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On the stability of a turbulent non-premixed biogas flame: Effect of low swirl strength

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ABSTRACT

Biogas like other low calorific value fuels has a very narrow stable region when operating in diffusion flame mode owing to their low burning velocity in conjunction with the unburned flow high velocity. This paper presents an experimental study on the effect of the burner geometry on the stability limits of a turbulent non-premixed biogas flame. The main focus of the study is on the role of the low swirl strength of the co-airflow, and the fuel nozzle diameter. The results revealed that the swirl plays a dominant role on the flame mode (attached or lifted) as well as on its operating/stability limits. However, the results revealed that the swirl effect prevails only at relatively moderate to high co-airflow velocity. That is, the swirl does not have an apparent effect at weak co-airflow when the flame is attached. Whereas, it becomes dominant at relatively high co-airflow velocity where the attached flame lifts off and stabilizes at a distance above the burner. Correlations were proposed to describe the lifted biogas flame blowout limits.

1. Introduction

Biogas is a renewable source of energy produced from anaerobic digestion process of organic matters which can be used to generate power and heat. The main component of biogas and natural gas is methane diluted with inert gases. However, despite negligible amount of inert gases in natural gas, biogas has significant amount of CO_2 such that the heating value of biogas is much lower than that of natural gas [1–3].

Burning of biogas like other low calorific value gases has several problems such as weak flame stability which results in combustion instabilities [4]. Feeble biogas flame stability arises from its low burning velocity and high gas flow velocity needed for achieving high energy release rate [5]. Therefore, designing combustion systems, which use low calorific value fuels, require knowledge about flame stability in that a stable flame must be maintained throughout the operation of the system [6]. In order to increase the stability limits, preheating of air or using catalyzers were found useful but still limited to premixed combustion [4,5]. It was also reported that premixed combustion of biogas–air yields pressure fluctuations at low frequency which consequently enhance instability [7]. Diffusion flames, which have more control over energy release and also safer operating conditions, are more desirable in practical combustors [5]. Studies of both attached and lifted flame of diluted fuels with low heating value components showed a decrease in the visible flame length, average temperature of various zones, flame radiant heat transfer, fuel pyrolysis rate, local concentration of emissions, and particulates formation [5]. A study of non-premixed laminar biogas-air flame showed that pressure has no effect on the visible flame height and the fuel dilution decreases the sooting propensity at constant pressure [8]. It was also reported that higher carbon dioxide concentration in methane fuel makes flame sooting more pressure dependent [8]. An experimental and analytical investigation on the stability parameters of turbulent, lifted, non-premixed flame of methane and ethylene diluted with nitrogen in a co-flow revealed that the flame lift-off height increases with the diluents concentration [1]. As a result of fuel dilution, the shape of the flame tapers inward and becomes more cylindrical [1,2]. Dilution of methane was found also to decrease the adiabatic flame temperature, and since the carbon dioxide specific heat increases faster with temperature in comparison with nitrogen and water vapor, it has the most influence on flame temperature [3,9]. It was reported that carbon dioxide is more effective than nitrogen to restrict the flammable zone and range [3,9].

Mixing low heating value gases with high heating value gases or burning with oxygen or oxygen enriched air could also increase the combustion stability of the low calorific value gases [5]. A study with four coaxial jets that make a piloted non-premixed oxy-combustion burner of a CH_4/BFG (blast furnace gases) mixture showed that using piloted methane–oxygen flame can expand the combustion operating range of low calorific value fuels [4]. Stability limits

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of a jet diffusion flame of two different methane–carbon dioxide mixtures (biogas) in a co-flow burner showed that increasing the amount of carbon dioxide narrows the flame stability range/limits, and the addition a small amount of hydrogen in the fuel enhances significantly these limits [10-6]. It was reported that adding high heating value gases such as hydrogen to the fuel enhances the flame stability range especially in the lean region but at the same time it could increase the amount of pollutions such as NOx and CO [11].

There is a published study which reported that large scales of turbulence produced by a mesh placed upstream of biogas flame were found to enhance the flammability limits [3]. Bluff-body has significant effect on the lift-off and stabilization of non-premixed turbulent jet flames in that bluff body makes the position of the flame base more dependent on the co-flow velocity rather than the jet velocity [12]. It was reported that the gap between the central jet and annular co-flow (i.e., bluff body) does expedite the formation of the inner recirculation zone (IRZ) especially at low swirl and Reynolds numbers [13]. The effect of asymmetric fuel nozzles and sudden expansion on jet characteristics of turbulent co-flowing free jets showed also improvement in the stability limits of non-premixed methane flame [14–18]. However, a recent study by the present authors on the stability limits of turbulent non-premixed biogas flame revealed that the effect of the fuel nozzle's orifice exit geometry is negligible in comparison with the effect of the fuel nozzle diameter and that of the co-airflow swirl strength [18].

Flame stabilization was found to depend also on the recirculation of heat and chemically active species promoted by swirling flows. For instance, cyclone/swirl burners have the advantage of introducing aerodynamic recirculations with low pressure drop [19]. A recent study showed that the rate of oxidation can be increased significantly through recirculation of small amount of the products into the reactants [3]. An experimental study revealed that, by rotating the nozzle, in order to produce a swirling central turbulent jet, the flame lift-off height reduced linearly with the rotational speed of the nozzle and consequently enhanced the stability limits [20]. A comprehensive experimental investigation on the effect of a swirling co-airflow on the stability of turbulent non-premixed methane-air and two other mixtures of methane and hydrogen showed a significant increase in the flame stability range [21]. However, another research group [22], who adopted a similar set-up to that of Feikema et al. [21], reported a drastic decrease in the flame stability range when diluting with an as high as 15% carbon dioxide. A detailed study on swirling turbulent non-premixed lifted flames revealed the existence of a strong internal recirculation zone which reversed the hot combustion products and stabilized the flame where a thin corrugated reaction zone of a flame with a short height was observed [23]. Similar study revealed the existence of a high velocity gradient in the inner shear layer and a coherent helical vortex (PVC) [24]. Measured mixture ratio revealed that the internal recirculation zone (IRZ) is fuel rich and the temperature in the IRZ is higher than the surroundings [24]. PVC was found to enhance the mixing and this led to rapid ignition of the mixture [25,26]. Furthermore, it was reported that due to the flame roll-up, the PVC was found to enlarge the flame surface [25].

It is clear from the reviewed literature above that there is a very limited number of published studies on the stability of biogas flames, especially for mixtures/surrogates with high concentration of carbon dioxide. This is even true for studies whereby boosters for enhancing the stability of this type of flames were not employed (e.g., addition of hydrogen, use of catalyzers). Therefore, the present paper employs passive techniques by investigating the effects of swirling co-airflow and fuel nozzle diameter on the stability limits of a biogas flame. The focus is on the stability parameters (e.g., lift-off, blow-out, and blow-off) of a turbulent non-premixed biogas surrogate flame (mixture of 60% methane and 40% carbon dioxide). The literature showed that compositions with high content of CO_2 (e.g., CH_4:CO_2 = 60%:40%) presents a challenge for stabilizing biogas flame (e.g., [6,10,22]).

2. Experimental set-up

The experimental setup consists mainly of a central fuel nozzle surrounded by a swirling co-axial air stream where the flow discharges into an open chamber at atmospheric conditions. Detailed description of the test facility, which was designed and fabricated in-house, was reported elsewhere [12,14,15], and hence only a brief and complementary information is provided here. The configuration of the top section of the burner, which includes the fuel nozzle and swirl generator, is presented schematically in Fig. 1(a). Fuel and co-airflow rates were controlled by flowmeters. Air flowmeters were calibrated in-house using venturi tube technique. 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. Air was supplied from a laboratory compressed line, and methane and carbone dioxide, having a purity of 99%, were supplied from compressed cylinders. A schematic diagram of the fuel/central nozzle geometry employed in the present study is shown in Fig. 1(b).

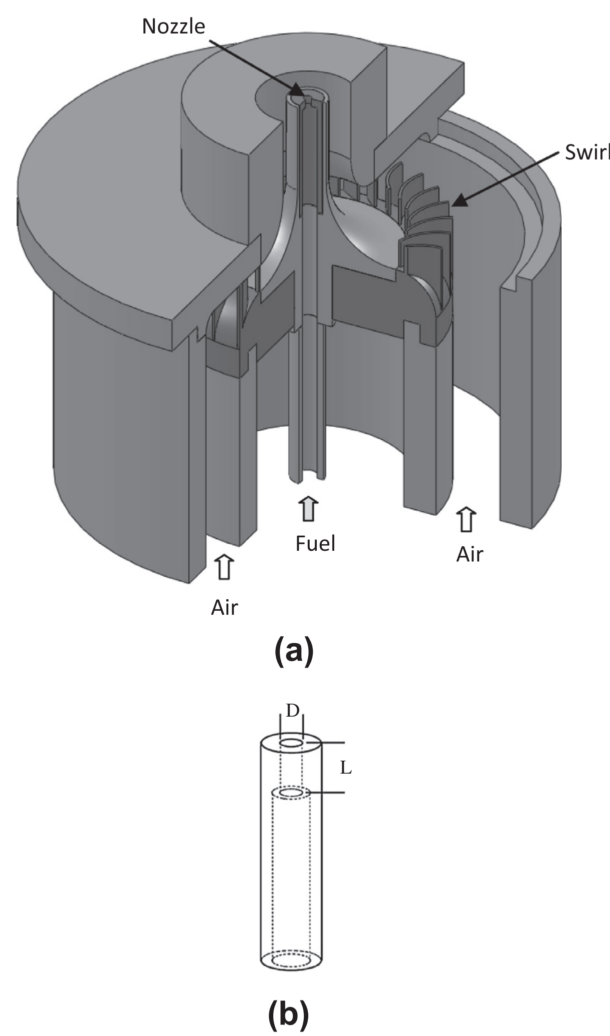

Fig. 1. Schematic diagram of the (a) burner top section and (b) fuel nozzle.