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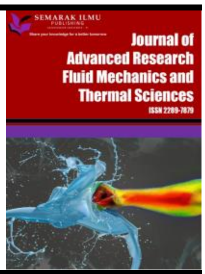


# Effect of Recirculation Ratio on the Combustion Characteristics of an Asymmetric Swirling Flameless Combustor using Biogas

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**ABSTRACT**

This study investigates the influence of recirculation ratio on the combustion characteristics of an asymmetric swirling flameless combustor. The recirculation ratio, defined as the ratio of the total recirculation mass flow rate to the primary air mass flow rate, plays a crucial role in determining the performance and emission characteristics of combustion systems. The asymmetric swirling flameless combustor offers potential advantages in terms of enhanced fuel flexibility, reduced pollutant emissions, and improved combustion stability. Through varying the recirculation ratio, the combustion performance and emission characteristics can be optimized to meet specific requirements. In this research, experimental investigations were conducted to analyse the effect of recirculation ratio on the combustion stability, temperature field and emission of the asymmetric swirling flameless combustion. From the results obtained, it was observed that recirculation ratio has significant effect on the performance of the combustor i.e., as the recirculation ratio increases due to decrease in the exhaust area, more uniform temperature and less emission was observed. At 30mm exhaust diameter and lean condition, average recirculation of 7.21 was obtained with 2ppm NOx emission and 118ppm CO emission along with uniform temperature in the combustion zone.

## 1. Introduction

Combustion is a chemical process involving the rapid oxidation of a fuel in the presence of an oxidizer, typically air or oxygen [1]. It is an essential energy conversion process used in various industries, including power generation, transportation and manufacturing [2]. Conventional combustion systems typically involve a flame, characterized by high temperatures and intense reactions. However, these conventional combustion processes often suffer from issues such as high pollutant emissions, inefficient fuel utilization, and combustion instability [3]. Conventional combustion processes exhibit several drawbacks, including the formation of nitrogen oxides (NOx) due to high flame temperatures, the generation of carbon monoxide (CO) and unburned

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hydrocarbons (UHC) due to incomplete combustion, and flame instability leading to combustion oscillations [4]. These challenges have led to stringent environmental regulations and the need for improved combustion technologies [5,6]. Flameless combustion, also known as distributed combustion or homogeneous combustion, offers a potential solution to overcome the limitations of conventional combustion. In flameless combustion, the fuel and air are mixed thoroughly, resulting in a nearly uniform mixture throughout the combustion chamber [7]. This homogeneous mixture is then combusted at relatively low temperatures and without a visible flame. The absence of a distinct flame makes flameless combustion unique and distinguishes it from conventional combustion processes[8]. Flameless combustion exhibits several key characteristics that make it an attractive alternative to conventional combustion. It operates at lower temperatures compared to conventional flames, resulting in reduced thermal NOx formation. Additionally, the nearly uniform mixture allows for more complete combustion, minimizing CO and UHC emissions [9-11]. Flameless combustion can accommodate a wide range of fuels, including gaseous, liquid, and solid fuels, with varying compositions and properties. This versatility makes flameless combustion suitable for diverse applications and alternative fuel sources. The distributed nature of flameless combustion promotes stability by minimizing flame fluctuations and combustion oscillations [12]. This improved stability contributes to reliable and efficient combustion operations. The lower flame temperatures associated with flameless combustion reduce thermal stresses on combustion chamber materials, leading to longer component lifetime and improved durability.

The benefits of flameless combustion has led to its application in various industries, including power generation, industrial furnaces, boilers, and gas turbines [13,14]. Flameless combustion has also found relevance in automotive engines and clean energy technologies such as fuel cells. Research on flameless combustion is of significant importance due to its potential to address environmental concerns, improve energy efficiency, and enhance the performance of combustion systems [15,16]. Through understanding the fundamental principles and optimizing the operating parameters of flameless combustion, researchers and engineers can develop innovative combustion technologies that minimize pollutant emissions, increase fuel flexibility, and enhance combustion stability. In recent years, researchers and engineers have been exploring innovative approaches to further enhance the performance and capabilities of flameless combustion systems [17]. One such advancement is the asymmetric swirling flameless combustor, which combines the benefits of flameless combustion with the unique characteristics of an asymmetric swirling flow field. An asymmetric swirling flow is characterized by the presence of a non-axisymmetric velocity field, where the flow exhibits rotational motion around the central axis but with variations in swirl intensity and direction across the cross-section of the combustion chamber [18]. This swirling flow is achieved through the design and arrangement of the air or fuel injection systems, such as tangential injection or the use of swirling vanes [19]. The asymmetric swirling flameless combustor is a combustion system that integrates the advantages of flameless combustion with the distinctive flow characteristics of an asymmetric swirling flow. This configuration offers unique possibilities for further optimizing combustion performance, stability, and emissions control. It promotes improved mixing of fuel and air, resulting in a more homogeneous mixture throughout the combustion chamber [20]. This enhanced mixing leads to a higher degree of fuel-air interaction and facilitates more complete combustion. The swirling flow pattern in the asymmetric combustor can increase the residence time of the reactants within the combustion zone. This extended residence time allows for better fuel utilization and enhanced combustion efficiency [21]. The non-axisymmetric flow field of the asymmetric swirling combustor contributes to better flame stability by reducing the likelihood of flame extinguishment and promoting stable combustion across a wider range of operating conditions. When parameters that are related to asymmetric swirling flow are adjusted, such as swirl intensity, swirl direction, and flow distribution, the combustion characteristics, including flame shape, flame temperature, and emissions, can be effectively controlled and optimized. The asymmetric swirling flameless combustor has potential applications in various industries, including power generation, industrial heating processes, and combustion-based propulsion systems. Its advantages in terms of improved fuel flexibility, enhanced combustion stability, and reduced pollutant emissions make it an attractive option for clean and efficient energy conversion. Ongoing research and development efforts focus on further understanding the complex interactions between the asymmetric swirling flow and flameless combustion. Computational modelling, experimental studies, and advanced measurement techniques are being employed to gain insights into the combustion characteristics, flame structure, and emission performance of the asymmetric swirling flameless combustor. These investigations aim to optimize the design and operation of the combustor for specific applications and operating conditions.

The recirculation ratio is a critical parameter that quantifies the ratio of the total recirculation mass flow rate to the primary air mass flow rate in a combustion system [22,23]. It represents the extent to which the combustion products are recirculated back into the combustion zone, influencing the overall flow and mixing characteristics within the system. The recirculation ratio plays a significant role in achieving optimal combustion performance in various combustion systems. It directly affects key factors such as flame stability, combustion efficiency, pollutant emissions, and operational flexibility [24,25]. In combustion systems, a certain level of recirculation is necessary to stabilize the flame. The recirculation of hot combustion products helps in maintaining a stable flame structure by providing heat and enhancing fuel-air mixing. A proper recirculation ratio ensures the flame remains anchored and prevents flame blowout or instability. The recirculation ratio has a direct impact on the combustion efficiency of a system. When recirculating hot gases, the recirculation process preheats the incoming fuel and air mixture, reducing the energy required for ignition and promoting more complete fuel combustion [26,27]. This results in higher combustion efficiency, improved fuel utilization, and reduced fuel consumption. Controlling pollutant emissions is a critical aspect of combustion systems. The recirculation ratio plays a crucial role in emission control by influencing the combustion process. Optimal recirculation can lower peak flame temperatures, reducing the formation of nitrogen oxides (NOx). Additionally, recirculation helps in achieving more uniform fuel-air mixing, minimizing the production of carbon monoxide (CO) and unburned hydrocarbons (UHC) [28,29]. When recirculation ratio is adjusted, combustion systems can be optimized to meet specific emission standards and environmental regulations. The recirculation ratio provides operational flexibility in combustion systems which allows for better control of combustion stability, flame shape, and emissions, enabling the system to operate efficiently across a wide range of operating scenarios [30-32]. Recirculation ratio is particularly crucial in flameless combustion systems. In flameless combustion, the recirculation of combustion products helps in creating a nearly uniform mixture and maintaining low flame temperatures [33,34]. The recirculation ratio determines the extent of mixing and recirculation, affecting the overall combustion characteristics, including flame shape, stability, and emission performance. Determining the optimal recirculation ratio is essential during the design and optimization of combustion systems. Through experimental investigations and computational modelling, engineers can analyse the effects of different recirculation ratios on combustion performance, emissions, and stability. This knowledge aids in the development of more efficient and environmentally friendly combustion systems tailored to specific applications. It influences flame stabilization, combustion efficiency, emission control, operational flexibility, and the design of flameless combustion systems [35,36]. When recirculation ratio is understood and optimized, engineers can develop combustion systems that offer improved efficiency, reduced emissions, and enhanced operational characteristics, contributing to sustainable and clean energy conversion. Despite the significant importance of recirculation ratio on combustion characteristics, there is no significant work that studies the effect of recirculation ratio in an asymmetric swirling flameless combustor using a renewable fuel such as biogas. Therefore, this work intends to determine the optimum recirculation ratio for an asymmetric swirling combustor operating in flameless mode using biogas by varying the flow rate of the exhaust gases that will give better performance of the combustor and lower pollutant emission, thereby providing valuable insight on the operating conditions for the combustor.

## 2. Methodology

### *2.1 Thermodynamics of Recirculation Ratio*

High Temperature Reactants: In flameless combustion, the recirculation ratio (Kv) is the ratio of the mass flow rates of the recycled exhaust gases $M_r$ to the total of the rates of the fuel and combustion air as shown in Eq. (1) below [37].

$$K_v = \frac{M_r}{M_i + M_f} \tag{1}$$

All the intensive characteristics (such as molar fraction and temperature) associated with large quantities that are carried within or outside of the chamber are connected to one another, according to the corresponding conservation equation. As a result, the relationship between Kv and temperature is defined as shown in Eq. (2) below [37]:

$$K_v = \frac{T_{mix} - T_i}{T_r - T_i} \tag{2}$$

Tmix denotes the temperature of the mixture inside the chamber, Ti the temperature of the air entering the chamber, and Tr the temperature of the exhaust gases being recirculated. Eq. (2) states that a high level of Kv is obtained when the mixture's temperature rises. "High Temperature of Reactants" (THTR) is the designation given to this temperature. Eq. (3) results in the mixture's oxygen molar fraction.

$$K_v = \frac{X_{O2,m} - X_{O2,i}}{X_{O2,r} - X_{O2,i}} \tag{3}$$

In this equation, the terms X(O2, m), X(O2,r), and X(O2,i) stand for the moles of oxygen in the chamber, the recirculated gases, and the input gases, respectively. It is important to note that since it's been assumed that the exhaust gases only contain burnt gases devoid of oxygen, the oxygen mole fraction in recirculated gases is taken to be zero, and Eq. (3) is changed to Eq. (4).

$$K_v = \frac{X_{O2,i} - X_{O2,m}}{X_{O2,i}} \tag{4}$$

Clearly, the most significant effects of the extremely low oxygen content inside the chamber are the high values of Kv that drive the combustion process into flameless mode. To increase the temperature of the injected fresh air jet and lower the oxygen content (to generate a hot and diluted oxidizer), hot reactive gases from the combustor must be entrained into it. The recirculation ratio (the ratio of the entrained flow mass to the jet flow mass) has been measured as a result of extensive research on the entrainment of the jet in this regard.

For the intended recirculation of hot and active species, partial entrainment of product gases into the injected air jets can be achieved. Correlations from Ricou [38] have been used to understand how the injected air jet and product gas characteristics affect the change of the recirculation ratio, which is defined as the mass of entrained product gases to the mass of injected air. The correlation, which is shown below in Eq. (5) and Eq. (6), was applied to a variable density, non-reacting air jet injected in a quiescent medium.

$$\text{Recirculated ratio (Kv)} = \frac{\dot{\mathrm{m}}_{\mathrm{rec}}}{\dot{\mathrm{m}}_{\mathrm{jet}}} \quad (5)$$

where

$\dot{\mathrm{m}}_{\mathrm{rec}}$ = recirculated mass flux
$\dot{\mathrm{m}}_{\mathrm{jet}}$ = initial jet mass flux

The analysis of the real burner confirms the well-known formula shown in Eq. (6) below for the jet entrainment[38]

$$K_v = 0.32\,\frac{x}{D}\sqrt{\frac{\rho_{furnace}}{\rho_{air}}} \quad (6)$$

where

$x$ = distance along the jet centreline;
D = jet diameter

## *2.2 Geometry and Configuration of an Asymmetric Swirling Combustor*

As seen in Figure 1 below, the study was carried out using an asymmetric swirling combustor. The combustor was made of two half-circles that are offset from one another in order to create the asymmetric shape needed for combustion. The experiment was conducted in High-Speed Reacting Flow Laboratory (HiREF) Laboratory of the Faculty of Mechanical Engineering at Universiti Teknologi Malaysia. Mild steel was used to construct the combustor so that it could endure the pressure and temperature of combustion. In order to have an even distribution of fuel and air, it is designed such that both the upper and lower portions of the asymmetric combustor contain inlets for air that are positioned appropriately while fuel was injected axially only. Additionally, each air and fuel port have a valve connected to it so that, if needed, the combustor's arrangement can be altered. The combustor has an external diameter of 450mm, a length of 300mm, and an internal diameter of 350mm that are separated by insulating material on either side that is 50mm thick. For this present work, the combustor was set to operate with ten (10) axial ports, eight (8) tangential air ports and 12 axial fuel ports.

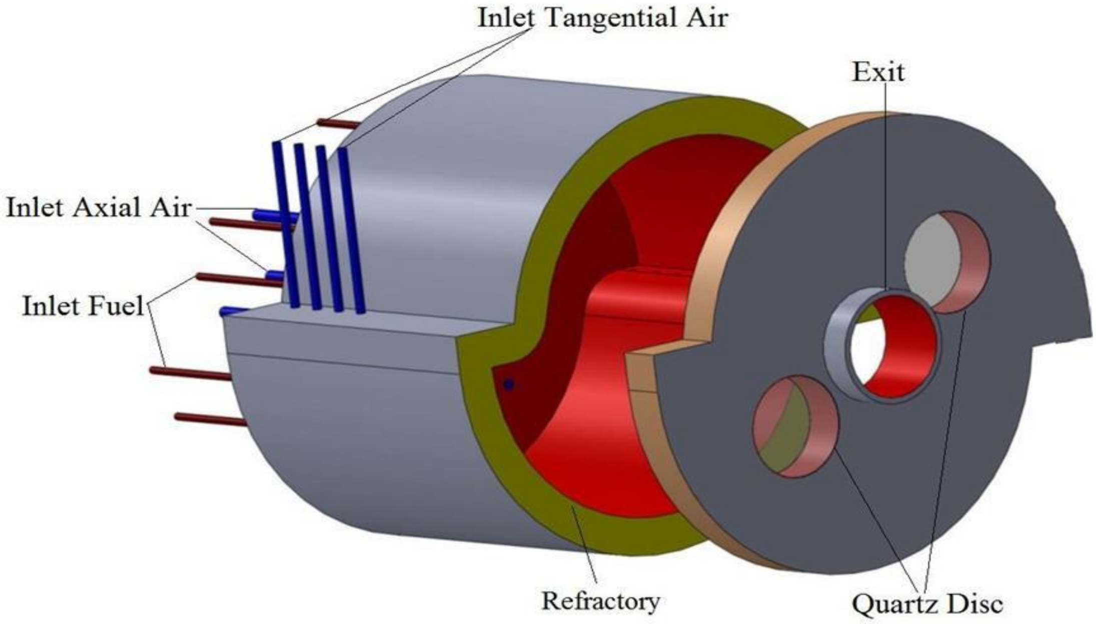



**Fig. 1.** Isometric view of an asymmetric swirling combustor [3]

From Figure 2, it is clear that thermocouples were inserted at six (6) distinct locations on top of the combustor, at distances of 60, 90, 120, 150, 210, and 270 millimetres from the inlet point, in order to measure the temperature of the combustion zone. Five quick-disconnect S-type thermocouples will be installed inside the combustion chamber to measure the temperature profile of the furnace (accuracy: 1.5°C or 0.25 percent of reading, whichever is greater; maximum range: 50°C to +1760°C). To detect air temperature during flameless combustion, a K type thermocouple will be installed at the air nozzle input (maximum range: 100°C to +1370°C, accuracy: 2°C or 0.75 percent of reading, whichever is greater). An S-type thermocouple will be inserted in the centre of the combustion chamber. To keep track of all temperatures, a Pico log data collection system (TC-08) will be employed. To gather temperature data, the TC-08 will be connected into a USB port on the computer and connected to the thermocouples. The TC-08 has an operational temperature range of -270 to +1820°C. Up to ten temperature measurements can be taken per second with the TC-08 due to its rapid conversion time (less than a second).


**Fig. 2.** Experimental setup of the asymmetric swirling combustor

Variable area flow meters will be used as the flow measurement system to track flow rates in the fuel and air flow metres during the experiment. Cole Parmer flow metres (maximum 3286.8 mL/min, minimum 231.3 mL/min, and standard accuracy) will be used to measure the flow of both methane and carbon dioxide. Dwyer VFB-55 flow metres with a maximum flow rate of 200 standard cubic feet per hour (SCFH) and standard accuracy will be used to measure the air flow. Since measuring gas emissions is crucial for this research, a substantial portion of the product line is made up of microprocessor-based gas analysers. For this operation, a KM9106 gas analyser will be used to evaluate the flue inside the exhaust hole. In less than 5 minutes of direct contact with the exhaust and sample, the KM9106 long and short probes can assess flue gas constituents. The gas analyser has a 1-meter-long temperature probe with a 1200°C temperature sensitivity that enables safe monitoring of flameless combustor gas emissions. Figure 3 depicts the experimental setup in general so that you can clearly see how it will be.

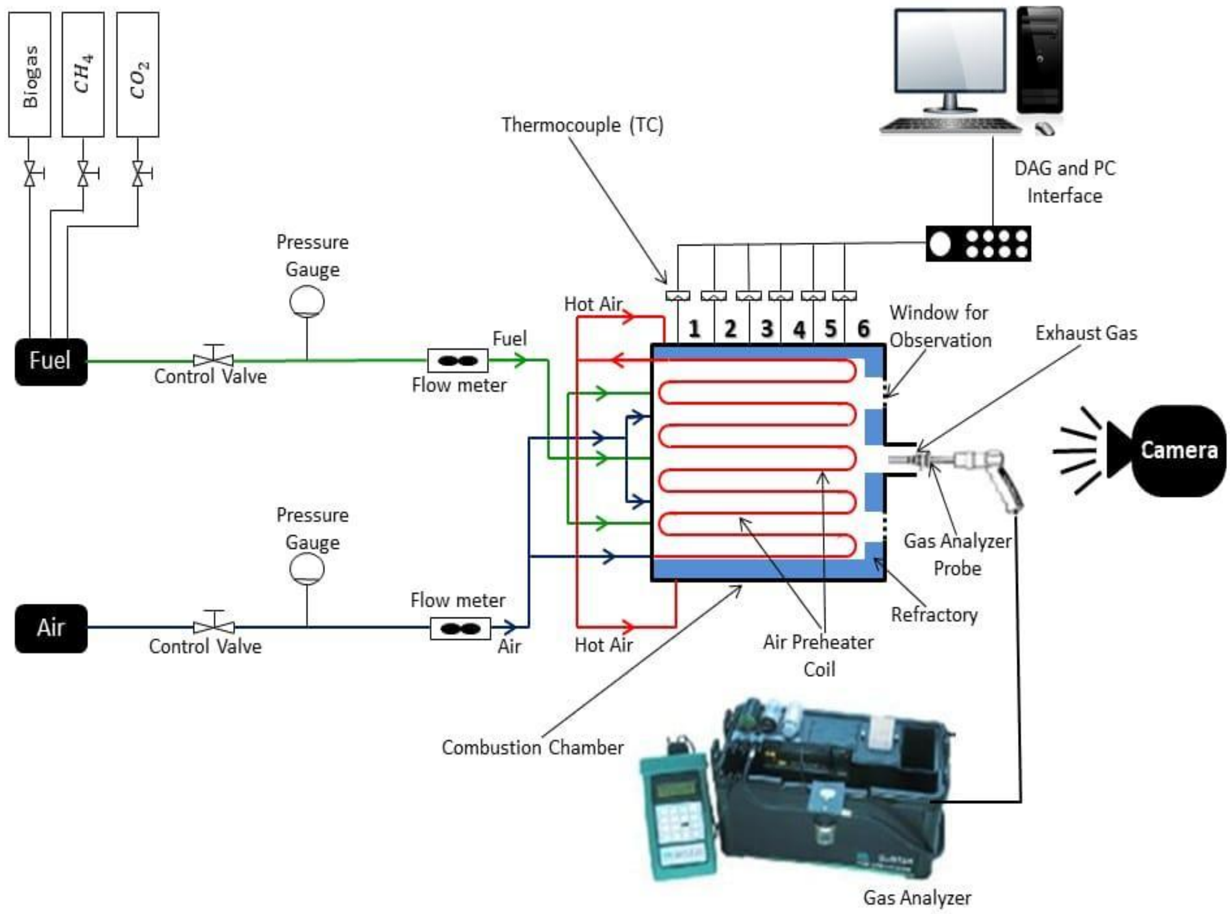



**Fig. 3.** Schematic diagram of the asymmetric swirling combustor

## *2.3 Experimental Procedure*

In all the swirling flameless combustion experiments, Liquefied Petroleum Gas (LPG) was utilized to heat the combustion chamber for around an hour using conventional combustion until the temperature of the combustion has already reached 1800 K which is higher than the auto-ignition temperature of the fuel that was used for flameless combustion (Synthetic biogas of 75% methane and 25% carbon dioxide). Due to the reduced energy content of biogas compared to LPG, the temperature will drop when the usual LPG combustion was switched to biogas combustion. The flow rates for the flameless combustion were set at constant air flow rate of ma= 5.3x10-3 kg/s and mf = 1.55x10-4 kg/s for lean condition, mf = 3.09x10-4 kg/s for stoichiometric condition and finally mf = 4.635x10-4 kg/s for rich condition. The temperature was then stabilized at roughly 1200K, where flameless combustion was made possible by high recirculation ratio. In order to continue the chemical process of combustion even in the absence of flame, high temperature was maintained and temperature measurements were made throughout the combustion zone, at the exhaust point, for each condition, while varying the flow rate, and the exhaust gases were measured using an exhaust gas analyzer. Also, in determining the recirculation ratio (Kv), Eq. (6) was used and Kv was determined at six (6) different points i.e., 50mm, 100mm, 150mm, 200mm, 250mm and 300mm. It is worth noting that all the inlet jets have the same inlet diameter of 5mm, density of the mixture was obtained at each point and average recirculation ratio was obtained by taken of the recirculation ratios at six (6) points in the combustor.

## 3. Result and Discussion

### *3.1 Recirculation Ratio in the Combustor*

Figure 4 below shows the variation of recirculation ratio along the axial distance of the combustor. It can be observed that for lean, stoichiometric and rich condition, recirculation ratio varies significantly with exhaust diameter. At lean condition, the recirculation ratio has an average value of about 5.39 at 40mm exhaust diameter, followed by 5.92 at 35mm exhaust diameter and 7.21 at 30mm exhaust diameter. The increase in the recirculation ratio is as a result of the decrease in the exhaust area, thereby decreasing the amount of exhaust gases that are leaving the exhaust point, the remaining products that do not leave are recirculated and mixed with the fresh incoming mixture of fuel and air, thereby reducing the oxygen concentration in the combustion zone. It was observed that flameless combustion was achieved in all the three (3) cases and was stable for all the cases. It is worth noting that the temperature inside the combustion zone was assumed to be the same in each condition since the combustion was operating in flameless mode and the temperature fluctuation is very minimal. Similarly, at stoichiometric condition, the recirculation ratio was observed to have average values of 5.46, 6.06 and 7.53 at exhaust diameters of 40mm, 35mm and 30mm, where the increase in recirculation ratio is associated with extensive mixing of the recirculated products and incoming reactants. Finally, at rich condition, the average recirculation ratios were recorded as 5.22, 5.64 and 6.44 at 30mm, 25mm and 20mm exhaust diameters just like the other conditions. When the three (3) conditions were compared, it was observed that stoichiometric condition produced higher recirculation, followed by lean and then rich condition. It is worth mentioning that for all the cases, stable combustion was achieved.

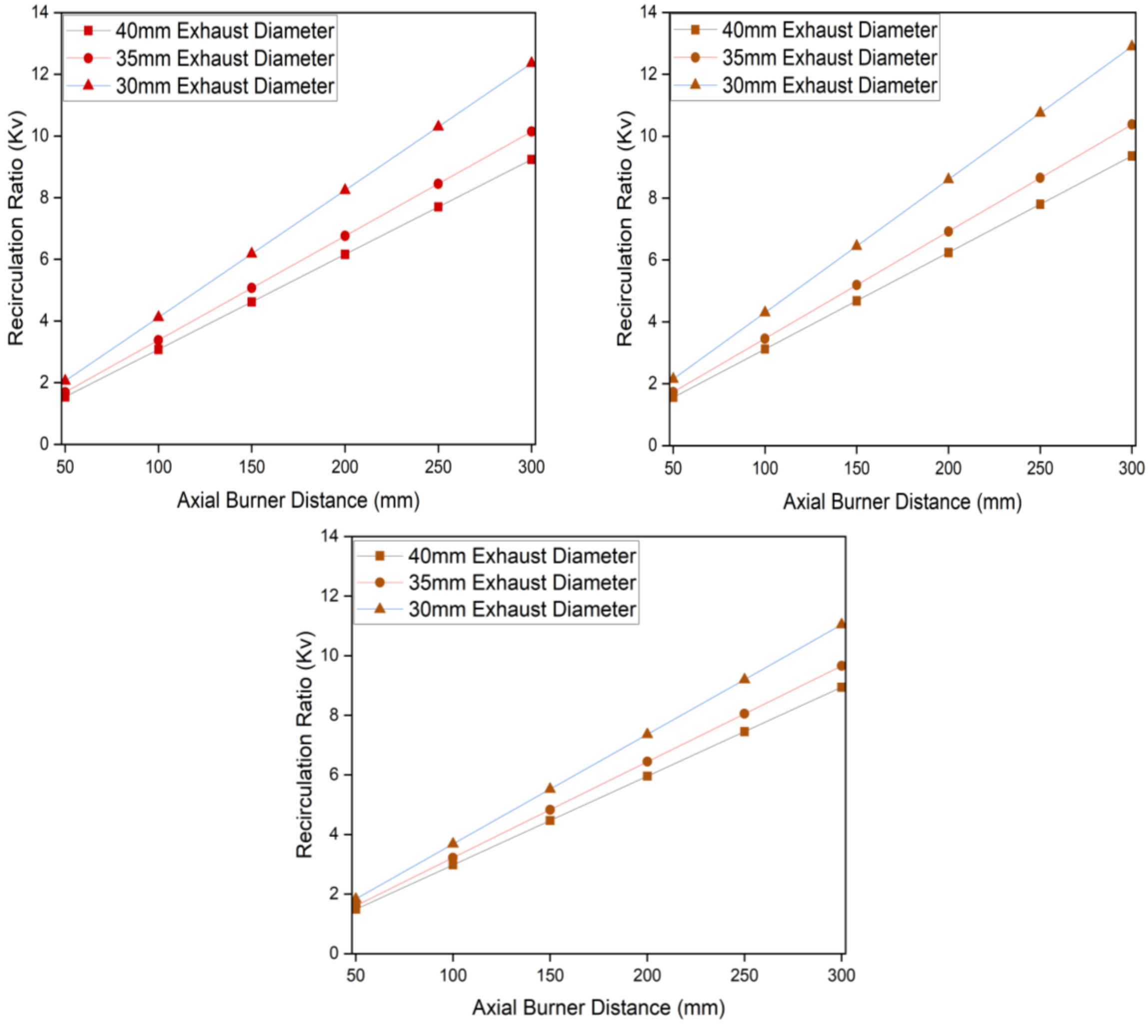



**Fig. 4.** Recirculation ratio vs axial burner distance for (a) lean, (b) stoichiometric and (c) rich conditions

### *3.2 Pollutant Emission*

NOx emission was measured at the exit of the combustor using an exhaust gas analyzer and the result was plotted as shown in Figure 5 below. Even though single digit NOx emission was observed in all the cases, it can be clearly seen that increasing recirculation ratio by reducing exhaust diameter reduces oxygen concentration across the cases and thereby reducing NOx emission. At 40mm exhaust diameter, the NOx was measured at 8ppm, at 35mm exhaust diameter it was 6ppm while for 30mm exhaust diameter was 5ppm all at rich condition. The decrease in NOx level is likely associated with increase in residence time as the exhaust diameter decreases, thereby increasing the recirculation ratio inside the combustion zone. At stoichiometric condition, the NOx was also found to decrease from 6ppm to 5ppm and 3ppm as the exhaust diameter decreases from 40mm to 35mm and 30mm. The pattern is also the same for lean condition which recorded the least emission compared to the stoichiometric and rich condition from 5ppm to 3ppm and 2ppm for 40mm, 35mm and 30mm exhaust diameters due to reduction in temperature.

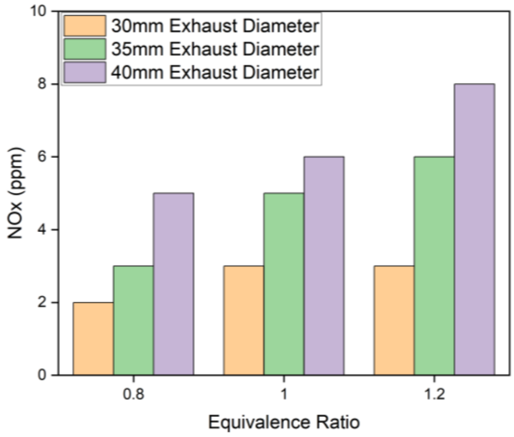



**Fig. 5.** NOx emission at different exhaust diameters

CO emission was observed to increase as the exhaust diameter increases due to lower recirculation in the combustion zone as shown in Figure 6 below. The lower recirculation ratio leads to incomplete combustion and dissociation of carbon dioxide into carbon monoxide arising from poor mixing as the diameter increases. Maximum CO was observed to be 275ppm followed by 208ppm and 150ppm for exhaust diameters of 40mm, 35mm and 30mm all at rich condition likely due to incomplete combustion arising from high amount of fuel in the combustion zone. For stoichiometric condition, the CO emission was observed to be 268ppm, 194ppm and 135ppm for 40mm, 35mm and 30mm exhaust diameter while for the lean condition, the CO level was observed to be minimal with values of 254ppm, 171ppm and 118ppm at 40mm, 35mm and 30mm compared to stoichiometric and rich likely due to low fuel content in the combustion zone, thereby having a complete combustion at the expense of lower temperature.

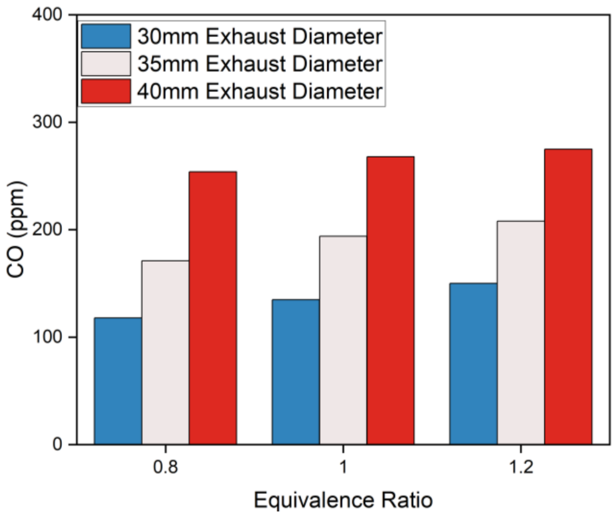
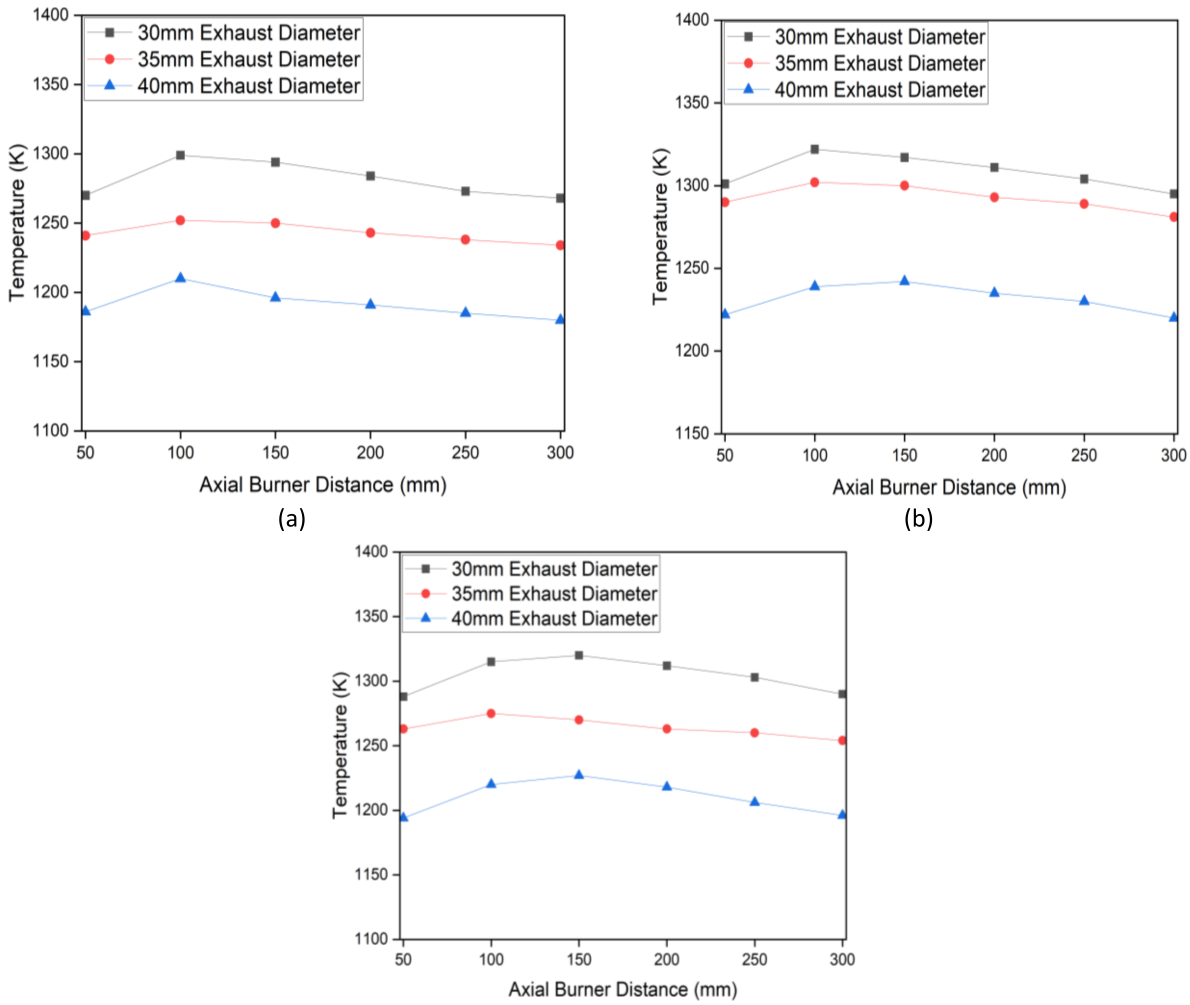



**Fig. 6.** CO emission at different exhaust diameters

*3.3 Temperature Field*

The temperature field in the combustion is a very important parameter to determine the combustion status as to whether it is in flame or flameless mode. Figure 7 below shows three (3) different graphs for temperature distribution inside the combustion zone at different exhaust diameters.

It was observed that in all the three (3) conditions, uniform temperatures have been achieved relatively. From Figure 7, it can be seen that higher temperature fields were observed at lower exhaust diameter and lower temperatures were observed at higher exhaust diameter likely due to higher heat transfer rate at the higher exhaust diameter. Also, it can be observed that there are slightly lower temperatures at the entrance and exit of the combustor due to spray vaporization and heat loss due to radiation. The temperatures in Figure 7(a) appears more uniform in 35mm exhaust diameter likely due to moderate recirculation and temperature fluctuation was observed at 30mm exhaust diameter due to extreme recirculation in the combustion zone. Figure 7(b) shows the temperature distribution along the centre line of the combustor at stoichiometric equivalence ratio using different exhaust diameters. It can be seen also that the temperature was increasing as the exhaust diameter was decreasing due to lower heat loss at the exhaust of the combustor. Slightly lower temperatures were observed at the inlet and exit of the combustor due to spray vaporization and heat loss at the exhaust part of the combustor. Also, at 30mm exhaust diameter, higher non-uniformity was observed at stoichiometric condition. Likewise Figure 7(c) shows similar pattern of higher temperature as the exhaust diameter reduces due to lower heat loss at the exhaust of the combustor. From the three (3) plots, it can be observed that more uniform temperature is observed at 35mm exhaust diameter for the lean, stoichiometric and rich conditions likely due to moderate recirculation, enough to sustain the combustion at flameless mode.



(c)

**Fig. 7.** Plot of temperature against axial burner distance for (a) lean condition, (b) stoichiometric condition and (c) rich condition

## 4. Conclusion

The work studied experimentally the effect of recirculation ratio in an asymmetric swirling combustor operating in flameless mode. By understanding and optimizing recirculation ratio, engineers can develop combustion systems that can offer improved efficiency, reduced emission and enhanced operational characteristics, contributing to sustainable and clean energy conversion. Three (3) different exhaust diameters were used at 30mm, 35mm and 40mm for three (3) different conditions, i.e., lean, stoichiometric and rich condition so as to determine the optimum condition for the combustor. From the results obtained, it can be concluded that exhaust diameter has significant effect on the recirculation ratio of the combustor at any instant condition. 30mm exhaust diameter produced the highest recirculation ratio at lean, stoichiometric and rich condition with values of 7.21 at lean, 7.53 at stoichiometry and 6.44 at rich condition. Pollutant emission NOx and CO were observed to be lowest at 30mm exhaust diameter in lean condition with 2ppm and 118ppm due to high recirculation and complete combustion. Uniform temperature was recorded nearly in all the conditions due to absence of flame signature and minimal fluctuation of temperature in flameless combustion and wider combustion zone, thereby subjecting the chamber to the same heating profile over time and enhancing efficiency. It can therefore be concluded that the optimum condition for the asymmetric swirling combustor operating in flameless mode is recirculation ratio of 7.5 in lean condition which gives better performance and lower emission.

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