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Experimental Investigation of Confined Premixed LPG-Air Flame Characteristics under Different Equivalence Ratio

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Abstract:
Premixed combustion has attracted considerable attention due to its high thermal efficiency, stable combustion characteristics, and potential for reducing pollutant emissions. The present study experimentally investigates the effect of equivalence ratio on confined premixed LPG–air flames stabilized by a bluff-body flame holder.
Experiments are conducted over an equivalence ratio of 0.8–1.2 while maintaining a constant blockage ratio, confinement ratio, and fuel mass flow rate of 0.5 g/s.
The results showed that increasing the equivalence ratio increased flame length but decreased the maximum flame temperature. Furthermore, NOx emissions decreased with increasing equivalence ratio due to the lower flame temperature, whereas CO emissions increased under fuel-rich conditions because of incomplete combustion.
These findings provide useful insights into the combustion and emission characteristics of confined premixed LPG flames and support the optimization of low-emission gaseous-fuel combustion systems.
Key Word*: Premixed combustion; LPG; Bluff-body stabilization; Equivalence ratio; Flame characteristics.*

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I. Introduction

The increasing global demand for energy [1] and increasingly stringent environmental regulations have intensified the need for combustion systems that provide high thermal efficiency with low pollutant emissions [2, 3]. Despite rapid advances in renewable energy technologies, fossil fuels remain dominant because of their high energy density, established infrastructure, and reliable supply [4]. Consequently, improving combustion efficiency while reducing greenhouse gases and pollutant emissions remains a major challenge in energy conversion and thermal engineering [5].

Liquefied petroleum gas (LPG) has gained considerable attention as a relatively clean and efficient fuel because of its high calorific value, low sulfur content, rapid ignition, and comparatively low carbon emissions [6]. Mainly consisting of propane and butane, LPG is widely used in residential heating, industrial furnaces, boilers, and distributed energy systems. Its availability and ease of storage also make it an attractive transitional fuel toward cleaner energy technologies [7].

Premixed combustion is widely employed because fuel and oxidizer are mixed before ignition, producing a relatively homogeneous combustible mixture [8]. Compared with diffusion flames, premixed flames can provide higher combustion efficiency, more uniform heat release, and lower emissions under appropriate operating conditions [9]. However, their behavior is strongly affected by parameters such as equivalence ratio (Φ), flow velocity, burner geometry, and confinement. These parameters influence flame stabilization, temperature distribution, flame shape, and pollutant formation [10].

Several experimental studies have investigated premixed gaseous flames with different burner configurations and stabilization techniques. Ibrahim et al. [11] examined premixed LPG flames stabilized by different bluff-body geometries and blockage ratios (B.R.) of 0.25–0.55 at an equivalence ratio of 1.85. Increasing the blockage ratio increased the maximum flame temperature and flame diameter while reducing flame length. Sellan and Balusamy [12] experimentally investigated stratified and premixed LPG–air flames and reported that mixture distribution significantly affected flame structure and stability, although temperature distribution and exhaust emissions are not considered. Vance et al. [13] demonstrated that flame stretch, heat loss, and preferential diffusion strongly interact near the flame base to control bluff-body flame stabilization.

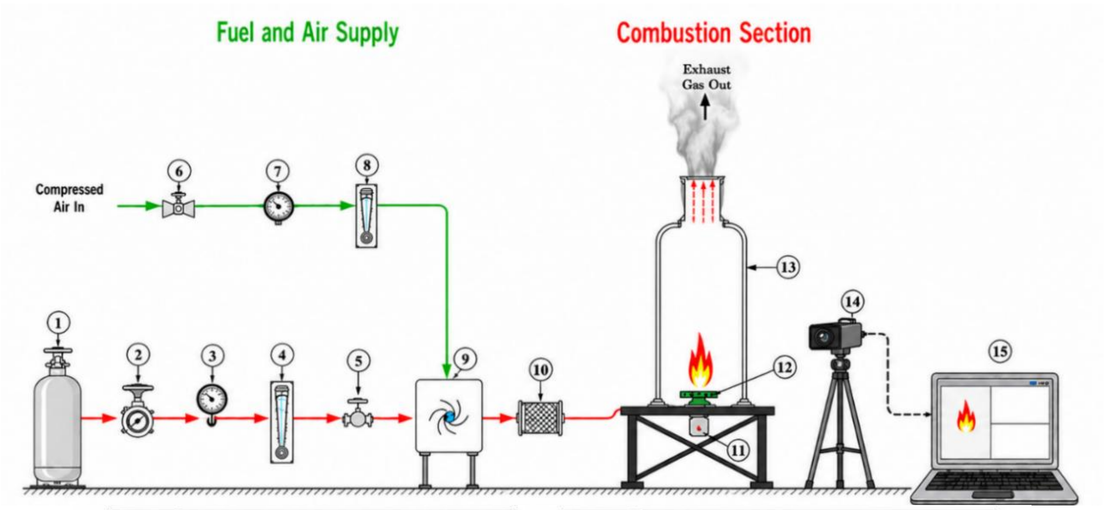
Badawy et al. [14] further showed that LPG flames are sensitive to premixing and turbulence, with improved mixture homogeneity promoting more stable combustion.

Recent research has also emphasized bluff-body stabilized premixed flames because of their effective stabilization mechanism and industrial relevance. The recirculation zone formed downstream of the bluff body plays a key role in flame anchoring, while bluff-body geometry and blockage ratio strongly affect flame shape, length, temperature, and emissions [15]. Nevertheless, many previous studies have focused primarily on flame stabilization [16], lean blow-off behavior [17], individual burner parameters, or numerical predictions [18]. Comprehensive experimental investigations simultaneously correlating flame appearance, temperature distribution, and exhaust-gas emissions for confined premixed LPG–air flames under identical operating conditions remain limited [19].

Therefore, the present study experimentally investigates the effect of Φ on the combustion characteristics of bluff-body stabilized premixed LPG–air flames in a confined cylindrical combustor. The confinement ratio (C.R.), B.R., and LPG mass flow rate ($\dot{m}_f$) are maintained constant. Flame behavior, temperature distribution, and exhaust-gas emissions are systematically evaluated to clarify the influence of equivalence ratio on combustion performance. The results provide a comprehensive experimental understanding of the relationship between mixture stoichiometry, flame characteristics, temperature field, and pollutant emissions, supporting the development of more efficient and environmentally friendly LPG combustion systems.

II. Experimental Setup

An experimental test rig is developed to investigate the effect of equivalence ratio on the combustion characteristics of premixed LPG–air flames. The system consists of an LPG supply line, compressed-air line, mixing chamber, combustor, and burner, as schematically shown in Figure 1. The fuel and air flow rates are controlled and measured using pressure regulators, control valves, pressure gauges, and rotameters. The LPG used in this study consisted of approximately 70% butane and 30% propane, with lower and higher heating values of 46.6 and 50.16 MJ/kg, respectively [20]. Its vapor density relative to air is 1.85, auto-ignition temperature is 410–580 °C, and boiling point ranged from −27 to −20 °C [21].

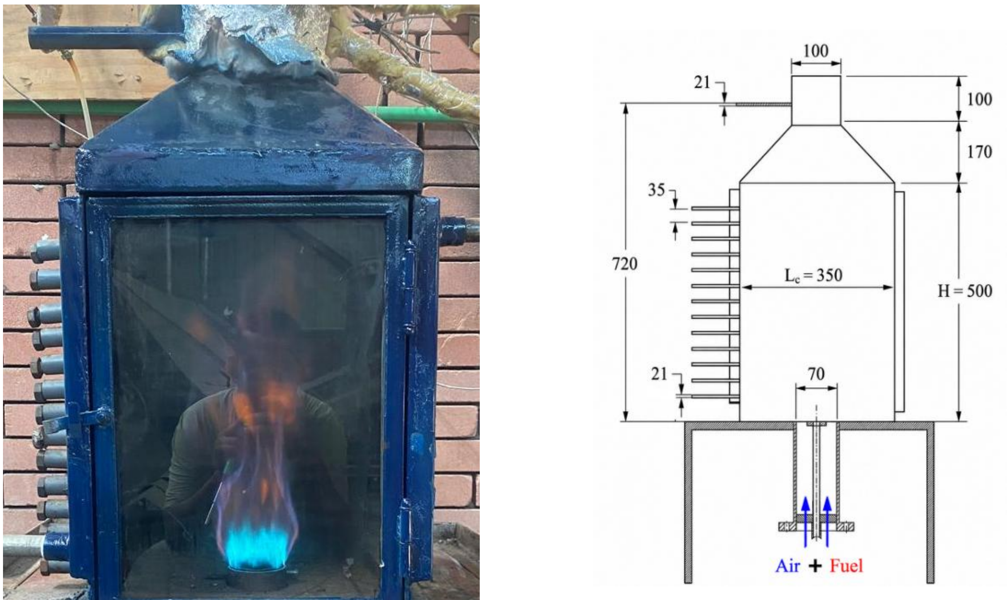


No.	Component
1	LPG Cylinder
2	Pressure Regulator
3	LPG Pressure Gauge
4	LPG Rotameter
5	Ball Valve (Fuel)
6	Air Valve
7	Air Pressure Gauge
8	Air Rotameter

No.	Component
9	Mixing Chamber
10	Flashback Arrester
11	Burner
12	Bluff body
13	Combustion Chamber (Combustor) with Stand
14	Camera (Flame Imaging)
15	Computer with Data Logging Software

Figure 1: A schematic diagram of experimental test rig.

The steel combustor has a cuboid configuration with a height of 500 mm and a C.R. of 5. Thirteen temperature measurement ports are distributed axially along one side, with a spacing of 35 mm, while a single outlet port is used for exhaust-gas sampling as shown Figure 2. A cylindrical steel burner head with a diameter of 70 mm and length of 200 mm is equipped with a disc-shaped bluff body having a diameter of 52 mm, thickness of 8 mm, and B.R. of 0.55. The B.R. is defined as the ratio of the projected bluff-body area to the burner-head area [22]. The combustor walls are cooled by a 20-mm-thick water jacket covering three sides, maintaining the wall temperature at approximately 303 K. The fourth side is fitted with a 10-mm-thick thermal glass window for optical observation of the flame.



All dimensions are in (mm).

Figure 2: A photograph & detailed dimensions of combustor.

Flame temperatures are measured using a bare-wire Pt–Pt/Rh (13%) Type-R thermocouple connected to a data acquisition system, with the recorded values averaged over the measurement period. Exhaust-gas concentrations are measured using a Testo 350 flue gas analyzer. Fuel and air flow rates are measured using Scientific Devices and Dwyer rotameters (SDAS and RMB-54D-SSV, respectively). The measurement ranges and accuracies of the instruments are summarized in Table 1.

Table 1: Measurement ranges, accuracies, and standard uncertainties of the experimental instruments.

Device	Measured parameter	Accuracy	Standard uncertainty	Measurement range
Digital multi-meter (UNI-T UT61B+)	Voltage	±0.5% of reading	0.3%	Up to 1000 V
Thermocouple (Type R)	Temperature	±0.5%	0.6 °C or 0.1%	-50 to 1760 °C
testo 350 flue gas analyzer	O_2	-	-	0 – 25 vol.%
	CO	-	-	0 – 10000 ppm
	CO_2	-	-	0 – 50 vol.%
	NO	-	-	0 – 4000 ppm
Scientific devices (SDAS) rotameter	Volume flow rate	±2% of full scale	-	0.1-1000 LPM
Dwyer (RMB-54D-SSV) rotameter	Volume flow rate	± 3% of full scale	-	5-95 LPM

III. Result and Discussion

The LPG premixed flame combustion characteristics are investigated at variable Φ of 0.8, 0.9, 1.0, 1.1, and 1.2 for disc bluff body shape, C.R. of 5 and B.R. of 0.55. The effects of changing the Φ on temperatures distributions, visible flame length and species concentrations are experimentally investigated and presented in the following sections. The Φ is changed by changing the air mass flow rate at constant $\dot{m}_f$ of 0.5 g/s.

The blow-off limits

The determination of the blow-off limits is a fundamental step in assessing the operational stability of premixed combustion systems, as it defines the range of operating conditions over which a stable flame can be maintained without extinction. In the present study, four bluff-body B.R.s (0.25, 0.35, 0.45, and 0.55) are experimentally investigated to evaluate their influence on flame stability and to identify the most suitable flame holder configuration.

Therefore, the blow-off limits of each bluff-body configuration are first determined, and the B.R. exhibiting the widest stable operating range is selected for the subsequent experiments. Based on the obtained stability limits, Φ range of 0.8 to 1.2 is adopted for the detailed investigation of flame characteristics, temperature distribution, and exhaust emissions. Figure 3 show the stable flame and blow-off regions for disc bluff body at different B.R.s. It is shown that, the flame stable region size increases by increasing B.R. as reported by Ibrahim et al [11].

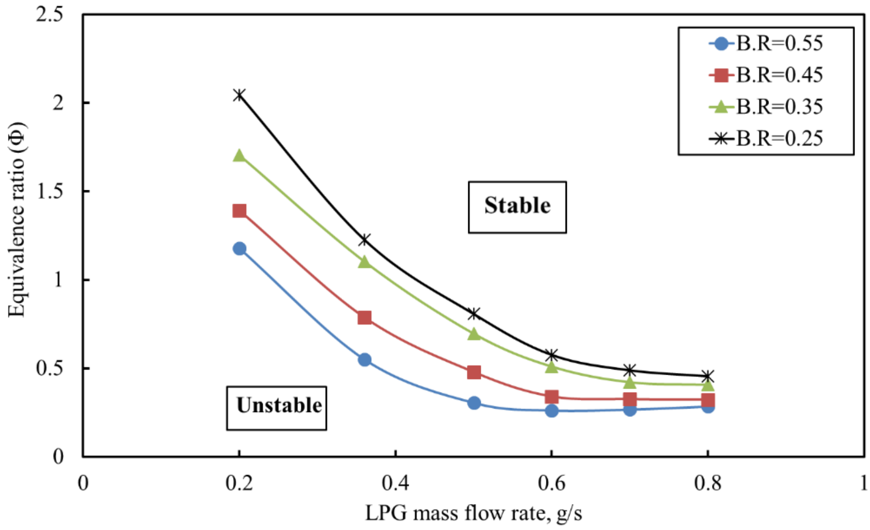


Figure 3: The stable flame and blow-off regions at different B.R.s for disc bluff body.

The temperature distributions

Figure 4 illustrates the effect of Φ on the temperature distribution of the disc bluff body at B.R. of 0.55 and $\dot{m}_f$ of 0.50 g/s. For all conditions, the flame remained stabilized along the combustor centerline, with the highest temperatures concentrated in the flame core and decreasing toward the walls due to heat losses and mixing with the surrounding gases. As Φ increased from 0.8 to 1.1, the high-temperature region (1300–1600 K) became wider and more continuous along the axial direction, indicating enhanced flame stability and heat release.

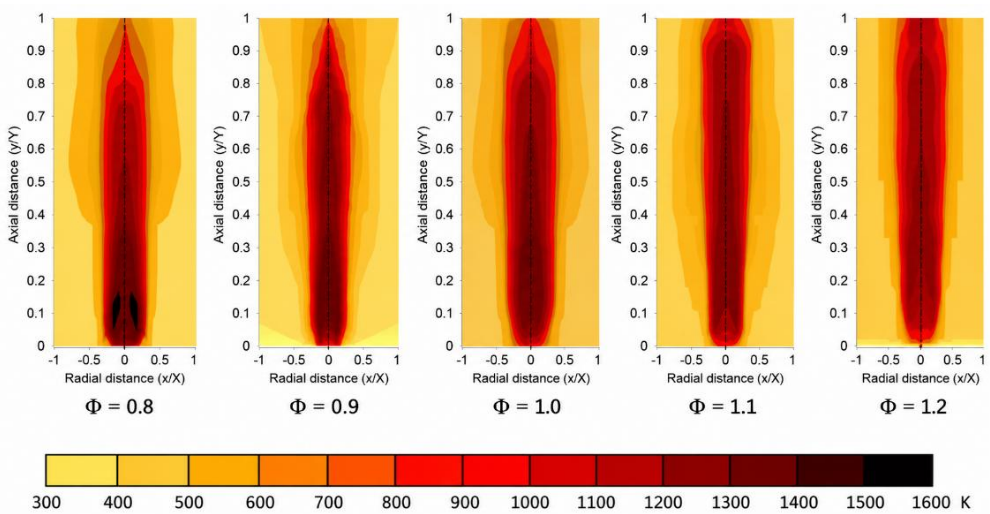


Figure 4: Effect of Φ on temperatures maps for disc bluff body [B.R. = 0.55 and $\dot{m}_f$ = 0.50 g/s].

At Φ = 0.8, a compact and intense high-temperature zone is observed due to the greater oxygen availability and higher reaction rate. At Φ = 1.2, however, the flame became longer while the peak temperature decreased because of oxygen deficiency under fuel-rich conditions, leading to reduced combustion intensity and incomplete oxidation. Overall, near-stoichiometric conditions (Φ ≈ 1.0) produced the most favorable temperature distribution, whereas richer mixtures resulted in longer flames with lower peak temperatures. The corresponding flame appearances are presented in Figure 5, where the flame becomes progressively longer and more vertically extended as the equivalence ratio increases.

Figure 5: Effect of Φ variation on flame shape for disc bluff body [B.R. = 0.55 and $\dot{m}_f$ = 0.5 g/s].

The visible flame length

Figure 6 illustrates the variation of dimensionless flame length (L/D) with Φ at B.R. of 0.55 and $\dot{m}_f$ of 0.50 g/s. The flame length remained nearly constant under lean and near-stoichiometric conditions, increasing slightly from 0.75 at Φ = 0.8 to 0.78 at Φ = 1.0, indicating a compact and stable flame. Beyond stoichiometric conditions, L/D increased to approximately 1.00 and 1.15 at Φ = 1.1 and 1.2, respectively, corresponding to about a 50% increase relative to Φ = 0.8. This elongation is attributed to reduced oxygen availability under fuel-rich conditions, which slows oxidation reactions and shifts the heat-release region downstream. The observed trend agrees with the flame images and temperature contours, while excessively rich mixtures may reduce combustion efficiency due to incomplete oxidation.

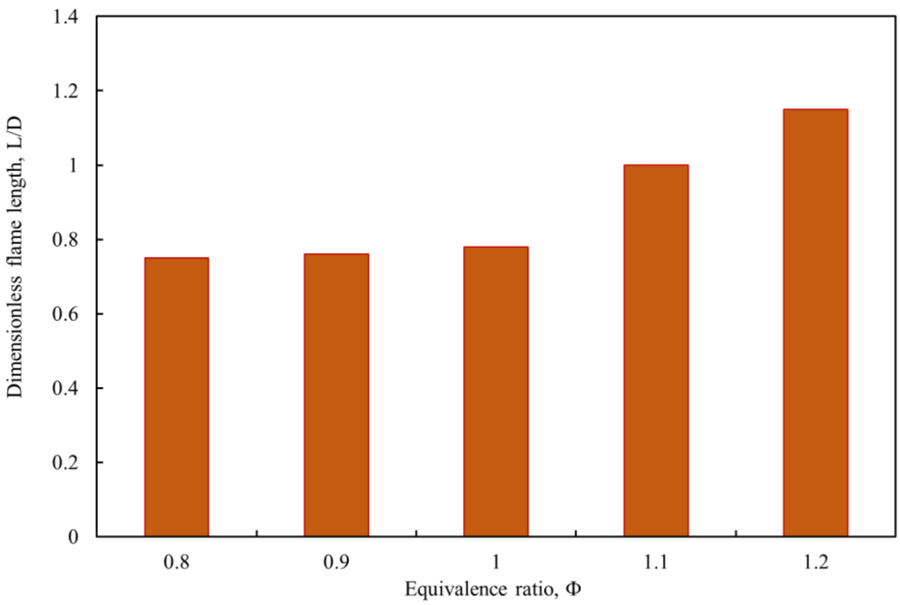


Figure 6: Effect of Φ on the flame length for disc bluff body [B.R. = 0.55 and $\dot{m}_f$ = 0.50 g/s].

The species concentrations

Figure 7 illustrates the effect of Φ on the species concentrations of exhaust gas. As the Φ increased from 0.8 to 1.2, the oxygen (O_2) concentration gradually decreased due to the increased fuel availability and higher oxygen consumption during combustion. Conversely, the carbon dioxide (CO_2) concentration showed a slight increase, indicating more complete oxidation near stoichiometric and slightly rich conditions.

The nitric oxide (NO) concentration continuously decreased with increasing Φ, which can be attributed to the reduction in flame temperature under fuel-rich conditions, thereby suppressing thermal NO formation. In contrast, the carbon monoxide (CO) concentration increased sharply at Φ > 1.0 as a result of oxygen deficiency, leading to incomplete combustion and enhanced CO formation.

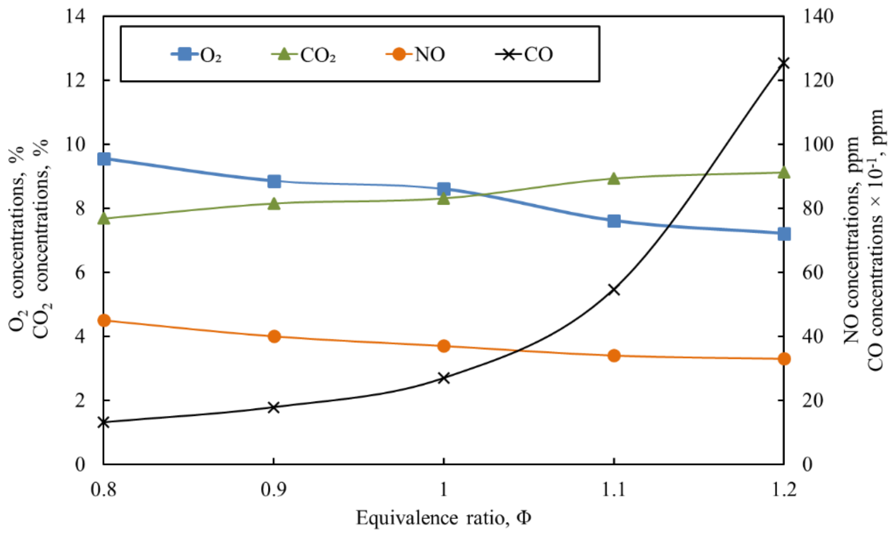


Figure 7: Centerline exit species concentrations for disc bluff body at different Φ [B.R. = 0.55 and $\dot{m}_f$ = 0.50 g/s].

IV. Conclusion

This study aimed to experimentally investigate how equivalence ratio influences premixed LPG flame behavior under varied conditions. The investigation is conducted at different equivalence ratio (Φ) of 0.8-1.2 and a fuel mass flow rate set at 0.5 g/s, blockage ratio of 0.55, and confinement ratio of 5. Based on the experimental findings, the following conclusions are drawn:

- At Φ = 0.8, the flame exhibited the most compact and intense high-temperature zone, resulting from an increased amount of oxygen leading to an increased reaction rate.
- The flame length remained nearly constant under lean and near-stoichiometric conditions, with values of approximately 0.75, 0.76, and 0.78 at Φ = 0.8, 0.9, and 1.0, respectively.
- The nitric oxide (NO) concentration continuously decreased with increasing Φ, because maximum core temperature at Φ = 0.8, while minimum core temperature at Φ = 1.2.
- The carbon monoxide (CO) concentration increased sharply at Φ > 1.0 as a result of oxygen deficiency, leading to incomplete combustion.

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