A Qualitative Study of the Effect of Asymmetric Fuel Nozzles on the Blow-out Limits of Non- and Swirling CH_4-air Diffusion Flames

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Introduction

Non-premixed turbulent flames in still air have been studied in the past (see, for example, [1-3], to cite only a few). These studies dealt primarily with flame lift-off, stability and structure. Vanquickenborne and Van Tiggelen [1] determined that lifted diffusion flame in still air remains stable at a height above the burner where stoichiometry is reached. Broadwell et *al.* [2] studied flame blow-out in still air for various gaseous fuels and burner diameters. These authors found a linear relationship between the blow-out velocity and burner diameter. Kalghatgi [3] also studied the lift-off heights and flame length of turbulent diffusion flames in still air. Kalghatgi [3] found that the flame lift-off increases linearly with the fuel jet exit velocity, and the flame length was correlated using a non-dimensional grouping number, which is called Richardon number. In an attempt to improve the flame blow-out limits, a newer approach was recently developed which consists of using multiple circular holes arranged in different geometric shapes such as circular, square and cross [4]. Lee et *al.* [4] determined that these arrangements led to a higher blow out velocity than for a single fuel circular nozzle. Methane flame with co-flowing no-swirling air was also studied by Upatnieks et *al.* [5]. It was found that an edge flame creates a region of low turbulence and velocity even when the turbulence level and the mean velocity are large in the undisturbed jet. There have been also recent studies on jet airflow issuing from asymmetric nozzles [6]. The main outcome of these studies showed that asymmetric nozzles increase the mixing and spreading of a jet. Out of the nine different asymmetric nozzles tested, the isosceles triangle shaped nozzles created the largest amounts of mixing with the circular nozzle being the least effective [6].

Swirling diffusion flames have been found to be more stable than their bluff body counterparts [7-8]. They are advantageous for their ability to reduce pollution formation. Tangirala et *al.* [7] found that mixing and flame stability increases with swirl number up to one, beyond which turbulent mixing and flame stability deteriorate. Recently, Masri et *al.* [8] applied advanced optical laser measurements techniques and found that the flame stability limits are broadened with high swirl number. Many other different experimental setups have been used to understand better swirling flames using multiple swirling air flows [9], having fuel nozzles angled with respect to the air flow [10] or both [11].

This brief literature survey showed that although substantial progress has been made in understanding non-premixed flames, final conclusions are still far from being established. Given the complexity of the problem and the variety of practical configurations, it is hardly surprising that satisfactory data that can be rationalized remain a significant challenge. The research program launched at the University of Manitoba aims at participating in the international effort to help better understand non-premixed turbulent flame phenomena. The preliminary results presented in this paper focuses on determining qualitatively the effect of asymmetric nozzles on the blow-out velocity limits of various swirling and non-swirling turbulent diffusion flames. The novelty of the present research resides in the combination of swirling combustion air and asymmetrical fuel nozzles to generate stable turbulent diffusion flames, where circular, rectangular, square and triangular nozzles were used to determine their effect on flame blow-out limits.

Experimental Facility

The University of Manitoba burner consists of a central fuel nozzle surrounded by an annulus of swirling or non-swirling air. To ensure a well developed gas flow in the pipe, the ratio of the length to diameter of the fuel pipe, *L/D*, was taken equal 150. The central nozzle, which is about 47 mm long and attaches to the fuel pipe, is interchangeable where four nozzles with different geometries were tested in the present study. The circular nozzle has a diameter 5 mm and the asymmetric nozzles have an equivalent effective (i.e. hydraulic) diameter. The rectangular nozzle has an aspect ratio of 2 while the square and equilateral triangle have an aspect ratio of 1. The annulus has an outer diameter of 36.6 mm and an inner diameter of 14.9 mm. The swirl generator vanes have an exit angle of 0, 25, 50 or 60 degrees corresponding to swirl number of 0, 0.31, 0.79 or 1.15, respectively. The formulae used to calculate the swirl number was taken from [12]. The swirl generator vanes are curved in order to reduce pressure loss. The fuel employed is 98% compressed methane, which is supplied from canisters while the compressed air was obtained from the building supply line. Due to limitations of the buildings air supply, the maximum airflow attained was 600 liters per minute which is equivalent to an average airflow velocity of 11.41 m/s. It is important to mention that the air and fuel velocities quoted in this study are averaged velocities based on readings from the gas and air flowmeters (i.e. rotameters) and the cross-sectional area at the burner exit. These rotameters have a very high accuracy. Two quartz quarls were used at the tip of the burner to push the flame away from the metal in order to reduce material damage at the nozzle exit [13].

Preliminary Results

The preliminary results presented in this paper concern an examination of the blow-out limits of methane air diffusion flame issuing from a central asymmetrical fuel nozzle surrounded by a zero- or higher swirl number airflow. Blow-out limits for both attached and lifted flames are presented below.

Attached flames

Figure 1 shows the effects of fuel nozzle geometry on the blow-out limits of a non-swirling methane flame (i.e. the annular co-flow air has a zero-swirl, i.e. $S = 0$). The flame for each nozzle shape exists only below the corresponding curve shown in this figure. This figure shows that the flame issuing from the circular, triangular and square nozzles have similar trend for their blow-out limits. However, among these three flames, the circular nozzle has the lowest blow-out velocity and the square nozzle has the highest blow-out velocity. The rectangular nozzle's flame blow-out limits lie between those of the circular and triangular nozzles up to a fuel velocity of about 6.3 m/s. Beyond this velocity, the rectangular nozzle flame blow-out limits becomes higher than that of the triangular for $V_f > 6.3$ m/s, and the circular for $V_f > 7$ m/s. Finally, for $V_f < 2.4$ m/s the flame blow-out limits for the circular and rectangular nozzles are exactly the same, however, only the flame issuing from the rectangular nozzle exists for V_f beyond 8 m/s.

The fact that the circular nozzle has the lowest blow-out limit may be attributed to its weak spreading and mixing rate compared to the other two asymmetric jets (i.e. the square and rectangle). The highest blow-out velocity shown by the square nozzle is slightly unexpected as Mi et *al.* [5] have shown that triangular nozzles have the best mixing characteristics. The discrepancy may be caused by the combustion which can alter turbulence characteristics and hence the mixing processes as Mi et al.'s studies were performed in still surroundings air. Experiments are currently underway to find out a convincing explanation.

An interesting phenomenon occurs for a co-flow of air with zero swirl. For the square and triangular nozzles, a small attached flame forms and creates a "pilot look-like" flame as the larger flame flickers at high fuel velocity (V_f above 5.8 *mls*). This flickering flame is a very small flame that is attached to the mouth of the fuel quarl and acts like a pilot flame. This "look-like" pilot flame is in turn attached to a much larger flame above it, which extinguishes and reignites every second or so. This flame accounts for the negative slope for the triangular and square as can be seen in Figure 1.

For the highest swirl number achieved in the present experiment, i.e. for S = 1.15, the flame blow-out occurs at low fuel velocities (depending on the nozzle shape) as shown in Figure 2. Recall that each flame exists below its corresponding curve displayed in Figure 2. It is important to note that the maximum air velocity that could be reached in the present study was around V_a = 11.41 m/s, and therefore, flame blow-out limits beyond this velocity are unknown at this stage. Figure 2 shows that at the fuel velocity below around V_f = 1.40 m/s, the flame blow-out conditions are similar for all the tested nozzles because of the extremely erratic nature of the flame. However, beyond V_f ~ 1.4 m/s, Figure 2 shows that for any given V_f the square and triangular nozzles stabilize the flame at the highest airflow velocity followed by the rectangular and finally the circular nozzle. In addition, Figure 2 shows that the asymmetric nozzles appear to follow a linear flame blow-out relationship between V_a and V_f while the circular nozzle begins with a linear relationship and then deviates at fuel velocity above 2 m/s.

Lifted flames

Figure 3 shows that for the case of zero-swirl, co-flowing air, the blow-out for high lifted turbulent flames appear to be independent of the nozzle shape. Note that the flame exists below the curves seen in Figure 3, but the flame might be stable to beyond V_f = 18.41 m/s, which is the maximum fuel velocity reached in the present experiment. In addition, for all the tested four nozzles, Figure 3 shows that the flame blow-out pattern follows a linear relationship between the air and fuel velocities. This is caused mainly by the extremely high liftoff of the flame. By the time the fuel jet has reached the flame, the jet structure mixes with the swirling co-flow air. It seems that the stoichiometric ratio of fuel to air is the main factor behind flame stability in this case.

For a relatively weak swirl, i.e. S = 0.30, the four nozzles have similar flame blow-out characteristics but there are slight differences as can be seen in Figure 4. Each flame exists below its corresponding curve displayed in Figure 4. These blow-out limits, indicated by the curves in this figure, may increase if the air velocity increases beyond its maximum value attainted in the present experiment. In addition, this figure shows that at low fuel velocities, below V_f = 6.40 m/s, the triangular nozzle has the best flame stability (i.e. blows-out at a relatively higher air velocity), followed by the rectangular, square and finally the circular nozzle. This seems to be consistent with the findings of Mi et *al.* [5] who studied the mixing characteristics of a jet airflow issuing from different asymmetric nozzles in still air. In the case of swirling co-airflow, the recirculation zone is believed to have much slower velocities and is more alike to that of still air than a zero swirl which could explain the similar trends compared to those of Mi et *al.* [5]. It is believed that as the air velocity increases (beyond V_a = 6.40 m/s), so does the strength of the recirculation zone, the flame is in less and less of a region that resembles still air based on our observations. Moreover, Figure 4 reveals that the trend for the most stable flame, based on blow-out limit, which occurs for the triangular nozzle, begins to deviate slightly at these higher air velocities (beyond V_a = 6.40 m/s). Nevertheless, the flame blow-out conditions for all the nozzles are quite similar, although not as similar as to those for the zero-swirl flames blow-out limits, which are presented in Figure 3. It is believed that this is caused by the flame liftoff which is smaller for the swirling flames compared with that of the non-swirling flames.

Summary

The main findings of the qualitative study presented in this paper are that asymmetric nozzles seem to improve the stability of attached turbulent diffusion flames. However, the asymmetric nozzles do not have a large effect on flame stability for lifted flames where the higher the lift, the less of an effect is manifested. The liftoff for weak swirl was much less than that of no-swirling flame. Once the flame liftoff becomes relatively large, it is believed that the superior mixing effects are lost through jet decay. The triangular nozzle provides, to some extend, the best flame stability (i.e. broader blow-out limits), which reaffirms our theory based on the work of Mi et *al.* [5]. An unexpected result is that the rectangular nozzle provides an equally stable flame, whereas Mi et *al.* [5] found that the mixing rate was considerably less. The rectangular nozzle provided a more stable flame than the circular nozzle but was below the other asymmetric nozzles. The fact that the triangular and square nozzles provide similar flame stabilities may suggest that mixing of these jets is somehow equalized by the chemical reactions and the swirling airflow. Experiments using LDV and PIV techniques are underway to map the exact flow characteristics for different nozzle and swirl configurations.

Acknowledgements

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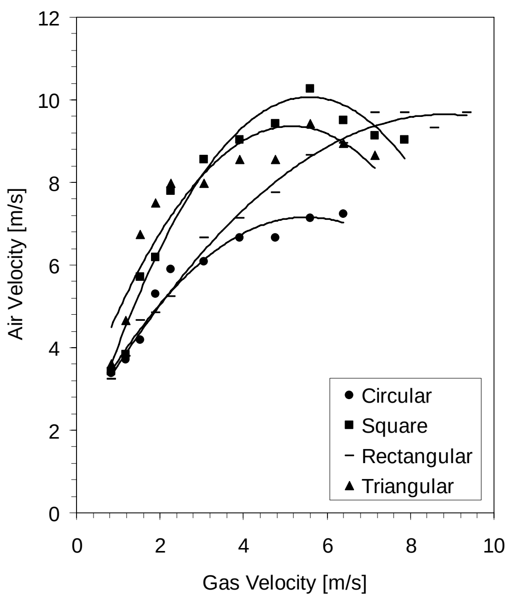

Figure1. Blow-out limits for no-swirl (attached)

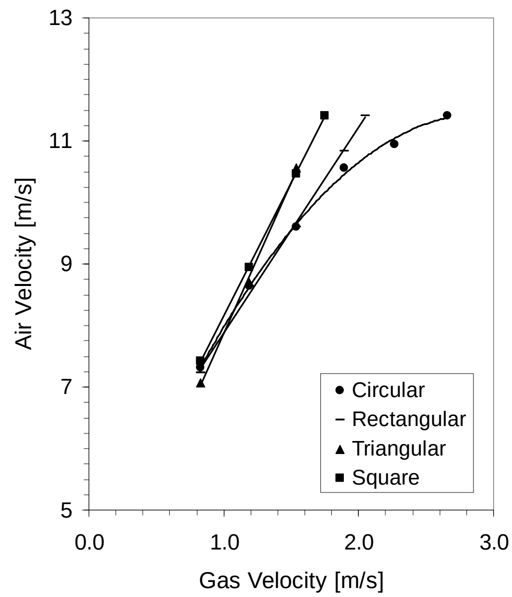

Figure 2. Blow-out limits for S = 1.15

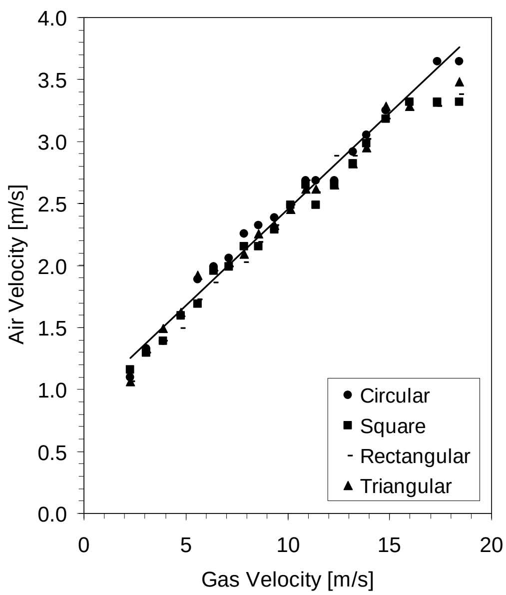

Figure 3. Blow-out limits for no-swirl (lifted)

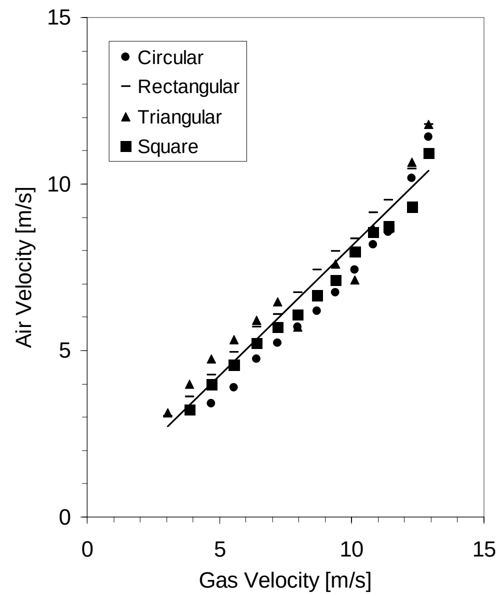

Figure 4. Blow-out limits for S = 0.31