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Experimental Investigation of Flame Stability and Temperature Profiles in an LPG-Fuelled Combustion System for Industrial Hot Air Generation

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ABSTRACT

A combustion system is used to produce hot air for a variety of industrial and commercial purposes. This system works by burning a fuel source like natural gas, propane, or diesel in a controlled mixture of fuel and air inside a sealed chamber. However, achieving steady combustion has proven to be difficult since specific air pressure and flow rates are critical. The goal of this experiment was to investigate the combustor's combustion characteristics, particularly flame stability and temperature profile. Low air flow rates required 3 bar of air pressure to ensure flame stability, whereas greater flow rates were able to do so at 2 bar. Air flow rates of 30 l/min and above demonstrated stable flames at a 3 bar pressure. It was found that higher air flow rates were important for flame stability, as a fully opened valve sustained the flame for up to 15 minutes compared to only 4 minutes with a half-opened valve. The temperature profile showed decreased stability at lower air flow rates. Additionally, the maximum temperature of the combustor reached 235 °C, below the auto-ignition range of LPG between 410 °C to 580 °C. Therefore, this study highlights the critical role of air flow rate and pressure in maintaining flame stability and thermal consistency in combustion systems. These findings support efforts to optimize operating parameters of this combustor for improved efficiency, safety, and reliability in industrial applications.

1. Introduction

Heavy dependence on fossil fuels continues to contribute significantly to environmental pollution and greenhouse gas emissions, posing challenges to global sustainability. In 2022–23, industrial consumption of Liquefied Petroleum Gas (LPG) rose by 11.5%, reaching 12.5 million tonnes compared to 11.2 million tonnes the previous year, as reported by the Ministry of Petroleum and Natural Gas. The food processing industry accounted for the largest share of LPG usage (30%), followed by textiles (20%) and chemicals (15%), with other sectors such as rubber, plastic, and paper also relying on LPG as a fuel source [1].

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Researchers seek alternative and sustainable energy to avoid or minimize pollution and fossil fuel consumption [2]. Flameless combustion, also known as Moderate or Intense Low-oxygen Dilution (MILD) combustion [3], is an advanced combustion technique that offers notable advantages over conventional methods. This process involves burning fuel without a visible flame front [4], which reduces temperature fluctuations and enables a more uniform temperature distribution within the combustion chamber [5]. By operating under lower temperature and oxygen conditions, flameless combustion achieves higher energy efficiency and significantly reduces the emission of pollutants [6].

Originally introduced in the 1970s, the concept of flameless combustion was developed to address the limitations of traditional combustion, such as high emissions and thermal inefficiencies [7],[8]. The core principle involves creating a homogeneous fuel–air mixture with a carefully controlled oxygen supply, which promotes stable and controlled combustion. This technique has proven effective in minimizing the formation of harmful emissions like carbon monoxide (CO) and nitrogen oxides (NOx), owing to its low-temperature operation [3],[6],[9]. As such, flameless combustion presents a sustainable solution for industries aiming to reduce their environmental footprint while maintaining effective heat generation.

LPG, composed primarily of propane and butane, serves as the primary fuel in the combustion process. Due to its relatively cleaner-burning properties, LPG produces fewer pollutants compared to other fossil fuels, making it a suitable option for environmentally conscious combustion systems. Research indicates that applying LPG in flameless combustion systems results in reduced NOx emissions. This is further enhanced by techniques such as double swirl flame configurations and staged combustion, which improve fuel–air mixing and temperature control [10]. Additionally, LPG supports stable combustion and consistent temperature profiles, which influence the chemical kinetics of the combustion process [11].

Recent studies have also explored the role of fuel modification in enhancing combustion efficiency and reducing emissions. For instance, blending hydrogen with compressed natural gas (CNG) has been shown to improve combustion characteristics, such as increasing adiabatic flame temperature and reducing CH_4 and CO emissions. A study using the CHEMKIN tool demonstrated that a 50% H_2–50% CNG blend resulted in a temperature increase from 2322 K to 2344 K, along with a 30–35% reduction in CH_4 mole fraction and a 26.6% increase in normalized CH_4 production. The presence of hydrogen also increased CO normalization and influenced free radical activity, contributing to emission reduction. Through NSGA-II optimization, this hydrogen blend was identified as the optimal solution for balancing thermal performance and environmental impact [12]. These findings further emphasize the importance of cleaner fuel integration and combustion strategies in achieving carbon neutrality.

In this study, a flameless combustor was integrated with a hot air generator to supply thermal energy for drying empty fruit bunches (EFB), with the aim of minimizing pollutant emissions during the drying process. The hot air generator provides the necessary heat, while the flameless combustor facilitates low-emission combustion. This paper presents experimental findings on the combustion characteristics of LPG within the flameless combustor, focusing on flame stability and temperature distribution under varying airflow and pressure conditions.

2. Methodology

This section provides a detailed explanation of the equipment and materials used in the experimental work. The calculation of the air-fuel equivalence ratio will also be presented here.

2.1 Experimental set-up

The experimental set-up was designed to conduct the data collection for evaluating the stability of the flame to combust at the spiral nozzle. LPG gas tanks were linked directly to the fuel flow meter, equipped with a pressure gauge, and connected to the fuel injection hole of the combustor. Similarly, an air compressor was connected to the air receiver tank, which was then linked to the air flow meter and then to the four air injection holes of the combustor. Five thermocouples were positioned at the combustor and connected to the Pico Log to record the temperature profile of the chamber. Figures 1, 2 and 3 illustrate the configuration of this experiment.

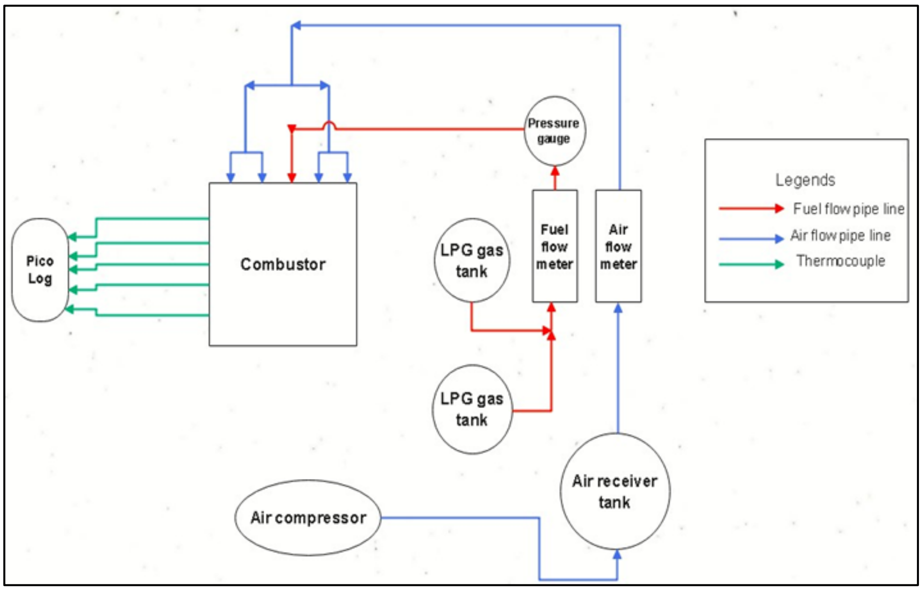

Fig. 1. Schematic diagram for experimental set-up

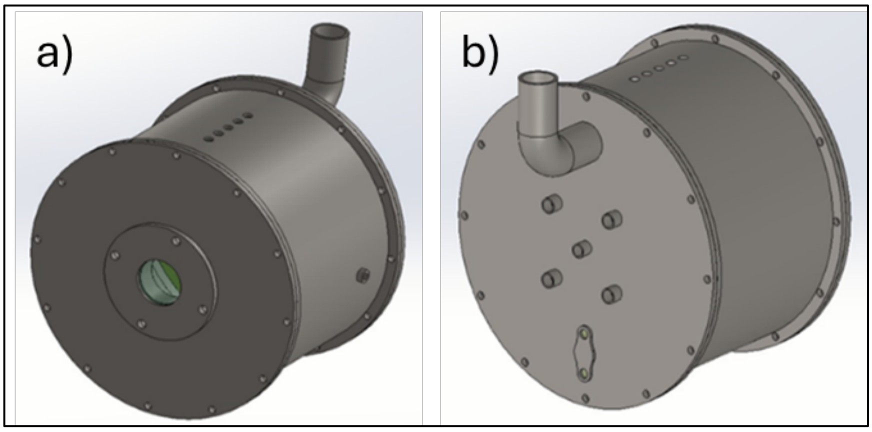

Fig. 2. Combustor, a) Left side, b) Right side

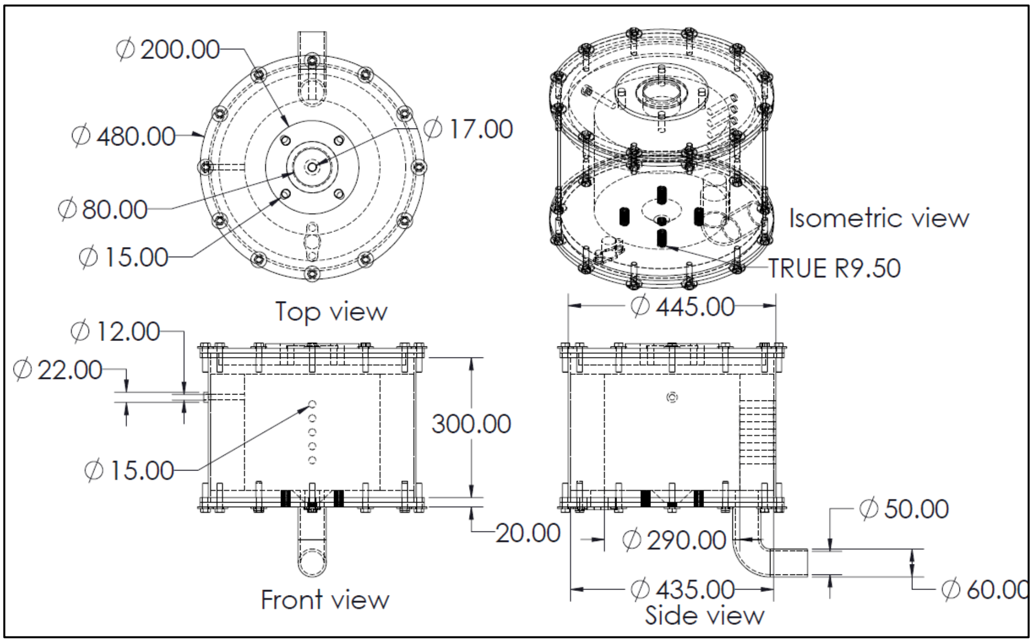

Fig. 3. Dimensions of the combustor

2.2 Stoichiometric and Air-Fuel Equivalence Ratio for LPG

Understanding the stoichiometric and air-fuel equivalence ratio (λ) for Liquefied Petroleum Gas (LPG) is important to optimize the combustion performance. The stoichiometric ratio represents the best proportion of air required to achieve complete combustion, ensuring that all fuel is effectively burned for maximum energy output with minimal waste. Operating near this ratio allows for greater combustion efficiency, a crucial criterion in industrial applications where fuel cost and energy use are critical. Additionally, the air-fuel equivalence ratio directly impacts pollutant formation, where low or high deviations from stoichiometric conditions can elevate emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). By investigating the air-fuel equivalence ratio, it has become the key to reducing emissions and allows LPG to have cleaner combustion. Therefore, to enhance the combustion efficiency, emissions control, and flame stability, as supported by previous studies [13]-[17], the determination of LPG's stoichiometric and the air-fuel equivalence ratio is crucial.

To evaluate the combustion behavior of hydrocarbon fuel such as LPG, it is important to understand the relationship between the stoichiometric and air-fuel equivalence ratio. The stoichiometric combustion equation represents the ideal chemical reaction in which a hydrocarbon fuel (C_xH_y) reacts completely with oxygen from the air to produce carbon dioxide (CO_2) and water (H_2O), without any excess fuel or oxygen. The general reaction is shown in equation (2.1).

$$C_xH_y + a\,(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76(a)\,N_2 \tag{2.1}$$

$$a = x + \frac{y}{4} \tag{2.2}$$

Where the stoichiometric coefficient a ensures complete combustion and is derived from the elemental balance shown in equation (2.2). This equation provides a basic calculation for both stoichiometric and air-fuel equivalence ratios, which are fundamental in combustion literature [18-21].

In the experiment, the LPG used contains 30% propane (C_3H_8) and 70% butane (C_4H_{10}). Hence, the stoichiometric equation of LPG can be written as follows:

$$0.3\ C_3H_8 + 0.7\ C_4H_{10} + 6.05\ O_2 + 22.75\ N_2 \rightarrow 3.7\ CO_2 + 4.7\ H_2O + 22.75\ N_2$$

Where, $a = 0.3(3 + \frac{8}{4}) + 0.7(4 + \frac{10}{4}) = \underline{\underline{\mathbf{6.05}}}$

The molecular weight of the air and LPG fuel needs to be calculated to substitute into the equation of the stoichiometric air-fuel ratio. The formula of molecular weight (MW) is as shown in equation (2.3).

$$MW = (\text{atomic mass of element}) \times (\text{subscript of elements}) \quad (2.3)$$

Where,
Atomic mass of Oxygen: 16 g/mol
Atomic mass of Nitrogen: 14 g/mol
Atomic mass of Carbon: 12 g/mol
Atomic mass of Hydrogen: 1 g/mol

The air composition contains 21% Oxygen (O_2) and 79% Nitrogen (N_2). The molecular weight of the air can be calculated as:

$$MW_{air} = (0.21 \times [16x2g/mol]) + 0.79 \times [14x2]g/mol)$$
$$= \underline{\underline{\mathbf{28.84\ g/mol}}}$$

The molecular weight of C_3H_8 and C_4H_{10} can be calculated as:

$$MW_{C3H8} = (3 \times 12\ g/mol) + 8 \times 1\ g/mol)$$
$$= \underline{\underline{\mathbf{44.00\ g/mol}}}$$

$$MW_{C4H10} = (4 \times 12\ g/mol) + 10 \times 1\ g/mol)$$
$$= \underline{\underline{\mathbf{58.00\ g/mol}}}$$

Since LPG consists of 30% C_3H_8 and 70% C_4H_{10}, the molecular weight of LPG can be calculated as:

$$MW_{LPG} = (0.3 \times 44.00\ g/mol) + 0.7 \times 58.00\ g/mol)$$
$$= \underline{\underline{\mathbf{53.80\ g/mol}}}$$

Next, substitute the value and molecular weight into the equation of the stoichiometric air-fuel ratio:

$$(A/F)_{stoic} = 4.76\ a\ (MW_{air} / MW_{LPG}) \quad (2.4)$$
$$(A/F)_{stoic} = 4.76\ (6.05)\ (28.84 / 53.80)$$
$$= \underline{\underline{\mathbf{15.44}}}$$

After that, determine the actual air fuel ratio $(A/F)_{act}$, for which the formula of the actual air fuel ratio is given as:

$$(A/F)_{actual} = \dot{m}\ air_{actual} / \dot{m}\ fuel_{actual} \quad (2.5)$$

By using one parameter of the experiment as an example, which is the air flow rate of 15 l/min and fuel flow rate of 1.2 l/min, the actual air-fuel ratio is calculated as follows:

$(A/F)_{act}$=15 l/min) ⁄ (1.2 l/min =**12.5**

Finally, air-fuel equivalence ratio can be determined by substituting the value of actual air-fuel ratio, (A/F)act and stoichiometric air-fuel ratio, (A/F) stoic into the equation of air-fuel equivalence ratio (λ).

$$\lambda = (A/F)_{act} \,/\, (A/F)_{stoic} \quad (2.6)$$

λ = 12.5 / 15.44= **0.81**

2.3 Parameters of study

The following tables present the experimental parameters used in this study. Table 1 and Table 2 outline the setups for Test 1 and Test 2, which were conducted to examine the effect of air flow rate on flame stability at pressures of 2 bar and 3 bar, respectively, across various air-fuel equivalence ratios (λ). Table 3 and Table 4 provide the parameters for Test 3 and Test 4, which were designed to investigate the influence of air flow rate on flame stability by adjusting the valve opening configuration (full and half opening) while keeping the pressure constant at 2 bar. Finally, Table 5 lists the distances of five thermocouples (T1 to T5) from the fuel inlet used in Test 5, which was carried out to analyze the temperature profile along the combustor. The positioning of these thermocouples is illustrated in Figure 4.

Table 1
Parameters for test 1

Air pressure (bar)	Air-fuel equivalence ratio (λ)	Fuel flow rate, $\dot{m}\ fuel_{actual}$, l/min	Air flow rate, $\dot{m}\ air_{actual}$, l/min
2	0.81	1.2	15
	1.08		20
	1.35		25
	1.62		30

Table 2
Parameters for test 2

Air pressure (bar)	Air-fuel equivalence ratio (λ)	Fuel flow rate, $\dot{m}\ fuel_{actual}$, l/min	Air flow rate, $\dot{m}\ air_{actual}$, l/min
3	0.81	1.2	15
	1.08		20
	1.35		25
	1.62		30

Table 3
Parameters for test 3

Air pressure (bar)	Valve opening configuration	Fuel flow rate, $\dot{m}\ fuel_{actual}$, l/min
2	Full opening	4

Table 4
Parameters for test 4

Air pressure (bar)	Valve opening configuration	Fuel flow rate, $\dot{m}\ fuel_{actual}$, l/min
2	Half opening	4

Table 5
Parameters for test 5

Length of each thermocouple from fuel inlet (cm)				
T_1	T_2	T_3	T_4	T_5
10	13	16	19	22

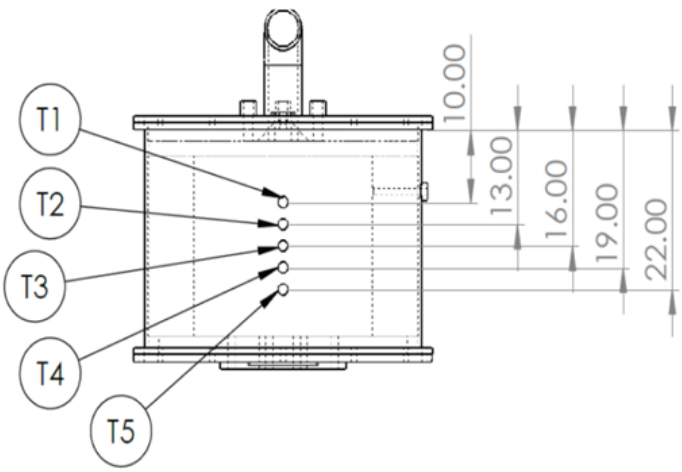

Fig. 4. Illustration of thermocouple from fuel inlet (combustor top view)

3. Results and Discussion

In this chapter, the analysis is focused on the flame stability concerning air pressure and air flow rate effects. Furthermore, the temperature profile of the combustor reveals how the flame stability trend is influenced by the air flow rate.

3.1 Effect of air pressure on combustion flame stability

Table 6
Combustion condition at air pressure 2 bar

Air fuel equivalence ratio, λ	Air flow rate, ṁ air (l/min)	Fuel flow rate, ṁ fuel (l/min)	Combustion	Flame condition
0.81	15	1.2	No	
1.08	20		No	
1.35	25		No	
1.62	30		No	

According to Table 6, no combustion was observed in the combustion chamber. This means that at an air pressure of 2 bar, the blowtorch flame was unable to reach the nozzle due to insufficient air flow in the chamber. As a result, it can be concluded that there was no noticeable combustion reaction or visible flame inside the combustion chamber under these conditions, as indicated by the flame condition in Table 6.

Table 7
Combustion condition at air pressure 3 bar

Air fuel equivalence ratio, λ	Air flow rate, ṁ air (l/min)	Fuel flow rate, ṁ fuel (l/min)	Combustion	Flame condition
0.81	15	1.2	No	
1.08	20		No	
1.35	25		No	
1.62	30		Yes, the flame sustained up to 21 minutes	

According to Table 7, it was observed that at an air pressure of 3 bar, the nozzle did not receive a flame from the blowtorch when the air flow rates ranged from 15 l/min to 25 l/min. This indicates that there was no significant combustion or visible flame inside the combustion chamber under these conditions.

However, when the air flow rate was increased to 30 l/min, the nozzle successfully received a flame from the blowtorch and maintained it for a considerable period of 21 minutes. Higher air flow rates, such as 30 l/min, improved the stability of the flame. It was also noted that the flame remained stable under lean conditions with an equivalence air-fuel ratio of 1.62.

Based on the overall results, it is evident that the flame stability was not consistently achieved. Therefore, it is crucial to ensure a sufficient and consistent airflow within the combustion chamber to achieve a stable flame. Based on the experimental findings, it is recommended to maintain an air pressure of 3 bar with an air flow rate of 30 l/min or higher to achieve stable combustion.

3.2. Effect of air flow rates on flame stability

The air flow rate will be controlled by the full opening and half opening of the brass gate valve. The fuel flow rate was increased and kept constant at 4 l/min. And the condition of flame stability will be recorded in Tables 8 and 9 below.

Table 8
Combustion and flame conditions for fully opening the brass gate valve

Test	Fuel flow rate, $\dot{m}$ fuel (l/min)	Combustion	Flame condition
1		Yes, the flame sustained for up to 15 minutes	
2	4	Yes, the flame sustained for up to 9 minutes	
3		Yes, the flame sustained for up to 12 minutes	

According to Table 8, three tests were conducted to assess flame stability by fully opening the brass gate valve. In the first test, the flame was sustained for 15 minutes, followed by 9 minutes in the second test, and 12 minutes in the third test. These results indicate that the flame was able to sustain for a duration ranging from 9 to 15 minutes.

According to Table 9, three tests were conducted to assess flame stability with the half-opening brass gate valve. In the first and second tests, the flame was sustained for 4 minutes, and in the third test, it was sustained for 3 minutes. These results indicate that the flame was able to sustain for a duration ranging from 3 to 4 minutes.

Table 9
Combustion and flame conditions for a half-opening brass gate valve

Test	Fuel flow rate, ṁ fuel (l/min)	Combustion	Flame condition
1		Yes, the flame sustained up to 4 minutes	
2	4	Yes, the flame sustained up to 4minutes	
3		Yes, the flame sustained up to 3 minutes	

Comparing the results from table 8 and 9, it is evident that the duration of flame sustainment at the nozzle is longer when the brass gate valve is fully opened. The flame was able to sustain for a maximum of 15 minutes compared to only 4 minutes with the half opening valve. This suggests that the higher flow rate achieved with the fully opened brass gate valve leads to better flame stability [22].

3.3 Temperature profile of the combustor

The results of experiments from the investigation of combustion performance inside the designed combustor are presented in this chapter. The main goals are to observe the temperature distribution along the combustor chamber and analyse flame stability under various air pressures and air flow rates. To shed light on the combustor's overall performance, the results are presented in detail via graphical representations. To illustrate the pattern of temperature variations across the combustor chamber, Figure 5 displays the temperature profile of the combustor with a half-opening brass gate valve.

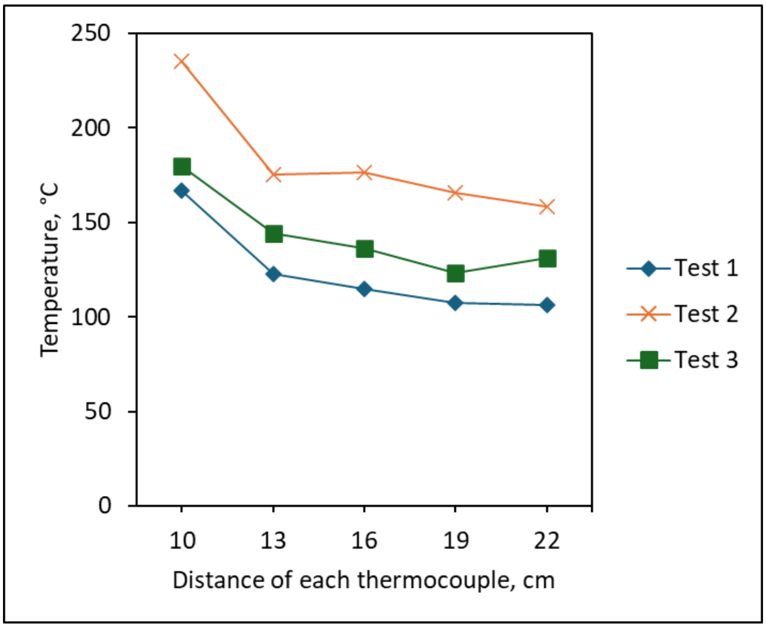

Fig. 5. Graph of Temperature profile vs Distance of each thermocouple

Figure 5 illustrates the temperature distribution along the combustor at five thermocouple positions (T1 to T5), located at distances of 10, 13, 16, 19, and 22 cm from the fuel inlet. Test 1, conducted at 2 bar air pressure, shows a consistent decline in temperature from approximately 166.69 °C at T1 to 106.28 °C at T5, indicating rapid heat loss and an unstable flame. In contrast, Test 2, performed at 3 bar air pressure, recorded the highest initial temperature of 235.54 °C at T1, with a more gradual temperature decrease down to 158.38 °C at T5. This suggests that increased air pressure significantly enhances combustion efficiency and flame stability. Test 3, which used a fully opened valve at 2 bar pressure, yielded a moderately improved temperature profile compared to Test 1, starting at 180.16 °C and ending at 131.52 °C. These findings confirm that higher air pressure contributes more effectively to stable combustion than increased air flow alone. Similar findings were observed by Ishak et al. (2024), which emphasized the critical role of air pressure and equivalence ratio in determining temperature distribution and flame characteristics in biomass gasification systems [23].

In a stable flame condition, the graph shows a consistent and sustained flame presence over time. It exhibits relatively steady temperature readings within a desired operating range, while a relatively flat line or a consistent waveform indicates stable and continuous combustion. Any fluctuations or variations in the flame or temperature would be minimal and controlled, indicating a stable combustion process within the combustor.

The experimental results indicate that the temperature graphs do not exhibit a consistent flat line or waveform. Instead, they consistently display a decreasing trend, which indicates the flame is unstable. The subsequent decrease in temperature was attributed to the insufficient duration of the combustion reaction taking place within the combustion chamber. The flame is extinguished within a short period of time, leading to the observed decreasing trend in temperature. This is primarily due to the insufficient air flow rate, which is supported by the fact that the brass gate valve was only partially opened, limiting the amount of air entering the combustion chamber. Previous researchers have demonstrated that changes in pressure and temperature can alter the air-fuel ratio significantly, which in turn impacts combustion characteristics and flame stability [24-25].

4. Conclusion

As a conclusion, the flame stability and temperature distribution of a custom-fabricated LPG combustor were experimentally investigated. The objective was to assess the capability of the system to achieve flameless combustion and to identify critical operational parameters. The novelty of this work lies in its experimental analysis of LPG combustion behaviour under varying air flow rates and pressures in a lab-scale combustor designed for hot air generation. This study also highlights the influence of design and operational limitations on flame stability.

Key Findings:

- Stable flame required 3 bar pressure at low air flow rates, while 2 bar was sufficient at higher air flow rates.
- A minimum of 30 l/min air flow was needed to maintain a stable flame with a 3 bar pressure setting.
- The flame was sustained for up to 15 minutes with a fully open valve, while it lasted only 4 minutes with a half-open valve.
- The temperature profile declined at lower air flows, indicating flame instability.
- The flame remained stable under lean conditions, but flameless combustion was not achieved.
- The maximum recorded temperature (235.54 °C) was well below the auto-ignition temperature of LPG (410–580 °C).

Limitations:

- Air quality issues, including moisture in the air compressor, affected combustion stability.
- The combustor design deviated from specifications; an oversized exhaust hole reduced air velocity and pressure, impacting flame behaviour.

Outlook for Future Work:

To improve the system's performance and move toward successful flameless combustion, future research should:

- Incorporate moisture control systems to ensure air quality.
- Explore preheating techniques or recirculation systems to help reach the LPG auto-ignition range.
- Investigate the impact of fuel-air premixing and swirl mechanisms on achieving more uniform temperature profiles.

In conclusion, this study provides valuable insights into the combustion performance of LPG in a lab-scale combustor. While challenges remain in achieving flameless combustion, the results highlight key factors influencing flame stability and suggest practical directions for enhancing future combustor design and operation.

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