Influence of Burner Material, Tip Temperature and Fuel Composition on Flashback Behavior of Jet Flames

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Flashback is a primary operability issue for low emission premixed combustion systems operated on hydrogen enriched fuels. Previous work investigated fuel composition impacts on flashback propensity and developed models to predict flashback propensity of hydrogen enriched fuel. In the current work, experiments were conducted with higher alkane concentrations which were not completed previously due to flame stabilization issues and heater constraints. To overcome those limitations, the rig was modified and a pilot flame was added. Flashback propensity of ethane and methane was compared and the effect of hydrogen addition was also examined. The addition of alkanes into hydrogen increases flashback resistance substantially, and ethane has a lower flashback propensity than methane. The analysis of variance (ANOVA) of current data further developed models to predict flashback propensity. However, they are not consistent with previously developed models because of the geometric differences of those test rigs in the previous work. The burner tip temperature, shown to help correlate flashback for hydrogen enriched fuels, was not found to be significant in correlating flashback data for alkanes.

1 Introduction

Boundary layer flashback
Flashback (FB) is the main operability issue associated with converting lean, premixed combustion systems from operation on natural gas to operation on high hydrogen content fuels. Currently, four mechanisms of FB have been introduced: (1) core flow FB, (2) boundary layer FB (BLF), (3) combustion induced vortex breakdown (CIVB) and (4) combustion instability induced FB[1]. In the present work, the BLF is of primary interest and a jet flame configuration is used as a first step due to its simplicity and previous study. The BLF mechanism was first proposed by Lewis and von Elbe [2,3]. The critical velocity gradient \( g_c \) was defined in an attempt to predict blow off and FB of laminar flame. This concept was further developed by numerous researchers for various parameters including fuel composition, burner geometry, mixture temperature and pressure, and materials [4–16]. Recently, more work has been conducted on the thermal coupling effects during flashback events [17,18]. Also, in the parallel work, some burner effects on flashback propensity have be found with hydrogen enriched flame [19,20], where correlations were developed to predict flashback propensity. However, the high alkane content fuel were not completed in the previous work due to the rig constraint [19] and this paper will present the investigation as a complement.

Critical velocity gradient
The critical velocity gradient \( g_c \) is the classical way to discuss FB in tubes[2] and most work regarding FB has used this parameter to describe and analyze FB [16,17,21]. Given this, it was also selected as the parameter to evaluate the FB propensity in the current work. E-1 presents the equation applying to turbulent flow, which was derived via the Blasius correlation [22].

In the parallel work, it has been shown that the temperature selected for \( g_c \) calculation substantially affects the correlation quality [19]. It is proved better to use burner tip temperature than inner temperature.

\[
g = \frac{0.03955Re^{0.75}u}{D} = \frac{0.03955\rho^{1.75}D^{0.75}}{\mu^{0.75}D^{0.25}}
\]
Quenching distance

The quenching distance and whether it is greater than the boundary layer thickness and/or penetration distance is significant in the determination of whether FB will occur as discussed above. According to Turns et al. [23], quenching distance can be defined as that diameter of a circular tube where a flame can no longer propagate and extinguish. The criterion for the situation in which a flame is quenched by a cold wall was further defined as when the rate of heat release by chemical reactions inside the slab is less than the rate of heat loss through the slab by conduction. As a result, the expression of quenching distance is developed as shown by Equation 2, where $AFT$, $T_{inlet}$ and $T_{tip}$ denote the adiabatic flame, inlet and wall temperature, respectively. The $b$ is an arbitrary constant introduced by Turns et al. [23]. It was defined as the ratio of local temperature gradient near the wall to that averaged through thermal boundary layer. In the current research, the constant $2\sqrt{b}$ is assumed to be 1.

$$d_q = \frac{2\alpha \sqrt{b}}{S_L} \sqrt{\frac{AFT - T_{tip}}{AFT - T_{inlet}}}$$

E-2

2 Methods

2.1 Experiment Setup

The test system applied is based on a system previously described [24]. This rig has been modified for better thermal control and temperature monitoring. More details can be found elsewhere [19,20]. Basically the jet burner is configured as 38 mm i.d. pipe. Fuel and air are introduced far upstream and are thus fully mixed prior to entering the jet burner pipe.

2.2 Test procedure

Two protocols were adopted in the current study to approach FB:

- Protocol I: Air flow rate was decreased once thermal equilibrium had been fully achieved on the burner rim. The AFT is held constant in each FB experiment. This unique method was introduced to simulate a typical practical gas turbine control strategy [23]. The test with a fixed AFT is also convenient to ensure the investigation is in the lean fuel combustion region.

- Protocol II: Air flow rate was held constant and the equivalence ratio was varied by increasing fuel flow rate in small steps. After each stepwise increase, thermal equilibrium was achieved at the burner rim. This procedure was employed extensively in previous studies.

2.3 Test parameters

The effect of fuel composition on FB has been systematically investigated previously [24]. In this previous work, the fuel space emphasizes high hydrogen content, i.e. high flame speeds, which pose the greatest risk for FB in practical systems [19]. However, the fuel with high content of alkane was not included. In this research, FB propensity of methane and ethane were compared. Single component fuel was tested as a reference. Binary mixtures of hydrogen-alkane were examined to mimic more practical conditions and survey the fuel interaction effects. Two levels mixing were selected in this test and the matrix is shown in Table 1.

<table>
<thead>
<tr>
<th>Composition</th>
<th>mix1</th>
<th>mix2</th>
<th>mix3</th>
<th>mix4</th>
<th>mix5</th>
<th>mix6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$ [%]</td>
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<td>50</td>
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<td>0</td>
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<td>C$_2$H$_6$ [%]</td>
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</table>

Legend in related figures

Table 1 Test matrix of alkane fuel

3 Results and analysis

In this section, the test results and associated discussion are presented. In the previous work, cases with less than 50% hydrogen were not reliable due to the constraint of heater and flame stabilization issues [19]. In the current work, the alkane fuels are examined and hydrogen is also blended in with concentrations lower than 50%. It compares the flashback propensity of different alkane fuel types (methane v.s. ethane).
Figure 1 (a) plots the test results in terms of critical velocity gradient (g_c) versus equivalence ratio (EQ). The g_c here is calculated using tip temperature. Open symbols denote the cases with methane, whereas the closed are for ethane. The critical velocity gradient when FB happens goes up as the EQ is increased. The FB propensity of pure ethane and methane is nearly the same, whereas the mixtures of methane/ethane with hydrogen yield different results. Ethane/hydrogen mixtures show lower flashback propensity than similar methane/hydrogen mixtures, e.g., for a given velocity gradient, FB will occur in methane/hydrogen mixtures at a lower EQ than ethane/hydrogen mixtures. On the other hand, if the FB propensity is evaluated using adiabatic flame temperature (AFT), as shown in Figure 1 (b), a similar conclusion can be made. Given the control dynamic in the practical engine, where flame temperature is held constant, the comparison in Figure 1 (b) provides more insights to the real world. As for the single component fuel, there is no significant difference between ethane and methane. When hydrogen is blended into the fuel, FB resistance is generally decreased. However, the effect of hydrogen addition to ethane mixtures is not as substantial as it is in methane mixtures. The methane mixture with 25% hydrogen has higher FB propensity than that of methane mixture. With the same velocity gradient, AFT for H_2-CH_4 (25%-75%) mixture when FB happens is lower than that of H_2-C_2H_6 (50%-50%). It suggests that addition of ethane to hydrogen enriched fuel can improve the FB resistance largely.

(a) EQ v.s. g_c
(b) AFT v.s. g_c

**Figure 1** Alkane test results in terms of equivalence ratio and flame temperatures (both are based on tip temperature).

In order to further reveal the physical principles behind FB, Figure 2 plots g_c versus laminar flame speed (S_L), either based on (a) inlet temperature (b) burner tip temperature. The laminar flame speed is calculated using Chemkin with the GRI 3.0 mechanism [25]. It is expected that laminar flame speed can correlate to some extent the flashback data presented in Figure 1. In Figure 2 (a), the data points of the ethane tests do collapse to an extent and show a trend that critical velocity gradient goes up with increased laminar flame speed. This illustrates the nature of FB, which is essentially a balance between burning speed and the flow velocity. However, the data points of methane are scattered throughout the figure with no correlation although the laminar flame speed still captures the trend of increasing FB propensity with increasing flame speed. Additionally, nearly all of the FB propensities of methane mixtures are relatively higher than those of ethane mixtures if the laminar flame speed is held constant. Figure 2 (b) plots the calculation results using burner tip temperature. Comparing with Figure 2 (a), data points in this figure scatter less, especially for ethane mixtures. However, the gap between pure methane and the hydrogen-methane mixtures is still significant. Therefore, laminar flame speed can capture the flame features of FB very well for ethane type mixture but it is limited when applied to other mixtures such as methane mixtures.
The raw data obtained were correlated using analysis of variance (ANOVA) with the following parameters: (1) EQ or AFT, and (2) fuel composition. The final selection of terms is based on the ANOVA results with terms having a p-value less than 0.0001 retained. E-3 and E-4 show the equations generated from the model using EQ and AFT, respectively. According to Figure 2, the tip temperature based $g_c$ correlates the data better than the inlet temperature based $g_c$ and it is chosen for the statistical model as a result. Units used in the correlation are presented in Table 2. Both of these two models yield high $R^2$ values (0.9020 and 0.9015, respectively) and Figure 3 presents the comparison between predicted and measured values.

In addition to the statistics based correlations, a model based on key physical parameters was developed, shown by E-5. It is developed using a similar methodology as in previous work [19,24], where the laminar flame speed, quenching distance, burner tip temperature and thermal diffusivity are selected to correlate the flashback propensity of various fuels. This correlation shows a good prediction potential that yields a $R^2$ of 0.9203. Shown by Figure 4, the predicted values match the measurement very well. Table 3 summarizes the predicted values using the above three models. The real $g_c$ values are selected from Figure 1 (b). As sketched by the red straight line, those data points cover the whole range of tested mixtures and yield approximately the same $g_c$. Based on these conditions, the predicted values are calculated using the models E-3, E-4 and E-5 respectively. Generally the models perform quite well in predicting the measurement results, but the error grows as hydrogen composition increases.

$$g_c = \left(46.48H_2 + 23.08CH_4 + 21.77C_2H_6 - 64.13EQ + 49.78H_2 \cdot C_2H_6 - 102.44H_2 \cdot EQ\right)^2$$  \hspace{1cm} \text{E-3}$$

$$g_c = \left(50.76H_2 + 108.88CH_4 + 105.82C_2H_6 - 0.069AFT + 56.29H_2 \cdot C_2H_6 + 3631.54CH_4 \cdot C_2H_6\right)^2$$  \hspace{1cm} \text{E-4}$$

$$g_c = \left(-5571.78 + 302.12S_L + 819.63\alpha - 0.61T_{tip} + 450479d_q - 12262.8S_L \cdot d_q - 68827.3\alpha \cdot d_q - 3.998S_L^2 - 7180478d_q^2\right)^2$$  \hspace{1cm} \text{E-5}$$

Table 2 Units for correlated parameters

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<th>Parameter</th>
<th>Unit</th>
<th>Parameter</th>
<th>Unit</th>
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<tr>
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<td>[-]</td>
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<tr>
<td>Temperature</td>
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<td>[cm/s]</td>
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<tr>
<td>Thermal Diffusivity</td>
<td>[cm$^2$/s]</td>
<td>$d_q$</td>
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Figure 3 Predicted vs Measured values of $g_c$ using Equations 3 and 4.

Figure 4 Predicted (E- 5) vs Measured $g_c$.

Figure 5 AFT v.s. Re

<table>
<thead>
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<td>AFT real [K]*</td>
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<td>$g_c$ real [1/s]**</td>
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<td>1150</td>
<td>243</td>
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</table>

Table 3 Estimated $g_c$ values and Re number
(*: the data lies on the red line in Figure 1 (b); **: predicted values using models based on the same conditions as measured; ***: estimation of Re number with AFT=1700K)

E- 6 and E- 7 are similar correlations developed previously for hydrogen enriched fuels [19]. Data used for these correlations were collected using a stainless steel burner. Although a similar methodology was applied, the models developed here for alkane fuels are quite different. It is mainly because different rigs were applied in the tests. In order to
stabilize an attached flame, a pilot flame was used for the tests with a high alkane concentration. In contrast, those results in previous tests with similar methane composition were screened out because the flame detached from the burner rim and lifted in the enclosure [19]. Furthermore, the injector dimension and thermocouple alignments are different. All of these resulted in inconsistent models. However, according to Figure 5, it can be predicted that FB would hardly happen in the turbulent region. Table 3 summarizes the predicted Re numbers if AFT is held at 1700K (This flame temperature is typical of practical dry low NOx engines). Most FB events at this flame temperature would happen within laminar or transient region (Re<2300) [26]. Therefore, in a practical application, it should not be a problem with respect to FB.

\[
g_c = (224.18H_2 + 9.36CO - 45CH_4 + 232.63H_2 \cdot CH_4 + 0.0331H_2 \cdot T_{\text{inlet}} - 0.213H_2 \cdot AFT)^2 \quad \text{E-6[19]}
\]

\[
g_c = (261.74H_2 - 30.69CO - 188.38CH_4 - 0.8H_2 \cdot T_{\text{tip}} + 0.424CH_4 \cdot T_{\text{tip}})^2 \quad \text{E-7[19]}
\]

At last, it should be pointed out that the above correlations were developed based on the data collected from the specific burner setup. It is not universally applicable across different burner designs. To investigate the limitations resulting from different burner geometry, extensive research has been done in a previous research [20].

4 Summary

The current work conducted tests with higher concentrations of alkane type fuels in contrast to other recent previous work where only high hydrogen content fuels were considered [17,19,20,24]. Previous work attempted experiments with higher alkane concentrations but was not completed due to flame stabilization issue and heater constraints[19]. The current work was able to circumvent these issues and attain a data set for analysis. From this data set, models were developed to predict FB propensity. Tip temperature does not significantly affects the correlation effects as shown in the previous work [19,24]. From the current test result, it is found that laminar velocity alone cannot capture the FB features. Some interaction exists among fuels which results in different FB propensity. The addition of hydrogen is found to reduce FB resistance. However, the effect is not as significant in methane mixtures as in ethane mixture. This discovery provides an insight to increase FB resistance by adding ethane into hydrogen enriched fuels.

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6 References


