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## The Effects of Piloting on Turbulent Flame Structure

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Pilot flames are commonly used to study turbulent flames as they present a means of preventing blow off at higher velocities. There are open questions regarding how pilot flames affect the main flame. This is true for both anchoring pilots, which are small pilot flames located at the base of the flame, and back-support pilots, which produce adiabatic or superadiabatic boundaries around the flame. The question of how the presence and size of pilot flames affect the properties of the main flames is important to understanding the behavior of the main flame. The purpose of this study is to explore how the presence of pilot flames affects the flame surface density, global consumption speed, and flame curvature statistics of a turbulent, premixed flame over a range of velocities. Natural gas was used as a fuel and the equivalence ratio was held constant at 1. Three different pilot flame configurations were used to explore the interaction between flame and pilot, including variations in the presence of both the anchoring pilots and the back-support pilots. The results of this study will affect our interpretation of flame sheet dynamics in a range of piloted flames.

**Keywords:** *Turbulent Flames, Stabilization, Pilot Flames*

### 1. Introduction

Piloting is used in many turbulent combustion experiments to help stabilize flames at high flow velocities and turbulence intensities. In this study, we focus on premixed flames only, as the structure and propagation of premixed flames is canonically different than that of non-premixed or even partially premixed flames. These piloting schemes vary between experiments, but typically can be put into two major categories: anchoring pilots, which are used to stabilize the base of the flame and prevent blow-off in higher velocity cases, and back-support pilots, which are used to produce an adiabatic or superadiabatic boundary layer to provide more favorable conditions for combustion. Table 1 provides examples of burners that have used pilot flames and describes the nature of the pilots used.

While the use of pilot flames is very common, it's unclear how these pilot flames change the structure and behavior of the turbulent flames they stabilized. The goal of this study is to begin to understand the impact of pilot flames on turbulent premixed flame behavior. In this particular study, we have found that the presence of pilot flames has a negligible effect on the turbulent global consumption speed and flame brush thickness of turbulent premixed flames.

**Table 1.** List of experiments that utilize pilot flames to study turbulent premixed flames.

Authors	Type of Pilot	Experimental Goal	Pilot Fuel	Pilot Equivalence Ratio
Skiba <i>et al.</i> (Michigan)[1]	Back-Support	Study of flame structure responses to extreme levels of turbulence	Methane	0.98
Zhou <i>et al.</i> (Lund)[2]	Back-Support	Exploration of the relationship between reactive scalar and jet speed	Methane	0.4
Won <i>et al.</i> (Princeton)[3]	Anchoring	Research of turbulent flame propagation's response to low temperature fuel chemistry	Methane	1.00
Yuen <i>et al.</i> (Toronto) [4]	Anchoring	Characterization of flame structure in thin reactions regime	Methane, Ethylene	Not Provided
Dunn <i>et al.</i> (Sydney) [5]	Anchoring	Studying the finite-rate chemistry effects of a premixed jet	Natural Gas	1.00
Venkateswaran <i>et al.</i> (Georgia Tech) [6]	Anchoring	Understand the effects of syngas fuel blends on turbulent consumption speed	Methane	0.9
Steinberg <i>et al.</i> (Michigan) [7]	Back-Support	Studying the effect of turbulence-flame interactions on flame stretch	Methane	Varying

## 2. Experimental methods

### 2.1 Main Burner Setup

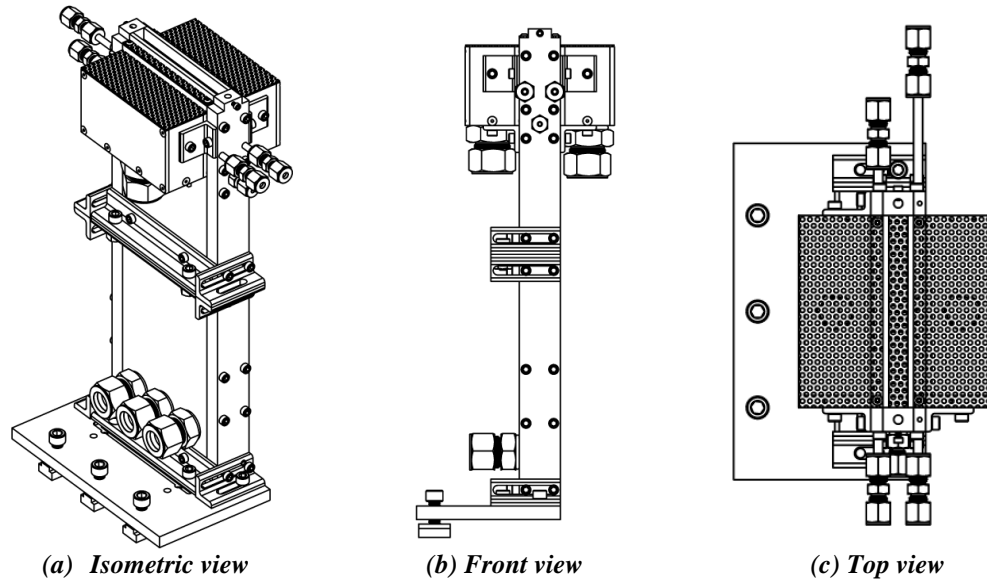
The experimental setup consists of a burner with an exit plane of dimensions 100mm x 10mm (Figure 1). The burner contains two stacked sections with heights of 178mm and 160mm. The first section contains the inlet for incoming flow of the air-fuel mixture and a ceramic honeycomb layer. The other section contains another honeycomb layer and two perforated plates. As a means of conditioning the flow of the air-fuel mixture (utilizing natural gas as the fuel and an equivalence ratio of 1), the flow is sent through both layers of honeycomb inside the burner prior to reaching the exit plane of the burner. The two perforated plates are placed at 30mm and 10mm upstream of the burner exit plane and are used to create turbulence in the flow field. The perforated plates, with a 3.175mm hole diameter and 40% open area, are able to generate a non-reacting average flow turbulence intensity of 18% at the exit of the burner. This turbulence intensity is normalized through the use of the bulk flow velocities.

### 2.2 Back Support Pilot Setup

The two identical back-support pilots each consist of rectangular exit planes with dimensions 90mm x 30mm. The exit plane of the back support pilots is 13mm upstream of the burner exit plane. The cavity of the back-support pilots is filled with ball bearings as a means of ensuring that that flow is relatively uniform throughout the entire rectangular pilot.

### 2.3 Anchoring Pilot Setup

The two identical anchoring pilots have a narrow rectangular exit plane with dimensions of 90mm x 4.8mm. The exit plane of the anchoring pilots is 6.4mm upstream of the burner exit plane. Similar to the back-support pilots, the anchoring pilots are filled with identical ball bearings and a layer of honey comb for flow conditioning.



**Figure 1:** Sketches of the experiment's burner: (a) Isometric view of the burner configuration in its entirety, (b) Front view of the burner, (c) Top view of the burner.

### 2.4 OH-Planar Laser-Induced Fluorescence

OH-PLIF measurements are performed at a sampling rate of 10kHz. This high-speed diagnostic system consists of a 532nm Nd:YAG laser (Edgewave) pumping a dye laser (Sirah Credo). The maximum power output from the dye laser at 10 kHz repetition rate is 0.3mJ/pulse. The dye laser is calibrated to the  $Q_1(6)$  line of the  $A^2\Sigma^+ \leftarrow X^2\Pi(1-0)$  band to excite the OH radicals at 282.94nm. A periscope and a set of three cylindrical lenses are used to obtain a collimated sheet with an approximate height of 21mm. A CMOS sensor camera (Photron FASTCAM SA1.1), coupled with an external intensifier (LaVision HS-IRO) and a 100 mm f/2.8 UV lens (Cerco) is used to acquire the images. A high transmissivity interference filter (LaVision 1108760 VZ) is used to reduce background noise. A more detailed description of this set up can be found in Ref. [8].

## 3. Results

### 3.1 Test Matrix

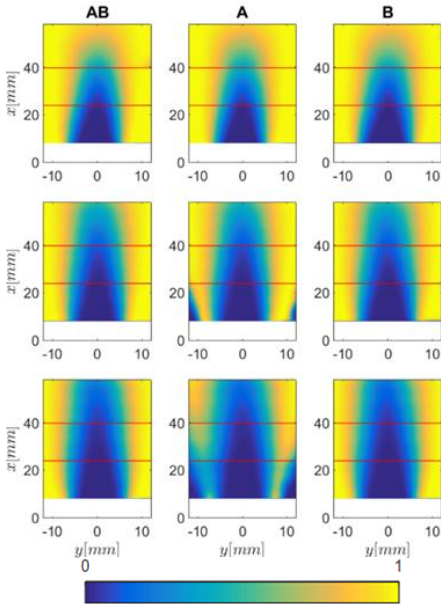
This study was run for three different pilot configurations, each over three different flow conditions with bulk flow velocities of 12m/s, 20m/s and 28m/s. The piloting configurations consisted of a condition where both anchoring and back-support pilots were used (denoted as "AB"), a condition where only anchoring pilots were used (denoted as "A"), and a condition where only back-support pilots were used (denoted as "B"). The test matrix in Table 2 provides the details of each of the nine cases examined in this study.

**Table 2.** Test matrix including variations in the bulk flow velocities, the Reynolds number based on the hydraulic diameter, and the pilot configuration for each case.

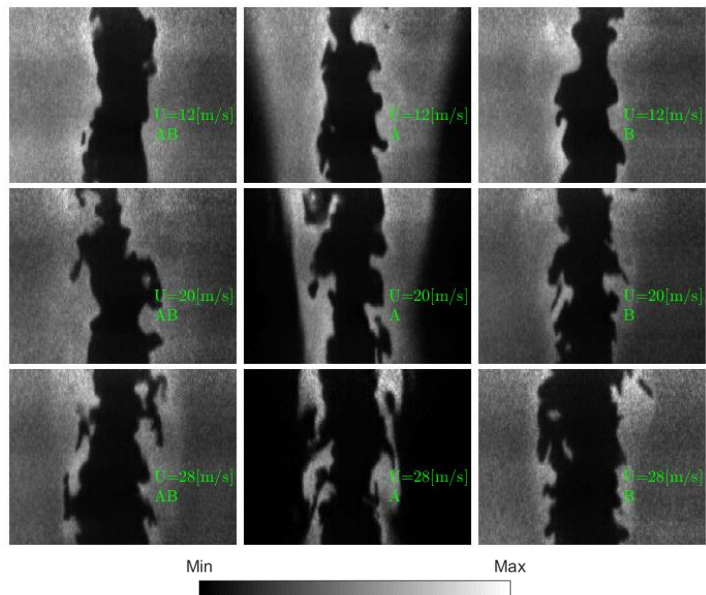
Case Number	Equivalence Ratio ( $\Phi$ )	Bulk Flow Velocity U [m/s]	Reynolds Number (Hydraulic Diameter)	Pilot Configuration	$u'$ [m/s]
12AB	1.0	12	15485	All	2.0
12A	1.0	12	15485	Anchoring	2.0
12B	1.0	12	15485	Back-support	2.0
20AB	1.0	20	25808	All	3.2
20A	1.0	20	25808	Anchoring	3.2
20B	1.0	20	25808	Back-support	3.2
20AB	1.0	28	36131	All	4.5
20A	1.0	28	36131	Anchoring	4.5
20B	1.0	28	36131	Back-support	4.5

### 3.2 Progress Variables

Figure 2 shows the stitched, time-averaged progress variables with red lines used to denote the three fields of view used for data collection, and Figure 3 shows an instantaneous LIF image of the flames in the first field of view. From the progress variable plots, there are no observable differences between the different pilot configurations as the time averaging diminishes any instantaneous topological differences that may exist in the flame structure. The instantaneous LIF views show the benefits that back-support pilots have on data collection. In the absence of back-support pilots, the absence of the additional OH around the flame makes edge detection and curvature calculations difficult and leads to a degree of ambiguity in regards to the behavior of the structure of the flame.



**Figure 2:** Stitched, time-averaged progress variable plots for each of the 9 cases.



**Figure 3:** Instantaneous LIF images of the first field of view for each of the 9 cases.

### 3.3 Flame Brush Thickness

By taking an average of the instantaneous binarized images from the experiment, time-averaged progress variables ( $\bar{c}$ ) were found and used as a means of calculating the flame brush thicknesses. According to studies conducted by Kheirkhah *et al.* [9] and Namazian *et al.* [10], the magnitude of the flame brush thickness can be approximated through the use of the maximum gradient of the progress variable in the cross-stream direction, as in Eq. 1.

$$\delta_t = \max\left(\frac{1}{\left|\frac{\partial \bar{c}}{\partial y}\right|}\right) \quad (1)$$

Figure 4 provides the plots of the flame brush thicknesses for each of the velocities versus downstream position. The results show that at each of the velocities tested, the presence or absence of pilot flames had little to no effect on the slope of the flame brush thickness plot.

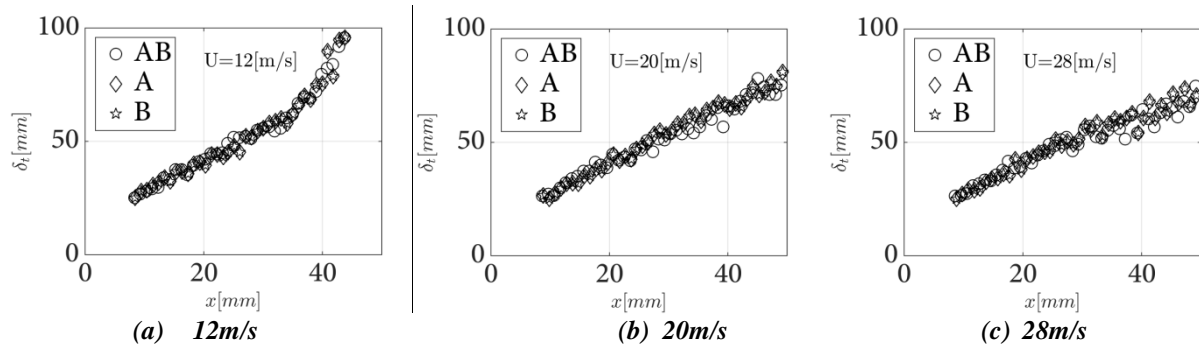


Figure 4: Flame brush thickness vs. position for bulk flow velocities of (a) 12m/s, (b) 20m/s and (c) 28m/s.

### 3.4 Turbulent Global Consumption Speed

The turbulent global consumption speed can be calculated in the equation that follows, where the total reactant mass flow rate is divided by the product of the reactant gas density and the surface area of a contour for a given progress variable, as in Eq. 2.

$$S_{T,GC} = \dot{m}_R / \rho_R A_{\bar{c}} \quad (2)$$

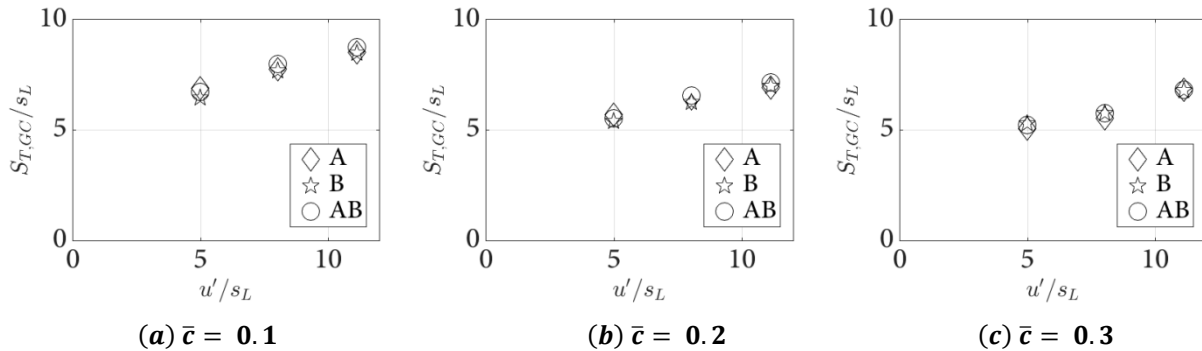


Figure 5: Turbulent global consumption speeds for progress variables of (a) 0.1, (b) 0.2 and (c) 0.3.

We have utilized three different values of progress variables to calculate global consumption speed ( $\bar{c} = 0.1, 0.2, 0.3$ ). The density of the reactants is taken at 300K. As we increase the bulk flow velocity, the turbulence intensity also increases and the global consumption speeds increase.

Conversely, as the progress variables increase, global consumption speeds decrease. This is due to the fact that larger progress variables result in a larger averaged surface area of the flame, as shown in Figure 5. As shown in the plots, there is virtually no difference in the global consumption speeds of flames when subjected to the various pilot flame configurations.

#### 4. Conclusions

In summary, the overarching implication of this initial work is that any potential effects that pilot flames could have on the global behavior of turbulent flames can be regarded as negligible. The slope of the flame brush thickness data appeared to be consistent across each of the pilot conditions and was merely a function of bulk flow velocity. Furthermore, the global consumption speeds of the turbulent flames were likewise unaffected by the pilots, and were affected only by the bulk flow velocity and the progress variable. With pilot flames being a resource so frequently used in the combustion community, it is essential to ensure that data has not been skewed as a result. In the future, the authors will continue to explore potential effects that pilots may have on the local behavior of these flames. In particular, we will consider the impact of piloting on flame wrinkling and the frequency of flame interaction events and flame hole formation.

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