

Experimental investigation on biogas flame stability in laboratory coaxial burners and gas stoves

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1 Introduction

The rise of the world population led to the increase of fossil fuels consumption and greenhouse gas emissions, responsible for climate change. In this perspective, the search of alternative fuels is crucial to prevent natural disasters. Biogas, the product of anaerobic digestion of biomass, is a renewable gas and a promising solution for replacing natural gas since it is composed of around 50-70% of CH₄. Biogas combustion is prone to instabilities, such as blow-off and flashback phenomena, under certain conditions influenced by fuel blend properties, dilution with CO₂ for instance [1]. These instabilities can lead to significant system damage, emphasizing the need for a thorough investigation of combustion properties, including flame characteristics, reaction dynamics, and efficiency. In the literature, some studies were interested in biogas combustion throughout different aspects. Dai et al. [2] studied biogas flame stability of blends up to 45% of CO₂ and highlighted the phenomenon of blow-off, yellow tipping and flame lifting. A comprehensive literature review conducted by Gao et al. [3] examines innovative technologies, such as Sideway Faced Porous Radiant Burners (SFPRBs) and swirling flow burners, which demonstrate exceptional efficacy in biogas utilization. The study highlights the critical role of structural optimizations, including advancements in burner design and the incorporation of swirl flows, in enhancing air-fuel mixing, heat transfer, and combustion stability. Furthermore, these advanced stove designs are reported to significantly reduce emissions, including carbon monoxide (CO) and nitrogen oxides (NO_x), by effectively controlling flame temperatures and promoting complete combustion. Jiao et al. [4] investigated a fully premixed, water-cooled biogas burner aimed at addressing challenges such as unstable combustion, inconsistent flame output, and low thermal intensity. Their experimental and numerical analyses revealed stable operation within CO₂ concentration ranges of 25–45% and excess air coefficients of 1.15–1.3. Higher CO₂ levels were found to reduce flammability and NO_x emissions, while increasing the excess air coefficients further minimized pollutant outputs. Abdulnaim et al. [5] conducted a detailed investigation into the combustion stability, thermal

structure, and emission profiles of biogas–methane–air flames in a double-swirl burner. The study found that elevated CO₂ concentrations reduced flame reactivity and stability, necessitating larger burners to accommodate longer flame lengths and extended residence times. However, the distributed heat release and the chemical effects of CO₂ facilitated ultra-low NO_x emissions. Ghabi et al. [6] investigated the potential of microsecond pulsed plasma (MPP) technology to enhance the stability, combustion efficiency, and emissions of biogas flames. While MPP slightly increased NO_x emissions due to elevated flame temperatures, it significantly reduced CO emissions by promoting more complete combustion. Overall, their research highlighted the strong potential of MPP for stabilizing biogas flames and optimizing combustion processes. Elhawary et al. [7] investigated the effect of nitrogen oxides (NO) on biogas combustion, focusing on flame stability, combustion characteristics, and emissions. Their research demonstrated that NO significantly increased the laminar burning velocity (LBV) of biogas, particularly in lean and stoichiometric mixtures, thereby counteracting the diluting effect of CO₂. These findings emphasize the importance of nitrogen oxides in enhancing the combustion dynamics of biogas flames. The present study presents an experimental investigation into biogas combustion stability using different burners and biogas blends. Two types of burners are used: a simple laboratory burner with a coaxial configuration and a biogas stove recently developed in Asia. The objective is to analyze flame behavior with different biogas mixtures and determine the possible operating range of these burners.

2 Experimental setup

Figure 1 show the experimental and the laboratory burner used in this work. The combustion system comprises a gas supply panel integrating all necessary connections for CH₄, CO₂, and air, alongside burners and a combustion chamber. The laboratory burner used for the experiments is placed in the bottom center of the chamber and designed to allow a vertical development of the flame. It is a coaxial burner consisting of three tubes, only two of which are operational in this study. These are coaxial jet burners, featuring a central fuel jet and an annular air jet. Two laboratory burners with different size of nozzles are used. For the first one (N°1), the inner diameter of the central tube is 4 mm, while for the second one (N°2), it is 6 mm. The second tube has an inner diameter of 10 mm for burner N°1 and 15 mm for burner N°2, with an outer diameter of 40 mm for both burners. A commercial biogas stove (Figure 2) is composed of nine burners with eight identical burners arranged in circle and a burner placed in the center of the circle with a different geometry. The stove is made of stainless steel and its maximum heat power is 3.25 kW. Each peripheral burner is composed of 8 holes with an inner diameter of 3 mm. Table 1 summarizes the flowrates of gases for some experiments. To examine the effect of biogas mixture on the combustion of biogas in coaxial laboratory burners, CO₂ concentration is varied in a range between 0 to 50% in the blend with a constant flame power (450W). As for the biogas stove, the variation of CO₂ concentration reached 70% of the blend with a constant flame power (1kW). ICCD PI-MAX 2 camera equipped with a UV Nikkor 105nm f/4.5s and wavelength-specific filters is used for chemiluminescence imaging characterizing the flame front. Images acquisition and data display and storage are managed by the software Winview. OH* is imaged to detect the flame front and height throughout a bandpass filter centered at 310nm with full width half maximum of 5nm. Canon EOS 77D camera, with an EFS 18-55mm lens and exposure time of 1/8s, was used to take direct photographs of the flame which will be compared with OH* images. To analyze exhaust gas pollutants and temperature, KIGAZ 500 and HORIBA PG250 analyzers are used.

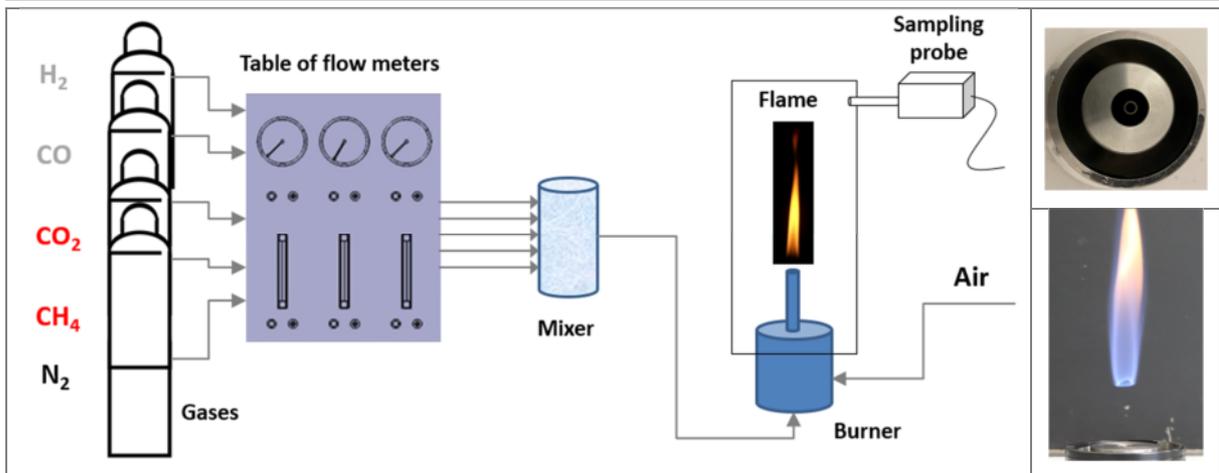


Figure 1: Experimental setup (left), burner laboratory (right top), example of flame (right bottom)



Figure 2: Commercial biogas stove, without flame (right), with flame (center) and one burner (right)

Table 1: Flowrates of gases for the laboratory burners “LB” (N°1, $\varnothing=4$ mm) and N°2, $\varnothing=6$ mm) and the biogas stove “SB”

%CO ₂	Q _{air} (l/min)		Q _{CH₄} (l/min)		Q _{CO₂} (l/min)	
	LB	BS	LB	BS	LB	BS
0	1,8	16,87	0,79	1,77	0	0
10	2	22,01	0,88	2,31	0,1	0,26
20	2,3	28,47	1,01	2,99	0,25	0,75
30	2,6	36,75	1,15	3,85	0,49	1,63
40	3	47,8	1,32	5,01	0,88	3,34
50	3,5	63,25	1,54	6,63	1,54	6,63
60	-	86,45	-	9,07	-	13,6
70	-	125,1	-	13,12	-	30,61

4 Results and discussion

The same experiment was conducted for both lab burners: CO₂ concentration was varied from 0 to 50% while the flame power and global equivalence ratio remained constant at 0.45kW and 4.2, respectively. Figure 3 summarizes the results of chemiluminescence of OH* for the burner N°1 with varied CO₂ concentration in the blend up to 35%, with a step of 5%. The results show that the CO₂ addition affects the flame behavior, especially in stabilization point and flame intensity. The images show that the lift-off height (H_{LO}) increases when the concentration of

CO₂ increases in the mixture. Beyond 35% of CO₂, the flame is blow out. With CO₂ addition, the laminar burning velocity and flame temperature decrease, which leads to the flame being moved away from the burner. When CO₂ fraction becomes high (>20%), the flame fluctuates a lot and blow off for 40% CO₂. This trend indicates that the higher presence of CO₂ can destabilize the flame and inhibits the combustion process. This is due to the dilution effect of the CO₂ that lowers the propagation speed and leads to a mismatch between the flame and the flow velocity. To broaden the range of CO₂ usage in the mixture, the laboratory burner N^o2 with an increased fuel tube diameter is used. From the OH* images, the liftoff height of flame is determined via image processing. Figure 4 shows the evolution of the liftoff height as a function of the CO₂ concentration of in the blend for the two laboratory burners.

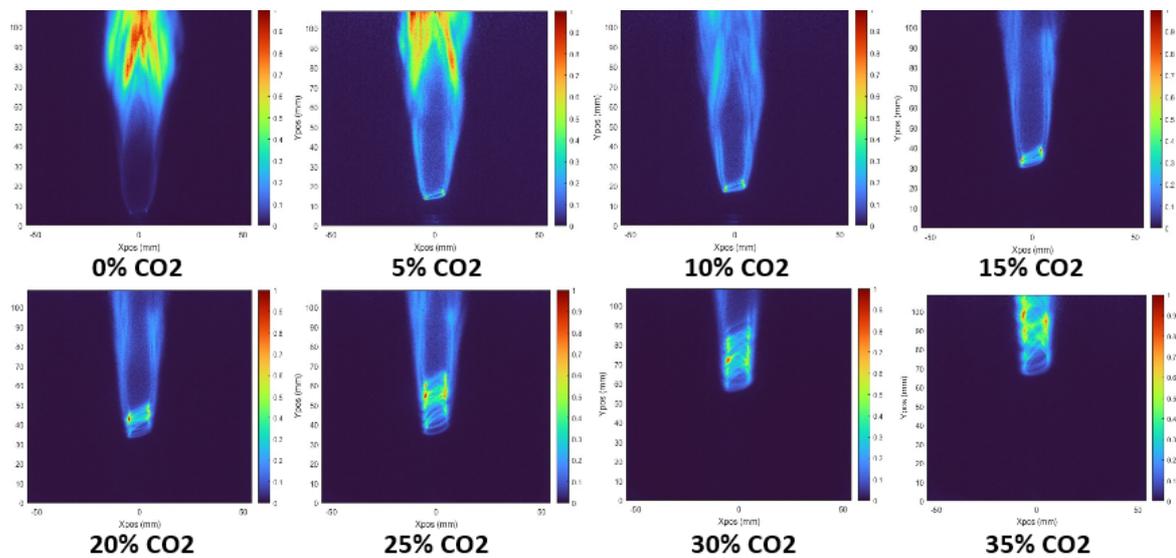


Figure 3: OH* chemiluminescence images with % CO₂ for laboratory burner N^o1 (Ø=4 mm).

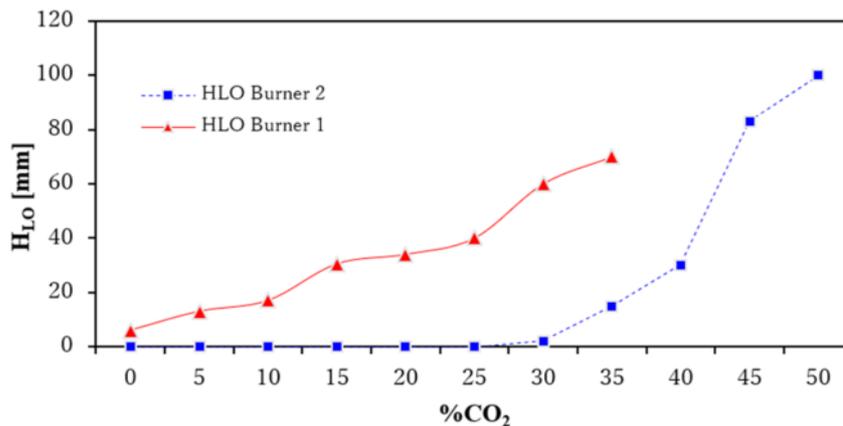


Figure 4: Lift-off height of flame with CO₂ for both lab burners N^o1 (Ø=4) et N^o2 (Ø=6 mm).

When the concentration of CO₂ in the blend increases, the lift-off height increases for both burners. In fact, H_{LO} increases from 5 mm to 70 mm between 0 and 35% of CO₂ for the burner N^o 1 for example. In comparison of the two injectors, it is observed that the flame started to lift off for the burner N^o2 from 30% of CO₂ while the lift-off started at 5% CO₂ for the burner N^o1. Therefore, the flame is more stable for the burner with the wider diameter. Actually, a higher

diameter reduces the flow velocity of the biogas mixture. This lower velocity helps match the flame speed, which is already reduced due to the high concentration of CO_2 , thereby preventing blow-off and enhancing stability. Two experimental approaches were employed to investigate the biogas combustion in biogas stove (with 0 to 70% of CO_2). In first set of experiments, the flame power was maintained constant with $P=1\text{kW}$. In the second set, the fuel flow was held constant with $Q_{\text{fuel}}=5,31\text{ L/min}$. Experiment conditions were held in atmospheric pressure and ambient temperature. In the current paper, only the results of the first approach are presented. The results of constant flow will be involved the extended paper for journal publication. Figure 5 illustrates the effect of the CO_2 fraction (0–60%) on the flame for a constant power of 1 kW. The top images are captured through direct photography, while the bottom images represent the mean chemiluminescence from the OH^* signal. These images were taken from a single burner in the biogas stove shown in Figure 2.

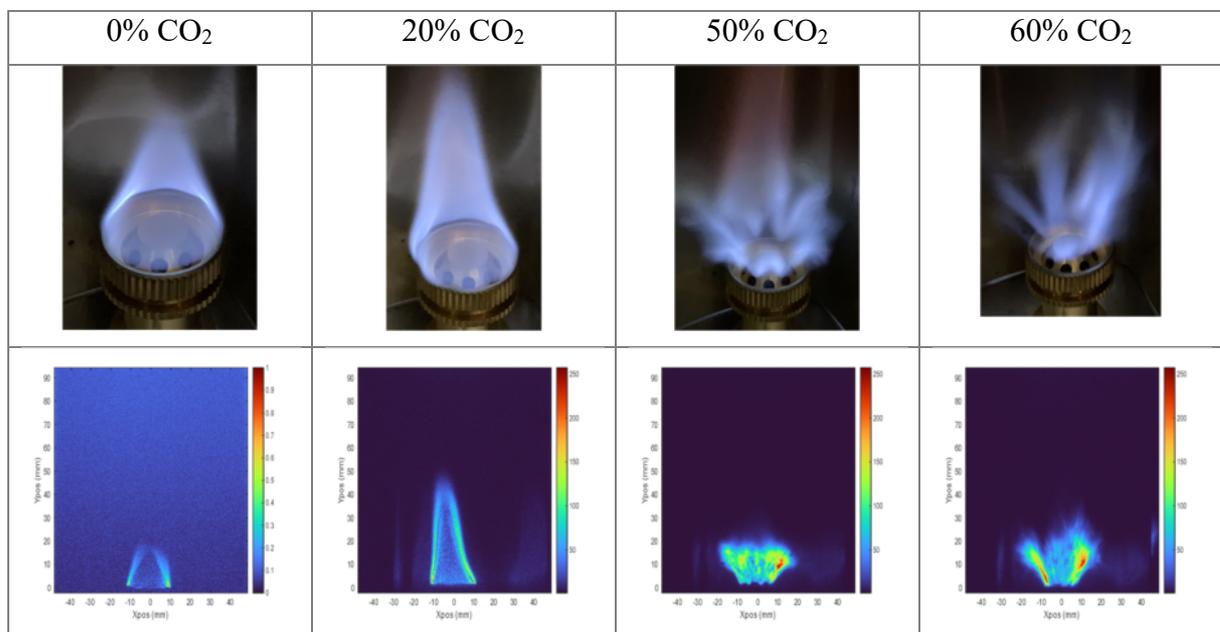


Figure 5: Real photos and OH^* chemiluminescence images with % CO_2 variation and a constant flame power ($P=1\text{kW}$) using biogas stove.

The results indicate the higher effects of CO_2 addition to methane on the flame shape and stability. An increase in CO_2 concentration (from 0 to 30%) is associated with an elongation of the flame height. At 40% of CO_2 , the flame stops in height and starts to open radially under the effect of the CO_2 dilution. At higher concentrations starting at 50% of CO_2 , significant transformations are observed. The flame shape transitions from an ellipsoidal structure to a distinct "flower-shaped" configuration. This shift is accompanied by a pronounced decrease in flame height and a marked increase in OH^* chemiluminescence intensity. Additionally, flame lift-off starts to appear as it's shown in the real photographs, signaling the onset of instability in the flame dynamics. Reaching 60% of CO_2 in the blend, the liftoff is accentuated and flame extinction was observed in some of the eight burners. At 70% of CO_2 , the flame has disappeared completely from the stove burners. These results demonstrates that this burner can operate from 0 to 50% of CO_2 . We conducted an analysis of the combustion gases; however, the results were inconclusive due to high dilution with ambient air. Therefore, these results are not included in this abstract.

5 Conclusion

In the present work, the effect of CO₂ concentration on biogas combustion was investigated using two different laboratory burners and a biogas stove. The experimental study involved varying the CO₂ concentration in the blend up to 35% for the laboratory burners and up to 70% for the biogas stove while observing the flame behavior during combustion. OH* chemiluminescence images were captured to detect the flame front and measure the lift-off height. The results demonstrate the significant impact of biogas composition on combustion for both the laboratory burner and the biogas stove. At higher CO₂ dilution levels (from 50%), the biogas flame becomes highly fluctuating and unstable. Beyond 65% CO₂, the flame in the biogas stove is completely blown off. This is due to the dilution effect of CO₂, which lowers the flame velocity and temperature, thereby reducing the flame stability domain. It is noted that decreasing the injection velocity by reducing the jet diameter can extend the flame stability domain, as observed in the laboratory burner.

Acknowledgments

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