Stability Limits of Non-Premixed Turbulent Biogas Flame: Effect of the Burner Geometry

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Key words: Biogas flame, Stability, Turbulent, Non-premixed

1 Introduction

Biogas is a renewable source of energy that can be used to generate power and heat as well as to reduce greenhouse gas emissions. Biogas is produced from landfill or digestion process (aerobic or anaerobic). The main component of biogas is methane which is diluted mainly with carbon dioxide and other inert gases. Therefore, biogas, which contains a significant amount of CO_2, has a heating value that is only about 60 percent of that of natural gas.

Burning of low calorific value gases has several problems such as flame stability due to low burning velocity (e.g., [1]). In order to increase the stability limits of low calorific value fuels, preheating of air or using catalyzers are useful techniques but they are limited to premixed combustion. Pressure fluctuations at low frequency were used to determine the instability of premixed combustion of biogas-air [2]. Diffusion flames, which have more control over energy release and also have safer operating conditions, are more desirable in practical combustors [3]. Studies of both attached and lifted flame showed that the visible flame length, average temperature of various zones, flame radiant heat transfer, fuel pyrolysis rate, local concentration of emissions, and particulate formation all decrease for diluted fuels with low heating value components [3]. A study of non-premixed laminar flame of biogas-air showed that pressure has no effect on visible flame heights for different dilutions and dilution decreases the sooting propensity at constant pressure; however, higher carbon dioxide concentration in methane fuel makes flame’s sooting more pressure dependent [4].

An experimental and analytical investigation on turbulent, lifted, non-premixed combustion of methane and ethylene flames diluted with nitrogen in a co-flow configuration was performed aiming at helping to design combustors that can operate on biogas [5]. Stability parameters of flame such as liftoff, reattachment, and radial stabilization distance were measured [5]. Results revealed that the flame lift-off height increases with the diluents concentration [5]. As a result of fuel dilution, the shape of the flame tapers inward and becomes more cylindrical [5-6]. Dilution of methane was found also to decrease the adiabatic flame temperature, and since carbon dioxide’s specific heat increases faster with temperature in comparison with nitrogen and water vapor, it has the most influence on flame's temperature. It was found that carbon dioxide is more effective than nitrogen in restricting the flammable zone and range [7-8].

Mixing low heating value gases with high heating value gases, burning with oxygen, or with oxygen enriched air could increase the combustion stability of the low calorific value gases [3]. A study with four coaxial jets of a piloted non-premixed oxy-combustion burner of a CH4/BFG (blast furnace gases) mixture showed that using piloted methane-oxygen flame can expand the operating range of the combustion of low calorific value fuels [9]. Stability limits of a jet diffusion flame of two different methane-carbon dioxide mixtures (biogas) in a co-flow burner showed that increasing the concentration of carbon dioxide narrows the flame stability range, and the addition of a small amount of hydrogen in the fuel enhances significantly these limits [10-11]. It was also shown that biogas flame stabilization is very sensitive to the fuel nozzle diameter [10-11].

Published literature showed that large scales of turbulence, produced by placing a mesh upstream of a biogas jet flame, tend to enhance flammability limits [7-8]. Bluff-body was found to significantly affect lift-off and stabilization of non-premixed turbulent jet flames where by the bluff body makes the flame base position more dependent on the co-flow velocity rather than jet velocity, and that the flame lift-off height becomes more dependent on the jet velocity in a lifted flame configuration [12]. Numerous studies have shown that flame stabilization depends on recirculation (generated by swirl generator) of heat and chemically active species (e.g., [1]). For example, a recent study showed that the rate of oxidation can be increased significantly through recirculation of small amount of the combustion products into the reactants [7].

The present paper aims at examining the stability parameters of a turbulent non-premixed biogas surrogate (mixture of methane and carbon dioxide) flame. In particular, the effect of swirling co-airflow and fuel nozzle geometry is investigated.

2 Methodology

The experimental setup consists mainly of a central fuel nozzle surrounded by a swirling air flow air stream (referred herein as co-airflow). Detailed description of the burner setup was described elsewhere [16]. A cyclone type mixing pipe, placed upstream of the fuel nozzle, is also used to ensure an adequate mixing between the biogas fuel components before its ignition which occurs in an open combustion chamber at atmospheric conditions.

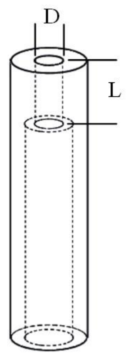


Figure 1. A schematic diagram of the fuel nozzle

Table 1. Experimental test conditions

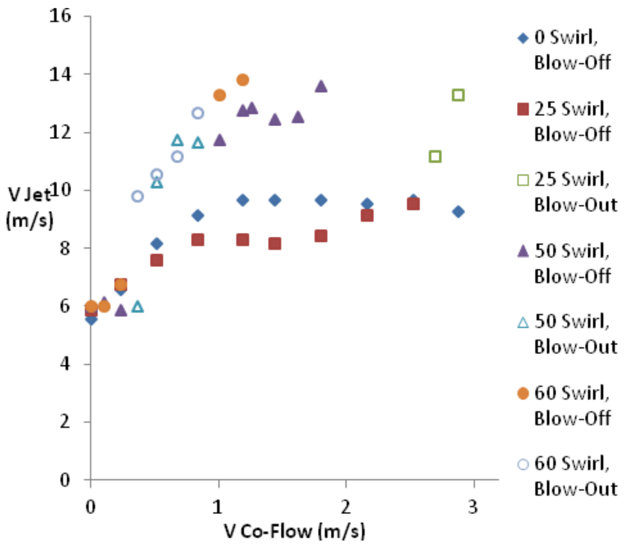
Nozzle Equivalent diameter, De (mm)	Nozzle orifice shape	Co-flow Swirl vanes angle, θ(°)	Nozzle aspect ratio, L/De	Volumetric ratio CH4-CO2
4.54	Circular, Triangular, Rectangular	0°, 25°, 50°, 60°	1	60% - 40%

A schematic diagram of the fuel nozzle geometry employed in the present study is shown in Fig.1. Three different nozzle geometries, namely circular, triangular and rectangular, were examined. All nozzles have identical equivalent orifice exit diameter. In addition, two different nozzle diameters with the same aspect ratio (L/De =1, where De is the equivalent diameter of the exit orifice of the nozzle) were used to study the effect of nozzle diameter but only the results of the larger one (De = 4.54 mm) will be reported here. The swirl strength of the co-airflow was achieved by varying the swirl vanes angle [16]. Flow rates of methane and carbon dioxide were controlled using high precision rotameters, and the volumetric ratio of carbon dioxide in the fuel was kept 40 percent during all experiments. Experimental test conditions are given Table 1.

3 Results and Discussion

3.1 Effect of Co-Airflow Swirl

The present experiment showed that using swirl in co-flow air extended the operability range of a biogas flame. Figure 2 shows that there is no stable lifted flame with zero-swirl co-airflow; however, stable lifted flame can be observed even for a co-flow with a low swirl number/strength. The data presented in this figure (Fig. 2) shows that the flame ceases completely at V_{co} greater than ~ 3 m/s for the zero-swirl.



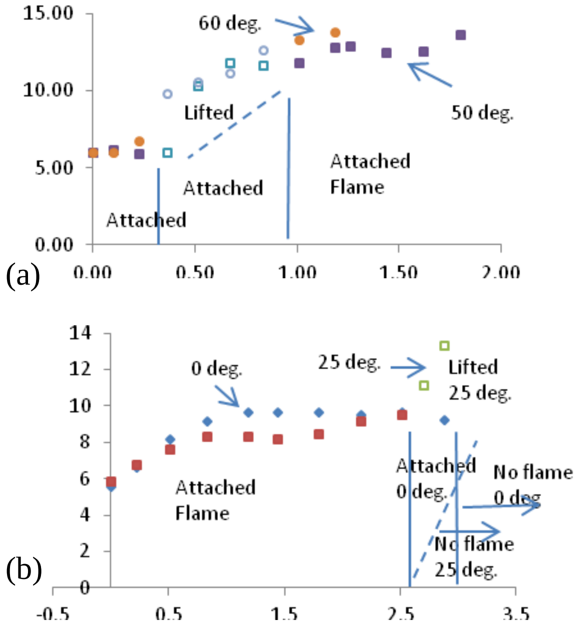


Figure 2. Effect of swirl number on the blow-off and blow-out limits of a circular nozzle having De = 4.54 mm and L/D = 1. Fig. 2(a) presents the data for the 50^0 and 60^0 swirls and Fig. 2(b) presents the data for the zero-swirl and 25^0 swirls

Figure 2 shows also that the stability limits (blow-off of attached flame) increases for the higher swirl numbers, and although the blowout limits are almost identical for the 50^0 and 60^0 swirl, they are different for the 25^0 swirl. That is, a lifted flame for the 25^0 swirl is observed at a higher co-airflow velocity whereas it is observed at lower co-airflow velocity range for the higher swirl numbers. Figure 2(b) shows that, at 25^0 swirl vanes angle, increasing the co-airflow velocity reduces slightly the flame blowoff velocity. However, further increase in the co-airflow velocity (V_{co}) beyond 2.5 m/s leads to a lifted flame which stabilizes above the burner, which then blows out with further increase in the biogas velocity (V_j). This figure shows also that increasing swirl vanes angle to 50^0 and then 60^0 changes completely the flame stability (i.e., blowoff or blowout) limits, as shown in Figure 2(a). At these high swirl numbers, the attached flame at low V_{co} (< 0.3 m/s) lifts and stabilizes in the range of V_{co} between ~ 0.3 m/s and ~1 m/s, and then reattaches again once V_{co} is increased above 1 m/s.

3.2 Effect of Fuel Nozzle's Orifice Exit Shape/Geometry

Figures 3 and 4 present, respectively, the effect of fuel nozzle's orifice exit shape/geometry on the biogas flame stability (blowoff and blowout) for zero-swirl and 25⁰ swirl co-airflow. Figure 3 shows that the blowoff velocity of the attached flame is the lowest for the circular nozzle and the highest for the triangular nozzle, and in between for the rectangular nozzle. Figure 4 presents a comparison of the flame stability between the triangular and circular nozzle for the 25⁰ swirl of the co-airflow. The blowoff velocity for both nozzles increases up to a V_{co} ~ 1 m/s, and then reduces slightly when increasing the co-airflow velocity up to V_{co}~ 1.60 m/s after which it increases again until V_{co} ~ 2.60 m/s. Further increase in V_{co} lifts the flame. Figure 4 shows also that the blowoff and blowout velocity for the circular nozzle is negligeably smaller than that of its counterpart triangular nozzle. A comparison of the results in Figures 3 and 4 shows that the 25⁰ swirl reduces the blowoff limits for similar co-airflow velocity range compared with zero swirl co-airflow. These figures suggest that the effect of fuel nozzle asymmetry/geometry prevails only in the absence of swirl in the co-airflow (Fig. 3) as it almost disappears completely in the presence of swirl (Fig. 4).

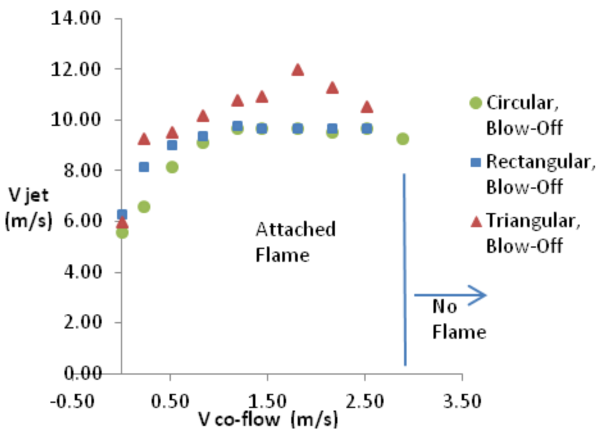


Figure 3. Effect of nozzle geometry on the blowoff of the 0^o vanes swirl flame (De =4.54 mm, L/De = 1)

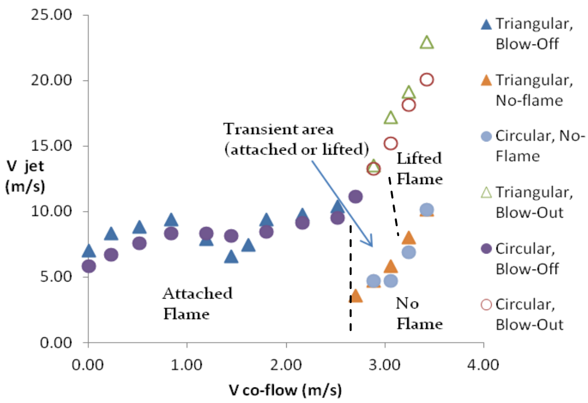


Figure 4. Effect of nozzle geometry on the stability limits of the 25^o vanes swirl flame (De = 4.54 mm, L/De =1)

3.3 Flame Shape and PIV Measurements

Figure 5 shows that the lower swirl number produces much larger and shorter lifted flames (Figs. 5(c)-(d)); whereas the lifted flames at high swirl number are thinner and taller (Figs. 5(a)-(b)) which are very similar to attached flames.

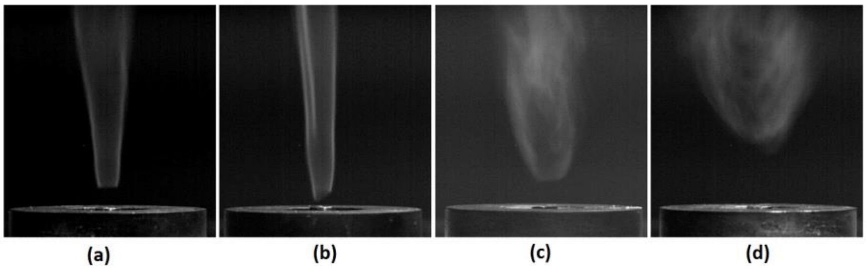
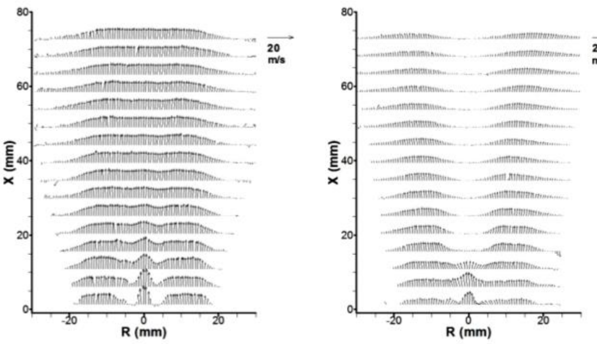


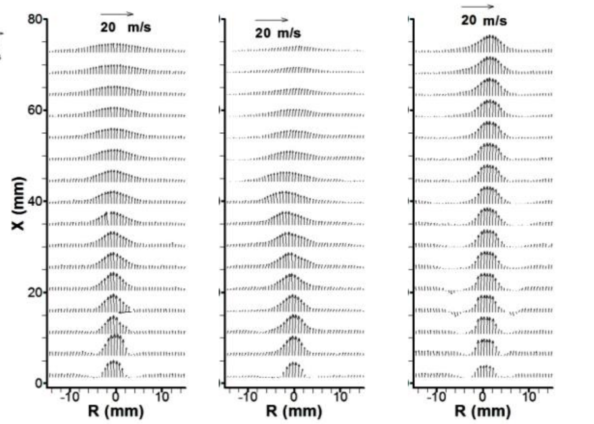
Figure 5. Lifted flame of the (a) 50^0 or 60^0 swirl at low co-airflow velocity (almost constant lift-off height), (b) 50^0 or 60^0 swirl at low co-airflow velocity close to reattachment, (c) 25^0 swirl at high co-flow velocity and low jet velocity, and (d) 25^0 swirl at high co-flow velocity and high jet velocity (lifted flame fluctuated between some modes)

Comprehensive PIV measurements were performed to characterize the velocity profiles and structures in the cold jet flow (isothermal) and jet flame in order to determine the reasons that explain the difference in the flame stability limits presented in Figures 2, 3 and 4. However, only a few sample data will be presented here due to limited space. Figure 6 presents a map of the axial mean-velocity vectors of the cold (isothermal) jet and its surrounding co-airflow. These two figures are intended to illustrate the effect of low (25°) swirl strength in comparison with its counterpart zero-swirl flow under conditions pertaining to a lifted biogas flame. The velocity vectors show that the lateral velocity profiles along the axial direction of the jet for zero swirl (Fig. 6(a)) exhibit almost no divergence in the jet direction. Whereas, the velocity vectors of the low swirl strength (Fig. 6(b)) reveals a noticeable recirculation zone downstream of the jet. Although the magnitude of the recirculation zone is somewhat weaker than that of the axial velocity of either the central/fuel jet or co-airflow, the presence of flame led to a significant growth in size and magnitude of the recirculation zone (the magnitude of the reverse flow increases and becomes comparable to the magnitude of the jet flow axial velocity – not shown here for space limitation). The main difference in the velocity vectors map between the zero swirl (Fig. 6(a)) and low swirl (Fig. 6(b)) is clearly shown in the central area of the jet where the flow is nearly stagnant in the case of the 25° swirl. This represents an ideal flow condition for the biogas lifted flame to occur/stabilize owing to its low burning velocity. In fact, this low velocity region acts as a flame holder. Figure 7 presents the mean-velocity vectors of the zero and low (25°) swirl strength in the cold flow as well as its corresponding jet flame under flow conditions pertaining to an attached flame (see Fig. 2). Figure 7 reveals the negligible effect of the low swirl strength at weak co-airflow (low exit velocity of the co-airflow) due to the absence of a recirculation zone in the central region of the jet flow. This is why the burner geometry does not have an apparent influence on the attached flame.



(a) Cold, S=0 (b) Cold, S=0.31

Figure 6. Axial mean-velocity vectors/map under conditions pertaining to a lifted biogas flame (V_j = 8.5 m/s and V_{co} = 5.24 m/s). (the magnitude of the velocity profiles/vectors can be measured using the 20 m/s vector scale shown in the map)



(a) Cold, S=0 b) Cold, S=0.31 b) Flame, S=0.31

Figure 7. Mean-velocity vectors map of jet flow under conditions pertaining to an attached flame (V_j= 6 m/s, V_{co} = 1.8 m/s). (the magnitude of the velocity profiles/vectors can be measured using the 20 m/s vector scale shown in the map)

4 Conclusions

Non-conventional fuel nozzles combined with swirl strength of co-airflow were employed in the present paper to examine their impact on non-premixed biogas-air flame. The main results can be summarized as follows. No lifted flame can be observed at zero-swirl co-airflow; however, the introduction of a swirl to the co-airflow resulted in the appearance of a lifted stable flame especially at low swirl strength. In addition, the swirl extended significantly the operability range of a biogas flame. High swirl numbers produced stable lifted flame only at relatively low co-flow velocity and the lifted flame shape is almost constant with very small fluctuations in the lift-off height. However, low swirl produced a lifted flame at high co-flow velocity. Moreover, the low swirl lifted flame appeared much larger than its counterpart at high swirl number which is an indication of better combustion performance. The results showed also that the geometry of the fuel nozzle has a noticeable effect on the biogas attached flame but almost unnoticeable in the presence of swirl. PIV measurement revealed that the onset of a recirculation zone downstream of the burner determine the nature of the flame as well as extends the stability limits of lifted flame.

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