# An Experimental Study of Spark Ignition of a Turbulent Biogas Fuel Jet

**M.A. Bassiony[1], A.E. Ebrahemi[1], C. Turquand d'Auzay[2], S.F. Ahmed[1,*] and N. Chakraborty[2]**

[1]Mechanical and Industrial Engineering Department, Qatar University, P. O. Box 2713, Doha, Qatar
[2]School of Engineering, Newcastle University, Newcastle Upon-Tyne, NE1 7RU, United Kingdom

## 1 Introduction

Energy shortage has become a major challenge worldwide due to the significant population growth and the tremendous amount of energy consumption [1]. Therefore, it becomes a global need to develop clean alternative fuels, which are domestically available, environmentally suitable and technically feasible. In this context, biogas has been recognized as one of the potential renewable and clean fuels, and its applications in industry are becoming progressively more popular [2].

Biogas is formed from anaerobic deterioration of organic composites, and its main components are methane ($CH_4$) and Carbon Dioxide ($CO_2$) with variations in their proportions [3]. The biogas composition depends on the production process and the type of the raw materials used. The combustion value of a biogas is directly related to its $CH_4$ concentration. The use of biogas is environmentally beneficial because methane is considerably lower in carbon content than conventional fuels [4]. Therefore, using biogas can reduce pollutant levels in exhaust gases, including emissions of solid particles and nitrogen oxides. Furthermore, using biogas will reduce greatly the high usage of fossil fuels, which in turn will ensure the sustainability of energy for future generations.

Spark Ignition of turbulent flames is a very important topic and is widely used in engines and industrial applications. Recently, fundamentals of the ignition of turbulent non-premixed flames have been investigated both experimentally and numerically [5-11]. It was found that the successful ignition is controlled by a number of local parameters, such as instantaneous mixture faction, flow velocity, turbulence intensity and strain rate as well as non-local conditions such as heat convection from the spark location to the flow. In addition, the flow field characteristics have to be favourable to support flame propagation and light up the whole flame [8]. However, the effect of $CO_2$ dilution on the ignition behaviour of turbulent non-premixed flames has not been investigated yet. Currently, $CO_2$ dilution is used extensively with exhaust gas recirculation (EGR) technique in engines to reduce $NO_x$ emissions. Therefore, the present work aims to study the ignition of biogas fuel with different $CO_2$ percentages.

**Correspondence to: sahmed@qu.edu.qa**

The ignition probability of turbulent non-premixed biogas jets was explored. A spark ignition of a turbulent jet of mixtures of $CH_4$ and $CO_2$ with different volumetric percentages of $CO_2$ ranging from 10-40%, to simulate the biogas fuel, has been considered.

## 2 Experimental Methods

Figure 1 shows the schematic diagram of the test rig used for investigating the ignition probability of biogas jet flames. It consists of a co-flow jet burner with a traversing mechanism holding a Teflon bar with two stainless steel electrodes, as shown in Fig. 1. The jet-nozzle was a stainless steel tube with a 5mm internal diameter that was installed in the centre of the burner (concentric) with a length-to-diameter ratio of 200 to ensure a fully-developed turbulent flow at the jet exit. The air co-flow had an inner diameter of 210 mm. The fuel jet velocity was about 12.5 m/s, while the co-flow air velocity was about 0.1 m/s to protect the fuel jet from the outside flow disturbances.

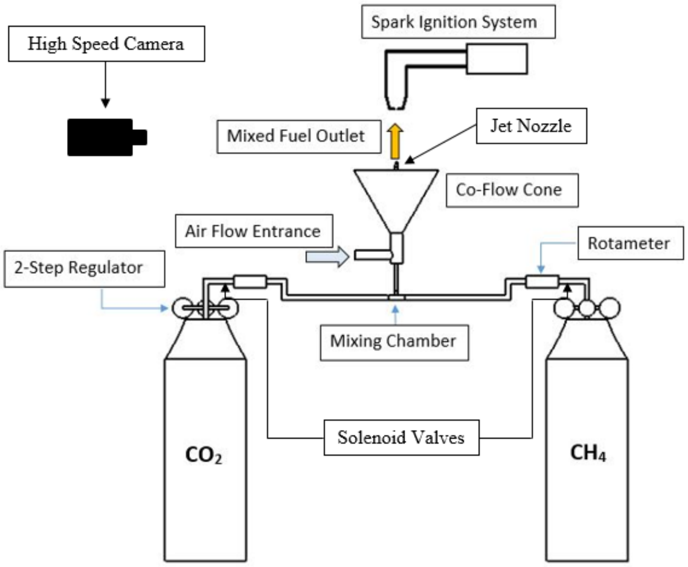

**Fig. 1**. Schematic diagram of the test rig.

Methane with 99.99% purity and carbon dioxide with 99.95% purity were supplied from pressurized cylinders to simulate biogas fuel. Two solenoid valves were for $CH_4$ and $CO_2$ to control their flows while conducting the experiments. $CH_4$ and $CO_2$ were mixed together far from the jet exit to form the biogas fuel jet. LZB Glass Tube flow-meters were used to measure $CH_4$, $CO_2$ and air flow rates. Three flow-meters were used one for each type of flow and all of them were calibrated with a maximum uncertainty of 5%.
The spark ignition system used contained a Flame Thrower® epoxy-filled ignition coil with an output voltage range of 0 to 40 kV connected directly to a capacitive circuit driver, which was mounted to a variable DC voltage power supply. An Arduino UNO micro-controller was connected to the circuit driver to dynamically control the spark duration, frequency and solenoid valves' operation. The spark ignition system was also equipped with high-voltage tension cable connected to the electrodes with a firmly fixed gap distance of 2 mm between the two electrodes. The experiment was fully automated to maintain repeatability and

efficiency during all conditions. The spark breakdown voltage and current signals were measured by Tektronix P6015A high-voltage probe and Person Electronics high-voltage current monitor MODEL 110. The output signals were sampled with 1MHZ using two channels of a TEKTRONICS TDS 3012 digital oscilloscope for characterization to ensure that the sparks have similar waveforms over the time. The maximum spark current was 500 mA and the spark electrical energy was 350 mJ with a spark duration of 400 ms to 600 ms.

A Photron® FASTCAM SA4 high-speed camera was used in the present work to visualize the ignition and flame propagation behaviour. For the conducted experiments, the camera was set at a resolution of 1,024 x 1,024 Pixels and frame speed of 3,600 fps.

## 3. Results and Discussion

### *A. Flame Visualization*

Visualization of the ignition and flame propagation for each biogas fuel composition was conducted to observe the effect of $CO_2$ increment in the biogas fuel on the ignition behaviour and flame propagation speed. In this experiment, the ignition was done at a 30 $d_j$ above the jet-nozzle, where $d_j$ is the nozzle jet diameter (5mm).

Figure 2 shows the ignition and flame propagation of the biogas fuel jet with composition of 80% $CH_4$ and 20% $CO_2$. It can be observed that the general behaviour is similar to the standard ignition behaviour of the spark ignition of $CH_4$ jets. However, this flame was characterized by a lighter color due to the increased amount of $CO_2$ in the fuel mixture, which led to a lower flame temperature. Likewise, the lift-off distance increased [12]. It should be mentioned that no stable flame could be established if the $CO_2$ percentage is increased above 30% at any location. Only initiation of a flame kernel initiation followed by a flame convection downstream can be observed if ignition from the same location has been attempted with 30 and 40% $CO_2$ biofuel, i. e. ignition at 30 $d_j$. This behaviour can be related to the fact that, at 30 $d_j$, the spark ignites different mixture fraction values as the $CO_2$ ratio in the fuel increased. More investigations are needed to fully understand the flame ignition and propagation behaviour of the biogas jet with different $CO_2$ contents.

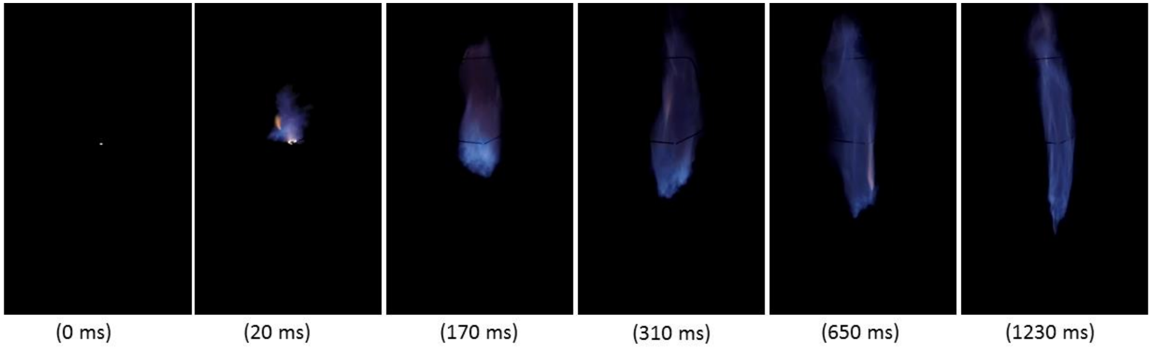

**Fig. 2**. Ignition and flame propagation of a biogas fuel jet with composition of 80% $CH_4$ and 20% $CO_2$. Spark at 30 $d_j$.

### *B. Ignition Probability*

In this work, the successful ignition is defined as the initiation of the flame kernel followed by a flame propagation and establishment of a stable flame. Any other behaviour is considered as a failed ignition as long as it does not result in a stable flame. It should be mentioned that the ignition probability has been measured by applying 50 sparks in all selected locations covering the whole flow field. Then, the number of successful ignition events was divided by the total number of ignition attempts. Figures 3 and 4 show the ignition probability contours for the cases of 100% $CH_4$ and 0% $CO_2$, and 80% $CH_4$ and 20% $CO_2$, respectively. It can observed from Fig. 3, for the 100% $CH_4$ case that the ignitability region extends from –12 $d_j$ to +12 $d_j$ in the radial direction, and up to 50 $d_j$ in the axial direction. The highest ignition probability is located as expected around the stoichiometric mixture fraction region. Away from this region, the ignition probability decays gradually until it reaches zero.

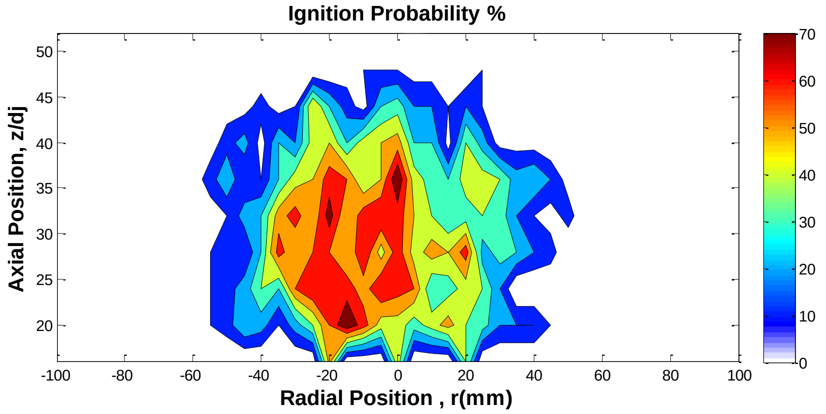

**Fig. 3**. Ignition probability contour of 100% $CH_4$ fuel jet.

It can be noted from Fig. 4 for the 80% $CH_4$ and 20% $CO_2$ biogas jet that the ignitability region shrinks considerably to about -8 $d_j$ to +8 $d_j$ in the radial direction and up to 40 $d_j$ in the axial one. This shows the strong effect of $CO_2$ dilution in the fuel on the ignition probability. However, high percentage of successful ignition (up to 90%) can be still achieved with this case in the region -2 $d_j$ to +2 $d_j$ in the redial direction, and about -20 $d_j$ to -30 $d_j$ in the axial direction.

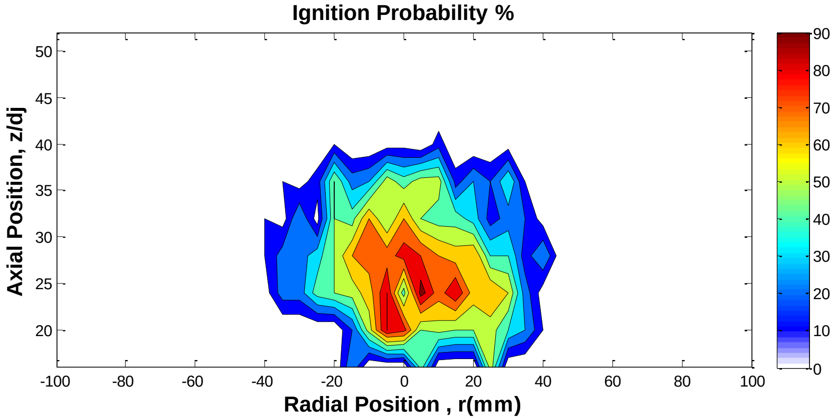

**Fig. 4**. Ignition probability contour of biogas jet flame with mixture of 80% $CH_4$ and 20% $CO_2$.

Figure 5 illustrates the axial ignition probability profile for different $CO_2$ percentages in the fuel. It can be observed that as the $CO_2$ ratio increases, the ignition probability decays in terms of both the ignitability region and the values. However, it is interesting to note that above 30% $CO_2$ dilution in the fuel, successful ignition was not possible at all and the ignition probability is zero everywhere. However, initiation of a flame kernel followed by a flame propagation downstream without establishment of a stable flame has been observed even with 40% $CO_2$ in the fuel. This was described as the second type of failed ignition in the series of ignition experiments done by Ahmed et al [5-8]. Figure 6 demonstrates the axial probability of just flame kernel initiation whether it has resulted in a stable flame or not. It can be observed that the axial profiles upstream of the jet flow of all $CO_2$ percentages are comparable. However, as the $CO_2$ ratio increases, the probability of initiating a flame kernel decreases, as shown in Fig. 6. This can be related to the upstream shift of the flammable mixture fraction as the $CO_2$ percentage increases in the fuel.

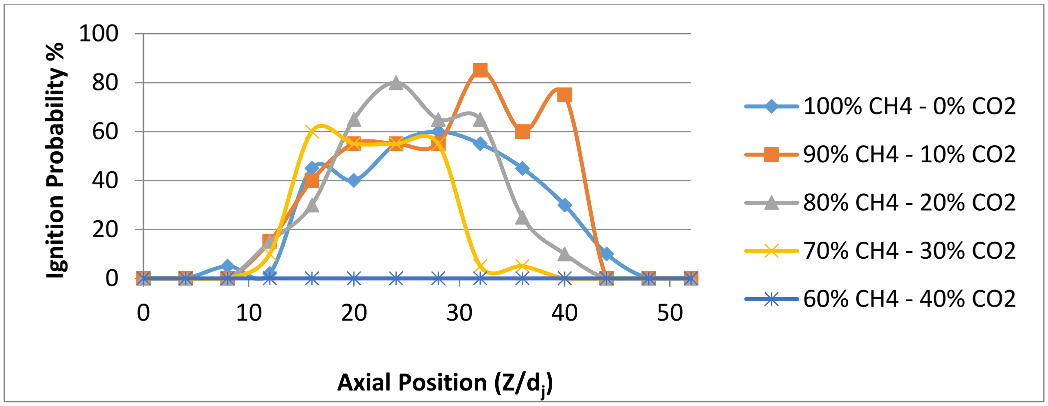

**Fig. 5**. Axial ignition probability profile along the jet centerline of different jet fuel compositions (Stable Flame).

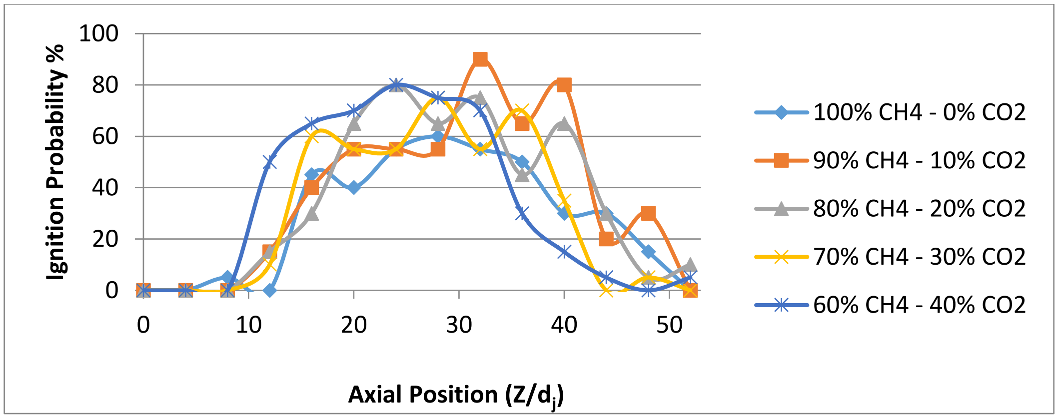

**Fig. 6**. Axial ignition probability profile along the jet centerline of different jet fuel compositions (Stable & Unstable Flame).

## 4. Conclusions

The spark ignition of biogas fuel jets with different $CO_2$ concentrations in the fuel, ranging from 10 – 40% by volume, has been studied experimentally. Visualization with high-speed imaging showed that the ignition and flame propagation behaviour of the biogas jet flame is similar to that of the standard methane jet. However, the redness of the flame decreases due to the reduction in the flame temperature with high $CO_2$ ratio. In addition, the ignition probability as well as the flame stability reduces as the $CO_2$ ratio increases. It was not possible to ignite the biogas jet and obtain a stable flame if $CO_2$ percentage in the fuel exceeds 30%. However, initiating a flame kernel after the spark without obtaining a stable flame was possible up to 40% $CO_2$ concentration in the fuel.

## Acknowledgments

This paper was made possible by the UK-Gulf Institutional Research Grant Fund. S.F Ahmed wishes to thank Qatar University for the support. The statements made here are solely the responsibility of the authors.

## References

1. Kadam, R., Panwar, N.L. (2017) Recent advancement in biogas enrichment and its applications. *Renewable & Sustainable Energy Rev.*, 73:892.
2. Verma, S. et al. (2018) An experimental investigation of exergetic performance and emission characteristics of hydrogen supplemented biogas-diesel dual fuel engine. *Int. J. Hydrogen Energy*, 43:2452.
3. Khan, I.U. et al. (2017) Biogas as a renewable energy fuel–A review of biogas upgrading, utilisation and storage. *Energy conv. management*, 150:277.
4. O'Shea, R. (2017) An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network. *App. Energy*, 208:108.
5. Ahmed, S.F,. Mastorakos, E. (2016) Spark ignition of a turbulent shear-less fuel-air mixing layer, *Fuel*, 164:297.
6. Ahmed, S.F,. Mastorakos, E. (2010) Correlation of spark ignition with the local instantaneous mixture fraction in a turbulent non-premixed methane jet, *Combust. Sci. Technol.*, 182:1.
7. Ahmed, S.F,. Balachandran, R., Marchione, T., Mastorakos, E. (2007) Spark ignition of turbulent non-premixed bluff-body flames, *Combust. Flame*,151:366.
8. Ahmed, S.F, Mastorakos, E.(2006) Spark ignition of turbulent lifted jet flames, *Combust. Flame* 146 :215.
9. Turquand d'Auzay C. et al. (2019) On the Minimum Ignition Energy and its transition in the localised forced ignition of turbulent homogeneous mixtures, *Combust. Flame*, 201:104.
10. Patel D, Chakraborty N. (2016) Effects of Fuel Lewis Number on Localised Forced Ignition of Globally Stoichiometric Stratified Mixtures: A Numerical Investigation, *Flow, Turb. Combust.*, 96:1083.
11. Chakraborty N, Hesse H, Mastorakos E. (2010) Effects on fuel Lewis number on localised forced ignition of turbulent mixing layers. *Flow, Turb. Combust.*, 84:125.
12. Merola, S.S. et al. (2017) Spectroscopic characterization of energy transfer and thermal conditions of the flame kernel in a spark ignition engine fueled with methane and hydrogen. *Int. J. Hydrogen Energy*, 42: 13276.