# A Comparative Study of Biogas/Air Flames Characteristics for Different Bluff-Body Burner Configurations

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https://doi.org/10.5109/7323338

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.700-706, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences
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# A Comparative Study of Biogas/Air Flames Characteristics for Different Bluff-Body Burner Configurations

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**Abstract:** *This study investigates the biogas/air bluff-body stabilized flames, focusing on the effects of different burner configurations on combustion characteristics. The configurations include bluff-body angles of 30°, 45°, 60°, and 90°, with positions adjusted upstream and downstream of the burner exit. The experimental setup involves a biogas mixture with varying $CO_2$ percentages, maintaining a constant thermal input. Results demonstrate that increasing $CO_2$ up to 10% enhances flame temperature and emissions, while higher concentrations reduce flame reactivity. The flat bluff-body (90°) produces the highest exhaust temperature due to its longer flame length, while the 60° angle results in lower temperatures with a wider, shorter flame. CO emissions decrease as the bluff-body moves upstream or downstream, correlating with higher temperatures, while NO emissions increase. Additionally, NO concentrations decrease with rising $CO_2$ percentages due to the dilution effect. These findings provide valuable insights for optimizing biogas bluff-body burners, contributing to more sustainable energy solutions.*

**Keywords:** Bluff-Body Burner; Biogas; $CO_2$ Dilution; Combustion Characteristics; Emissions.

## 1. INTRODUCTION

The extensive use of fossil fuels in power generation leads to environmental pollution and the depletion of traditional energy resources, necessitating a transition to alternative, cleaner energy sources. Biogas is anticipated to play a crucial role in the future energy mix as it represents a sustainable and biodegradable alternative to fossil fuels [1]. Produced from agricultural, animal, and urban waste, biogas is a viable energy source primarily composed of approximately 55% methane ($CH_4$) and 45% carbon dioxide ($CO_2$), with trace amounts of nitrogen ($N_2$), hydrogen ($H_2$), carbon monoxide (CO), and sulfur compounds. The composition of biogas varies depending on its source. For instance, biogas generated from digesters processing organic waste typically contains 60%–70% $CH_4$ and 30%–40% $CO_2$, whereas biogas from landfills often comprises 45%–62% $CH_4$ and 24%–50% $CO_2$ [2], [3]. Despite its advantages, the variable composition of biogas due to different feedstocks and fermentation processes presents significant challenges for its use in combustion systems [4]. Another challenge lies in optimizing combustion systems to minimize emissions of pollutants, such as carbon monoxide (CO) and nitrogen oxides ($NO_X$), which can result from incomplete or excessive combustion [5]. Therefore, it is crucial to regulate and improve combustion systems for the efficient and environmentally friendly utilization of novel fuels [6].

Biogas has numerous applications across various industries, including energy production, vehicle fuel, and heating [7]. It serves as an alternative to natural gas (NG), which contributes to climate change through the emission of greenhouse gases [8]. By capturing and utilizing methane that would otherwise be released into the atmosphere, biogas plays a significant role in mitigating global warming. Methane's global warming potential is significantly higher than that of $CO_2$, making its capture and use particularly advantageous for climate change mitigation [1], [9]. Additionally, biogas offers several benefits for rural development, such as improved waste management, fertilizer production, and revenue generation.

The combustion of biogas presents significant challenges due to its high $CO_2$ content, which results in a lower heating value and decreased flame stability compared to natural gas (NG) [1], [10]. The effects of $CO_2$ dilution on the combustion of hydrocarbon fuels in both premixed and non-premixed flames have been studied extensively [11], [12]. $CO_2$ dilution impacts combustion in four primary ways: (1) reducing the concentration of reactive species, (2) lowering the flame temperature, (3) decreasing radiative heat transfer from hot gases, and (4) affecting chemical kinetics. These changes influence the flame by altering conditions such as flame structure, flame speed, and flame temperature, as well as pollutant emissions.

In premixed flames, where biogas and air are homogeneously mixed, the presence of $CO_2$ significantly extends the ignition delay and reduces the burning velocity [11]. For turbulent non-premixed jet flames, increasing $CO_2$ dilution results in a lower flame velocity and an increased flame liftoff height [13] . While biogas combustion can reduce $NO_X$ emissions, it may lead to higher levels of CO and unburned hydrocarbons (UHC), depending on the specific operating conditions. Despite these challenges, biogas has the potential to serve as an alternative fuel in combustion systems if the increased CO emissions can be mitigated [14].

In recent years, bluff-body stabilized turbulent jet non-premixed flames have garnered significant attention due to their wide range of applications, including industrial furnaces, afterburners, and gas turbine combustors [15] . The bluff-body flame holder offers several advantages, such as enhanced fuel-air mixing, improved combustion product mixing, and easier control over the combustion process. During flame stabilization, the hot gas recirculation behind the bluff-body aids in reigniting gas mixtures, thus stabilizing the flame [16] . Additionally, the extended residence time downstream of the bluff-body further contributes to flame stability through other mechanisms. Bluff bodies have been effectively used to enhance heat transfer and reduce flame length in gas turbines and steam boilers [17]. Due to these benefits, bluff-body flame stabilization is the preferred method for both premixed and non-premixed flames. Moreover, a central fuel jet, often positioned along the axis of an annular channel, passes through the center of the bluff-body to stabilize a non-premixed flame.

The geometry of bluff-body burners can be modified by adjusting the bluff-body's shape, position, and blockage ratio. Most studies have experimentally examined the combustion characteristics of burners with bluff-body geometries concerning premixed and non-premixed flames [18], [19]. Our focus was on non-premixed flames due to their inherent combustion safety benefits, such as flashback tolerance, operational versatility, and widespread use in residential and industrial applications. Yang et al. [20] investigated the impacts of blockage ratio on flame stability and patterns, indicating that increasing the ratio shifts the major response region upstream to the recirculation zone's interior side. Furthermore, Esquiva et al. [21] found that a tulip-shaped bluff-body stabilizes the flame more effectively than a disk-shaped one when examining different bluff-body shapes. Kumar and Mishra [22] analyzed the influences of disk-shaped bluff-body size on LPG-$H_2$ jet diffusion flames, demonstrating that increasing the bluff-body's diameter reduced the flame length by enhancing reactant mixing and causing the reaction region to spread across the bluff-body.

Previous investigations have thoroughly examined the effects of bluff-body shape and position on flame instabilities and structure. Tong et al. [23] conducted experimental and computational studies on methane/air diffusion flames, revealing the formation of outer and inner recirculation regions and shear layers downstream of a disk-shaped bluff-body. They found that optimal flame stabilization occurs when the bluff-body is positioned above the annular stream exit. In another study, Tong et al. [24] experimented with stable and unstable methane-air non-premixed flames using a conical bluff-body across various Reynolds numbers, identifying three unstable behaviors—lift-off, split, and split-flashing—at high fuel Reynolds numbers. Yen et al. [25] recommended employing a rifled cone in the central fuel stream and a disc-bluff-body to enhance turbulence strength in non-premixed flames. Their results showed that increased firing numbers elevated the maximum temperature while reducing NO concentration. Alfazazi et al. [26]investigated the combustion characteristics of ammonia-hydrogen non-premixed bluff-body-stabilized flames. Their findings indicated that reducing the $NH_3$ ratio produces longer, more stable flames with decreased thermal radiation, whereas higher $NH_3$ levels in the fuel mixture led to reduce NO emissions.

A review of the literature reveals a significant gap in the understanding of non-premixed flame characteristics in bluff-body burners operating with biogas fuel. This paper aims to address this gap by investigating the effects of the bluff-body's shape and position—whether above, below, or at the same height as the annular stream exit—on the biogas jet diffusion flame from the bluff-body burner, maintaining a constant thermal input. The study seeks to provide insights into the optimal utilization of bluff-body burners for biogas applications and to enhance the understanding of the chemical and physical processes involved in such flames. The research will include visual imaging, as well as measurements of exhaust temperature and emissions for biogas flames, to examine flame structure. The findings will advance the understanding of biogas as a viable alternative fuel, contributing to the development of more sustainable energy solutions.

## 2. EXPERIMENTAL APPROACH

### 2.1 Bluff-body burner and experimental setup.

Fig. 1 illustrates the details of the bluff-body burner assembly utilized in this study. The burner features an annular channel with bluff-body angles of 30°, 45°, 60°, and 90° located at the center, as specified in Fig. 2. The bluff-body has a central pipe (jet) diameter of 5 mm and an outer diameter of 24 mm (fixed blockage ration), both of which are removable and adjustable. Fuel is introduced through the central pipe, while airflow is directed into the surrounding annular channel. This channel is equipped with a 15° converging quarl, featuring a 33 mm internal diameter at the exit, designed to create a strong recirculation zone to enhance flame stability.

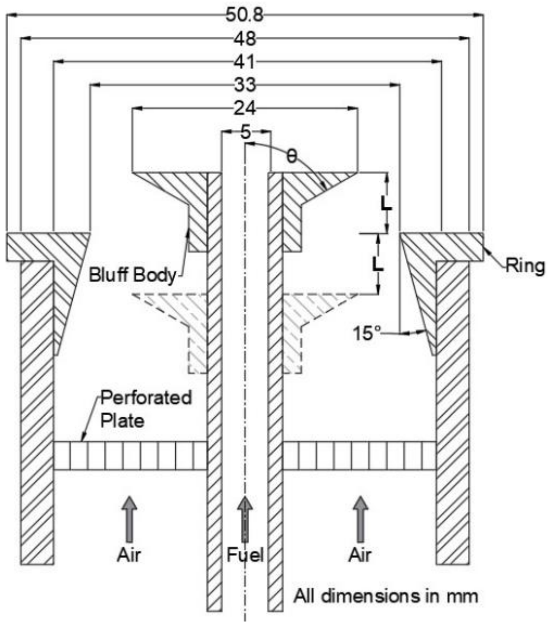



Fig. 1. Bluff-body burner assembly.

The distance from the upper surface of the bluff-body upstream and downstream of the annular airflow channel exit, denoted as L mm, is also depicted in Fig. 1. The burner configurations vary with the parameter L, with values of 0, 5, 10, and 15 mm. At L = 0, the upper surface of the bluff-body aligns with the annular airflow channel exit. At L = 5, 10, and 15 mm, the upper surface of the bluff-body is positioned either above or below the annular airflow channel exit. To simplify the presentation, locations outside the burner are designated with positive L values, whereas locations inside the burner are assigned negative L values. Additionally, as shown in Fig.

1, a perforated plate is inserted into the annular airflow channel to ensure a consistent annular airflow before it exits the channel.

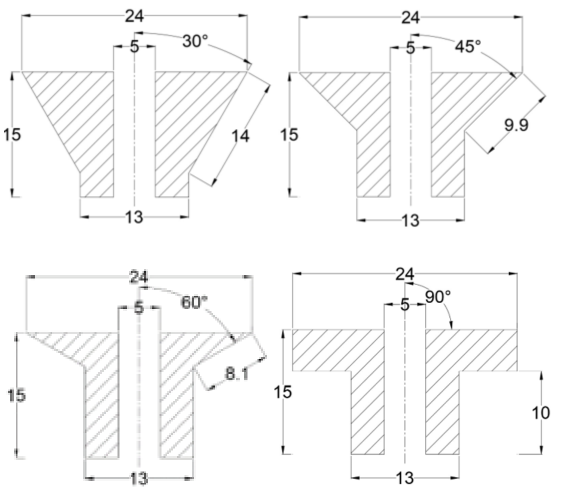


Fig. 2. The four bluff-body design (dimensions in mm).

The experimental setup is depicted schematically in Fig. 3. The experiments were conducted using biogas as fuel, with its composition (i.e., $CO_2/CH_4$ blend) represented by varying the $CO_2$ fractions (%$CO_2$) in the central stream. The flow rates of $CO_2$, $CH_4$, and air were regulated by needle valves and metered using SIARGO digital mass flow meters, models MF5706 and MF5712, with an accuracy of ± (2+0.5FS)%. All flames were contained within a rectangular combustor measuring 300 mm by 300 mm by 500 mm, as shown in Fig. 3. The combustor's side walls were fitted with rectangular quartz glass windows to allow optical access.

A high-resolution digital camera (NIKON D5100, with a resolution of 16.2 megapixels and a 65 mm lens) was used to capture detailed visual images. The camera settings were configured to f/10, 1/4 shutter speed, and 640 ISO. Exhaust temperatures were measured downstream of the flame at the combustor chimney using an uncoated type S thermocouple (platinum/platinum 10% rhodium). The use of small thermocouple wires (125µm) resulted in a 2~3% radiation loss, consistent with the repeatability inaccuracy, thus negating the need for radiation adjustment. Exhaust flue gases were analyzed using a LANCOM gas analyzer model 6500, which measures $O_2$, CO, and NO concentrations.

## 2.2 Experimental Program

The investigation program is divided into two distinct stages: investigating the effect of bluff-body angle (θ) and position (L). Table 1 presents a comprehensive overview of the details for each stage. Throughout the investigation, the air flow rate was maintained at a constant 70 SLPM, and the methane flow rate remained steady at 6.5 SLPM. $CO_2$ was introduced as a percentage of methane (%$CO_2$ = 0 to 0.3), with the methane flow rate kept constant.

Table 1. Details of test cases in the investigation program.

| Run Group | %$CO_2$ [-] | θ (°) | L (mm) |
|---|---|---|---|
| I | 0:0.3 | 30°, 45°, 60°, Flat | 0 |
| II | 0:0.3 | 60° | −15:+15 |

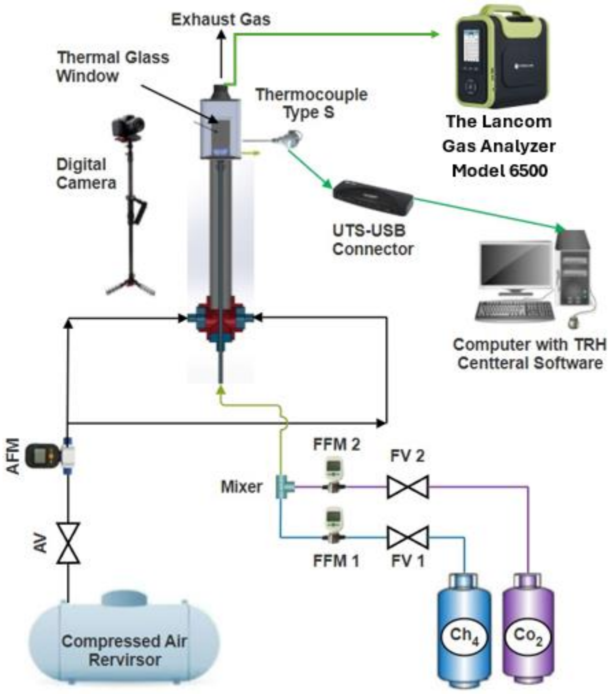


Fig. 3.The schematic diagram of the experimental setup.

## 3. RESULTS AND DISCUSSION

### 3.1 Visual Flame Structure

Figure 4 illustrates the impact of %$CO_2$ on the flame's apparent structure at θ = 60° and L = 0mm. It is evident that increasing %$CO_2$ results in a shorter and narrower flame. Additionally, the flame luminosity decreases as %$CO_2$ increases. The higher thermal capacity of carbon dioxide introduces a preheating effect, which enhances the burning velocity. This increase in burning velocity subsequently reduces the flame dimensions and luminosity due to higher soot oxidation rates.


%$CO_2$ = **0.0** **0.1** **0.2** **0.3**

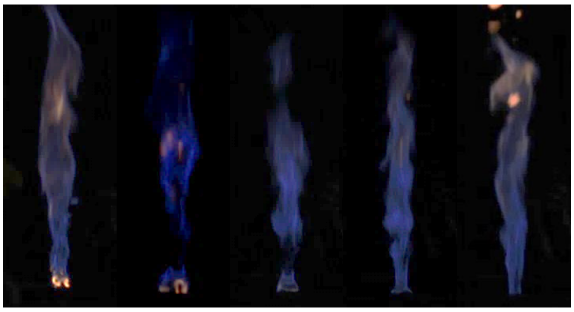
Fig. 4. Change in apparent flame structure with increasing %$CO_2$ at θ = 60° and L = 0mm.

Figure 5 depicts the effect of θ on the flame's apparent structure at %$CO_2$ = 0.3 and L = 0mm. The figure indicates a minor influence of θ on flame dimensions. However, the bluff-body with θ = 60° produces a relatively wider and smaller flame, suggesting improved air-fuel mixing. This enhanced mixing is reflected in the lower luminosity due to increased soot oxidation rates. Conversely, the flat bluff-body (90°) exhibits a noticeable soot ring at the burner exit due to the intense air flow deflection, which also results in a longer flame length.

θ = 30° 45° 60° Flat (90°)

Fig. 5. Change in apparent flame structure with increasing θ at $\%CO_2 = 0.3$ and L = 0mm.

Figure 6 shows the effect of L on the flame's apparent structure at $\%CO_2 = 0.3$ and θ = 60°. Adjusting the bluff-body position influences the early flame region, specifically the flame neck. As the bluff-body is moved upstream within the burner, the flame neck diminishes and the recirculation zone behind the bluff-body becomes immersed inside the burner. Furthermore, the soot ring observed at the beginning of the flame disappears as the bluff-body position is lowered, transitioning the flame from a diffusion to a partially premixed combustion mode.



L = +15 +5 0 -5 -15

Fig. 6. Change in apparent flame structure with decreasing L at $\%CO_2 = 0.3$ and θ = 60°.

### 3.2 Exhaust Temperature

Figure 7 illustrates the effect of $CO_2$ percentage ($\%CO_2$) on the exhaust gas temperature at various bluff-body angles (θ) with L = 0mm. The data reveals that the exhaust gas temperature increases with $\%CO_2$ up to 10%, after which it declines with higher $CO_2$ percentages. This behavior can be explained by the dual role of $CO_2$, encompassing both physical and chemical effects, as noted in our previous research [6]. The physical effect, characterized by the high thermal capacity of $CO_2$, is prominent at lower $CO_2$ levels (up to ~15%), while the chemical effect, which reduces the mixture's reactivity, becomes dominant at higher $CO_2$ percentages. Concerning the influence of the bluff-body angle (θ), the flat bluff-body (90°) results in the highest exhaust temperature due to its longer flame length. In contrast, the 60° angle produces a lower exhaust temperature because it generates a wider and shorter flame.

These findings highlight the intricate balance between $CO_2$ percentage and bluff-body geometry in determining combustion efficiency and temperature profiles. At lower $CO_2$ percentages, the thermal capacity of $CO_2$ enhances the flame's stability and temperature by redistributing heat within the combustion zone. This leads to more complete combustion and higher exhaust temperatures. However, as $CO_2$ percentage increases beyond 10-15%, its chemical effects become more pronounced, inhibiting reaction rates and resulting in a decrease in exhaust gas temperature. This transition underscores the importance of optimizing $CO_2$ levels to maintain efficient combustion processes.

The impact of bluff-body angle on flame characteristics further explains the role of geometric factors in combustion dynamics. A flat bluff-body (90°) extends the flame length, facilitating prolonged heat release and higher exhaust temperatures. Conversely, a 60° bluff-body angle produces a wider and shorter flame, leading to lower exhaust temperatures due to quicker heat dissipation and reduced residence time for combustion reactions. This geometric influence on flame structure is critical for designing burners that balance temperature control and combustion efficiency.

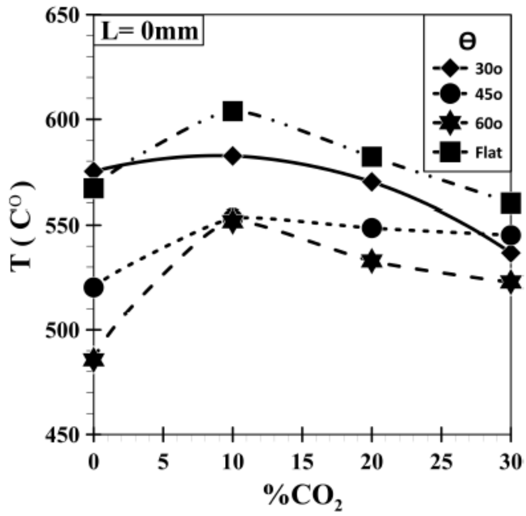



Fig. 7. The effect of $\%CO_2$ on the exhaust gas temperature at different θ and L = 0mm.

Figure 8 depicts the impact of the bluff-body position (L) on exhaust gas temperature at varying $CO_2$ percentages ($\%CO_2$) with a bluff-body angle (θ) of 60°. The W-shaped trend observed in all curves indicates two distinct combustion modes influenced by the bluff-body position. The first mode, diffusion combustion, extends from the bluff-body location at the burner rim (L = 0 mm) to L = +15 mm (outside the burner). The second mode, premixed combustion, ranges from the bluff-body position at $L < 0$ mm to $L = -15$ mm (inside the burner). The effect of $\%CO_2$ on exhaust gas temperature is notably different for each combustion mode, depending on whether the bluff-body is located inside or outside the burner. In the diffusion combustion mode ($L \geq 0$ mm), exhaust gas temperatures initially increase with $\%CO_2$ of 10% and 20%, followed by a decrease at 30% $CO_2$. Conversely, in the premixed combustion mode ($L < 0$ mm), a similar effect is observed near the burner rim (at $L = -5$ mm), where temperatures rise with 10% and 20% $CO_2$. However, this trend reverses as the combustion transitions to partial (L = −10 mm) and then fully premixed (L = −15 mm) modes.

The observed increase in exhaust gas temperature with low $CO_2$ levels (10% and 20%) in both combustion modes can be attributed to the role of $CO_2$ in enhancing the mixing and reaction rates within the flame. $CO_2$, as an inert gas, absorbs heat and redistributes it within the combustion zone, promoting more uniform and efficient combustion processes. However, at higher $CO_2$ concentrations (30%), the thermal capacity of $CO_2$ likely leads to a dilution effect, and the overall temperature decreases due to the lower reaction rate of the mixture.

In the premixed combustion mode, the role of $CO_2$ shifts as the bluff-body position changes. Near the burner rim (L = −5 mm), the increase in temperature with 10% and 20% $CO_2$ suggests that the premixing of fuel and air is still beneficial, leading to more complete combustion. As the bluff-body moves further inside the burner (L = −10 mm and L = −15 mm), the premixing becomes more dominant, and the excess $CO_2$ starts to act as a heat sink, lowering the flame temperature.

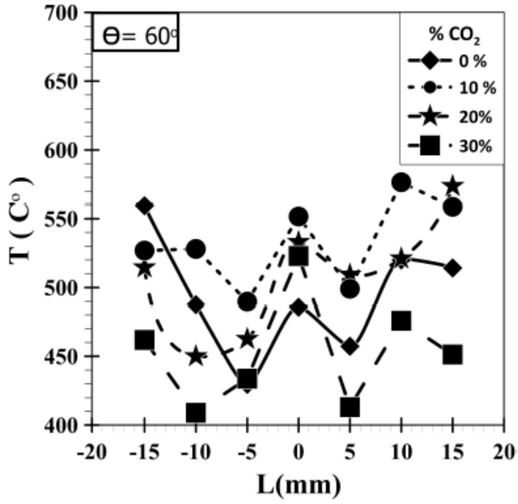



Fig. 8. The effect of L on the exhaust gas temperature at different $\%CO_2$ and θ = 60°.

### 3.3 Exhaust Emissions

Figures 9 and 10 illustrate the impact of $CO_2$ percentage on CO and NO emissions at varying bluff-body angles (θ) with a fixed position (L = 0 mm). There is a direct correlation between exhaust gas concentrations and exhaust temperature: higher exhaust temperatures indicate more complete combustion, leading to lower CO and higher NO concentrations.

The 60° bluff-body, which generates a lower exhaust temperature, results in higher CO and lower NO concentrations. In contrast, the flat bluff-body, which produces a higher exhaust temperature, results in lower CO and higher NO concentrations.

As $CO_2$ percentage increases up to 20%, the exhaust gas temperature rises, subsequently decreasing CO concentrations. However, further increases in $CO_2$ percentage to 30% lead to a rapid rise in CO concentration due to the physical and chemical effects of $CO_2$ dilution. Regarding NO concentration, it decreases with increasing $CO_2$ percentage due to the dilution effect of $CO_2$.

Figures 11 and 12 illustrate the effect of bluff-body position (L) on CO and NO concentrations. As observed from the exhaust gas temperature results, the temperature increases with both increasing and decreasing L. Consequently, CO concentration decreases as the bluff-body is moved either upstream or downstream of the burner exit. Conversely, NO concentration increases with the bluff-body's movement in either direction relative to the burner exit. However, it is noteworthy that NO concentrations decrease with increasing $\%CO_2$.

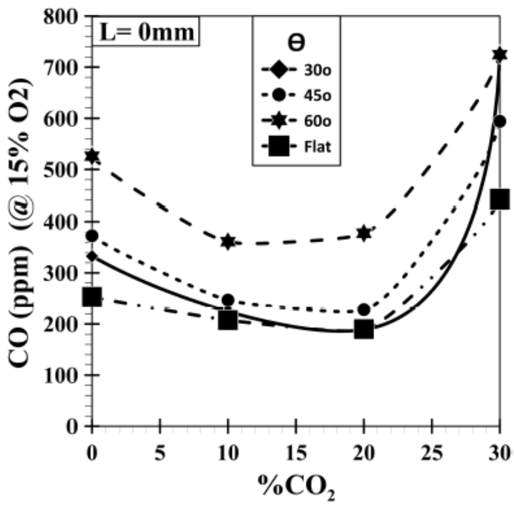



Fig. 9. The effect of $\%CO_2$ on CO emissions at different θ and L = 0mm.

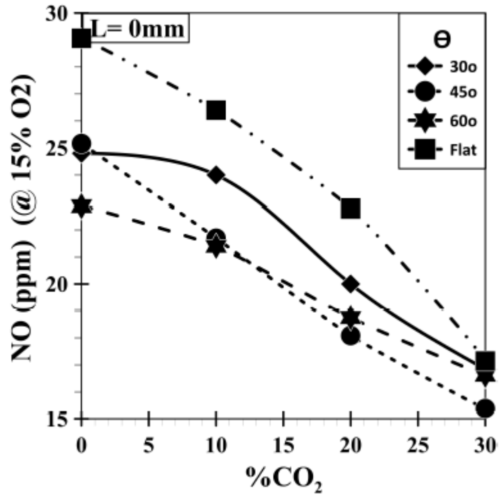



Fig. 10. The effect of $\%CO_2$ on NO emissions at different θ and L = 0mm.

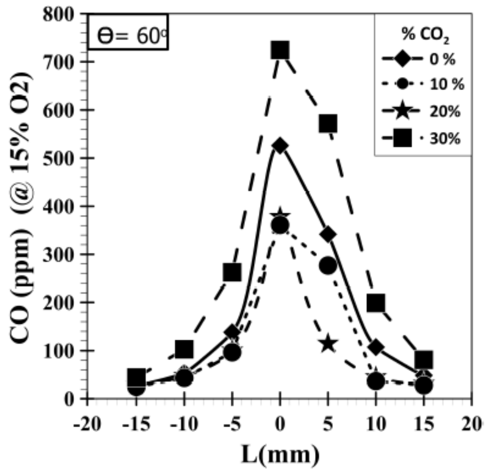



Fig. 11. The effect of L on CO emissions at different $\%CO_2$ and θ = 60°.

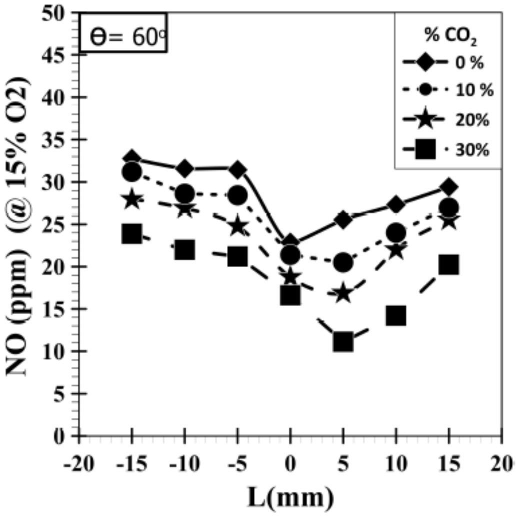



Fig. 12. The effect of L on NO emissions at different %$CO_2$ and θ = 60°.

## 4. CONCLOUSION AND FUTURE WORK

This study investigated the impact of bluff-body burner configuration and $CO_2$ percentage on the combustion characteristics of non-premixed biogas/air flames. The results highlight the intricate balance between physical and chemical effects of $CO_2$ and the geometric adjustments of the bluff-body on flame structure and exhaust temperature and emissions.

The key findings include:

1. *Flame Structure:* Increasing $CO_2$ percentage led to a shorter and narrower flame, with reduced luminosity, attributed to enhanced burning velocity and soot oxidation. The bluff-body angle had a minor influence on flame dimensions, though a 60° angle improved air-fuel mixing, indicated by lower luminosity and higher soot oxidation rates. Adjusting the bluff-body position impacted the early flame region, transitioning from diffusion to partially premixed combustion modes.
2. *Exhaust Gas Temperature*: The exhaust gas temperature initially rises with increasing $CO_2$ percentage up to 10%, due to the physical effect of $CO_2$'s high thermal capacity. Beyond this point, the temperature declines as the chemical effect, which reduces the mixture's reactivity, becomes more significant. Among the bluff-body angles studied, the flat bluff-body (90°) produced the highest exhaust temperature due to its longer flame length, while the 60° angle resulted in lower exhaust temperatures due to a wider, shorter flame.
3. *Emissions*: CO emissions decreased as the bluff-body was moved either upstream or downstream from the burner exit, corresponding with increases in exhaust gas temperature. Conversely, NO emissions increased with the same adjustments in bluff-body position but were mitigated by higher $CO_2$ concentrations, which act as a diluent, lowering flame temperatures and NO formation.

This comprehensive analysis enhances the understanding of biogas combustion dynamics, providing valuable insights for optimizing burner design and operation to achieve more efficient and environmentally friendly energy solutions. The findings underscore the importance of considering both physical and chemical effects of $CO_2$, as well as geometric factors in bluff-body configurations, to effectively control flame stability and emissions in biogas/air combustion systems.

Building on the results of this study, future research could explore several avenues to further optimize biogas combustion in bluff-body burners:

a) *Detailed Chemical Kinetics*: Investigating the detailed chemical kinetics of biogas combustion, particularly at higher $CO_2$ concentrations, could provide a deeper understanding of the reaction pathways and the formation of intermediate species.
b) *Advanced Imaging Techniques*: Employing advanced imaging techniques, such as laser-induced fluorescence (LIF) and particle image velocimetry (PIV), can offer more detailed insights into the flow field and combustion dynamics.
c) *Computational Fluid Dynamics (CFD) Simulations*: Conducting CFD simulations to complement experimental findings can help in predicting the behavior of biogas flames under various operating conditions and geometries.
d) *Hybrid Combustion Systems*: Investigating hybrid combustion systems that combine biogas with other renewable fuels, such as hydrogen or syngas, could enhance combustion efficiency and reduce emissions further.

We believe that addressing these aspects in future studies will contribute to the development of more efficient and environmentally friendly biogas combustion systems, thereby supporting the transition to sustainable energy solutions.

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