Effect of Fuel Nozzle Geometry on the Stability of Non-Premixed Turbulent Methane Flame

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Abstract

An experimental assessment of the effect of fuel nozzle geometry on the stability of turbulent, non-premixed methane flame is presented. The burner consists of a central fuel nozzle surrounded by an annulus of co-airflow. Four nozzles with different geometries having similar exit cross-sectional areas but different internal/orifice geometry (circular, rectangular, square and triangular) were tested. The main focus of the present study was on determining the flame lift-off, blowout and reattachment velocities, which are indicators of the stability of non-premixed methane flame. The flow mean velocity and turbulence profiles along the centreline plane were also measured. The experimental data revealed that both the lift-off and blowout velocities of the asymmetric nozzles' flames (i.e. rectangular and triangular) are higher than those of the square nozzle and circular nozzle (i.e. axisymmetric). In addition, these results showed that beyond a specific co-airflow rate, reducing the fuel exit velocity does not result in the flame reattachment; but instead, the lifted flame extinguishes before it settles down on the burner. The base of the lifted flame, which changes depending on the jet fuel exit velocity, stabilizes right downstream of a local minimum of the u'/U profile.

1 Introduction

Jet diffusion flames (non-premixed combustion) are used in various engineering combustion power systems because of their safe operation (e.g. absence of flashback). However, there are several aspects of these types of flames which are still less understood such as the stabilization mechanism. Understanding these important aspects will lead to improving the performance of combustion systems (e.g., efficiency, safety, and emissions). In the last decades numerous published studies were devoted to understanding the stability mechanisms of non-premixed combustion (e.g. [1-8]). Although these studies brought tremendous progress in understanding these flames, there is still a lack of comprehensive knowledge on the governing mechanisms. For instance, there exist diverse stability theories which can be used to fairly explain a particular case; however, they fail to apply to other different flow cases. This is not surprising because of the great complexity associated with these types of reacting flows (e.g. coupled chemical reactions with turbulence). Nonetheless, this presents an outstanding opportunity for researchers to strive for developing additional experimental and theoretical/numerical work in order to help advance our understanding of the physics of these complexes flow configurations.

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Most of published results concerning the stability of non-premixed flames were conducted using axi-symmetric fuel nozzle (e.g., [1-3, 7-8]). However, recent studies examined the impact of asymmetric fuel nozzles on the overall performance of diffusion flames and in particular their stability (e.g., [3-5]). It was demonstrated that these non-symmetric fuel nozzles have the potential of inducing various turbulent structures when compared with their counterparts' axisymmetric nozzles. Thus, the stability map of non-premixed flames appeared to be wider as a consequence of these flow structures (e.g., [3-5]). The present study is a continuation of the efforts being undertaken by the senior author of this paper to help understand the stability features of non-premixed flames issuing from asymmetric fuel nozzles. Therefore, in the present experiment four nozzles with different geometries were tested. Unlike in [3-5], the fuel nozzles tested in the present study have a sudden contraction profile. The stability of the ensuing flames was examined via determining the lift-off velocity, as well the blowout and reattachment velocities. In addition, the flow axial mean velocity profiles were measured to help understand the flame stabilization governing mechanisms.

2 Experimental set-up

The experimental set-up employed in this study was described in details in our previous publications ([3-5]). Therefore, only a brief description is given here. Figure 1 presents a schematic diagram of the burner test facility. It consists of an interchangeable nozzle attached to a central supply pipe which is connected to a supply cylinder of fuel via a flow control panel – not shown here. The central (fuel) pipe is surrounded by an annulus which is used for supplying co-airflow, which delivered from a laboratory supply line. The fuel (methane) is supplied from a compressed cylinder. Each fluid (methane or air) mixes with seeding particles prior to discharging into the atmosphere. The seeding particles used in this study are powders of Ti_2O, which have a nominal diameter of the order of 1 μm. After seeding the gaseous fuel in a seeding chamber, the fuel flows through a pipe of 7.62 mm in diameter, and then discharges into the ambient through a nozzle (which is attached to the end of the pipe), as shown in Fig. 1. The seeded air is supplied to the burner through four equally-spaced tangential ports of the outer annulus as indicated in Fig. 1. The air travels upwards in the outer annulus through a set of screens and honeycombs before discharging into the atmosphere from an annular cylindrical block surrounding the fuel nozzle.

The tested four nozzles having different geometries of the exit orifice, which are circular, rectangular (with an aspect ratio of 2), triangular (an isosceles triangle), and square, are shown (top view) in Figure 2. All these nozzles, which have the same external diameter and length, have approximately the same equivalent orifice diameter (D_e) of 4.5 mm. In the present experiment, the test conditions consisted of varying the nozzle geometry, the fuel jet exit velocity (U_j), and the co-airflow exit velocity (U_{co}). In this paper, only a very low-momentum co-airflow with a maximum exit velocity of 1.5 m/s was examined.

Dantec Dynamics two-dimensional particle image velocimetry (PIV) technique was used to measure the centerline mean velocities and their mean fluctuating components (using adaptive correlation) in the streamwise and radial directions of the reacting jets. Instantaneous image pairs of 2000 data points for each test case were collected and processed to determine the orthogonal mean velocities, U and V, and their mean fluctuating components (u' and v').

3 Results and discussions

Lift-off, blowout and reattachment velocities of non-premixed methane flame are presented below. The aim was to examine the effect of the central fuel nozzle geometry in conjunction with the co-flow strength. The effect of nozzle asymmetry on these elements of flame stability is discussed using the PIV measurements of the reacting flow velocity profiles along the jet flow centerline plane. The lift-off velocity, which is defined as the jet exit velocity at which the flame completely detaches from the nozzle, is measured visually by gradually increasing the fuel jet exit velocity, for different nozzle geometries. The co-flowing air exit velocity is also fixed until the flame detaches completely from the nozzle. Figure 3 presents the flame lift-off velocity as a function of the co-airflow exit velocity for different nozzle geometries. The general trend displayed in this figure demonstrates that the lift-off velocity does not change significantly when varying the co-airflow rate, but it is higher for rectangular and triangular nozzles (basically, nozzles with asymmetric geometry) followed by the square nozzle and then the circular nozzle (nozzle with axisymmetric cross-sectional area). This can be related to the higher mixing between the fuel and co-flowing air (as a consequence of higher turbulence intensities at the exit of these nozzles as can be seen later on in Fig. 4-b) of asymmetric nozzles compared with their counterparts axisymmetric nozzles. Thus, it makes it increasingly difficult for the flame base to lift off from the nozzle. This is consistent with the stability theories of Vanquickenborne and Van Tiggelen [6], and the findings of Coats and Zhao [7].

Flame blowout velocity (defined here as the jet exit velocity at which the flame completely extinguishes) is also presented in Fig. 3. It shows that the blowout of the lifted non-premixed methane flame, in general, decreases slightly as the co-flow exit velocity, U_{co}, increases from 0 to 1.5 m/s. More importantly, this figure reveals that similarly to the lift-off trend, the blowout velocity of the rectangular and triangular nozzles flames are generally greater than those of the square and circular flames regardless of the co-airflow rate.

Flame reattachment velocity, which is defined as the jet exit velocity at which the lifted flame re-attaches to the burner rim again, was determined via visual observations by gradually reducing the jet fuel flow rate until the flame completely attaches to the burner. The results for different co-flow rates are also presented in Figure 3. It shows that increasing the co-airflow rate results in a decrease in the reattachment velocity. Furthermore, this figure shows that for air co-flow rates higher than a specific value ($U_{co} \approx 0.6\, m/s$), the lifted flame cannot re-attach to the burner rim; instead it blows out when reducing the jet fuel flow rate.

Figure 4-a presents the velocity contours for a typical lifted flame where it shows that the flame base is stabilized in the mid-field of the fuel jet ($15 < x/D_e < 25$). The edge of the flame base, which is obtained via image processing of instantaneous images of the flame using MatLab software, is also depicted on the velocity contours. It is found that the flame base has a hollow in the center, which in line with published findings [8].

The axial turbulence intensity (u'/U) along the centerline of the jet flow for the lifted flame base in the near field is presented in Figure 4-b. Similar diagrams are shown, respectively, in Figs. 4-c and 4-d, for the fuel jet conditions at which the flame base is stabilized in the mid- and far-field regions. From these figures (Figs. 4-b, 4-c and 4-d), it is found that slightly before the mixture meets the flame base, the centerline axial turbulence intensity (u'/U) appears to reach a local minimum value. This is an interesting finding which will help advance our understanding of the non-premixed hydrocarbon flames stability mechanism.

4 Conclusions

The main concluding remarks are summarized as follows:

- In general, the lift-off velocity does not change significantly with varying the co-airflow rate. However, it is higher for the rectangular and triangular nozzles followed by the square and the circular nozzles. This is due to the higher mixing between fuel and co-flowing air of the asymmetric nozzles (i.e. rectangular and triangular nozzles) compared with that of axisymmetric nozzles (i.e. square and circular nozzles).
- The flame blowout, generally, decreases slightly as the co-airflow exit velocity increases. Moreover, similarly to the findings of the lift-off, the blowout velocity of the rectangular and triangular nozzles is generally greater than that of the square nozzle and circular nozzle flame regardless of the co-airflow exit velocity.
- Increasing the co-airflow exit velocity (i.e. flowrate) results in reducing the flame reattachment velocity. Moreover, the lifted flame does not reattach for co-airflow velocities greater than $U_{co} \approx 0.6\, m/s$ when decreasing the fuel jet exit velocity (i.e. flowrate).
- It appears that there is a strong correlation between the lifted flame base and the axial turbulence intensity u'/U profile. It is found that the base of the lifted flame stabilizes just downstream of a local minimum of the axial turbulence intensity.

References

[1] Pitts WM. (1988). Assessment of theories for the behaviour and blowout of lifted turbulent jet diffusion flames. Proc. Combust. Inst. 22: 809.

[2] Kalghatgi GT. (1984). Lift-off heights and visible lengths of vertical turbulent jet diffusion flames in still air. Combust. Sci. Technol. 41(1): 17.

[3] Iyogun CO. and Birouk M. (2009). On the stability of a turbulent non-premixed methane flame. Combust. Sci. Technol. 181(12): 1443.

[4] Iyogun CO. and Birouk M. (2009). Stability of a Turbulent Jet Methane Flame Issuing from an Asymmetrical Nozzle with Sudden Expansion. Combust. Sci. Technol. 181(1): 1.

[5] Iyogun OC., Birouk M. and Kozinski AJ. (2011). Experimental investigation of the effect of fuel nozzle geometry on the stability of a swirling non-premixed methane flame. Fuel. 90(4): 1416.

[6] Vanquickenborne L. and Van Tiggelen A. (1966). The stabilization mechanism of lifted diffusion flames. Combust Flame. 10(1): 59.

[7] Coats CM. and Zhao H. (1989). Transition and stability of turbulent jet diffusion flames. Proc. Combust. Inst. 22(1): 685.

[8] Lyons KM. (2007). Toward an understanding of the stabilization mechanisms of lifted turbulent jet flames: Experiments. Prog. Energy Combust. Sci. 33(1): 211.

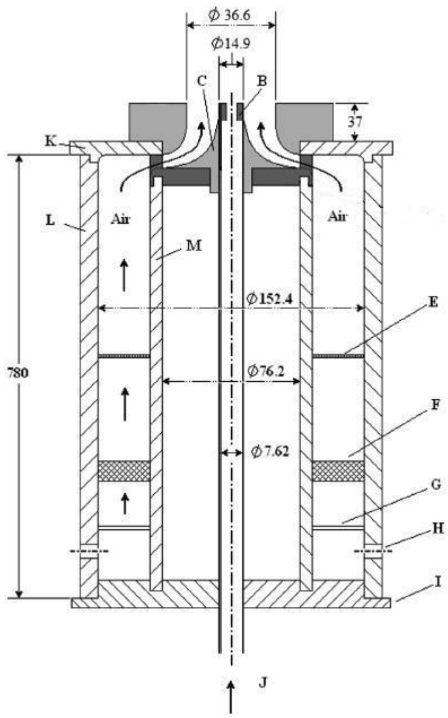

Figure 1. Schematic of the experimental burner set-up: B=nozzle, C=nozzle holder, E=fine screen, F=honeycomb, G=coarse screen, H=four equally spaced tangential air ports, I=bottom plate, J=methane gas flow, K=top plate, L=outer chamber, M=inner chamber [3].

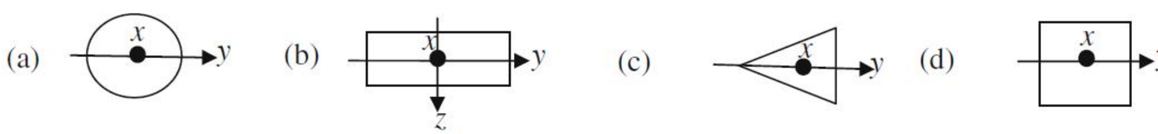

Figure 2. Nozzle geometries (and PIV measurements planes: x-y and x-z). (a) Smooth pipe or contracted circular nozzle, (b) Rectangular nozzle, (c) Equilateral triangular nozzle, and (d) Square nozzle [3].

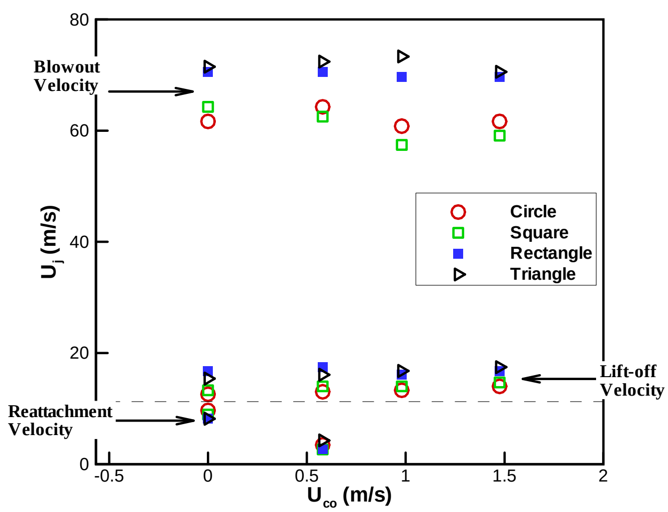

Figure 3. Comparison of the flame lift-off, blowout and reattachment velocities for different nozzles at different co-airflow exit velocities.

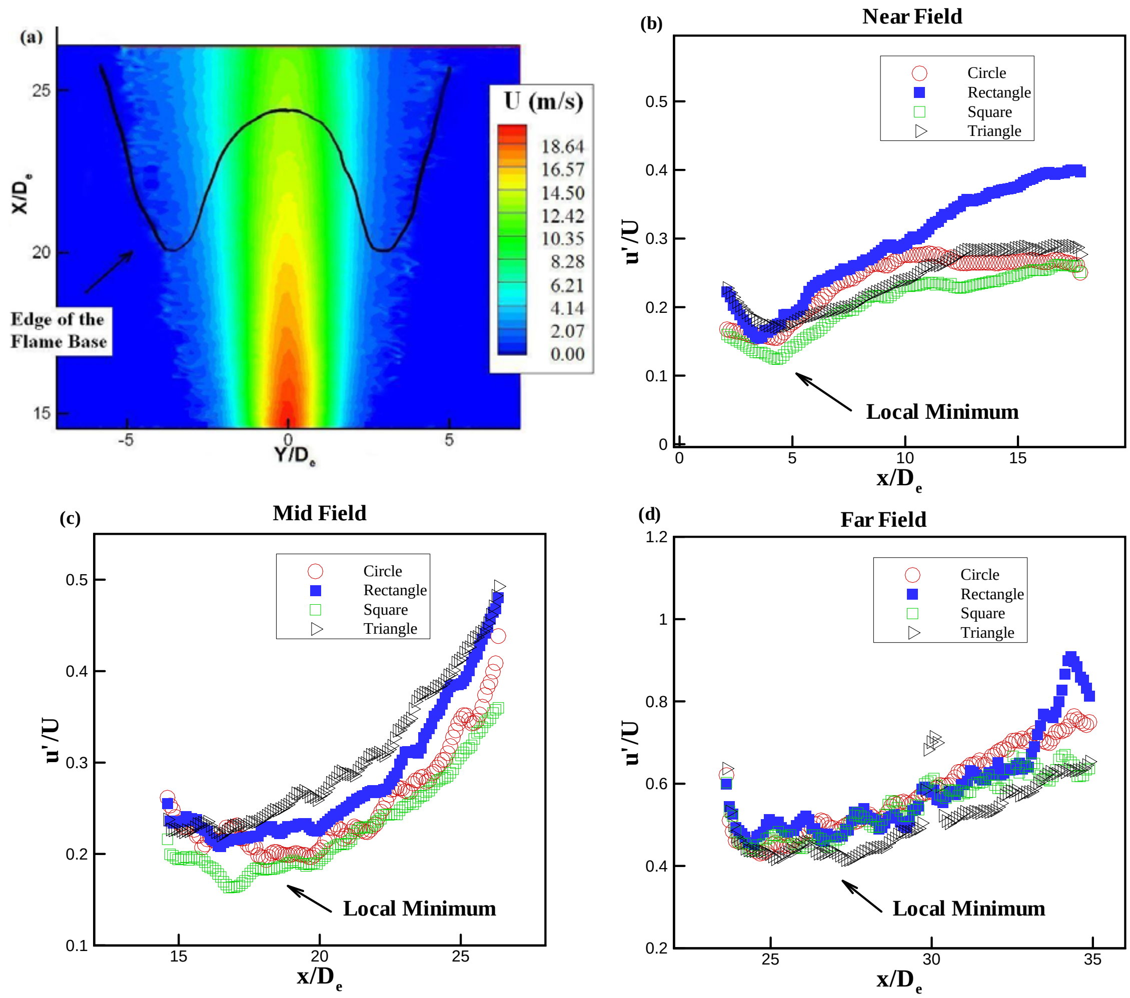

Figure 4. PIV measurements of the reacting jet. (a) a typical velocity contours for the lifted flame which also shows the flame base, and the $u^{'}/U$ profiles for (b) the flame base stabilized in the near-field ($U_j = 12\ m/s$), (c) the flame base stabilized in the mid-field ($U_j = 18\ m/s$), and (d) the flame base stabilized in the far-field ($U_j = 24\ m/s$).