Pressure and Fuel Effects on the Flame Brush Thickness of H₂/CO Flames

Prabhakar Venkateswaran  Andrew Irby  Andrew Marshall  Jerry Seitzman  Tim Lieuwen
Georgia Institute of Technology, Atlanta, GA 30332

This paper presents a systematic study of the sensitivities of the flame brush thickness to the turbulence intensity, H₂/CO ratio, and pressure. In particular, data is reported for H₂/CO ratios ranging from 30/70 to 90/10 by volume, and pressures up to 20 atm. Several key findings are reported. First, the flame brush thickness is shown to be a weak function of the fuel composition and stoichiometry at constant \( u'_L/U_o \), even though the corresponding turbulent consumption speed, \( S_{T,GC} \) varies. This result is consistent with findings reported in the literature, and is shown here to persist for a much wider range of H₂/CO mixtures, pressures and turbulence intensities than for which data were previously available. This observation is explained by attributing the turbulent flame brush characteristics to large-scale turbulent diffusion processes, which are independent of the instantaneous flame topology and characteristics. Second, the pressure is observed to augment the turbulent flame brush thickness at fixed \( u'_L/U_o \). For instance, a factor of ten increase in pressure results in an enhancement of the flame brush thickness by as much as a factor of two when \( S_{T,0} \) is held constant across pressure.

Introduction

This paper describes an experimental investigation of pressure and fuel composition effects on the flame brush thickness of turbulent, premixed flames. The turbulent flame brush indicates the spatial region over which the instantaneous turbulent flame fronts are located [1], which can be related to the time averaged heat release distribution normal to the flame. From a practical stand-point, the turbulent flame speed, \( S_T \), and flame brush thickness, \( \delta_{FBT} \), control the spatial distribution of the time averaged heat release in a combustion system that, in turn, influence a variety of other combustor parameters, such as emissions and thermoacoustic instability boundaries [2]. In addition, the turbulent flame speed and flame brush thickness provide useful quantities with which to benchmark and critically evaluate combustion codes [1, 3].

In the review article by Lipatnikov and Chomiak [3], the average progress variable profiles through the flame brush was argued to follow a self-similar profile when the distance through the flame brush is normalized by the local flame brush thickness. In other words,

\[
\langle c \rangle = \langle c \rangle(\xi)
\]

where \( \xi \) is given by:

\[
\xi = \frac{X_{c=0.5} - X}{\delta_{FBT}}
\]

The normalization given in Eq. (2) was shown to collapse the average progress variable profiles obtained from various experimental configurations (Bunsen, rod-stabilized and counterflow), for primarily hydrocarbon-air mixtures, by measuring various scalar quantities
such as temperature, species concentrations and density. The collapsed data was seen to follow a complimentary error function profile, as shown in Figure 1.

![Figure 1: Variation of the average progress variable through the flame brush. The dimensional distance is defined in Eq. (2). Figure reproduced from Ref. [3].](image)

The self-similarity of the average progress variable distribution offers useful simplifications of the Favre-averaged progress variable equation, given in Eq. (3), to a one-dimensional problem which may be more tractable to analytical treatment [3].

\[
\frac{\partial}{\partial t} \left( \bar{\rho} \bar{c} \right) + \frac{\partial}{\partial x_j} \left( \bar{\rho} \bar{u}_j \bar{c} \right) = -\frac{\partial}{\partial x_j} \left( \rho \bar{u}' c \bar{w} \right) + \bar{\rho} \bar{W}
\]

(3)

Taylor’s theory of turbulent dispersion, given by Eq. (4), is often utilized to model the evolution of the turbulent flame brush [3, 4]. In the limit of large \( u'_{rms}/S_{L,0} \), it has been argued that the flame surface dynamics tend toward that of a passive scalar interface. Equating the flame brush thickness to the dispersion of fluid particles in an isotropic turbulent flow field leads to:

\[
\delta_{FBT}^2 = 2 u'_{rms} l_L t_F \left\{ 1 - \frac{\tau_L}{t_F} \left[ 1 - \exp \left( -\frac{t_F}{\tau_L} \right) \right] \right\}
\]

(4)

In Eq. (4), \( l_L, \tau_L, u'_{rms} \), and \( t_F \) are the Lagrangian length scale, Lagrangian time scale, turbulence intensity and flame development time respectively. In spherically expanding flames, \( t_F \) is the time taken for the point of interest to propagate from ignition. In Bunsen flames, \( t_F \) is the time taken to convect from the burner exit to the point of interest on the flame brush. Limit expressions for Eq. (4) show a linear and square root dependence of flame brush thickness upon flame development time for small and large time, respectively [4].

\[
\delta_{FBT} = \begin{cases} 
\frac{u'_{rms} t_F}{\sqrt{2 u'_{rms} l_L t_F}} & t_F \ll \tau_L \\
\frac{t_F}{\sqrt{2 u'_{rms} l_L t_F}} & t_F \gg \tau_L
\end{cases}
\]

(5)

Since the flame is treated as a passive scalar in this development, other reacting flow effects, such as heat release and flame propagation, are not present in Eq. (4). However, many sets reported in the literature follow the scaling given by Eq. (4), such as from Bunsen [5, 6] and V-shaped flames [3, 7]. It has been suggested that Eq. (4) may not hold in more
complex flow fields where the inhomogeneity of the turbulence field and factors such as heat release could become more prominent [1].

Of particular interest to this study are pressure and fuel effects on $\delta_{FBT}$. Several studies on negative Markstein length mixtures have shown that fuel composition exerts very important influences on the turbulent flame speed [5, 8-10]. It has been argued that these effects are controlled by the highly curved leading points of the flame, where the stretched laminar burning velocity can achieve values that can significantly exceed the laminar, unstretched flame speed, $S_{L,0}$ [10-13]. In their review, Lipatnikov and Chomiak [3] suggest that fuel composition exerts minimal influence on $\delta_{FBT}$. However, further data are needed to more fully explore this point over a broader range of conditions and turbulence intensities.

Similarly, the influence of pressure on the flame brush thickness has not been extensively documented in the literature. To the authors’ knowledge, only Griebel et al. [6] have investigated the influence of pressure on the flame brush thickness, and they reported that pressure did not have an influence on the centerline flame brush thickness. We will discuss significance of this particular definition of flame brush in this paper.

In this work we seek to address these open questions by investigating the sensitivities of the flame brush thickness to $\text{H}_2/\text{CO}$ ratio, equivalence ratio and pressure over a wide range of turbulence intensities.

**Methods**

**Experimental facility**

This section summarizes the experimental facility utilized in this study, more details can be found in Ref. [9, 10, 14]. The burner configuration utilized is a piloted Bunsen burner, depicted in Figure 2(a). The burner is contoured to inhibit boundary layer growth and to ensure top hat profiles in the mean and fluctuating velocities at the exit. The flat stoichiometric $\text{CH}_4/\text{air}$ pilot flame is stabilized on a sintered plate fixed around the burner nozzle. The burner is then placed inside a fully remotely operable and optically accessible pressure vessel shown in Figure 2(b). Turbulence is generated upstream of the burner with a variable turbulence generator, whose characteristics are detailed in Ref. [14] and [15].
Figure 2: Schematic of (a) Bunsen burner configuration and (b) high pressure facility. All marked dimensions in mm.

The chemiluminescence from the turbulent flames was captured with a 1024 x 256 pixel resolution Princeton Instruments 16-bit intensified charge-coupled device (ICCD). A 105 mm, f/4.5, UV camera lens was used since this lens is sensitive in the visible and ultraviolet regions (~220-650 nm) and, hence, is capable of capturing both OH* and CO₂*.

Flame brush thickness calculation

The methodology employed to calculate the flame brush thickness is detailed in Venkateswaran [16] and summarized here. The flame brush thickness is calculated as the distance between the \( \langle c \rangle = c_{\text{min}} \) and \( \langle c \rangle = c_{\text{max}} \) contours in the direction normal to the local \( \langle c \rangle = 0.5 \) contour. The calculations are performed on the images obtained from Abel transforming the line-of-sight integrated chemiluminescence images. The \( \langle c \rangle = 0.5 \) contour is then identified, and intensities along the normals are fit with a Gaussian profile. The locations of each progress variable, \( x_{\langle c \rangle} \), along the normal were then determined by solving Eq. (6), where \( \mu \) and \( \sigma \) are the mean and standard deviation of the Gaussian fit to the intensity profile and \( \text{erf} \) is the error function.

\[
\langle c \rangle = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x_{\langle c \rangle} - \mu}{\sigma \sqrt{2}} \right) \right]
\]

The flame brush thickness is calculated up to a height above the burner where the \( \langle c \rangle = 0.15 \) contours from the left and right flame brush cuts intersect. The flame brush thickness is
reported in this paper as the distance between the $c_{min} = 0.3$ and $c_{max} = 0.7$ contours. As detailed in the lead author’s thesis, alternative definitions of $\delta_{FBT}$, such as the distance between the $<c> = 0.2$ and $<c> = 0.8$ contours and as $(d\langle c\rangle/dx)^{-1}$, did not change the conclusions presented here [16].

**Experimental conditions**

Flame brush thickness sensitivities are analyzed from two sets of experiments. In the first set of experiments the mixture equivalence ratio and H$_2$/CO ratio were varied simultaneously to maintain the mixture $S_{L,0}$ at 0.34 m/s. The equivalence ratios were also adjusted across pressures to maintain the same $S_{L,0}$. These experiments were conducted with a 12 mm diameter burner at a mean flow velocity of 50 m/s. The conditions at which data were acquired for this experiment are summarized in Table 1.

Table 1: Mixtures and conditions corresponding to the constant $S_{L,0}$ experiments conducted with the 12 mm diameter burner at a mean flow velocity of 50 m/s.

<table>
<thead>
<tr>
<th>H$_2$ (%)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$, 1 atm</td>
<td>0.61</td>
<td>0.55</td>
<td>0.51</td>
<td>0.48</td>
</tr>
<tr>
<td>$\phi$, 10 atm</td>
<td>0.84</td>
<td>0.75</td>
<td>0.70</td>
<td>0.66</td>
</tr>
<tr>
<td>$S_{L,0}$ (m/s)</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the second set of experiments, H$_2$/CO ratios, equivalence ratios and pressures were all simultaneously such that $S_{L,0}$ was no longer held constant, which allowed us to access a broader range of conditions. These experiments were conducted with a 20 mm diameter burner, and the conditions are summarized in Table 2.

Table 2: Mixtures and conditions corresponding to the experiments for variable $S_{L,0}$ studies.

<table>
<thead>
<tr>
<th>H$_2$ (%)</th>
<th>$\phi$, 5 atm</th>
<th>$\phi$, 10 atm</th>
<th>$\phi$, 20 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.55, 0.61</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.45, 0.50</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>0.4</td>
<td>0.32, 0.40</td>
</tr>
<tr>
<td>$U_o$ (m/s)</td>
<td>25</td>
<td>25</td>
<td>15</td>
</tr>
</tbody>
</table>

**Results and Discussion**

The sensitivities of the flame brush thickness to the turbulence intensity, pressure, and fuel composition are presented in this section. Flame brush thicknesses are plotted as a function of the flame coordinate, $s$, which is defined as the distance from the burner exit along the $<c> = 0.5$ contour. Also plotted are one-sided error bars that reflect the effect of image resolution on the flame brush thickness. Since a minimum of two pixels are required to resolve the flame brush thickness, the flame brush thickness that is calculated represents an upper bound of its true value.
**Effect of turbulence intensity**

In this section, the influence of turbulence intensity on the flame brush thickness for the constant $S_{L0}$ data is analyzed. Figure 3 plots the flame brush thickness as a function of the flame coordinate for various $u'_{rms}/U_o$ for 30/70 and 70/30 $H_2/CO$ ratios at 10 atm.

![Figure 3](image.png)

Figure 3: Variation of flame brush thickness as a function of the flame coordinate for (a) $\phi = 0.84$, 30/70 $H_2/CO$ mixture and (b) $\phi = 0.70$, 70/30 $H_2/CO$ mixture, both at 10 atm. Measurements obtained for the 12 mm diameter burner at 50 m/s.

A few observations can be made from Figure 3. First, note that at each $u'_{rms}/U_o$, the flame brush thickness grows monotonically in the downstream direction from the burner exit, which is consistent with the notion that the flame brush thickness is controlled by turbulent diffusion. Second, the rate of increase of $\delta_{FBT}$ increases monotonically with turbulence intensity, also consistent with the turbulent diffusion scaling concepts.

**Effect of fuel composition**

This section presents data obtained while varying the $H_2/CO$ ratio at constant mixture $S_{L0}$. Figure 4 plots the turbulent flame brush thickness as a function of the flame coordinate for various $H_2/CO$ mixtures at $u'_{rms}/U_o$ of 0.12 and 0.19 at 10 atm. There appears to be a slight increase of $\delta_{FBT}$ with $H_2$ content, although these variations are within the measurement resolution. For reference, the corresponding variation in global turbulent consumption speeds for these same mixtures is about 20% [9, 10]. Other data obtained in the same facility at 1 atm and similar values of $u'_{rms}/U_o$ show the same insensitivity of $\delta_{FBT}$, even though $S_{T,GC}$ varies by a factor of 2 as $H_2/CO$ ratio is varied from 30/70 to 90/10. These data support the conclusions from Lipatnikov and Chomiak, that fuel composition exerts minimal influence on $\delta_{FBT}$, even while it substantially alters $S_T$ [12].
Figure 4: Variation of flame brush thickness as a function of the flame coordinate for various H\textsubscript{2}/CO ratios whose mixture S\textsubscript{L,0} has been held fixed. Measurements shown are obtained with the 12 mm diameter burner at (a) \( u'_{rms}/U_0 = 0.12 \) and (b) \( u'_{rms}/U_0 = 0.19 \) for a mean flow velocity of 50 m/s and pressure of 10 atm.

Although not shown here, other comparisons in Venkateswaran [16] between data at a fixed H\textsubscript{2}/CO ratio but varying equivalence ratios show essentially no influence of equivalence ratio on \( \delta_{FBT} \).

**Effect of pressure**

This section presents measurements of pressure effects, starting with constant S\textsubscript{L,0} studies. Figure 5 plots the turbulent flame brush thickness as a function of the flame coordinate for a 50/50 H\textsubscript{2}/CO mixture at \( u'_{rms}/U_0 \) of 0.12 and 0.19 at 1 and 10 atm.

Figure 5: Variation of flame brush thickness as a function of the flame coordinate for a H\textsubscript{2}/CO ratio of 50/50 at 1 and 10 atm at (a) \( u'_{rms}/U_0 = 0.12 \) and (b) \( u'_{rms}/U_0 = 0.19 \). Measurements obtained at a mean flow velocity of 50 m/s using the 12 mm diameter burner.
These data show that the rate of growth of $\delta_{FBT}$ is higher at 10 atm than at 1 atm, when $S_{L,0}$ is held constant across data. In addition, Figure 6 plots the influence of pressure when $S_{L,0}$ is not held constant and, again, pressure is observed to augment the turbulent flame brush thickness. This pressure augmentation occurs despite a few factors. First, referring back to Table 2, the mean flow velocity at 20 atm is lower than at 10 atm, which suggests that $u'_{rms}$ is lower at 20 atm. Second, at fixed $\phi$ and H$_2$/CO ratio, an increase in pressure results in a reduction in $S_{L,0}$.

This observed influence of pressure is a new finding, since Griebel et al. [6] reported that the flame brush thickness was independent of the pressure. However, as discussed in the introduction, the flame brush thickness in Ref. [6] was determined at the centerline of the flame brush where the thickness is also affected by flame wrinkling and flapping of the flame branch originating from one side into the other. As such, additional physical processes control the flame brush thickness in this region that are not present in the regions where the flames are developing. We minimized this effect by stopping at values where the $\langle \varepsilon \rangle = 0.15$ values from the two flame branches intersect.

Figure 6: Variation of flame brush thickness as a function of the flame coordinate for a 70/30 H$_2$/CO mixture for $\phi = 0.40$ at 10 and 20 atm at (a) $u'_{rms}/U_0 = 0.14$ and (a) $u'_{rms}/U_0 = 0.16$. Measurements obtained using the 20 mm diameter burner.

To further investigate this pressure effect, Figure 7 plots the ratio of the flame brush thickness at 10 atm to the flame brush thickness at 1 atm for the 50/50 and 70/30 H$_2$/CO mixtures respectively from the constant $S_{L,0}$ studies. The ratio is not calculated near the burner exit where the measurement resolution and pilot flame effects influence the calculation.
Figure 7: Ratio of the flame brush thickness at 10 atm to the flame brush thickness at 1 atm as a function of the flame coordinate for the (a) 50/50 H\textsubscript{2}/CO and (b) 70/30 H\textsubscript{2}/CO mixtures.

Some observations can be made from Figure 7. First, the ratio of flame brush thickness grows roughly linearly with the distance along the flame coordinate, before apparently saturating. The cause of this saturation is unclear, but the location where the saturation starts corresponds to the location where a change in the slope of the 1 atm data in Figure 5 is seen. Second, the ratio of flame brush thicknesses increases with $u'_{rms}/U_0$ suggesting that the turbulence has a stronger augmenting effect on the flame brush thickness at higher pressures.

Figure 8 explores the influence of fuel composition on this ratio, by comparing the ratios of the 50/50 and 70/30 H\textsubscript{2}/CO mixtures at $u'_{rms}/U_0 = 0.12, 0.15$, and $0.19$, while $S_{L,0}$ is held constant across the mixtures. Although the ratio exhibits a weak dependence on the fuel composition at the lower turbulence intensity, this effect disappears at the higher turbulence intensity.

Figure 8: Effect of fuel composition on the ratio of the flame brush thickness at 10 atm to the flame brush thickness at 1 atm at (a) $u'_{rms}/U_0 = 0.12$ (b) $u'_{rms}/U_0 = 0.15$ and (c) $u'_{rms}/U_0 = 0.19$

One potential source for these observed pressure effects are Darrieus-Landau (DL) instabilities. The role of DL instabilities on the turbulent flame speed has been discussed in Ref. [12, 17, 18], who suggest that it augments and has little effect on the turbulent flame speed at low and high turbulence intensities, $u'_{rms}/S_{L,0} \sim 1$ and $>>1$, respectively [17].
However, we are not aware of any work that has discussed the influence of the DL instability on $\delta_{FBT}$.

Reynolds number effects are another potential source for these systematic pressure effects since the Reynolds number varies linearly with pressure. However, the turbulence characteristics and growth rates of the mixing layer and fully developed region of the jet do not have a Reynolds number dependence through which the pressure can exert an influence [4]. As a result, it is not obvious that this should be an important effect, although this issue warrants further investigation.

**Comparisons to Passive Scalar Model predictions**

In this section, comparisons between the data presented in the earlier sections and the predictions from the model given by Eq. (4) will be made. To recall, Eq. (4) is derived by assuming that at large turbulence intensities, $u'_{int}/S_{L0} \gg 1$, the flame elements are convected along by the turbulent flow as a passive scalar. Following Ref. [7], $\tau_L$ is estimated as $l_{int}/u'_{max}$, $l_L$ is calculated as $l_L = U_0 \tau_L$ and the flame development time is calculated as $t_F = y/U_0$, where $y$ is the axial distance from the burner to the average flame. Note that the distance is considered along the axial coordinate and not the flame coordinate. Figure 9 and Figure 10 plot comparisons between the model by Eq. (4), and the actual data for two H$_2$/CO mixtures at 1 atm and 10 atm respectively.

![Comparison between the actual normalized flame brush data (circles) and model (line) given by Eq. (4) for (a) 50/50 and (b) 90/10 H$_2$/CO mixtures at 1 atm and constant $S_{L0}$ obtained using the 12 mm diameter burner.](image-url)
Before commenting on the comparisons between the data and the model, it is worthwhile to revisit the expressions for Eq. (4) in the limit of small and large \( t_F/\tau_L \), given by Eq. (5). In the limit of small \( t_F/\tau_L \), the flame brush thickness is predicted to vary linearly with the flame development time, while at large \( t_F/\tau_L \), the flame brush thickness varies as the square root of the development time. Due to the limitations in the image resolution, it is unclear whether the flame brush thickness near the flame base, where \( t_F/\tau_L \ll 1 \), varies linearly with the flame development time. Further downstream, the flame brush thickness growth rate is predicted to vary as the square root of the flame development time, which is not observed with the data. However, the square root dependence has been reported previously in Ref. [3, 7] for rod-stabilized V-shaped flames geometry.

The absence of the saturation in the data may be attributed to the geometry of the flame brush. In the rod-stabilized flames, the two sides of the flames do not merge with increasing downstream distance, while in the Bunsen flame they do merge. As a result, since the flame brush thickness calculation is this work seeks to minimize the effects of flame interaction, the region considered may not proceed far enough downstream to see this effect. It is also interesting to note that although the model generally over-predicts the data, the model over-predicts the 1 atm data by a greater margin than it does the 10 atm data.

**Conclusions**

In this paper we present the results of a detailed study characterizing the influence of fuel composition and pressure on the turbulent flame brush. The key findings of this work are as follows. First, the flame brush thickness is shown to be independent of the fuel composition and equivalence ratios, over a broad range of fuel mixtures, turbulence intensities and pressure, which are consistent with classical turbulent diffusion scaling concepts. Second, at fixed \( u'_{rms}/U_0 \) the pressure is observed to augment the flame brush thickness. In addition, the ratio of the flame brush thickness at 10 atm to 1 atm increases as \( u'_{rms}/U_0 \) increases,
suggesting that the pressure augments the flame brush thickness to a greater degree at higher turbulence intensities. The mechanism by which pressure affects the flame brush thickness is uncertain at this point. Potential mechanisms, which will need to be explored in future works, include enhancement of Darrieus-Landau instabilities and Reynolds number effects on growth rate and turbulence characteristics of the jet shear layer and potential core.

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References


