occurs when there is an upstream propagation of the recirculation zone in swirl-stabilized burners.

Two prototype injectors were tested to evaluate induced flashback characteristics in the High Pressure rig at Solar. The two primary flashback mechanisms observed were Boundary Layer Flashback and Flashback due to Combustion Instabilities.

Prototype 1

For the first prototype injector (**Figure 1**), flashback was induced at high flame temperatures in Solar Turbine's High Pressure Single Injector Rig (HP SIR). Flashback initiated near the injector outer wall and the flame propagated upstream to the air holes at the base of the centerbody (see **Figure 1**), where subsequent flame holding was observed.

Bulk equivalence ratio was also calculated and compared for conditions where flashback was induced. Equivalence ratio is defined as follows:

$$\phi = \frac{AFR_{stoich}}{AFR_{actual}}$$

Where AFR_{stoich} = The air-fuel ratio at stoichiometric conditions (where all the fuel is consumed)

Where AFR_{actual} = The air-fuel ratio at actual conditions.

The calculated bulk equivalence ratio for these cases correlated to conditions where peak laminar flame speeds occur. This reaffirmed the idea that fuel-rich zones contribute to flashback by driving the flame speeds higher.

It was also concluded that a critical velocity gradient near the wall was achieved when the flame speed of hydrogen exceeded the flow velocity near the outer wall in the boundary layer, which allowed flashback to occur.

Prototype 2

The second prototype injector (**Figure 1**) design eliminated the air holes at the base of the centerbody. The primary motivation for this was to determine the effect on flashback and the flame holding that was observed near the air holes.

With this prototype, flashback was observed near the centerbody walls at Lean Blow Out (LBO) conditions as well as near the outer walls at extreme T_{flame} conditions. T_{flame} refers to the calculated equilibrium temperature using the measured total fuel and airflow through the injector. It was concluded that flashback driven by oscillations at lean-blow out and the elimination of air holes contributed to flashback at LBO, while conditions similar to prototype 1 resulted in flashback at high T_{flame} conditions.

The HP rig tests can provide operating conditions where flashback may be induced for prototype 1 and prototype 2; however, they do not provide an insight or explanation as to why flashback may be induced

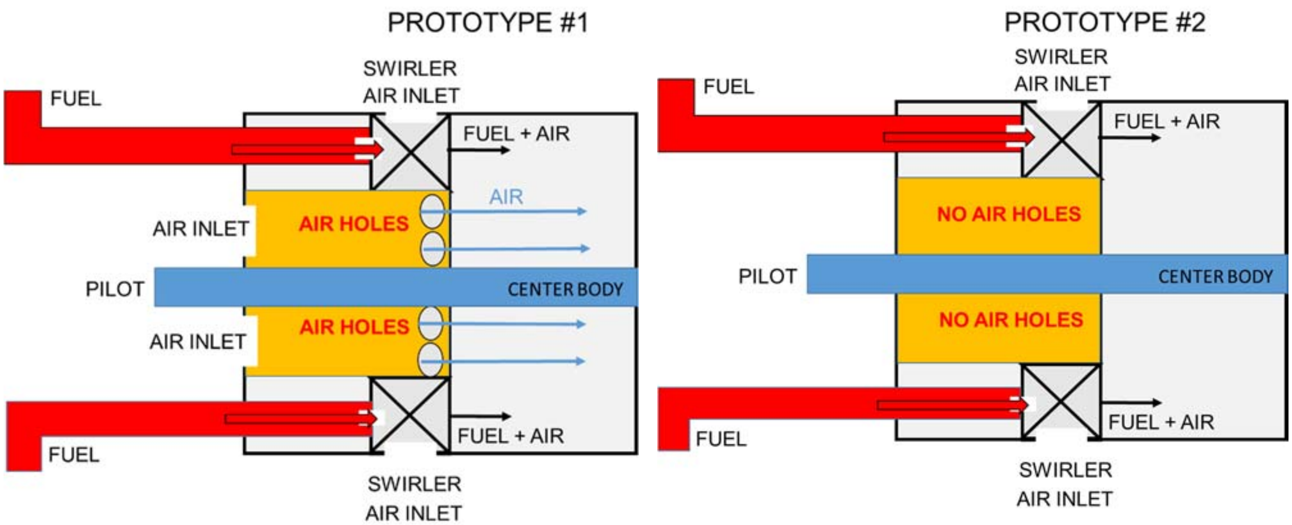

Figure 1 - Biomass Injector Prototype 1 (left) and Prototype 2 (right)

Introduction

Flashback has been observed for two prototype lean-premix injectors at extreme conditions. For prototype #1, which was designed with air holes to introduce high velocity air into the centerbody region, flashback was observed at high T_{flame} conditions only. For prototype #2, which was designed without air holes, flashback was observed at two extreme conditions, both at high T_{flame} as well as Lean Blow Out conditions.

The goal of this project was to correlate this observed flashback behavior at extreme conditions for prototype #1 and prototype #2 from the HP SIR tests, with their respective air-fuel mixing profiles and to identify possible trends. Methane concentrations (% vol.) are measured radially outward from the outer diameter of the centerbody to the outer injector wall and are used to produce a complete air-fuel mixing profile at the injector exit. These profiles can provide an insight into the performance of the injector with respect to;

1. Emissions – Fuel-rich regions can lead to hot spots and higher flame temperatures, resulting in more thermal NOx.
2. Operability – An engineer will become more aware of how injector design features or changes affect the profile and therefore operability on the HP SIR or engine
3. Oscillations – Conditions that produce oscillations on the High Pressure rig or engine can be tested on the mixing rig to help develop a more complete picture of the relationship between air-fuel mixing profiles and oscillations.

Mixing Rig Experiments

The Mixing Rig, shown in Figure 2 was utilized at the Solar Turbines Combustion Testing facility. The rig operated at ambient conditions and was capable of flowing Natural Gas and Nitrogen blends to simulate the Wobbe Index of syngas mixtures. Airflow through the injector was set up to simulate the percentage pressure drop at which flashback was induced in the HP SIR . Fuel mixture was injected through the fuel circuit but not ignited.

Figure 2 shows the experimental setup. Fuel lines supplied mixture of Nitrogen and Natural Gas to simulate the range of Wobbe Indices of Syngas. Sufficient entrance length of the air passage was provided to ensure fully developed flow was achieved before the air reached the injector.

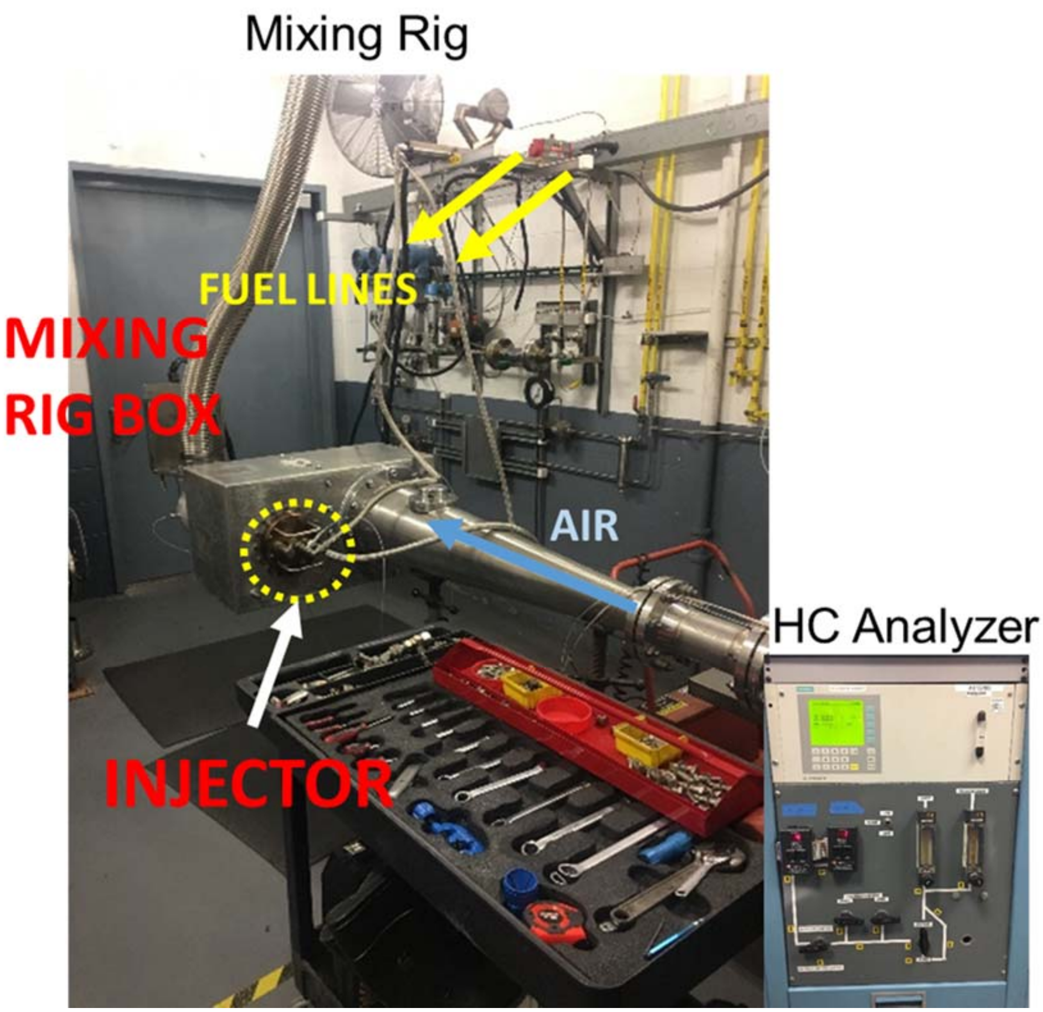

Figure 2 - Mixing Rig Experimental Setup and HC Analyzer

Scaling

Natural gas and nitrogen blend was used to represent the fuel for the injector in the Mixing Rig. The fuel flow rate and volumetric percentage of each fuel component were adjusted to simulate Syngas Wobbe Index,

$$\textbf{Wobbe Index} = \frac{\textit{Heating Value}}{\sqrt{\text{Specific Gravity}}}\left(\frac{\text{BTU}}{\text{scf}}\right)$$

A parameter known as Flow Function was used to scale the air flows at ambient conditions. The momentum flux ratio for the reference case was used to scale the fuel flow required for the corresponding ambient, mixing rig set-up.

Flow Function

$$\frac{W_{A_{ref}}\, T_{ref}^{.5}}{P_{ref}} = \frac{W_{A_{rig}}\, T_{rig}^{.5}}{P_{rig}}$$

Momentum Match

$$\frac{J_{\text{Fuel ref.}}}{J_{\text{Air ref.}}} = \frac{J_{\text{Fuel Rig}}}{J_{\text{Air Rig}}}$$

$$J_{\text{Fuel}} = \rho_{\text{fuel}} V_{\text{fuel}}^2$$
$$J_{\text{Air}} = \rho_{\text{Air}} V_{\text{Air}}^2$$

Results and Discussion

AIR-FUEL Normalized Mixing Profiles (CH4 % Vol.)

Figure 3 shows the normalized air-fuel mixing profiles at the simulated test conditions in the mixing rig. Three of the four simulated test conditions were scaled from HP SIR conditions in which flashback had been induced.

Air Holes (Prototype 1)

For prototype 1 with the air holes, it becomes evident that the air dilutes the region near the centerbody. It becomes richer radially outward towards the outer injector walls.

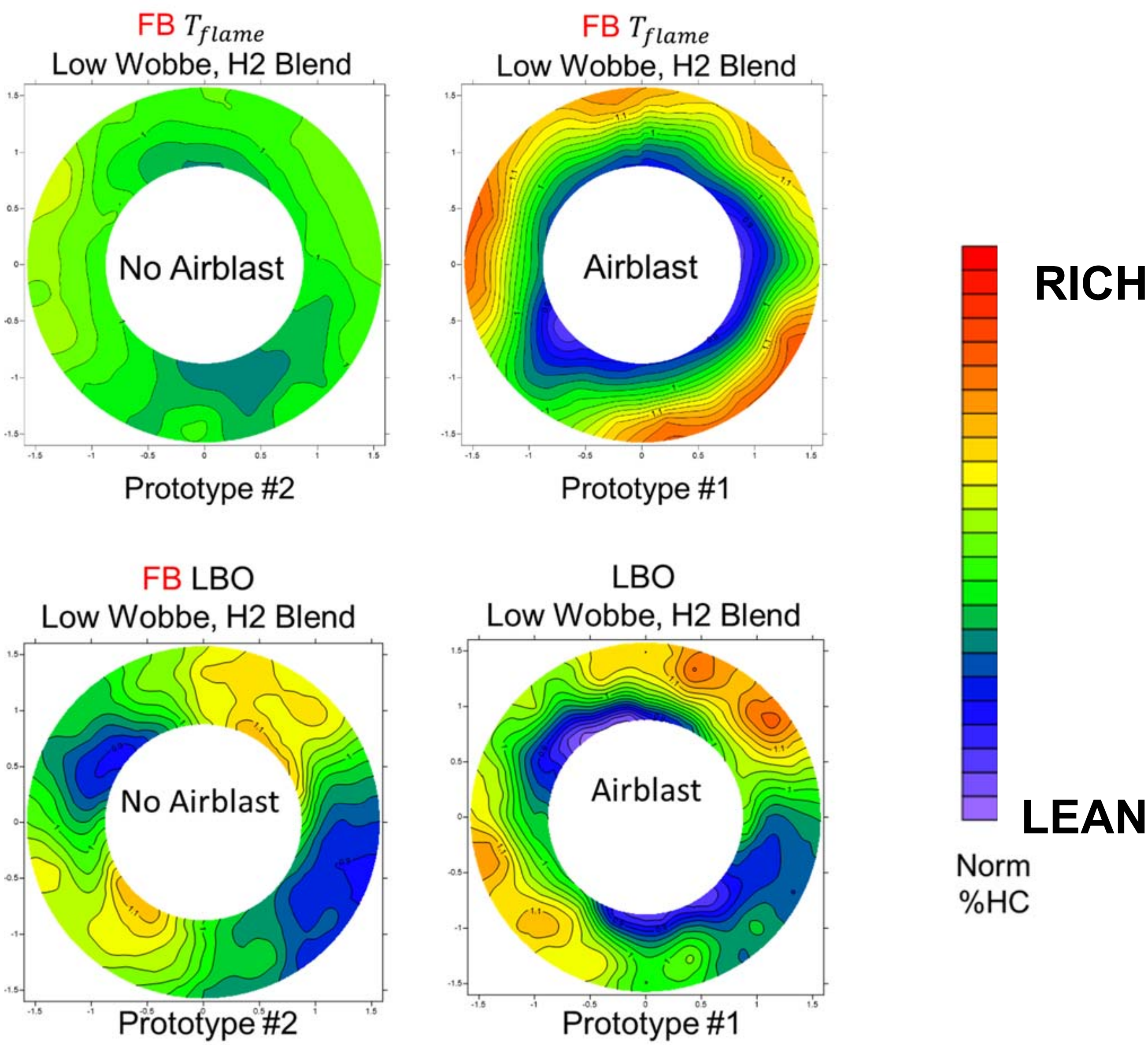

Figure 3 - Air-Fuel Mixing Profiles

Flashback at extreme T_{flame} for prototype #1 occurred near the outer injector wall. This can be attributed to the increase in the fuel rich zone that is seen in this region, which leads to an increase in the flame speed of the mixture. In addition to the higher flame speeds, the low velocities at the boundary layer increases the risk of flashback occurrence.

Higher equivalence ratio near the outer wall of the injector correlates to conditions where peak laminar flame speeds occur. This gives a clearer picture and reaffirms initial conclusions regarding induced flashback for this injector; that high flame speeds in the outer wall region near the boundary layer can induce flashback.

Prototype #1 did not flashback at Lean Blow Out conditions. This centerbody region is leaner compared with prototype 2.

No Air Holes (Prototype 2)

For the injector without the air holes (Prototype #2), a different air-fuel mixing profile is generated for both the LBO case and the extreme T_{flame} case. Without the air holes, the centerbody region is more fuel-rich compared with the air hole case.

For the high T_{flame} case, flashback was still induced at the outer walls of the injector, similar to the Prototype #1. This is due to the fuel-rich region and high flame speeds that still exist near the boundary layer on the outer wall for this case.

For the LBO case, flashback was induced more frequently near the centerbody walls with this prototype. The air-fuel mixing profile shows a fuel-rich region near the centerbody, as opposed to the lean region seen in the air hole case for the LBO case. Due to the combustion instabilities present at LBO, combined with the fuel-rich region near the centerbody, conditions exist where this design is more susceptible to induced flashback.

Conclusions

Key conclusions for prototype 1 are presented:

- Injection of high velocity air into the injector through air holes near the centerbody prevents fuel-rich regions around the centerbody wall. This suppresses flashback at LBO conditions
- At high flame temperatures, fuel-rich regions exist near the outer wall of the injector. The increase in flame speed of the mixture leads to induced flashback in the boundary layer (**Figure *4***).
- The air-fuel mixing profile supports the high pressure rig observations and explains why flashback is induced under certain conditions with this prototype

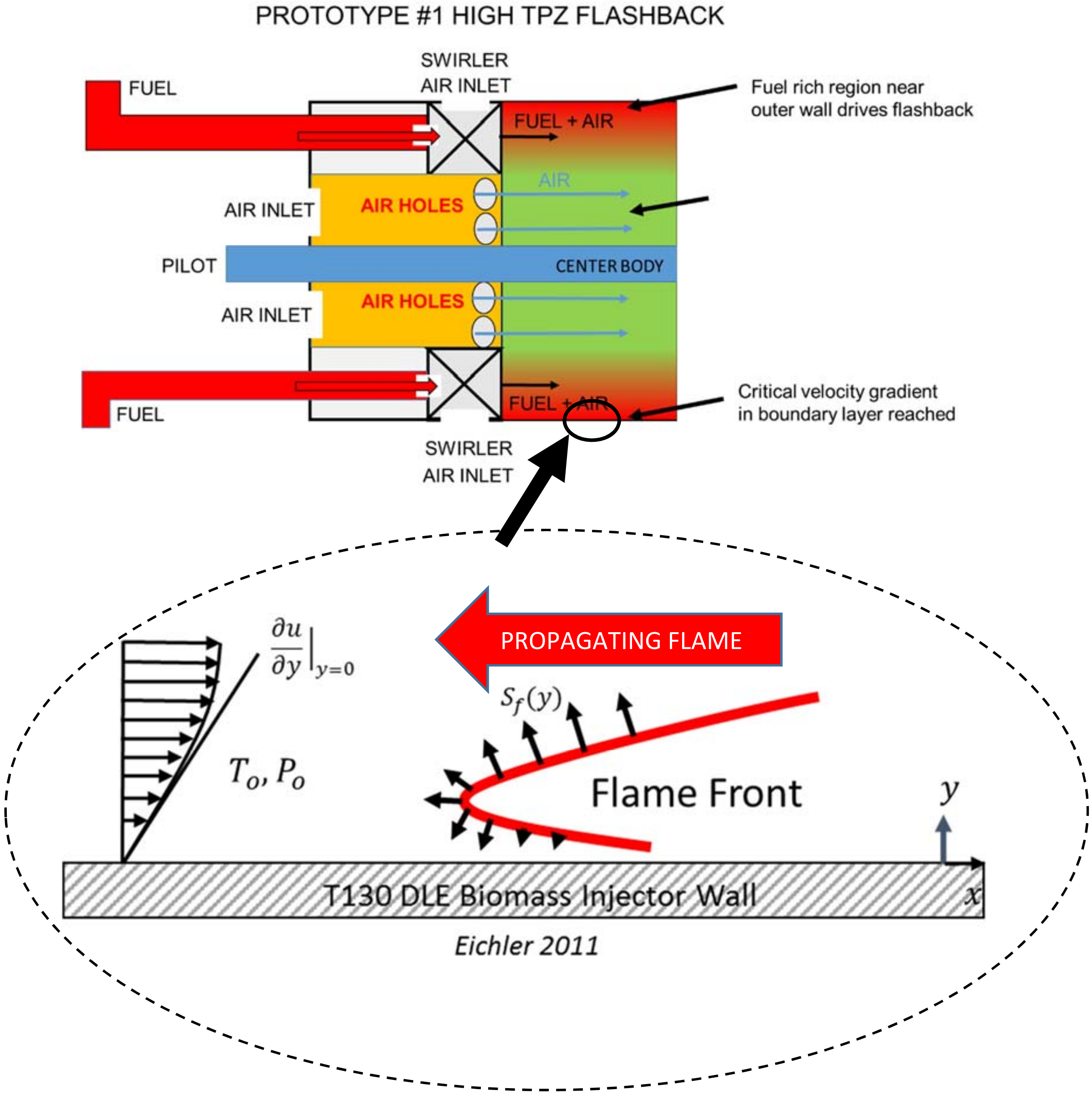

Figure 4 - Flashback Observed for Prototype 1 *[5]*

Several key results for prototype 2 are presented:

- With no air holes, a fuel rich region develops around the centerbody wall. Near LBO conditions, this fuel rich region at the centerbody combined with pressure oscillations due to flame extinction and re-ignition promotes flashback (**Figure *5***)
- At high flame temperatures, fuel-rich regions exist near the outer wall of the injector. The increase in flame speed of the mixture leads to induced flashback in the boundary layer, similar to prototype 1.
- The air-fuel mixing profile supports the high pressure rig observations for prototype 2 and can provide insight into why flashback is induced at both high flame temperature and near lean blow out condition

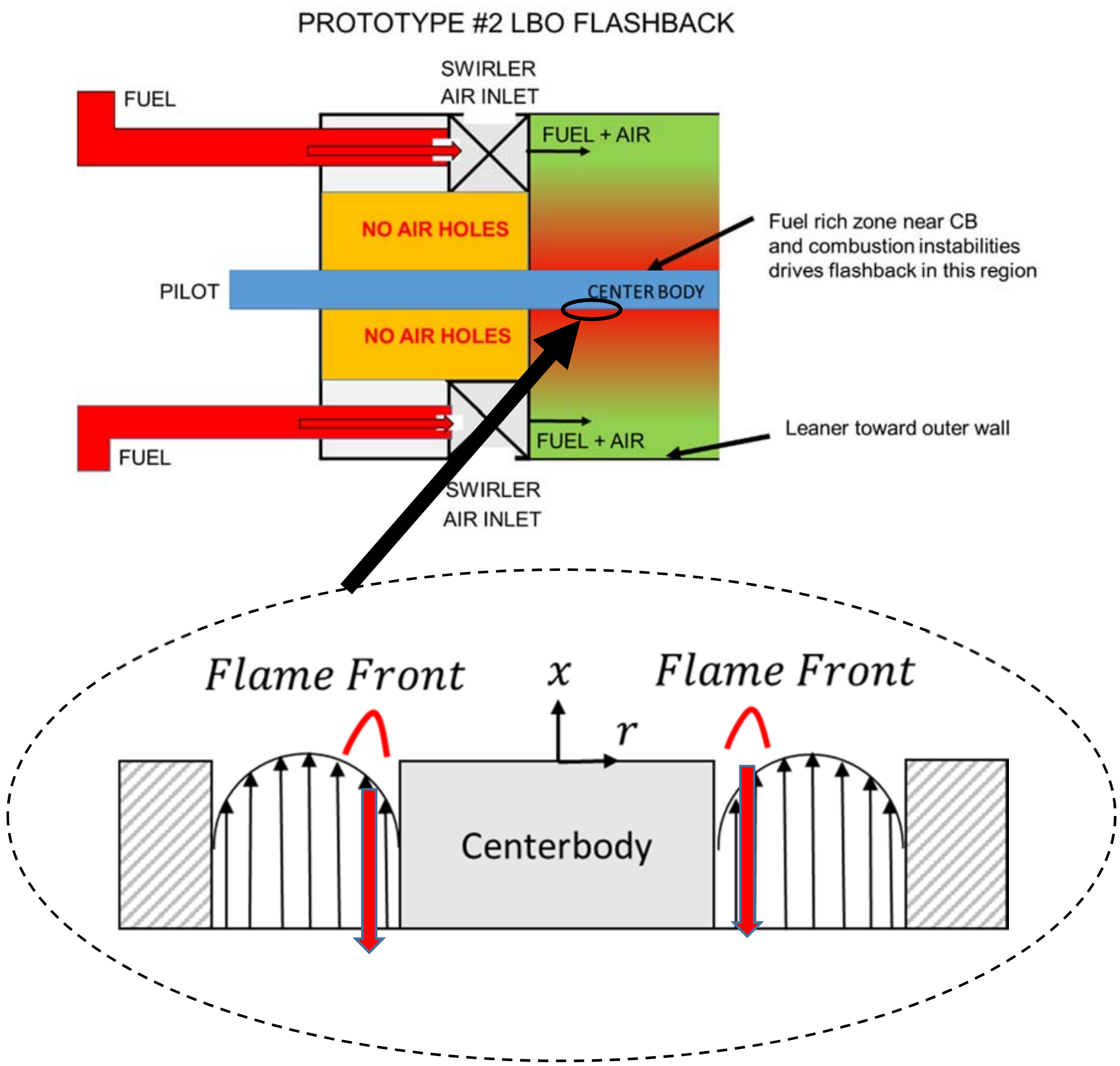

Figure 5 - Flashback Observed for Prototype 2

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