Effect of Inner Swirl Angle on Flame Stability of a Double-Swirl Burner with Biogas-Methane Co-Firing

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Abstract: *This paper studies how the inner swirl angle affects the flame stability of a double-swirl burner with biogas-methane co-firing. Biogas is a renewable fuel that is produced from organic waste by anaerobic digestion, it can be mixed with methane as an act to save methane fuel as well reduce CO_2 emissions. However, biogas has combustion challenges due to its high CO_2 content. The double-swirl burner is a technology that can improve combustion performance and reduce nitrogen oxide emissions. This study investigates different inner swirl angles with various CO_2 fractions in biogas and assesses their effects on flame stability and flame appearance. The paper finds that a higher CO_2 fraction and inner swirl angle make the flame less stable and requires more fuel, and also changes the flame shape. The paper gives insights into improving the double-swirl burner for biogas-methane co-firing.*

Keywords: Biogas; Methane; Double-Swirl Burner; Flame Stability

1. INTRODUCTION

A variety of organic waste sources, including landfill, agricultural residues, and municipal solid waste, can be used to produce biogas, as a renewable and biodegradable fuel. Biogas is generated by an anaerobic digestion process, whereas the bacteria decompose organic matter in the absence of oxygen into methane (CH_4) and carbon dioxide (CO_2). While biogas may also include traces of other gases such as hydrogen (H_2), nitrogen (N_2), and sulfur (S) compounds. The grade and calorific value of biogas are defined by the CO_2 content, which usually varies from 25% to 50% CO_2 by volume [1].

Biogas has numerous potential applications in different sectors, such as electricity generation, heating, and transportation fuel [2]. It can replace natural gas (NG), which emits greenhouse gases and causes climate change [3]. However, biogas also has some drawbacks that limit its widespread use [4]. For instance, biogas may have lower reactivity and higher CO_2 content than NG, which can impair its combustion performance and stability. Therefore, conventional burners need to be modified or replaced to ensure efficient and clean combustion of biogas [5].

Biogas is anticipated to have a significant role in the future energy mix, as it provides a renewable and biodegradable alternative to fossil fuels. The International Energy Agency (IEA) predicts that biogas will have a growing share in the total gaseous fuel supply until 2050 [6]. Biogas can also help reducing global warming by capturing and utilizing methane that would otherwise leak into the atmosphere and has a higher global warming potential than CO_2 [7]. Moreover, biogas can offer multiple benefits for rural development, such as waste management, fertilizer production, and income generation [8]. Therefore, biogas is a versatile and sustainable energy option that merits more attention and support.

Dealing with the fluctuating composition of biogas presents a major challenge in its combustion, as it is influenced by the practical feedstock and the production process involved. For example, the East Natuna gas field in Indonesia, one of the world's largest gas reserves, has a high CO_2 content of up to 71%, which poses difficulties for its development [9]. Another challenge is to optimize the combustion systems to minimize pollutant emissions, such as nitrogen oxides (NO_X) and carbon monoxide (CO), which may arise from incomplete or excessive combustion [10]. Controlling and optimizing combustion systems during the use of new fuels is essential for environmental and economic reasons.

Biogas combustion poses significant challenges due to its high CO_2 content, which results in reduced heating value and flame stability compared to natural gas. The CO_2 dilution negatively impacts mixture reactivity, flame temperature, and ignition delay time [11]. Biogas combustion can achieve lower NO_X emissions but with higher CO and UHC emissions, depending on the operating conditions. Swirl flames are particularly effective in reducing NO_X emissions from biogas combustion, but they also increase CO and UHC emissions compared to pure methane flames [12]. Therefore, biogas may be a viable alternative fuel for gas turbine combustors if the CO emissions can be controlled adequately [13].

Methane serves as the predominant component in both biogas and natural gas (NG), offering a clean-burning fuel that primarily generates water and CO_2 when combusted [14]. Methane has been involved in many combustion applications such as Lean Burn Gas Engines (LBGEs) [15]. However, methane is also a potent greenhouse gas that contributes to climate change when leaked into the atmosphere [16]. Therefore, it is essential to optimize methane combustion to minimize its environmental impact and maximize energy conversion. One promising approach to achieve this is co-firing methane with biogas, which can reduce methane consumption and CO_2 emissions per unit of energy output. The co-firing process can also enhance the combustion performance and stability of biogas which may vary depending on its composition and reactivity. Methane combustion is a complex process that involves multiple steps and intermediate species, requiring careful control and optimization to avoid flame instabilities and pollutant emissions, such as nitrogen oxides (NO_X) and carbon monoxide (CO).

The double-swirl burner, a promising technology for premixed combustion, incorporates two swirling streams of fuel and air to create a powerful recirculation zone within the flame core. This recirculation zone acts as a flame holder and enhances flame stability, mixing, and overall combustion efficiency. In addition, double-swirl burners can reduce nitrogen oxide (NO_X) emissions by operating under overall lean conditions and can adapt to different fuels types and fuel blends by changing the swirl intensity and the equivalence ratio of each stream [13]. While the swirl intensity is a non-dimensional parameter that measures the angular momentum given to the flow by the burner geometry and influences the flow field, the flame shape, the flame stability, and the pollutant emissions of the burner. Therefore, various studies have explored the effect of swirl intensity on different aspects of combustion using different fuels and burner configurations [17]. However, there is a scarcity of systematic studies on the effect of swirl intensity on biogas-methane co-firing in double-swirl burners.

The objective of this work is to investigate the influence of the inner swirl angle on the characteristics of a double-swirl burner operating with biogas-methane co-firing. The inner swirl angle is defined as the angle between the inner swirler blades and the burner downstream direction, which affects the degree of mixing between the inner and outer streams and the recirculation in the combustion chamber. This study aims to provide insights into the optimization of double-swirl burners for biogas-methane co-firing applications and to enhance the understanding of the physical and chemical processes involved in such flames. The experimental results include the stability limits and flame shapes of biogas-methane co-fired flames at various inner swirl angles are analyzed and discussed in detail.

2. METHODOLOGY

This study aims to examine the combustion characteristics of a premixed methane-air flame in a double-swirl burner with biogas co-firing and inner swirl intensity variation. The biogas composition is simulated by CO2 dilution in the inner stream with different CO2 fractions. The double-swirl burner design enables independent control of the inner and outer swirl intensities. The previous studies [18, 19] provide a detailed description of the double-swirl burner design and the experimental setup.

2.1 Burner Test Rig

Fig. 1 shows the double swirl burner configuration with two concentric swirling streams. It has a central 45° bluff body. A 15° diverging cone (quarl) is installed in the outer stream to create a significant outer recirculation zone to enhance flame stabilization. The outer stream is kept under a constant swirling degree with a swirl number, *S*, of 0.49 corresponding to a 30° swirler. While the inner stream swirling degree is controlled by changing the swirler angle to 30°, 45°, or 60°. Table 1 shows the different swirl numbers of the inner stream used in the current study. The swirl numbers are calculated according to the formula provided by [20].

As shown in Fig. 2, all issuing flames are confined in a rectangular combustion chamber with a cross-section area of 185×185 mm and a length of 300 mm. The side walls of the combustor are equipped with quartz glass windows to enable optical access.

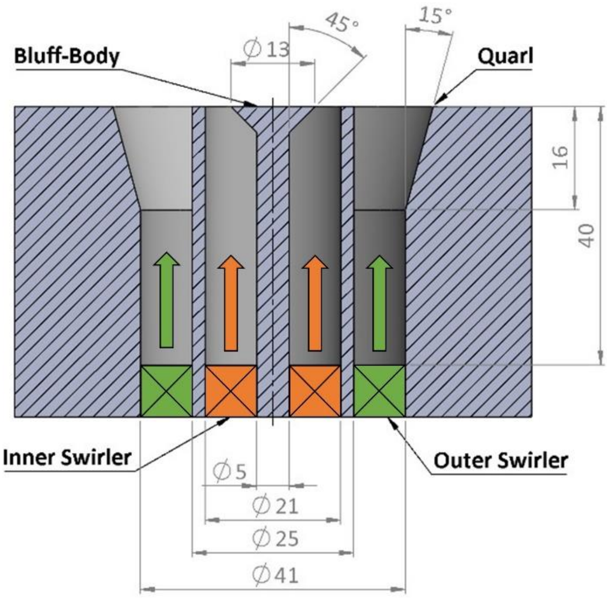

Fig. 1. The double-swirl burner configuration (all dimensions are in mm). The inner stream is in orange, while the outer stream is in green.

Table 1. Different inner stream swirl configurations.

Inner stream configuration	1	2	3
Swirl angle	30°	45°	60°
Swirl number	0.41	0.72	1.24

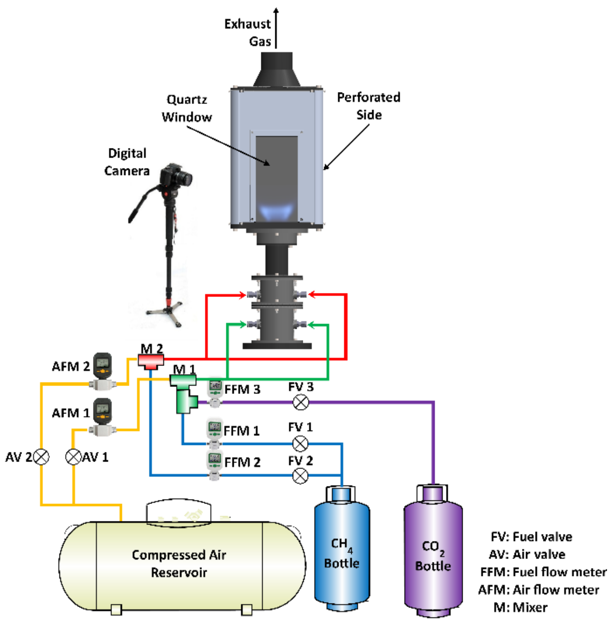

Fig. 2. The experimental test rig (the double-swirl burner, gas supply lines, control valves, and flowmeters).

2.2 Techniques/Test Conditions for Experiments

The inner stream is made up of various CO_2/CH_4/air-premixed mixtures with varying CO_2 mole fractions,

x_{CO_2}, which may be calculated as

$$x_{CO_2} = \frac{V_{CO_2}}{V_{CO_2}+V_{CH_4}} \quad (1)$$

where V_{CO_2} and V_{CH_4} are the volume flow rates of CO_2 and CH_4 in the inner stream, respectively. To increase overall flame stability, the outer stream provides a lean CH_4/air-premixed mixture. SIARGO digital mass flow meters of models MF5706 and MF5712 with an accuracy of (2.0+0.5FS)% were used to control and monitor the flow rates of CO_2, CH_4, and air. The inner and outer premixed mixtures are routed to two settling chambers at the burner's base. The inner stream air bulk jet velocity is kept constant at $U_{a,in}$ = 5 m/s, whereas the outer stream bulk velocity is kept constant at $U_{m,out}$ = 3.2 m/s. These velocities are calculated using the relevant flow rates and stream exit area; dimensions are shown in Fig. 1. The outer stream equivalency ratio, Φ_{out}, is fixed at 0.55, while the inner stream fuel is reduced till the flame blew out. The overall equivalence ratio, Φ_{OV}, is estimated based on the total fuel and airflow rates in both inner and outer streams which is given by:

$$\Phi_{OV} = \frac{\left(\frac{A}{F}\right)_{st,OV}}{\left(\frac{\dot{m}_{a,in}+\dot{m}_{a,out}}{\dot{m}_{f,in}+\dot{m}_{f,out}}\right)} \quad (2)$$

where $\left(\frac{A}{F}\right)_{st,OV}$ denotes the overall stoichiometric air-to-fuel ratio, $\dot{m}_{a,in}$ and $\dot{m}_{a,out}$ signify the inner and outer air mass flow rates, respectively, and $\dot{m}_{f,in}$ and $\dot{m}_{f,out}$ are the inner and outer fuel mass flow rates, respectively. A NIKON camera model D5100 with a resolution of 16.2 megapixels and a lens of 65 mm, f/10, 1/4 s shutter speed, and ISO = 640 was used to capture direct flame photos.

3. RESULTS AND DISCUSSION

The flame stability limits were investigated by operating the combustor with a premixed CH_4/air mixture in both streams until the thermal equilibrium of the chamber wall was reached. The inner stream fuel contains a CO_2 mole fraction, x_{CO_2}, which ranged from 0 (pure methane) to 0.4, with a maximum increase step of 0.1 (to account for a wide range of biogas composition). The inner stream equivalence ratio, Φ_{in}, is reduced by decreasing the inner stream fuel flow rate while maintaining the outer stream equivalence ratio, Φ_{out}, and CO_2 volume fraction, x_{CO_2}, in the inner stream fuel constant until the flame went out. The lean blowout limit is the smallest level of Φ_{in} required to maintain a stable flame. This approach is used with a set inner air velocity, $U_{a,in}$, of 5 m/s, a fixed outer mixture velocity, $U_{m,out}$, of 3.2 m/s, and Φ_{out} of 0.55 and 0.65. The flame blow-off points on the stability map are measured at least three times, and the standard deviation in the data is shown by the error bar on the plots.

Fig. 3 illustrates how the stability of biogas/methane/air-premixed flames fired by the double-swirl burner is affected by the fraction of CO_2 in the biogas and inner swirler angle θ_{in}. The stability diagram is constructed by varying the CO_2 mole fraction in the inner fuel blend, x_{CO_2}, from 0 to 0.4, and the inner stream equivalence ratio, Φ_{in}, for different values of the inner swirler angle, θ_{in}. The outer stream equivalence ratio, Φ_{out}, and the axial velocity at the inlet, $U_{a,in}$, are kept constant at 0.55 and 5 m/s, respectively. As shown in Fig. 4, the overall lean blow-off equivalence ratio, Φ_{ov}, which is defined as the ratio of the total fuel and air supplied to both streams, increases with x_{CO_2} for all values of θ_{in}. This implies that the flame becomes more prone to blow-off as the inner fuel is diluted with CO_2 and becomes leaner. This trend is consistent with our previous work [18], which reported that CO_2 addition shifts the lean blow-off limit of the inner stream to higher values of Φ_{in}.

The variation of the lean blow-off limit with x_{CO_2} is also influenced by the swirl angle, θ_{in}. For low θ_{in} (30° and 45°), the lean blow-off limit mildly raises at low levels of x_{CO_2} (≤ 0.2), but it rapidly increases at higher x_{CO_2}. This can be attributed to the adverse effects of CO_2 on biogas combustion, such as reducing the flame temperature and reaction rates [18]. In addition, CO_2 diminishes the flammability and laminar burning velocity of biogas/air mixtures [21], as well as their extinction strain rates [22], which deteriorate their stability. Increasing the content of CO_2 in CH_4/air mixtures has three main impacts on the flame stabilization: (i) it decreases the reaction rates, (ii) it alters the mixture stoichiometry, and (iii) it weakens the mixture's flammability. These impacts are manifested in Fig. 3 by the increase of the lean blowout equivalence ratio with CO_2. However, these impacts are insignificant for low CO_2 concentrations (x_{CO_2} ≤ 0.2), where the enhanced radiative heat transfer due to CO_2 may compensate for the reduction in laminar burning velocity by preheating the mixture upstream of the reaction zone [23]. This might explain why the lean stability limits are slightly expanded at low CO_2 concentrations. Moreover, increasing θ_{in} enhances the flame stretch rate, which also shifts the stability limits to higher values.

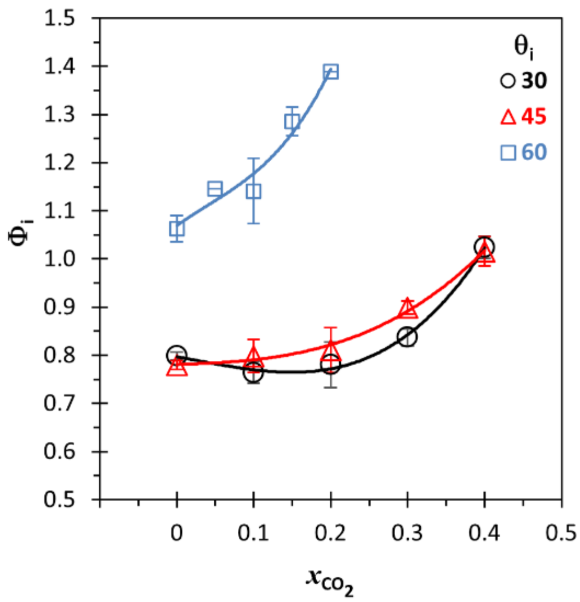

Fig. 3. The biogas-methane flame stability maps with different inner stream swirl angles, θ_{in} (x_{CO_2} versus Φ_{in} at Φ_{out} = 0.55).

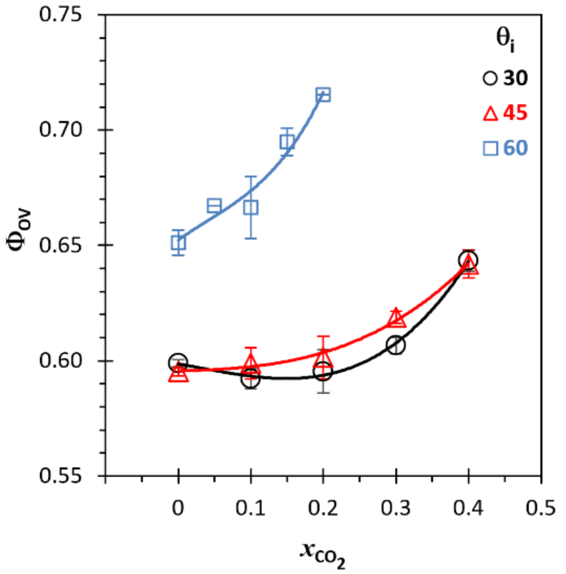

Fig. 4. The biogas-methane flame stability maps with different inner stream swirl angles, θ_{in} (x_{CO_2} versus Φ_{OV} at Φ_{out} = 0.55).

Biogas flame stability is a critical parameter for efficient combustion. The CO_2 content in biogas modifies the stability map, resulting in changes in the flame blow-off limit. Increasing the CO_2 fraction in the biogas increases both the inner stream lean blow-off limit and the overall flame blow-off equivalence ratio, making it harder for the flame to be sustained at lower equivalence ratios. However, sustaining flame stability can be achieved by increasing the outer stream equivalence ratio (Φ_{out}).

The effect of CO_2 fraction on flame blow-off limit can be explained by physical and chemical mechanisms. Physically, the existence of CO_2 in biogas reduces its heating value and reactivity, resulting in a lower flame temperature and increased burner size. This necessitates a longer residence time for efficient combustion. Chemically, CO_2 affects the kinetics of combustion reactions, particularly those involving radicals such as OH and H. CO_2 can act as a radical scavenger, while it is reducing the radical pool and slowing down the chain-branching reactions that sustain combustion [18].

Fig. 5 and Fig. 6 illustrate that increasing the CO_2 fraction in biogas shifts the flame blow-off limit curve to higher inner stream equivalence ratios, indicating that more fuel is required in the inner stream to maintain flame stability. Increasing the swirl angle of the inner stream likewise shifts the flame blow-off limit curve to higher inner stream equivalence ratios. On the other hand, increasing the outer equivalence ratio reduces both the inner and overall equivalence ratios, thereby supporting flame stabilization and requiring less fuel consumption in the inner stream. Additionally, reducing the inner swirler angle or increasing the outer equivalence ratio allows for the use of biogas in the inner stream with higher CO_2 percentages. These conclusions can contribute to the development of efficient and sustainable combustion systems.

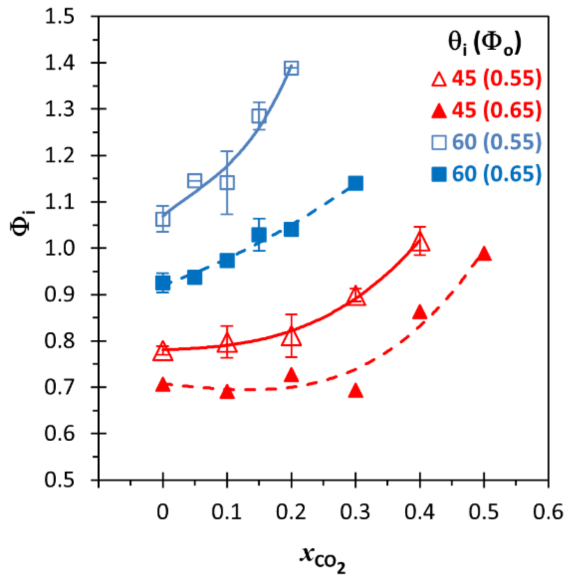

Fig. 5. The biogas-methane flame stability maps with different inner stream swirl angles, θ_{in}, and Φ_{out} (x_{CO_2} versus Φ_{in}).

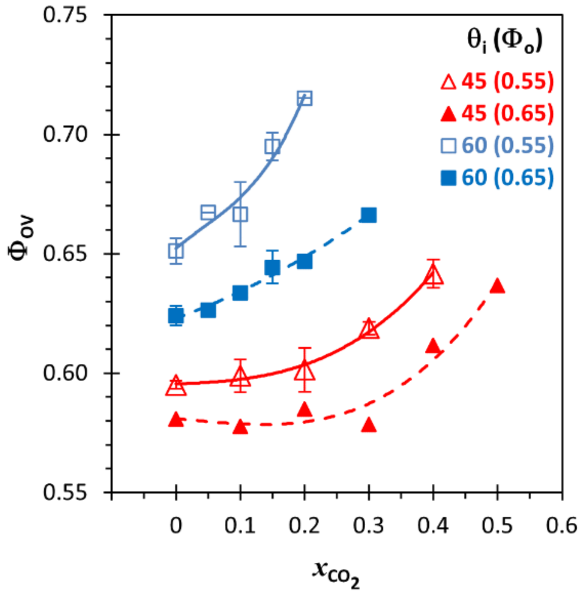

Fig. 6. The biogas-methane flame stability maps with different inner stream swirl angles, θ_{in}, and Φ_{out} (x_{CO_2} versus Φ_{OV}).

The flame morphology is influenced by the inner swirler angle, θ_{in}, which controls the degree of swirl and the axial velocity of the inner stream. A higher θ_{in} leads to a stronger swirl and a lower axial velocity, which affects the flame shape and stability.

Fig. 7 illustrates the direct broadband images of three flames with Φ_{in} = 1.1 and x_{CO_2} = 0.1, which are selected based on the performed flame stability map. These flames have a compact V-shape with sharp blue edges that are anchored to the inner swirling tube and expand downstream of the burner exit. The flames are attached to the burner exit and do not show any tendency to lift off, whilst indicating that the flow velocity is sufficiently low to allow the flame to stabilize. The flame front is visible along the shear layer and widens downstream as the flame interacts with the surrounding air. Additionally, a faint blue inner zone is observed in the center of the flame, which indicates the presence of an internal recirculation zone (IRZ) that provides heat and radicals to sustain the combustion. As θ_{in} increases, the flame height decreases and the flame width increases, as shown in Fig. 7. This can be explained as a higher θ_{in} enhances the swirl intensity and reduces the axial momentum of the inner stream, which leads to a shorter and wider IRZ. Furthermore, the flame front diverges as the inner rich stream mixes with the outer lean stream, which may reduce the flame stability due to excessive dilution by CO_2. This effect is more pronounced for higher θ_{in} values, as the inner stream has a lower axial velocity and a higher radial velocity, which facilitates the mixing with the outer stream.

These flame images are not quantitatively comparable, even though they were obtained at the same flow conditions. Also, these flames are stabilized by $\Phi_{in} \geqslant 1$, implying that the biogas in the inner stream mixture contributes significantly to the energy density of these flames. The changes in the flame morphology are similar to those reported by [12] for biogas flames in a single swirl burner, however the current flames are more stable compared to the single swirl flames. This may be attributed to the dual swirl configuration, which provides better control over the mixing and combustion processes.

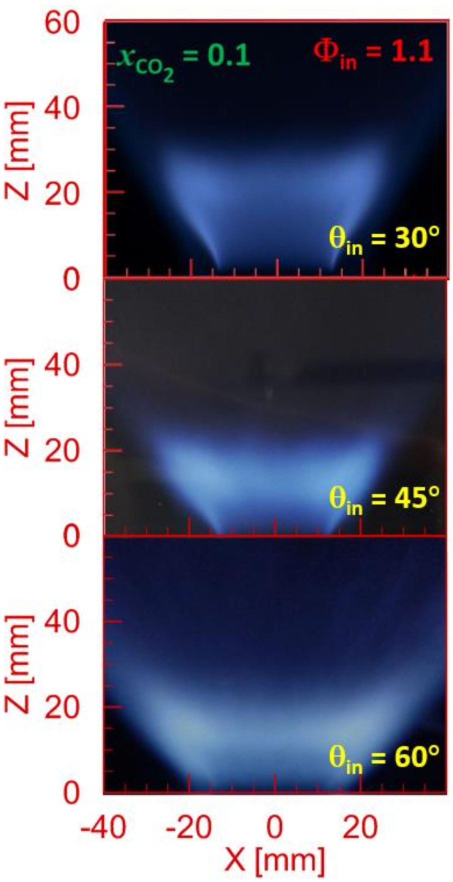

Fig. 7. Time-averaged broadband images show the changes with increasing θ_{in} at Φ_{in} = 1.1 and x_{CO_2} = 0.1.

4. CONCLUSION

The paper presents an experimental study on the effect of inner swirl angle on the flame stability of a double-swirl burner with biogas-methane co-firing. The results have demonstrated that the CO_2 fraction in biogas and the inner swirl angle have significant effects on the flame blow-off limit and morphology. The main conclusions from the study can be summarized in following points:

- Increasing the CO_2 fraction in the biogas has shifted the flame blow-off limit curve to higher inner stream equivalence ratios, making it harder for the flame to be sustained at lower equivalence ratios.
- Increasing the swirl angle of the inner stream also shifts the flame blow-off limit curve to higher inner stream equivalence ratios, but it has less impact than increasing the CO_2 fraction in biogas.
- Increasing the outer stream equivalence ratio supports flame stabilization and requires less fuel in the inner stream.
- The flame morphology is influenced by the inner swirler angle, with a higher angle which resulting in a shorter and wider internal recirculation zone and a wider flame front.

The outcomes of this study have important implications for the design and optimization of double-swirl burners for biogas-methane co-firing applications, as well for the understanding of the underlying physical and chemical mechanisms of biogas-methane co-firing.

However, this study has some limitations, such as the use of a constant outer stream swirl angle. While future work could explore different outer swirl angles, in addition to other parameters such as Reynolds number to further investigate the effect of inner swirl angle on the flame stability of a double-swirl burner with biogas-methane co-firing.

5. REFERENCES

[1] Atelge, M.R., Krisa, D., Kumar, G., Eskicioglu, C., Nguyen, D.D., Chang, S.W., Atabani, A.E., Al-Muhtaseb, A.H., and Unalan, S., Biogas Production from Organic Waste: Recent Progress and Perspectives, Waste and Biomass Valorization 11(3) (2018) 1019-1040.

[2] Tagne, R.F.T., Dong, X., Anagho, S.G., Kaiser, S., and Ulgiati, S., Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa, Environment, Development and Sustainability 23(10) (2021) 14799-14826.

[3] Golmakani, A., Ali Nabavi, S., Wadi, B., and Manovic, V., Advances, challenges, and perspectives of biogas cleaning, upgrading, and utilisation, Fuel 317 (2022).

[4] Kabeyi, M.J.B., Olanrewaju, O.A., and Messineo, A., Biogas Production and Applications in the Sustainable Energy Transition, Journal of Energy 2022 (2022) 1-43.

[5] Muvhiiwa, R., Hildebrandt, D., Chimwani, N., Ngubevana, L., and Matambo, T., The impact and challenges of sustainable biogas implementation: moving towards a bio-based economy, Energy, Sustainability and Society 7(1) (2017).

[6] IEA, World energy outlook 2022. 2022, IEA, Paris, France.

[7] Ahmadi Moghaddam, E., Ahlgren, S., Hulteberg, C., and Nordberg, Å., Energy balance and global warming potential of biogas-based fuels from a life cycle perspective, Fuel Processing Technology 132 (2015) 74-82.

[8] Pilloni, M. and Abu Hamed, T., Small-Size Biogas Technology Applications for Rural Areas in the

Context of Developing Countries, in Anaerobic Digestion in Built Environments. 2021.
[9] Suhartanto, T., York, A.P.E., Hanif, A., Al-Megren, H., and Green, M.L.H., Potential utilisation of Indonesia's Natuna natural gas field via methane dry reforming to synthesis gas, Catalysis Letters 71(1/2) (2001) 49-54.
[10] Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., and Cecinato, A., Environmental impact of biogas: A short review of current knowledge, J Environ Sci Health A Tox Hazard Subst Environ Eng 53(10) (2018) 899-906.
[11] Du, D., Axelbaum, R., and Law, C.K. The influence of carbon dioxide and oxygen as additives on soot formation in diffusion flames. in Symposium (international) on combustion. 1991. Elsevier.
[12] Aravind, S., Gohiya, R.K., Prakash, R.S., and Sadanandan, R., Effects of CO_2 dilution on partially premixed CH_4-air flames in swirl and bluff body stabilized combustor, Proceedings of the Combustion Institute 38(4) (2021) 5209-5217.
[13] Hoda, A., Rahman, T.M.R., Asrar, W., and Khan, S.A., A Comparative Study of Natural Gas and Biogas Combustion in A Swirling Flow Gas Turbine Combustor, Combustion Science and Technology 194(13) (2021) 2613-2640.
[14] Khudhair, R. and Jung, Y. Environmental and Economical Evaluation of Liquified Natural Gas Vehicles Promotion Program in The City of Baghdad. in Proceedings of the 8th International Exchange and Innovation Conference on Engineering & Sciences (IEICES 2022). 2022. Kyushu University, Fukuoka, Japan (Hybrid).
[15] Abdelhameed, E. and Tashima, H. An investigation on the behavior of the torch flame in the LBGE combustion process. in Proceedings of the 8th International Exchange and Innovation Conference on Engineering & Sciences (IEICES 2022). 2022. Kyushu University, Fukuoka, Japan (Hybrid).
[16] Tang, Z., Zhang, T., Luo, D., Wang, Y., Hu, Z., and Yang, R.T., Catalytic Combustion of Methane: From Mechanism and Materials Properties to Catalytic Performance, ACS Catalysis 12(21) (2022) 13457-13474.
[17] Khan, F., Elbaz, A.M., Saxena, S., Mannaa, O., and Roberts, W.L., Effect of CO2 Dilution on Methane/Air Flames at Elevated Pressures: An Experimental and Modeling Study, Energy & Fuels 35(3) (2021) 2639-2653.
[18] Abdulnaim, A., Elkholy, A., Elmously, M., Moneib, H., Roberts, W.L., and Elbaz, A.M., On the Stability and Characteristics of Biogas/Methane/Air Flames Fired by a Double Swirl Burner, Flow, Turbulence and Combustion (2023).
[19] Elbaz, A.M., Albalawi, A.M., Wang, S., and Roberts, W.L., Stability and characteristics of NH3/CH4/air flames in a combustor fired by a double swirl stabilized burner, Proceedings of the Combustion Institute 39(4) (2023) 4205-4213.
[20] Beér, J. and Chigier, N., Combustion aerodynamics, 2 ed.: Malabar, Florida: Krieger. 1983.
[21] Pizzuti, L., Martins, C.A., and Lacava, P.T., Laminar burning velocity and flammability limits in biogas: A literature review, Renewable and Sustainable Energy Reviews 62 (2016) 856-865.
[22] Qin, W., Egolfopoulos, F.N., and Tsotsis, T.T., Fundamental and environmental aspects of landfill gas utilization for power generation, Chemical Engineering Journal 82(1-3) (2001) 157-172.
[23] Williams, T.C., Shaddix, C.R., and Schefer, R.W., Effect of Syngas Composition and CO2-Diluted Oxygen on Performance of a Premixed Swirl-Stabilized Combustor, Combustion Science and Technology 180(1) (2007) 64-88.