EXPERIMENTAL STUDY OF THE EFFECTS OF SWIRL AND AIR DILUTION ON BIOGAS NON-PREMIXED FLAME STABILITY

by

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An experimental investigation of the stability limits of biogas in a swirling non-premixed burner has been carried out. A mixture of 60% methane and 40% carbon dioxide was used to reach the typical biogas composition. Vane swirlers with 30°, 45°, and 60° angles were used to make the swirling air. The biogas stability limits and flame behavior under swirling conditions were tested. Besides, effects of air dilution with nitrogen and carbon dioxide on biogas stability limits were investigated. The results show that using swirl can enhance the flame stability limits approximately four or five times comparing to non-swirling air stream. Adding N_2/CO_2 *to the air had negative effects on the flame stability but no changes were observed in the flame structure. The maximum air dilution was also obtained when 27% and 15%* N_2 *was added to the swirling air under strong and weak swirl, respectively.*

Key words: *biogas, swirl combustion, dilution, non-premixed flame*

Introduction

Rapid depletion of fossil fuel sources, technologies in the production and the utilization of renewable fuels have advanced markedly in recent years. Biogas is one of the renewable fuels which is produced by anaerobic digestion of biodegradable materials such as biomass, sewage, green wastes and energy crops, and also gasification of wood or other biomass. The composition of biogas varies depending upon the origin of the anaerobic digestion process. The most important biogas components are methane (CH_4) and carbon dioxide (CO_2). Biogas typically has CH_4 concentration around 50% but advanced waste treatment technologies can produce biogas with 50-75% CH_4. Due to the great amounts of CO_2 present in the mixture the heating value of biogas is around 510 Btu/ft^3 (whilst the heating value for CH_4 and natural gas (NG) are around 1010 Btu/ft^3 and 870 Btu/ft^3, respectively) [1, 2]. Biogas can be compressed much like NG and CH_4 and used to power engines and to generate either heat or mechanical power and run any type of heat engine [3]. In practical applications, flame stabilization is one of the most important issues of fundamental combustor design for utilizing such poor fuels instead of fossil fuels. The stable flame has to be maintained during the combustion system operation to keep away the quenching. So, flame extinction limits must be taken into account in designing such systems. The fundamental studies have been carried out to examine the stability limits (including liftoff, blow off, and blowout) in co-flow or swirling air stream and different models and

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physical mechanisms have been proposed to delineate the liftoff and blowout behavior of CH_4 and CH_4/CO_2 mixture. Kalghatgi [4] investigated the blowout of non-swirling jet flames and showed that blowout velocity of gases or mixtures can be estimated based on the initial properties of the fuel. Chao *et al*. [5] examined the blowout velocities of inert-diluted methane (CH_4), propane, and hydrogen jet flames in the turbulent regime in non-swirling air stream. They also validated the experimental data with Kalghatgi [4] results. Feikema *et al*. [6, 7] conducted a lot of experiments and investigated the effect of swirl on blowout limits of CH_4 and CH_4/H_2 blends in a non-premixed burner. They showed the enhancement of flame stability by the use of swirl and also estimated the blowout velocity of non-premixed swirling flames.

Many researchers have been tried to increase the flame stability limits by adding hydrogen (H_2) to the fuel. In former studies, H_2 was added to fossil fuels mostly to CH_4. Schefer [8] and Schefer *et al.* [9] could improve the flame stability limits by adding H_2 to CH_4-air flame. The results from Schefer [8], Schefer *et al*. [9] show that a H_2 enriched methane-air flame has an increased resistance to strain because of the increase of the flame velocity. The similar results also obtained by Jackson *et al*. [10] using small amount of H_2. Karbassi and Wierzba [11] examined the effect of H_2 addition on the stability limits of methane jet diffusion flames. Leung and Wierzba [12] found the same results of adding H_2 to methane diffusion flame. Moreover, they studied the effect of adding H_2 to biogas on increase of the flame stability limits. The swirling air has also been applied in many combustion systems, namely industrial burners, internal combustion engines, and gas turbine combustion chambers in order to increase the stability limits and reduce the pollutant emissions [13]. Cheol *et al*. [14] examined the blowout limits of landfill gas (LFG) and landfill gas mixed liquefied petroleum gas in a swirling non-premixed burner. Combustion of biogas was tested in a low swirl burner by Weber and Strakey [15]. It was observed that the low swirl injector would stabilize premixed low energy flames exceptionally well. Biogas combustion in flameless mode has also been of interest of previous studies. Colorado *et al.* [16] confirmed that flameless combustion is highly flexible to burn conventional fuels and bio-fuels as well and showed that biogas could be used in a conventional flameless burner without any specific modifications. Biogas combustion in internal combustion engines has been studied for evaluating the performance and rate of pollutants of the engines. Bedoya *et al.* [17] showed the increase in performance and also the decrease in carbon monoxide (CO) emissions by using biogas in a dual fuel engine. Crookes [18] studied the effect of various biofuels on performance and emissions of spark and compression ignition engines. They found out that using biogas can result a considerable reduction in NO_x and CO emission of the engine.

As the biogas can be widely used in future industry, study the principals of low-calorific biogas combustion seems to be an essential topic for research. The aim of this study is to evaluate the biogas flame behavior and stability limits under swirling conditions. Moreover, as there is almost no any reports regarding the effect of air dilution on non-premixed biogas with swirling air, it is important to find the biogas flame stability range under air dilution condition. In the present study the stability limits of biogas flame under weak and strong swirl conditions are investigated to find out the amount of flame stability enhancement. Flame stabilization with diluted air has also been examined and the critical conditions are obtained.

Experimental apparatus

In order to examine the effect of swirl, a non-premixed laboratory-scale burner was designed and tested. A schematic diagram of the apparatus including the swirl burner and fuel feed lines is shown in fig. 1. The swirl burner has a centrally located fuel delivery tube which is coaxial with the swirling air flow. Swirling motion is imparted through 30°, 45°, and 60° van swirlers

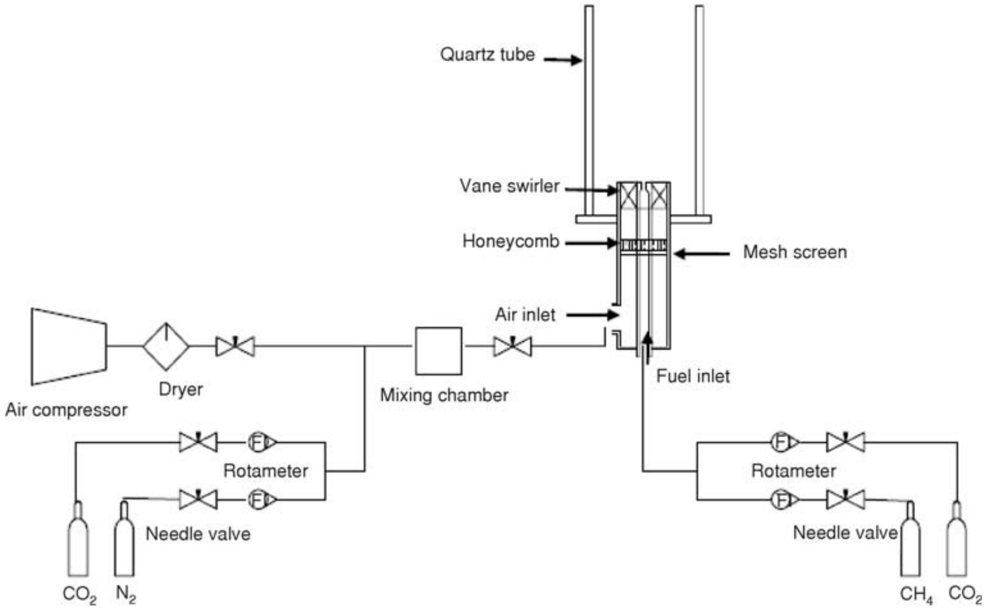

Figure1. Schematic of apparatus

in the air stream, each having eight swirl vanes as shown in fig. 2. The inside and outside diameter of the swirlers are 20 mm and 75 mm, respectively, with 35 mm height. The fuel is injected axially through a 3 mm diameter nozzle. A fixed combination of 60% CH_4 and 40% CO_2 was used to achieve the properties of sample biogas. The CH_4 and CO_2 were supplied from high pressure cylinders and mixed within a manifold prior to the burner inlet. Combustion air was supplied at the ambient temperature of a compressor after passing through an air dryer. For the sake of creating a uniform flow of the oxidizer, the oxidizer was passed through a mesh screen and a honeycomb respectively. The N_2 and CO_2 gases which were used as air diluents, were also supplied from high pressure cylinders. In order to ensure a homogenous mixture of oxidizer, air and diluents were mixed together inside a mixing chamber before entering to the burner. The whole mixture has to pass through a 380 mm height of burner. The volumetric flow rates of all gases were measured separately by calibrated ball rotameters (0-500 standard liter per minute) with accuracy of ±0.2% of full scale controlled by using needle valves. A cylindrical quartz tube with 140 mm diameter and 800 mm height is located on the burner rim in order to confine the flame from the ambient air. The global features of flames were observed using a high resolution color digital camera (Canon Powershot G6 with resolution 3072 × 2304). The Flame extinction limits were measured by direct observation.

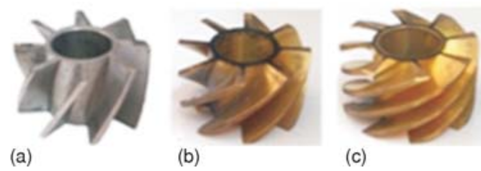

Figure 2. Vane swirlers (a) 30°, (b) 45°, (c) 60°

The sequence of the experimental tests is summarized in tab. 1. All experiments took place under atmospheric conditions (P = 89 kPa and T = 20 ºC).

Table 1. Experimental conditions tested

Biogas compositions	Case	Vane swirler angle [degree]	Volume fraction of diluents (N_2/CO_2) added to air	Results
60% CH_{4+} 40% CO_2	1	30	5.0%, 10%	Blowoff, liftoff, blow out velocities [ms^{-1}]
	2	45	5.0%, 10%	Liftoff, blow out velocities [ms^{-1}]
	3	60	5.0%, 10%	Liftoff, blow out velocities [ms^{-1}]

Results and discussion

Effects of swirling air on biogas stability limits

In order to investigate the effect of swirl on biogas flame stability, different swirlers with 30°, 45°, and 60° vane angles were used for creating weak and strong swirl streams [13]. In each experiment, the air velocity was kept constant and the fuel velocity was increased gradually by 1 m/s. For covering a wide range of experiments, the air velocity was varied within the range of swirling velocity values from 0.4 m/s to 1.2 m/s for strong swirl and up to 1.7 m/s for weak swirl condition. The swirling air velocity was increased by 0.1 m/s according to the range of the flame stability.

Results show different behaviors under weak and strong swirl conditions. Under weak swirl condition (with swirl vane angle 30° and swirl number 0.46*) it was observed that the flame behavior depended on the swirling air velocity. It was observed when the air velocity was less than 1.36 m/s, blow off happened. The attached flame suddenly becomes extinct and there is no flame liftoff.

There is no re-circulation zone in low air velocities and the flame blows off in very low fuel exit velocities [13]. When the swirling air velocity is increased to more than 1.36 m/s, a re-circulation zone is created and causes the flame extinction at higher fuel velocities. In this case, the biogas flame tends to lift off and stabilize at a certain location of the burner exit when the fuel velocity reaches a specific limit called liftoff velocity. By increasing the fuel velocity, the flame can no longer stabilize at the downstream of the burner rim and blows out. When a lifted flamed goes for extinction by increasing the fuel velocity, it is called flame blow-out. Biogas flame cannot resist in non-swirling or low-swirling conditions because an insignificant change in fuel flow rate can cause the flame blows out. So, this flame cannot be used in practical combustion systems. The results of stability limits of biogas flame under weak swirl condition with 30° vane swirler are presented in fig. 3.

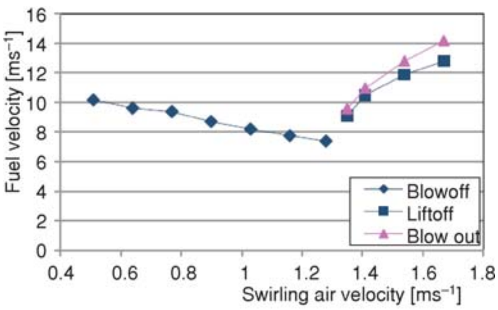

Figure 3. Flame stability limits under weak swirl condition (with swirl vane angle of 30°)

Using vane swirlers 45° and 60° impose strong swirl to the air stream with swirl numbers of 0.8 and 1.41, respectively. The results for the strong swirling conditions show as fuel velocity increases, the flame lifts off at first and then extinguishes for higher fuel velocities. This behavior was observed for both 45° and 60° vane swirlers. This is because of the presence of re-circulation zone in strong swirl conditions

* The degree of swirl imparted to the flow by the swirl generator is characterized by the swirl number

even in low swirling air velocities [13]. It was also observed that using a simple technique (a 60° vane swirler) can enhance the stability limits of biogas flame around five times higher than low swirl or non-swirling air stream. The stability limits of biogas with 45° and 60° vane swirlers are presented in fig. 4. Flame blowout limits were obtained with varying the swirling air velocity between 0.2 m/s to 1.4 m/s. Typical flame images of biogas flame under different swirl conditions are shown in fig. 5.

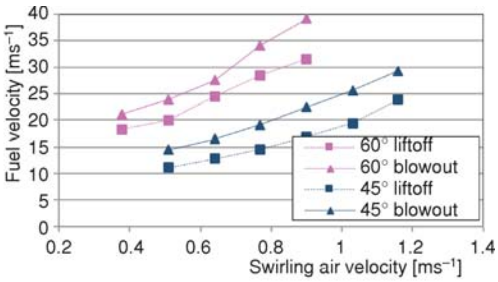

Figure 4. Flame stability limits under strong swirl condition (with swirl vane angle of 45° and 60°)

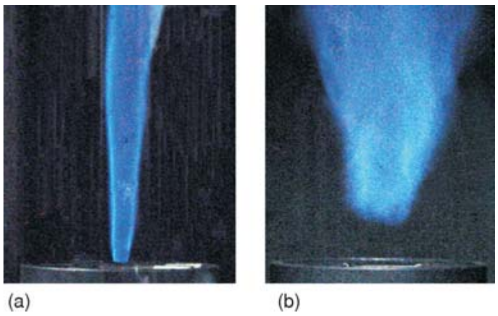

Figure 5. Flame images of biogas; (a) attached flame for 30° swirler, U_{air} = 0.64 m/s, U_{fuel} = 8 m/s, (b) lifted flame for 60° swirler, U_{air} = 0.64 m/s, U_{fuel} =26 m/s

To the knowledge of the authors, there is no general model to predict the blow out limits for biogas in swirling air stream. The only available model to estimate the flame extinction velocities for CH_4 in swirling burner was presented by Feikema *et al*. [7]. It was reported that the blowout velocity of a flame, depended on the swirling air velocity and the swirl strength. When the swirl number is lower than a critical value (lower than 0.6), the air velocity must be large enough to create re-circulation zone in the combustion zone. When the swirl number is higher than 0.6, the re-circulation zone is created even in low air velocities. It was also mentioned that the maximum fuel velocity should scale linearly with the air velocity and the slop of the fuel velocity *vs.* air velocity line should be proportional to the swirl intensity. In the current study, the results are in good agreement with Feikema *et al*. [7] model from the qualitative point of view. In figs. 3 and 4, it is observed that the blowout velocities of biogas, scale linearly with the air velocity for all three swirl vane cases. The maximum slope of blowout velocity *vs.* air velocity line was obtained for 60° swirler. The authors have not been able to generalize and develop any correlation due to the absence of experimental data of the critical angular velocity. So, the validation of the model is neglected by the authors in the current study and only the general and qualitative aspects of the model have been noticed.

Effects of air dilution with N_2 and CO_2

Air dilution has a significant role in feasible applications either in laboratories or industries. In the current study, it has been discovered that the stability limits of low-Btu biogas can be improved by the use of swirl around four or five times higher than co-flowing air stream. With that extended range of stability, the effects of adding diluents to the oxidant side (swirling air) can be easily studied regardless of any premature flame extinction. The aim of this study, is to figure out the biogas flame structure with the presence of diluents in the swirling air and also the amount of the reduction in stability limits under weak and strong swirling conditions. Meanwhile, it should be added that the entire experiments of air dilution sections either in low or high swirl condition, are the same as the no-dilution experiments.

Effects of air dilution under weak swirl condition

In order to study the effect of air dilution with N_2/CO_2 on biogas flame behavior and also flame stability, two typical percentages of diluents (5% and 10%) were chosen to be added to the swirling air in each case of study. In first part, the experimental tests were carried out to examine the effect of adding N_2/CO_2 to the swirling air on stability limits of biogas combustion under weak swirl condition (using 30° vane swirler). The air velocity was varied within the range of swirling air velocity from 0.4 m/s to 1.36 m/s. In that range of air velocity, only the blow off was occurred. No changes have been observed in flame behavior and structure comparing to the no-dilution condition. As expected, adding some diluents to the swirling air causes a slight decrease in blow off velocity limit which is the only discrepancy observed in dilution experiments. The results of blow off velocity *vs.* oxidizer (diluted air with N_2/CO_2) velocity are presented in fig. 6. According to our previous knowledge, adding CO_2 to the air stream reduces the blow off velocity more than adding N_2 at the same percentage of CO_2. This is because of that CO_2 has higher heat capacity (C_p) than the N_2 and causes higher reduction in the flame temperature and makes the flame less stable. Therefore the flame will be blown off earlier by adding CO_2 rather than air dilution with N_2. According to the results, when the value of swirling velocity of oxidizer kept constant at 0.64 m/s, the blow off velocity is 9.61 m/s in no-dilution condition. Adding 5% CO_2 reduces the blow off velocity to 7.75 m/s but this velocity is about 9 m/s in the case of adding 5% N_2 to the air. This result shows the impact of adding CO_2 comparing to the N_2 to the swirling air. Adding 10% CO_2 to the swirling air reduces the blow off velocity 41% comparing to the no-dilution condition. The maximum percentage of air dilution with CO_2 was obtained by adding 10% CO_2 to the air. No flame was observed with more than 10% CO_2 added to the swirling air. It was also found out that the stability limit was influenced by swirling air velocity. Increasing the oxidizer velocity from 0.5 m/s to 1.03 m/s causes an increase of 2.6 times for the blow off velocity. According to the results, it can be realized that biogas combustion in co-flow or non-premixed low-swirl air stream is not that much feasible to be applied in real combustion systems. The air dilution is also a parameter that makes the flame so susceptible to instability. Therefore, using biogas in high-swirl air stream could be an effective way for applying biogas for real applications.

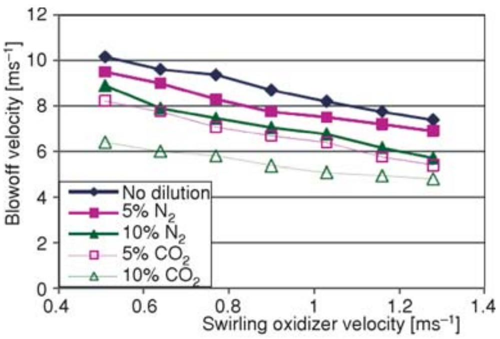

Figure 6. Blowoff velocities *vs.* swirling oxidizer (mixture of air and N_2/CO_2) velocity; swirl vane angle of 30°

Effects of air dilution under strong swirl condition

The advantage of applying high swirling air comparing with low swirling air is the extremely extended range of stability limits. Therefore, the high swirling air could be diluted and used for biogas combustion without any early extinction. All the experiments in this section were conducted entirely as the same as the no-dilution part and effects of air dilution with N_2 and CO_2 were examined under strong swirling conditions (using 45° and 60° vane swirlers) to investigate the flame behavior and stability limits of biogas. The oxidizer velocity range is between 0.2 m/s to 1.41 m/s. No changes were observed in flame behavior comparing to undiluted air results (for both 45° and 60° vane swirlers), but the liftoff and blowout velocities are declined. According to the results, some significant issues are discussed.

Figure 7, represents the lift off velocity as a function of swirling velocity of oxidizer (diluted air with N_2/CO_2) for swirl vane angle of 45°. The liftoff velocity for no-dilution condition was compared to the cases in which 5% and 10% N_2 or CO_2 was added to the swirling air, separately.

Among the conducted experiments, it was observed that the minimum liftoff velocity was obtained by adding 10% CO_2 to the swirling air. Adding 10% CO_2 to the swirling air causes 44% reduction in liftoff velocity comparing to the no-dilution condition. This reduction in liftoff velocity is just around 17% for diluted air with 10% N_2.

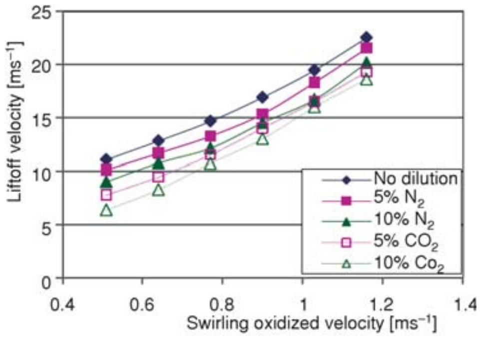

Figure 7. Liftoff velocities *vs.* swirling oxidizer (mixture of air and N_2/CO_2) velocity; swirl vane angle of 45°

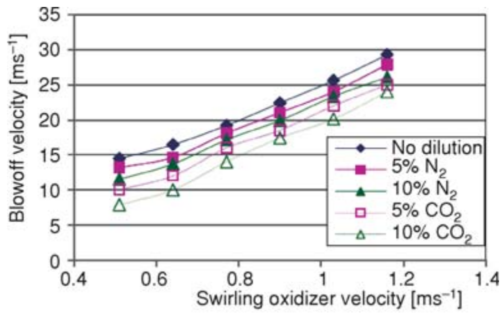

Figure 8. Blowout velocities *vs.* swirling oxidizer (mixture of air and N_2/CO_2) velocity; swirl vane angle of 45°

The tests mentioned above, were continued by increasing the fuel exit velocity to reach the blowout limits. The results are plotted in fig. 8 for N_2 and CO_2 addition to the swirling air. The significant impact of adding CO_2 on blowout velocity is also observed. According to the results, it is calculated that the blowout velocity for 10% dilution by CO_2 is about 9.1 m/s which is 44.6% lower than the no-dilution case. Also the blowout velocity for diluted air with 10% N_2 is 17% lower than no-dilution condition.

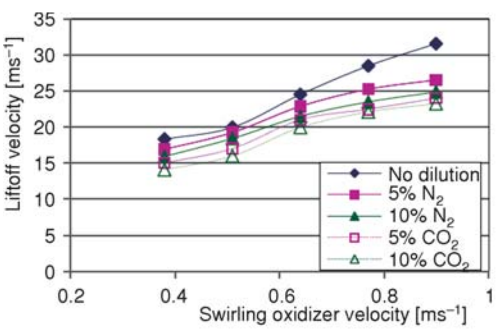

Figure 9. Liftoff velocities *vs.* swirling oxidizer (mixture of air and N_2/CO_2) velocity; swirl vane angle of 60°

The experiments above were repeated for swirl vane angle of 60° and liftoff and blowout velocities were examined. The results are presented in figs. 9 and 10, respectively.

The stability limits reduces due to the air dilution with N_2/CO_2. Adding 10% CO_2 reduces the liftoff and blowout velocities around 17% comparing to no-dilution case. This amount is just around 11% for diluents N_2. Therefore, it can be understood that using 60º swirler is influenced less than 45º swirler by negative effects of air dilution. As a result, biogas combustion in such high swirling air stream is a feasible way to make biogas get used in real applications along with air dilution.

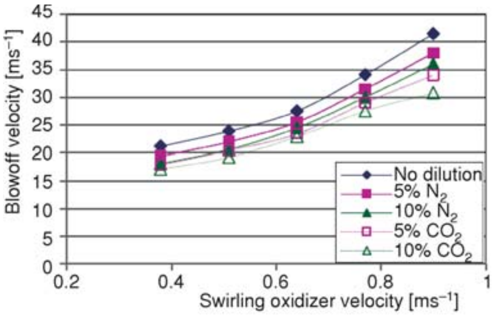

Figure 10. Blowout velocities *vs.* swirling oxidizer (mixture of air and N_2/CO_2) velocity; swirl vane angle of 60°

Comparing the results of blowout limits with diluted air for all three vane swirlers shows that the behavior of the biogas flame by increasing the fuel velocity is the same as biogas flame under no-dilution condition and it seems that biogas flames behavior are insensitive to air dilution but the stability limits are concerned.

Effects of diluents concentration

Figure 11(a) shows the blowoff/blowout limits as a function of the percentage of volume of N_2 added to swirling air when the oxidizer velocity is kept constant. In these sets of experiments the value of swirling oxidizer has been kept constant to 0.64 m/s. The maximum percentage of adding N_2 for each vane swirler is indicated by the arrows on fig. 11. It shows that for 60° swirler, it is possible to add 27% N_2 to the swirling air, whereas this value is 24% for 45° vane swirler. It can be realized that swirl can enhance the capability of air to get diluted by N_2 or also CO_2. Under weak swirl condition, the biogas flame is not very stable. Therefore, only a small amount of N_2 could be added to the air. It was observed that the flame would be blown out by adding more than 15% of N_2 to the swirling air.

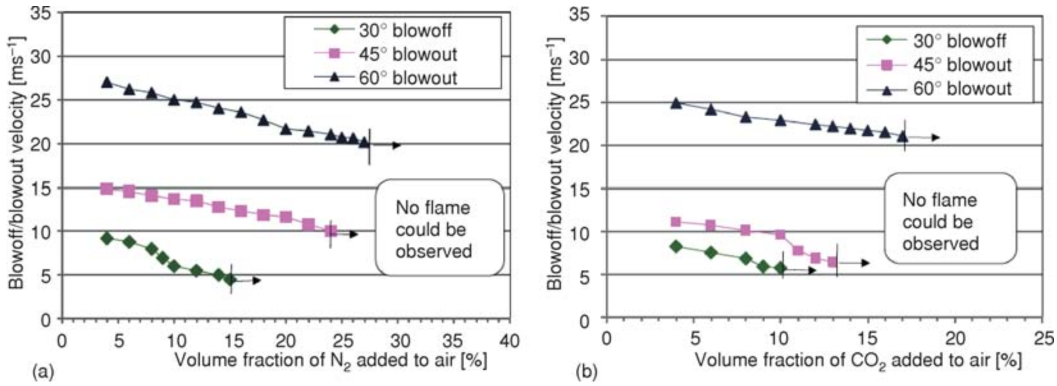

Figure 11. Blow off/blowout velocities as a function of the volume fraction of N_2/CO_2 present in swirling air

Figure 11(b), shows the results of adding CO_2 to the air. The maximum dilution with CO_2 is less than dilution with N_2. The maximum air dilution by CO_2 for 60° vane swirler was obtained by adding just 17% CO_2 to the air. By using 45° swirler, only 14% CO_2 could be added to the air. This value was reduced to 10% CO_2 when 30° swirler was used. No flame could be observed by adding more diluents gas.

Conclusions

An experimental study of biogas combustion in a swirl non-premixed burner was conducted. It was found that using swirl can enhance the stability limits of biogas up to four or five times more than non-swirl combustion, so that it can be used as a simple technique in practical applications. It was observe that in low-swirl condition (using 30º swirler) the biogas flame attaches to the burner rim and a slight increase in fuel velocity causes the flame blows off. In high-swirl condition (45º and 60º swirlers), by increasing the fuel velocity the flame lifts off and stabilizes at the downstream of the burner and blows out for higher fuel velocities. Although biogas is a low-caloric fuel, air dilution is also possible by the use of swirl. Herein, 17% CO_2 or 27% N_2 was added to the air whereas without swirl, air dilution was impossible especially in low swirl condition. Swirl improves the flame stability and air dilution diminishes it. In this study we just concentrated on the stability of biogas flame with swirling air and air dilution. Further study is firmly required to investigate the effect of above mentioned parameters on the combustion emission of biogas. As the swirl and air dilution can reduce the amount of NO_x emission, study the biogas emission quantitatively is essential for future work.

References

[1] Board, N., *Handbook on Biogas and its Applications*, National Institute of Industrial Research Publishers, New Delhi, 2004
[2] Walsh, J. L., *et al.*, *Biogas Utilization Handbook*, Georgia Tech Research Institute Publishers, Atlanta, Geo., USA, 1988
[3] Kapdi, S. S., *et al*., Biogas Scrubbing, Compression and Storage: Prospectus and Prospective in Indian Context, *Renewable Energy, 30* (2005), 8, pp. 1195-1202
[4] Kalghatgi, G.T., Blowout Stability of Gaseous Jet Diffusion Flames, Part I: In Still Air,*Combustion Science and Technology, 26* (1981), 5, pp. 233-239
[5] Chao,Y. C., *et al*., Effects of Dilution on Blowout Limits of Turbulent Jet Flames, *Combustion Science and Technology, 176* (2004), 10, pp. 1735-1753
[6] Feikema, D., *et al*., Enhancement of Flame Blowout Limits by the Use of Swirl, *Combustion and Flame, 80* (2004), 2, pp. 183-195
[7] Feikema, D., *et al.*, Blowout of Non-Premixed Flames: Maximum Coaxial Air Velocities Achievable, with and without Swirl, *Combustion and Flame, 86* (1991), 4, pp. 347-358
[8] Schefer, R. W., Hydrogen Enrichment for Improved Lean Flame Stability, *International Journal of Hydrogen Energy, 28* (2003), 10, pp. 1131-1141
[9] Schefer, R. W., *et al.*, Combustion of Hydrogen-Enriched Methane in a Lean Premixed Swirl-Stabilized Burner, *Proceeding,* The Combustion Institute, Sapporo, Japan, 29 (2002), Jan., pp. 843-851
[10] Jackson, G. S., *et al*., Influence of the H_2 on the Response of Lean Premixed CH_4 Flame to High Strained Flows, *Combustion and Flame, 132* (2003), 3, pp. 503-511
[11] Karbassi, M., Wierzba, I.,The Effect of Hydrogen Addition on the Stability Limits of Methane Jet Diffusion Flames, *International Journal of Hydrogen Energy, 23* (1998), 2, pp. 123-129
[12] Leung, T., Wiezba, I., The Effect of Hydrogen Addition on Biogas Non-Premixed Jet Flame Stability in a co-Flowing Air Stream, *International Journal of Hydrogen Energy, 33* (2008), 14, pp. 3856-3862
[13] Gupta, A. K., *et al*., Swirl Flows, Abacus Press., Cambridge, UK, 1984
[14] Hwang, C.-H., *et al*., Flame Blowout Limits of Landfill Gas Mixed Fuels in a Swirling Non-Premixed Combustor, *Energy and Fuels, 22* (2008), 5, pp. 2933-2940
[15] Weber, J. M.,Strakey, P. A., Low Swirl Combustion of Simulated Biogas, National Energy Technology Laboratory, US Department of Energy, Morgantown,W. Va., USA, 2008
[16] Colorado, A. F., *et al*., Performance of a Flameless Combustion Furnace Using Biogas and Natural Gas, *Bioresource Technology, 101* (2010), 7, pp. 2443- 2449
[17] Bedoya, I. D., *et al*., Effects of Mixing System and Pilot Fuel Quality on Diesel-Biogas Dual Fuel Engine Performance, *Bioresource Technology, 100* (2009), 24, pp. 6624-6629
[18] Crookes, R. J.,Comparative Bio-Fuel Performance in Internal Combustion Engines, *Biomass and Bioenergy, 30* (2006), 5, pp. 461-468

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