Enhancing the stability limits of a low swirl non-premixed turbulent flame

Meghdad Saediamiri[1], Madjid Birouk[1,*] and Janusz A. Kozinski[2]
[1]Department of Mechanical Engineering, University of Manitoba, Winnipeg, Canada
[2]Lassonde School of Engineering, York University, Toronto, Canada

1 Introduction

Biogas is a renewable source of energy which can be burned to produce heat or power. However, burning of biogas like other low calorific value gases has several problems such as weak flame stability which results in combustion instabilities (e.g., [1]). This is attributed primarily to the low burning velocity of low calorific value fuels (e.g., [2]). A passive approach (i.e., no dilution with high calorific value fuels (e.g., [3-4])) that can benefit the stabilization of such low heating value gases is using swirling flow mechanism [15]. It was reported that flame stabilization depends strongly on the recirculation of heat and chemically active species promoted by swirling flows (e.g., [5, 6-14] to cite only a few). An experimental study on the effect of swirling co-airflow on turbulent non-premixed methane-air showed a significant increase in the flame stability range [7]. However, another research group [8], who adopted a similar set-up to that of Feikema et al. [7], reported a significant shrink in the flow conditions within which a stable flame may operate when diluting with an as high as 15% carbon dioxide. A strong internal recirculation zone (IRZ) with high velocity gradient and coherent helical vortex (PVC) was found directly responsible for stabilizing a swirling turbulent non-premixed lifted flame [9-10]. The PVC was found to enhance the mixing between reactants which consequently led to rapid ignition of the mixture [11-12] where the PVC was found to enlarge the flame surface due to flame roll-up [11]. A recent study of non-reacting swirling flow, revealed that the size and shape of the recirculation zone (vortices) as well as the pitch of the helical vortices can be significantly influenced by the magnitude of the centerline velocity [13]. Masri and co-workers [14] used a burner with a large bluff body and showed that a combination of the central jet velocity and strength of swirl has great control on the formation and position of the second recirculation zone downstream of the burner. It was also reported that frequent extinction and re-ignition at the root of a lifted swirling flame results in flame blowout when the characteristic time exceeds the PVC oscillation time [10]. It was also found that, closer to the lower blowout limit, the lifted flame with a low fuel to air ratio would not withstand the high strain rate and hence extinguishes due to the imbalance between heat production and dissipation which results in a high scalar dissipation rate [20]. A recent study showed the intermittent local flame extinction caused by local strain rate as a consequence of high local scalar dissipation rate [21]. It is clear from the briefly reviewed literature above that the dynamic of the recirculation zone induced by a swirl can be influenced by other factors such as the central jet velocity in a co-axial flow configuration. This is confirmed in a recent study by the present authors who examined the stability of non-premixed biogas flame in a swirling flow where different fuel pipe/nozzle diameters were used [15-16]. In particular, it was found that, for low swirl strength, increasing the centerline jet velocity at

Correspondence to: madjid.birouk@umanitoba.ca

constant co-airflow velocity convects the recirculation zone farther away from the nozzle exit which precipitates the blowout of a lifted flame [15-16]. This was believed to be directly associated to the central jet decay where larger nozzle diameter produces slower jet decay. Therefore, the main objective of the present study is to develop and examine a fuel nozzle geometry that yields a faster decay of the jet flow without affecting its volumetric flow capacity. This is achieved by discharging the fuel through a central hole and several surrounding/peripheral smaller holes/slots. The main aim is to stabilize a lifted flame much closer to the nozzle exit and more importantly to create conditions which allow a stable lifted flame to operate over a much wider range of flow conditions.

2 Experimental Set-up and Methodology

The experimental setup consists mainly of a central fuel nozzle surrounded by a swirling co-axial air stream (called thereafter co-airflow) where the flow discharges up into an open chamber at atmospheric room conditions. Detailed description of the test facility was reported elsewhere [16-18], and hence only a brief and complementary information is provided here. The configuration of the upper/top section of the burner, which includes the fuel nozzle and swirl generator, is shown schematically in Fig. 1(a). The newly developed fuel nozzle geometries are shown in Fig. 1(b). All fuel nozzles have the same exit area with an equivalent diameter of 3.75 mm. Nozzle (N_2) has 7 slots/holes; a central hole with a diameter of 1.4 mm surrounded by six peripheral smaller slots with each has a diameter of 1.4 mm discharging with an angle of 15°. A summary of the two fuel nozzle geometries is given in Table 1. A 600 mm long cyclone-type mixing pipe, which is placed upstream of the fuel nozzle, is used to ensure that the biogas fuel components (CH_4 and CO_2) are fully mixed prior to burning. The type of swirl generator employed here is schematically reported elsewhere [18]. In the present study, only the 25º- angle vanes swirl generator (called thereafter low-swirl) is used. Fuel and co-airflow rates were controlled using, respectively, Matheson and Brooks flowmeters. The test conditions consisted of varying the fuel and co-airflow exit velocity (flow rate), and fuel nozzle geometry. The volumetric ratio of carbon dioxide in the fuel (methane) was kept 40 percent during all biogas experiments. The procedure for determining the stability map (i.e., attached or lifted flame, blow-off or blow-out) of the turbulent non-premixed biogas or methane flame consisted of increasing gradually the volumetric flowrate of the fuel at a constant co-airflow conditions until the attached biogas or methane flame blows off or the lifted flame blows out (that is, in both cases, the flame ceases to exist). The flow limits (ranges) of the blow-off of an attached or the blow-out of a lifted flame were obtained by repeating the experiment several times and taking an average value (the repeatability of the experiments, generally 4 to 5 tests at a given condition, was found to be within ±5%). The flow field was characterized using two-dimensional Dantec Dynamics PIV system where 2000 pairs of instantaneous images for each test condition were collected. The PIV instantaneous images were processed using adaptive correlation with 32 pixels × 32 pixels and 16 pixels × 16 pixels interrogation area (where the latter was adopted in the present analysis). A 50% window overlap was adopted. The PIV data was exported to Tecplot software and further post-processing was carried out with the aid of an in-house developed c++ code to determine the flow characteristics such as velocity vectors and streamlines.

3 Results

Figure 2 presents the stability map of a low swirl strength (S = 0.31) turbulent non-premixed biogas-air and methane-air flames of the two different nozzles (see Table 1 for the nozzles dimensions). This figure shows that the attached flame of biogas occurs at relatively low co-airflow velocity for both nozzle geometries where the blow off limits occur at approximately Vc = 4 m/s and 1.5 m/s for N_1 and N_4, respectively. Beyond these co-airflow exit velocities, a transient region is observed. For N_1 nozzle, the biogas flame transforms from attached to lifted in the co-airflow range up to Vc ~ 6.7 m/s. In the co-airflow range up to Vc ~ 7.7 m/s, no attached flame was observed for N_4. The stability map of the N_4 flame is shown in Fig. 2 for up to only Vc ~ 15.4 m/s (but it extends much beyond this range).

Figure 2(a) presents the effect of fuel nozzle geometry on the stability limit of a low swirl biogas-air flame. This figure indicates that the N_4 nozzle with several peripheral holes substantially increase the stability limits in comparison with the single hole nozzle (N_1). Fig. 2 (b) presents the effect of fuel nozzle geometry on the stability limits of a low swirl methane-air flame which surprisingly reveals that the stability limits are not significantly changed with the geometry of the nozzle. Note that no flame zone below the lower blow-out limit at high co-airflow velocity transits into an attached flame for the N_4 nozzle. Figure 2(c) presents the effect of fuel composition on the stability limit of a low swirl flame of the single hole nozzle (N_1). This figure reveals that there is a substantial decline in the stability limits of a low swirl methane-air flame by diluting methane with CO_2 (i.e. Biogas). However, Fig 2(d) indicates that the N_4 nozzle geometry significantly enhances the stability limits of biogas flame where there is no significant difference in the stability limits as a result of dilution of methane with CO_2. These results suggest that the flame stability limit is controlled by chemical characteristics of the fuel at low-co airflow velocity where the effect of swirl is negligible, whereas at higher co-airflow velocity it is controlled by the flow characteristics.

Figure 3 presents photographs of methane flame of nozzle N_4. Fig. 3(a) presents a typical attached flame at low co-airflow velocities which is similar to biogas flame. However, Figs. 3(b-d) show the transient transformation of the flame from attached to lifted. In fact, this transition was found to happen only for methane flame. Fig 3(e) presents a typical lifted flame at high co-airflow velocities which is short,large and burns completely in blue color due to high mixing rate. These types of lifted flames are common between methane and biogas. Figure 4 shows typical images of the lifted flame of N_4 nozzle at constant co-airflow velocity (i.e., Vco = 5.6 m/s) and varying fuel jet velocity (starting from a very low fuel jet velocity up to closer to upper blow-out limit). These images reveal that the flame lift-off height does not change significantly with the fuel jet exit velocity. This is advantageous over the other nozzles with which the fuel jet flow was found to have a noticeable influence on the liftoff height and upper blowout limit. Another interesting observation is that the lifted flame of the N_4 nozzle was found insensitive to disturbances even at the proximity of the upper blow-out limit conditions where high speed imaging revealed that the base of the lifted flame is highly stabilized.

A recent study by the present authors on the stability limit of a low swirl turbulent non-premixed biogas-air flame revealed that the dominant character of the upper blowout limit is the 3-D shear layer [19]. However, the present PIV data (not shown here due to space limitations) revealed that the flame upper limit is very much controlled by the strength/momentum of the fuel jet where the small peripheral jets decay much faster than the central jet and hence do not have a significant impact on the dynamics of the recirculation zone. The lower blowout limit was found to be controlled by the imbalance between heat production and dissipation which results in a high rate of scalar dissipation [20, 15]. The fact that the lifted flame closer to the lower blowout limit sits closer to the nozzle exit, which is a high strain rate region, combined with low fuel flowrate results in a weak equivalence ratio of the presumably partially premixed fuel-air mixture upstream of the fame base [10]. Consequently, the lifted flame with a low fuel to air ratio (i.e., weak equivalence ratio) would not withstand the high strain rate and hence extinguishes [10]. This emphasizes the importance of the fuel flowrate and the mechanism of mixing (swirl strength which in turn depends on the co-airflow momentum) in determining the lower blowout limit [15].

4 Conclusions

The effect of fuel nozzle geometry on the stability of a low swirl turbulent non-premixed biogas-air flame and methane–air flame was examined. Although the two nozzles which have the same equivalence flow area (that is, the same equivalence diameter), each nozzle resulted in a different flame stability map. The nozzle having several peripheral slots produces the largest flame stability map. This is attributed to the rapid decay of the fuel jets and their interactions with the recirculation zone, both of which have a dominant role on the stability of turbulent non-premixed flame. According to the literature, stability of the root of a lifted flame, which acts as a source of auto ignition, has a significant effect on the stability of the entire flame [10]. Fuel nozzle geometry has a strong effect on the flow structure especially close to the nozzle exit in the root of the lifted flame. The flow recirculation zone appeared to sit closer to the nozzle exit even when varying the fuel jet velocity for N_4 nozzle. Thus the jet induced by the N_4 nozzle creates the most stable root of the lifted flame which is the ideal conditions for a biogas flame to sustain itself. At conditions approaching the upper blow-out limit (that is at high fuel jet flow rates), the fuel jets issuing from N_4 nozzle still does not have strong momentum to convect the recirculation zone away from the nozzle exit. These results suggest that the N_4 nozzle strongly alters the ensuing flow structures and hence fuel-air mixing which consequently predominate over the impact of fuel chemical characteristics.

Acknowledgements

The financial support provided by the Natural Sciences and Engineering Research Council (NSERC) and Manitoba Hydro is gratefully acknowledged.

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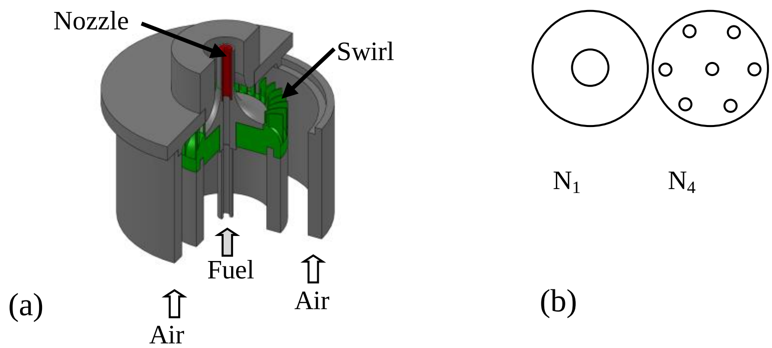
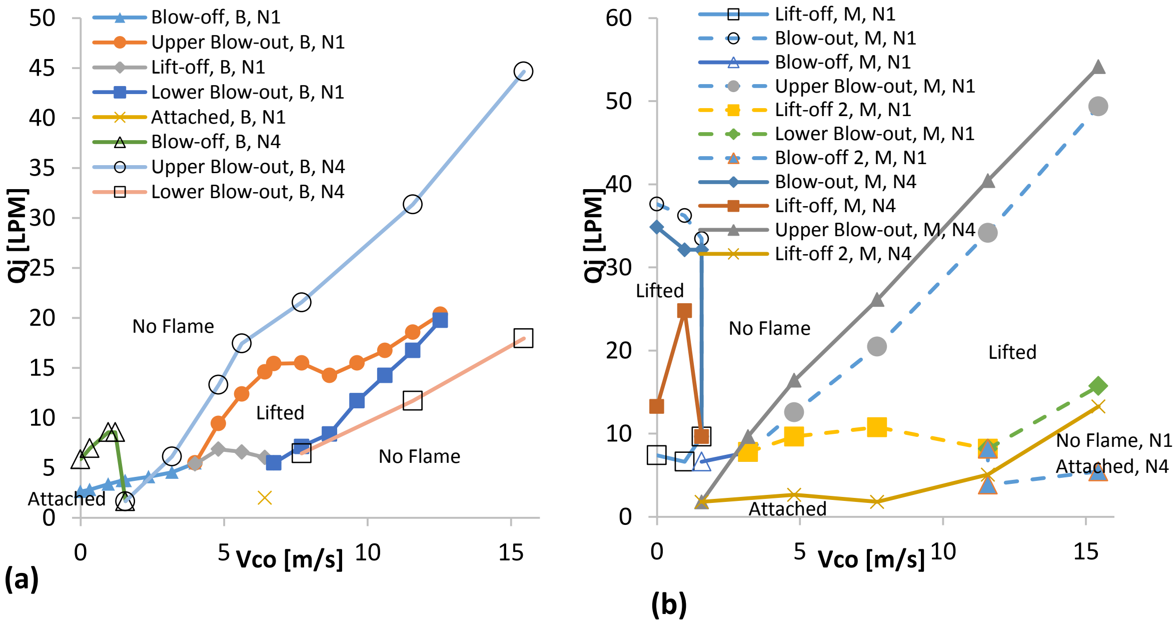


Figure 1. A schematic diagram of (a) the burner’s flow exit section, and (b) fuel nozzle geometry



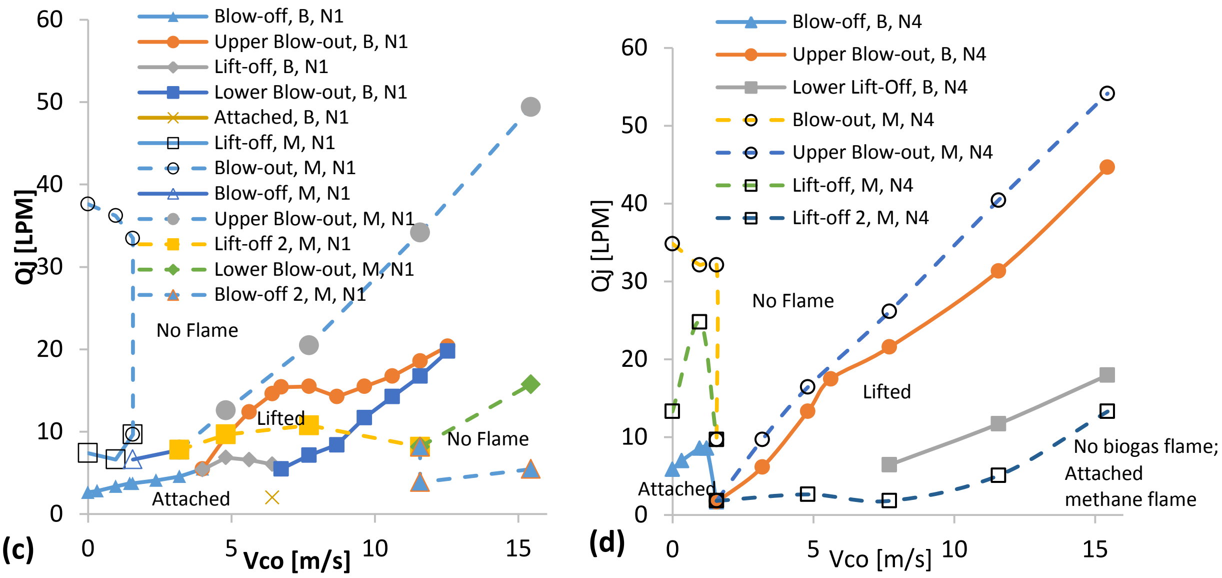
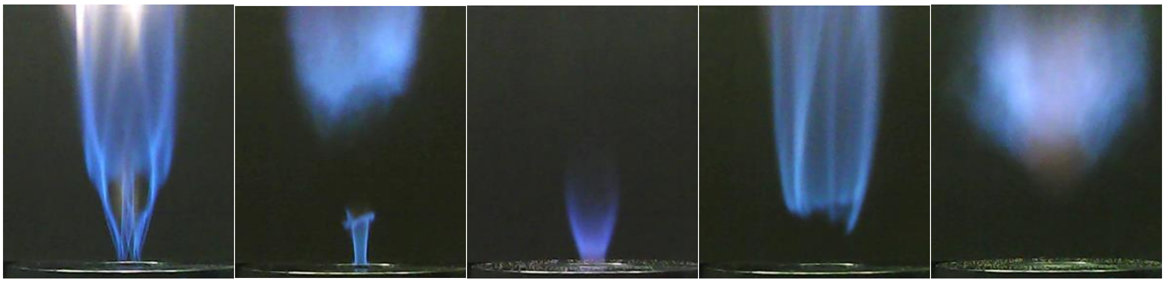


Figure 2. Stability limits of turbulent non-premixed swirling (a) biogas flame with N_1 and N_4 nozzles, (b) methane flame with N_1 and N_4 nozzles, (c) biogas and methane flame with N_1 nozzle, and (d) biogas and methane flame with N_4 nozzle.



(a) (b) (c) (d) (e)

Figure 3. Photographs of methane-air flame of nozzle N_4

Figure 4. Lift-off height of biogas flame of nozzle N_4

Table 1: Fuel nozzle geometry

Nozzle/specifications	N_1	N_4
Central hole diameter, D_c (mm)	3.75	1.42
Peripheral holes diameter, D_p (mm)	0	1.42
Number of peripheral holes	0	6
Peripheral holes exit angel, β (°)	0	15
Equivalence diameter, D_e (mm)	3.75	3.75