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Experimental study of the impact of flue gas recirculation on the combustion characteristics of LPG diffusion flame

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ABSTRACT

This study aimed to experimentally evaluate the impact of the Flue Gas Recirculation (FGR) on the combustion parameters of a diffusion flame of Liquefied Petroleum Gas (LPG) within a cylindrical combustor model. A flue gas recirculation system is employed to facilitate the recirculation of combustion gases. The combustion gases are then blended with the primary air stream to mitigate the emissions of nitrogen monoxide (NO) that arises from the elevated temperature within the combustor tube. For all operating settings, the Air to Fuel mass Ratio (AFR), Equivalency Ratio (Φ), swirl number (S), and Thermal Load (T.L.) were fixed at 40, 0.4, 0.5, and 21 kW, respectively. The experimental testing rig consists of a gaseous fuel line, an airline, a flue gas recirculation line, a burner head, and combustor tube. The impact of the varying FGR percentages, which are 0, 5, 8, 11, 14, 17, and 20 % are investigated. The experimentally observed and reported data include temperature distributions, exhaust species concentrations, dimensionless visible flame length, and heat transfer to cooling water. The findings showed different outcomes were seen when the flue gas recirculation fraction was increased from 0 % to 20 %. This led to a decrease in the axial flame temperature, flame length, heat transfer to cooling water, NO concentration, and O2 concentration. On the other hand, when the flue gas recirculation % rose, the concentrations of CO2 and CO showed a rise.

Keywords: *Recirculation of flue gas, Diffusion flame, Reduction of NOx*.

1. Introduction

The combustion processes, which encompass the burning of fossil fuels are our society's primary energy source. Unfortunately, the consumption of fossil fuels is increasing at a rapid pace. These fuels are necessary for a variety of uses, including transportation, industrial combustion in furnaces, power generation, boilers, and home heating. However, this combustion leads to the release of harmful pollutants, including nitrogen oxides (NOx), carbon monoxide (CO), soot, and unburned hydrocarbons (HC). In large urban areas, these flue gas emissions from district heating facilities harm human health and the environment. Nitrogen oxides are extremely detrimental. They are recognized as the predominant gaseous pollutants emitted from the combustion of natural gas [1-4].

In response to this concern, numerous researchers have conducted extensive research to find ways to decrease NOx emissions from utility and industrial boilers. Consequently, modifications have been implemented to the burners of these boilers to meet the progressively stringent emissions standards. As a result, there has been a widespread acceptance of burners that improve combustion efficiency and effectively lower emissions of NOx in most newly manufactured boilers. Extensive research has been conducted to prevent the generation of NOx, resulting in the development of various combustion technologies. These include better air-fuel mixing, split flame, lean-burn premixed combustion, fuel/air staging, and FGR. Among these techniques, FGR is one of the most widely utilized methods to reduce NOx emissions from combustion [5-8]. Two main forms of recirculation are used in FGR: internal and external. Flue gas is recirculated outside of the combustor and added to the combustion air in this research, which uses external recirculation.

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Abdelaal et al. [9] examined how FGR affects oxyfuel burning. The outcome demonstrates that the flame grows shorter, more steady, and changes from yellow to blue as the FGR ratio increases. As the FGR ratio rises to the blow-off condition, the concentration of NOx reduces, but the concentration of carbon monoxide (CO) also rises. The efficiency of the boiler in oxy-combustion was investigated by Kim et al [10]. The combustor's input O_2 concentration rose from 34.7% to 38.5% by volume. As a result, the system's efficiency reached a remarkable value of 99.6%, resulting in a net efficiency of 43.1%. Many investigators have separately analyzed the recirculation of different exhaust gases in oxy-combustion [11-12].

Pan et al. [13] examined how FGR affected industrial premixed burners' combustion stability and NOx emissions. They found an 85% decrease in NOx emissions when FGR was increased from 0% to 20%. However, they also found that combustion instability occurred when the FGR exceeded 10%.

The effect of FGR on premixed CH_4 /air flames, on NOx and flame temperature are studied and compared to cases without FGR by Lipardi et al. [14]. The findings suggest that dilution-induced decreases in oxygen concentration result in a fall in the reference flame speed. Furthermore, an increase in nitric oxide (NO) generation inside the flame front is associated with this decrease in flame reactivity. However, the decreased oxygen content lowers the rate at which thermal NO is formed, lowering NOx *concentration. Heng Li et al. [15] have examined the flame* properties of premixed methane at different dilutions. The simulation results indicate that as the concentration of added gases (N_2, H_2O, and CO_2) increases in the oxygen/methane flame, both the adiabatic flame temperature and laminar burning velocity decrease gradually.

The effect of wet and dry FGR is studied by Ditaranto et al. [16]. The results revealed that wet flue gas recirculation (WFGD) results in lower NOx emissions compared to dry flue gas recirculation (DFGD) due to the combined thermal and kinetic effects, where the increased heat capacity contributes to the reduction in NOx. The decrease in flame temperature plays a significant role in achieving low NOx levels. Additionally, Kim et al. [17] compared the effects of dry and wet flue gas recirculation (FGR) in a pressurized oxy-combustion power plant in order to see how they affected efficiency. The results showed that wet FGR attained an efficiency around 3.5% greater than dry FGR. Additionally, because of the reduced NO content in the wet FGR system, nitrogen oxides (NOx) removal efficiency was shown to be greater in that research. Comparing the power plant system with wet FGR to a first-generation oxy-combustion power plant running at atmospheric pressure, there was a noticeable 10% increase in net efficiency.

The effects of External Flue Gas Recirculation (EFGR) and Internal Flue Gas Recirculation (IFGR) on flame properties are the subject of numerous experimental and numerical studies [18-21]. There are noticeable drops in NOx emissions when the IFGR is raised. The decrease in thermal-type NOx generation is the cause of this drop in NOx emissions. Compared to standard combustion circumstances, the maximum flame temperature dropped as the EFGR ratio grew.

Excess air impact on temperature and NOx emissions is investigated [22-23]. The result indicated that the FGR with excess air coefficient causes better temperature uniformity. The NOx emission decreases when FGR is between 28-40% and an excess air coefficient of 1.15. The emission level increases at an FGR of 15 % with an equivalence ratio of 0.9. Thermal efficiency increased by about 4.9% as the heat transfer rate increased. Elevating FGR up to 20 % tends to increase in CO emission level.

The effect of FGR in a boiler was investigated by Liu et al. [24]. It is observed that by increasing the flue gas recirculation (FGR) to 16.43%, there is an increase in heat transfer, leading to a decrease in temperature and oxygen content. The reduction of NOx emissions is decreased by approximately 40%. The effect of FGR in a double-heat boiler is illustrated by Deng et al. [25]. The results indicate that several changes were observed with higher flue gas recirculation (FGR) levels of up to 20%. The temperature decreased, reducing the concentrations of O_2, CO, and NOx. Pourhoseini et al. [26] conducted a study on the impact of tangential flue gas recirculation (TFGR) using natural gas on axial flame temperature, as well as NOx and CO emissions. The findings revealed that utilizing TFGR enhances the heat transfer characteristics of the flame, which lowers the temperature of the flue gas exiting the furnace. Specifically, at a TFGR ratio of 70%, the rate of NOx emissions was found to be 55% lower compared to a TFGR ratio of 0.

Yu et al. [27] conducted a comparison between air-induced exhaust gas recirculation (EGR) and fuel-induced flue gas recirculation (FGR) in a CH_4/air non-premixed flame. The study found that the Fuel-lined EGR method achieved a reduction rate of approximately 49% in NOx emissions with an FGR ratio of 15%. On the other hand, the air-induced method achieved a maximum reduction rate of approximately 45% with an FGR ratio of 25%. One of the main causes of air pollution is flue gases from gaseous fuel-fired combustion plants. In addition to some species of concern, such as sulfur and nitrogen oxides, these exhaust gases include carbon dioxide (CO_2) quantities. These substances are all undesirable byproducts of power plants. Measurable consequences of climate change are linked to greenhouse gases, particularly CO_2 and N_2O [28].

The majority of LPG is produced via natural gas separation and crude oil refinement. Hydrocarbons like propane (C_3H_8) and butane (C_4H_{10}) make up the majority of LPG. LPG is colorless, odorless, heavier than air, lighter than water, and has a high heating value. Because LPG has a flame temperature of between 1900 and 2000 °C, it may be used as fuel for transportation, industrial facilities, petrochemicals, and domestic cookery. LPG has specific hose safety requirements when used for transportation, when it is compressed into pressurized cylinders further safety requirements have been developed for LPG use in various applications, such kitchen burners and cylinders [1,3,7,8,31,32].

Based on the previous review, significant efforts have been made to improve combustion characteristics by implementing (FGR) and decreasing NO emissions. Recycled flue gases were extracted using a customized compressor. Because of its strong resistance to heat and corrosion, the compressor blade material is appropriate for use in flue gas applications. Therefore, the main objectives of the present study are to investigate the characteristics of the LPG diffusion flames under different FGR percentages (0 %, 5 %, 8 %, 11 %, 14 %, 17 %, and 20 %) at thermal load (T.L.) of 21 kW, air to fuel ratio (AFR) of 40, equivalence ratio of 0.4 and swirl number (S) of 0.5 and their effect on temperature maps, centerline axial temperature, heat transfer to cooling water, dimensionless flame length and species concentrations.

2. Experimental Test Rig

An experimental test rig was developed to find out how FGR affects the LPG diffusion flame combustion characteristics. The FGR ratio is the ratio of the mass recirculated exhaust gas divided to the total mass of flue gas. The experimental test rig consists of an airline, a LPG fuel line, a flue gas recirculation line, a burner head, and a test section (combustor). Fig. 1 shows the experimental test setup. The airline consists of an air blower, a control valve, an air duct, an orifice, a U-tube water manometers, and an air swirler. A globe valve controls and regulates the amount of airflow. To monitor the combustion, air travels through the tube and an aperture that is coupled to a U-tube water manometer.

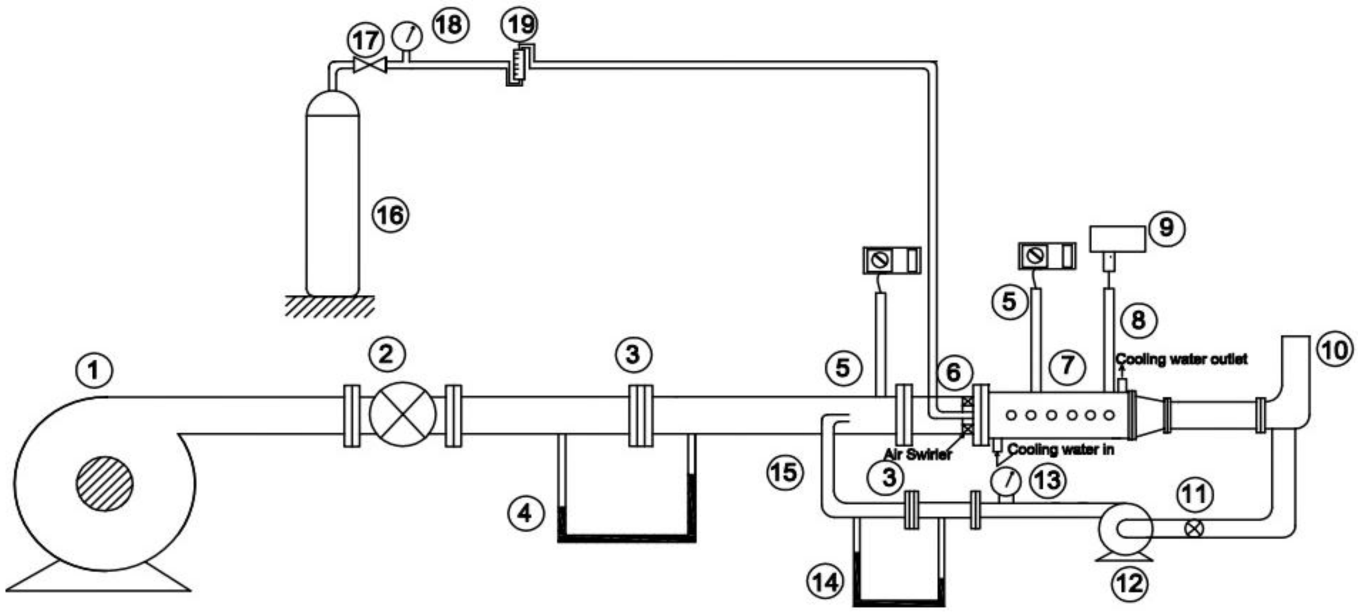
The LPG fuel is composed of 70 % butane and 30 % propane by volume, respectively and is received in a pressurized container. The fuel flows through a pressure regulator valve which is used to maintain a constant pressure in the pressure gauge. The fuel flow rate out of the regulator can be controlled by the fuel control valve and the pressure regulator screw handle. A pressure gauge

is used to measure the pressure inside the fuel container and to help in the observation of pressure during the experiment. The FGR line consists of a control valve, a special air blower, a pressure gauge, a gas tube, an orifice and a U-tube mercury manometer. The
control valve regulates and controls the amount of flue gas. To measure the flue gas flow rate, the flue gas travels through a pipe and an aperture that is attached to a U-tube mercury manometer. The burner consists of a pipe with an inner diameter of 100 mm, with an air swirler is installed inside it. A central fuel tube with 8 mm diameter fuel nozzle at its exit is located inside the burner pipe and is maintained at the center of the air swirler. Fig. 2 displays the burner dimensions and detailed design together with the mixing chamber. To ensure consistent mixing, of combustion air and FGR, the FGR line is placed 1000 mm away from the burner head. The test section is horizontal cylindrical steel tube with an outside
diameter of 150 mm and a length of 500 mm. The test section is water-cooled. There are nine measurement ports along the length of the test section. Each port has an inner diameter of 16 mm used to insert the measuring probes and to allow for flame monitoring. The axial distance between any two adjacent ports, along the combustor, is 50 mm as shown in Fig.3. The temperature was measured, from the combustor's centerline to the wall, by a thermocouple at spots which are 10 mm a part.

A bare wire thermocouple, type R was used in this investigation to measure the local mean temperature. The signal's mean value and the associated gas temperature values were measured, and the results are shown in K as a function of location. An infrared AO2000 series gas analyzer was used to measure the concentration of the gas products of CO_2, CO, and NO. An O_2 measurement Magnos 206 was used to measure the O_2 concentration. Additionally, a rotating vane is used to detect and determine the air and flue gas recirculation velocities.
The measuring ranges and accuracies of the used instruments are illustrated in Table 1

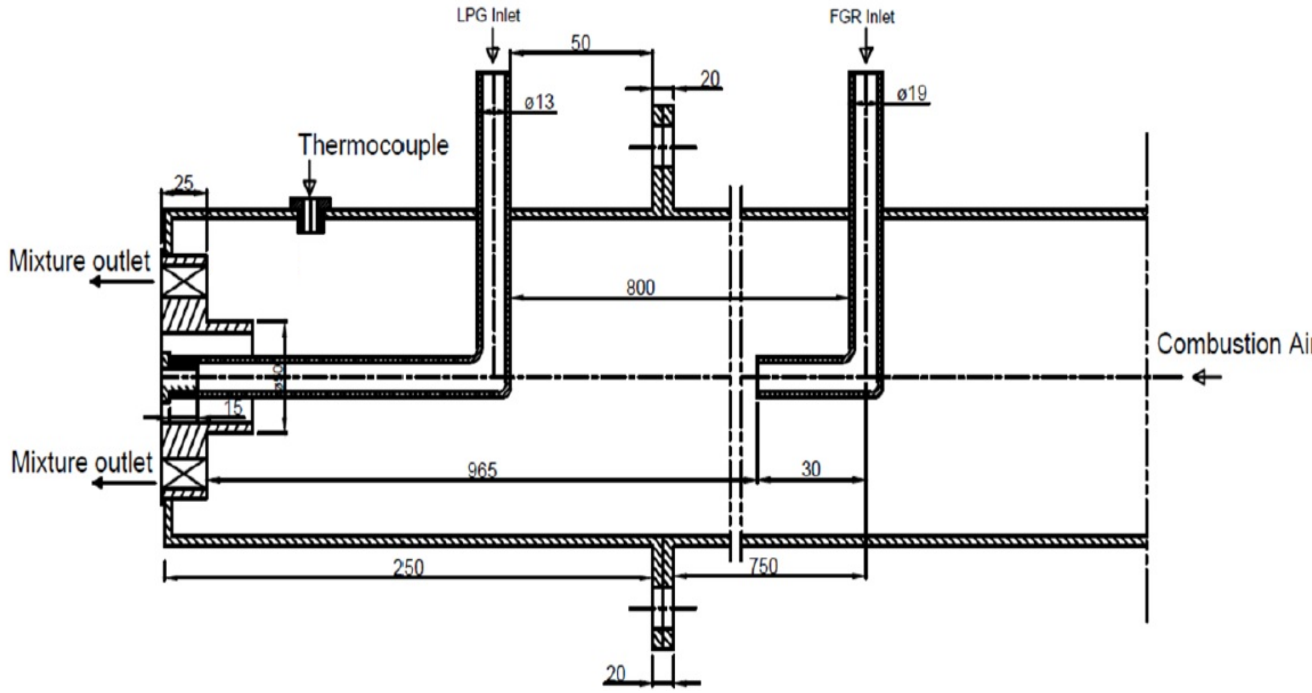
Device		Range	Accuracy	Standard uncertainty
Thermocouple (type R)		-50 to 1760°C	±0.5%	0.6°C or 0.1%
Infrared analyzer gas	CO_2	0 -100 vol. %	1 %	-
	CO	0 - 5 vol. %	1 %	-
	NO	0 - 5000 ppm	1 %	-
	O_2	0 – 21 vol. %	0.5 %	-
Scientific devices rotameter		0.1-1000 L/min	±2% of full scale	-
Dwyer rotameter		5-95 L/min	± 3% of full scale	-
rotating vanes anemometer (Testo 435)		0- 40 m/s	±0.6 m/s	0.2 m/s or 0.5%

Table 1: Measuring instruments ranges and accuracies.



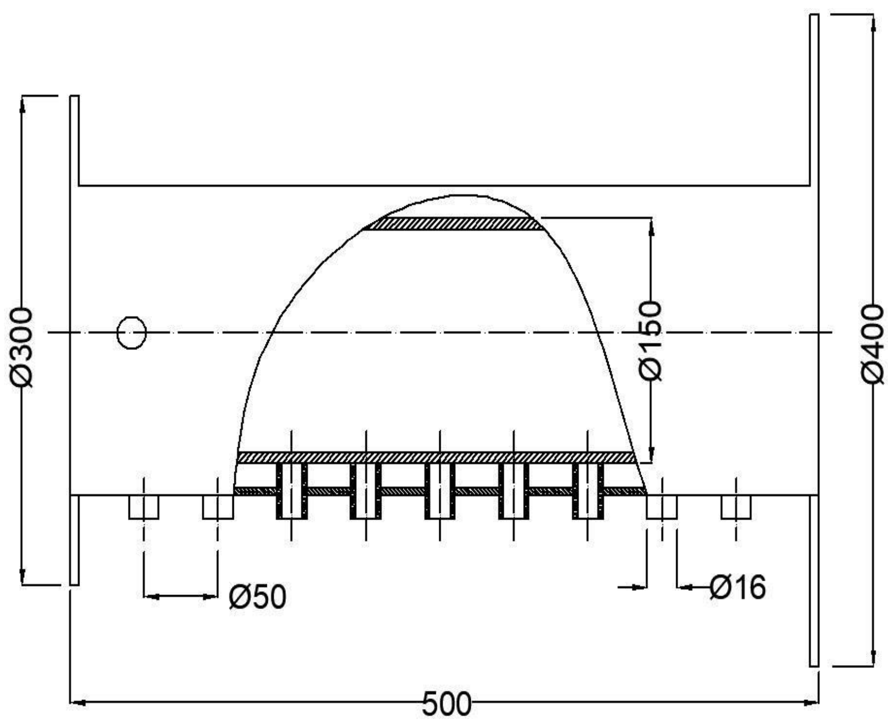
1. Air blower
2. Control valve
3. Orifice
4. U-tube water manometer
5. Thermocouple
6. Burner
7. Combustor
8. Suction probe
9. Data acquisition
10. Chimney
11. Control valve
12. Gas blower
13. Pressure gauge
14. U-tube mercury manometer
15. Flue gas hose
16. LPG cylinder
17. Needle valve
18. LPG pressure gauge
19. Rotameter

Fig.1. The configuration of the experimental test rig



All dimensions in mm

Fig.2 The burner's intricate structure with the mixing chamber



All dimensions in mm

Fig.3 The structure of combustor

3.Results and Discussion

This research examines and evaluates many flame properties, including the temperature pattern, the axial temperature distribution, the amount of heat transmitted to cooling water, the visible flame length, and the species concentration. Those properties were evaluated at different ratios of flue gas recirculation to the combustion air. Typically, those ratios changed from 0% to 20%. The mixture average temperature was found to be around 318K. The values of AFR, Φ, S, and T.L. are 40, 0.4, 0.5, and 21 kW, respectively. Those values were maintained constant throughout all the experiments guarantee consistency. Table 1 shows the different the values of the parameters studied are given in Table 2.

Table 2: The different studied parameters.

FGR, %	AFR	Φ	T.L., kW	S
0, 5, 8, 11, 14, 17, and 20	40	0.4	21	0.5

The equation of the complete combustion of LPG is given by:

$0.3\ C_3H_8 + 0.7\ C_4H_{10} + 6.05\ (O_2+3.76\ N_2) = 3.7\ CO_2 + 4.7\ H_2O + 6.05\ N_2$…………………..…………………….………..(1)

and, the equivalence ratio = $(F/A)_{act} / (F/A)_{theoretical}$

Based on the flue gas density of the combustion products in reference [29], the flue gas density at an average temperature of 318 k was computed. The stated flue gas density of the combustion products in the cited literature is 1.11 kg/m^3 at the standard temperature of T = 273 K. Thus, the density of the flue gas at an average temperature of 318 K may be computed using the ideal gas equation of state for flue gas ($p = \rho_{flue\ gas} RT$), at constant molecular weight or R = 8.314 J / mol.K. as follows:

$\rho_{flue\ gas} /1.11 =273/318$ ……………………..(2)

$\rho_{flue\ gas} = 0.952\ kg/m^3$ ………………………(3)

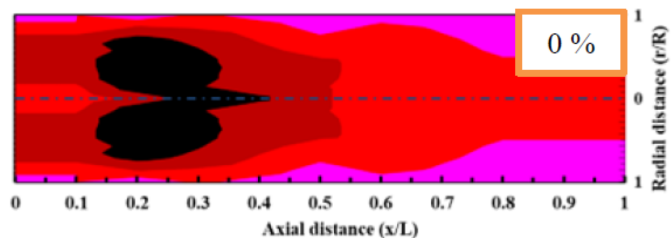
The mass flow rate of FGR is calculated from the following equation:

$\dot{m}_{flue\ gas} = \rho_{flue\ gas} * Q$ ………………………….(4)

where, Q stands for FGR volume flow rate.

3.1 Temperature patterns

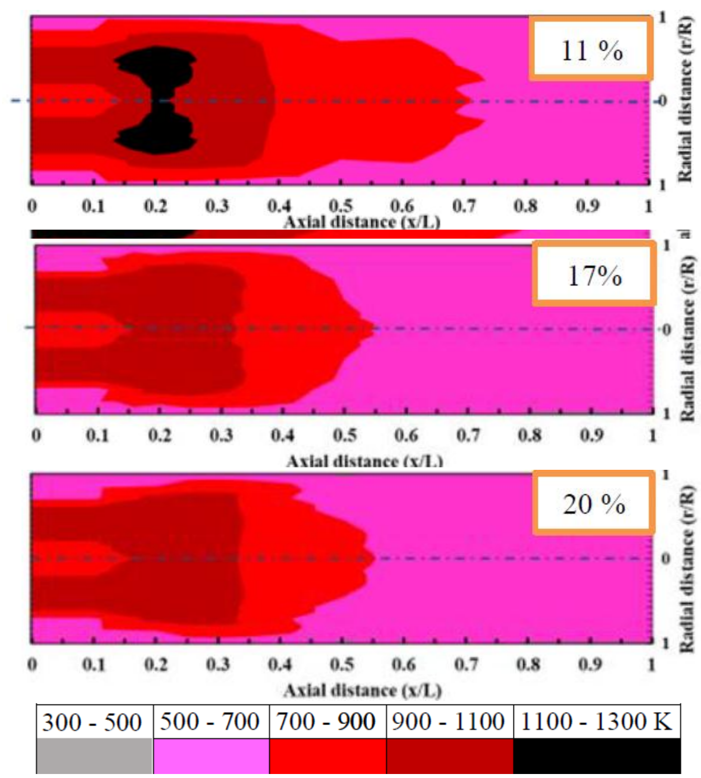
To provide a thorough picture of the temperature patterns, the study measured the inflame temperature distributions in both radial and axial directions. The temperature map was chosen because it gives an accurate picture of the radial and axial temperature distributions inside the combustor tube. Five zones comprise the temperature map, and each zone temperature range is represented by a distinct color. The radial and axial temperature distributions under various operation circumstances were visualized using Excel. Fig. 4 illustrates how temperature maps are affected by the combustion air and flue gas recirculation. The FGR with different percentages of 0 %, 5 %,8 % 11 %, 14 %, 17 %, and 20 % were added to the combustion air. The first map at 0 % represents the temperature map for the normal combustion case (without FGR). The other four maps represent the temperature patterns at FGR percentages of 5, 11, 17 and 20. At the normal combustion (i.e., at 0 %), the high-temperature region which is represented by black color and its temperature ranges from 1100 to 1300 K was happened to occurred between x/L = 0.12 and x/L = 0.43 and the flame length was relatively long. By increasing the FGR percentage from 0 to 20, Fig. (4), the length of the flame decreased while its diameter increased and shifts upstream nearest the burner exit. For FGR percentage higher than 11 % the high-temperature regions disappeared from the temperature map because the temperature levels inside the combustor tube were decreased. In general, the addition of FGR results in generating inert gases, such as CO_2, having varying mass flow rates, which lowers the temperature along the combustor tube. Additionally, the FGR stream enhances the air heat capacity during combustion, improves the air-fuel mixing



rate and lowering the temperature. So, the FGR has an impact on the extent of the high-temperature zone.

Fig.4 Effect of FGR % on the temperature patterns [AFR = 40, Φ = 0.4, T.L. = 21 kW and S = 0.5]

From experiments, the distributions of centerline axial inflame temperature for various FGR percentages are shown in Fig.5 at



AFR of 40, Φ of 0.4, T.L. of 21 kW and S of 0.5. It is observed that the inflame temperature initially increases as the axial distance from the burner increases until it peaks at x/l≈0.3 then it falls with increasing the axial distance. As the FGR percentage increases, the inflame temperature decreases the highest temperature regions migrate upstream resulting in a shorter flame. Since FGR contain inert gases like CO_2, which absorb combustion heat and lower flame temperature, it may be assumed that increasing the FGR percentage causes the maximum temperature to fall.

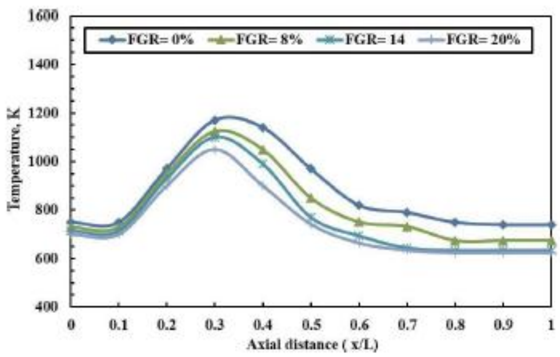


Fig. 5. Effect of FGR % on axial flame temperature [AFR = 40, Φ = 0.4, T.L. = 21 kW and S = 0.5]

3.2 Heat transfer to cooling water

The heat transferred to cooling water can be calculated by:

$$Q_w = \dot{m}_w * cp_w * (T_{wo} - T_{wi}) \quad \text{……………………….(5)}$$

Where, T_{wo} is the cooling water temperature at the outlet (K), T_{wi} is the cooling water temperature at the inlet (K), cp_w is the specific heat of the cooling water (kJ/kg. K), and $\dot{m}_w$ is the mass flow rate of the cooling water (kg/s). A digital thermometer was used to monitor the cooling water temperature at the intake and outflow, while a water rotameter was used to measure the mass flow rate of the cooling water. Although the ratio of the heat transfered between the combustion products and cooling water Q_w/Q_{in} as a fraction of the input thermal load is lowered, there is an enhancement of the convective heat transfer between them due to decreasing direct radiation from the flame as its temperature declines. Figure 6 illustrates the approximately 45% drop in Q_w/Q_{in}.

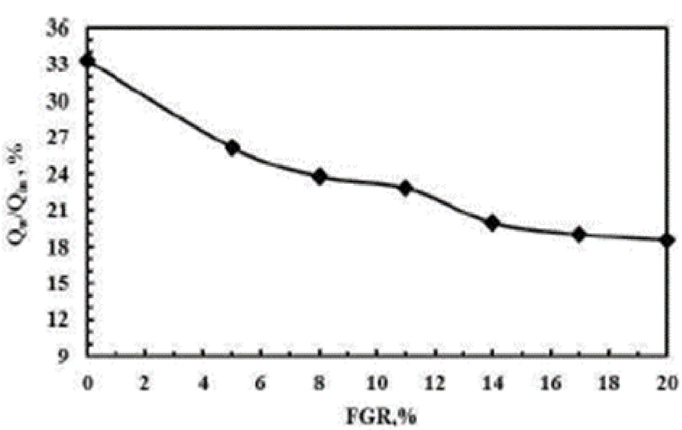


Fig. 6 Effect of FGR on Qw /Qin [AFR = 40, Φ =0.4, T.L. = 21 kW and S = 0.5]

3.3 The dimensionless flame length

Figure 7 shows the impact of FGR on the dimensionless flame length (L_f / L) with an AFR of 40, Φ of 0.4, S of 0.5, and T.L. of 21 kW. It is shown that increasing the FGR percentage from 0 % to 20 % decreases in the ratio of (L_f / L). This occurs because recirculating flue gases reduces the oxygen content due to prior combustion. As a result, increasing flue gas recirculation (FGR) lowers the oxygen concentration in the combustion zone. It is demonstrated that as the FGR% grew from 0 to 20, the L_f / L fell by around 43.3 %.

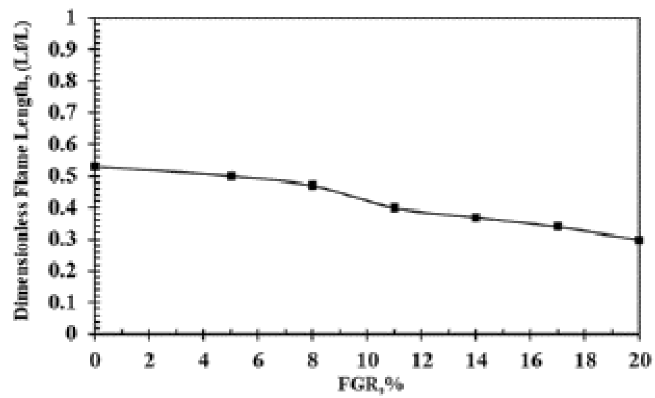


Fig. 7 Effect of FGR % on dimensionless flame length at [AFR =40, Φ =0.4, T.L. =21 kW and S=0.5]

3.4 The species concentrations

FGR is a useful technique for reducing NO [9–12]. Figure 8 shows the relationship between FGR and NO. It can be seen that as the FGR percentage increases, the NO ppm decreases. Adding combustion products to the combustion air results in lower flame temperatures. The inert gases mixed with these products absorb heat, which reduces peak hearth temperatures—a key factor in the formation of NO. Additionally, when flue gas recirculation (FGR) is implemented, the reduced oxygen levels in the combustion zone further contribute to this effect. Since NO formation is highly dependent on the availability of oxygen and this can suppress the formation of NO. Moreover, the oxygen content is reduced as the unburned hydrocarbon with injected FGR reacts with O_2 and produce CO_2. Consequently, the NOx levels are reduced from 90 ppm to 5 ppm. In addition, in the produced NO is reduced by about 44 % when compared to normal combustion. The effects of the FGR percentage on the exhaust O_2, CO_2 and CO and are also shown in Fig.8. It is observed that increasing the FGR percentage causes a decrease in O_2 concentrations by about 36.7 % from normal combustion. As the FGR percentage increases, the mixing rate is enhanced and, therefore, the time required for chemical reactions to diminish is decreased [30-32]. Moreover, the concentration of CO_2 was observed to increase by approximately 63.2 % compared to normal combustion. The concentration of CO is elevated by approximately 39%. From Table 3, it is concluded that utilizing FGR at different percentages causes a remarkable decrease in NO concentration by about 44 % due to the provision of inert gases in the combustion products. Furthermore, there was a drop in temperature within the combustor volume. As a result, the concentration of NO dropped. In the combustion zone, the concentrations of CO and CO_2 are raised by around 63.2 % and

39 %, respectively. There was a about 43.3 % and 34 % decline in the L_f/L and Q_w/Q_{in}, respectively 34 %, respectively.

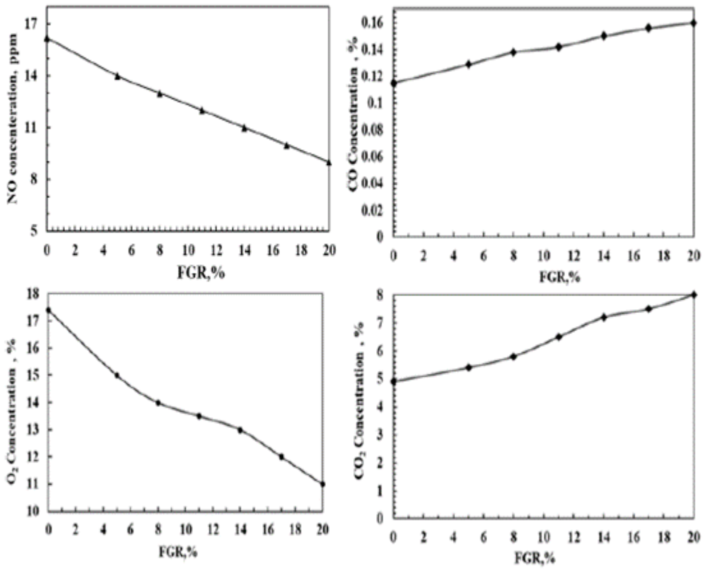


Fig. 8 Effect of FGR on species concentrations [AFR = 40, Φ =0.4, T.L. = 21 kW and S = 0.5].

Table 3: Different LPG diffusion flame characteristics, measured and mean values at different FGR %.

Characteristics	**FGR, %**						
	5	**8**	**11**	**14**	**17**	**20**	**Mean value**
NO, ppm	14	13	12	11	10	9	11.5
CO_2, %	5.4	5.8	6.5	7.2	7.5	8	6.7
CO, %	0.129	0.138	0.143	0.15	0.156	0.164	0.146
O2, %	15	14	13.5	12	12	11	13.08
L_f/L	0.5	0.47	0.4	0.37	0.34	0.3	0.39
Q_w/Q_{in}	26.19	23.8	22.85	20	19.04	18.75	21.74

A comparison between the current study and previous research is shown in Table 4. It is evident from contrasting the current study with other investigations that the FGR has a major impact on the NO reduction. Abdelaal et al. [9] report that when FGR is used up to 40%, the amount of NOx is reduced from 90 ppm to 5 ppm, as well as the flame temperature is dropped by around 25%. According to Kim et al. [11], NO emission exceeds 100 ppm when the FGR ratio increases to 60%. The experimental results showed that the decrease in NO emission in the FGR oxy-fuel combustor had a substantial impact for FGR ratios greater than 40%. According to Yu et al. [23], the application of EGR reduced CO and NOx concentrations and increased thermal efficiency. According to Yu et al. [27], the fuel-induced EGR method's maximum temperature range is found to be restricted, which explains why it has been demonstrated to be more effective than the air-induced EGR method in lowering NOx emission. According to Pan et al. [33], NOx emissions decrease as FGR increases. When FGR was raised from 0% to 20%, the NOx emission roughly dropped by 85%. Moreover, the FGR% range employed in this study coincided with that found in previous studies.

Table 4 A comparison between the present study and the previous works.

References	**FGR %**	**Fuel type**	**investigation**	**conclusions**
The current study	0:20	LPG	Experimental	NO decreased 44 %
Abdelaal et al. [9]	0:40	Kerosene	Experimental	NO decreased 95 %
Kim et al. [11]	0:65	Not existed	Experimental	NO decreased 85 %
Yu et al. [23]	0:20	Methane	Experimental & Numerical	NO decreased 40%
Yu et al. [27]	0:30	CH_4	Experimental	NO decreased 45 %
Pan et al. [33]	10:20	Natural gas	Numerical	NO decreased 85%

4. Conclusions

The results of the present study indicate that the following conclusions can be drawn by adjusting the FGR percentage while maintaining a thermal load of 21 kW, an equivalency ratio of 0.4, a swirl number of 0.5, and an air-to-fuel mass ratio of 40:

The results of present study indicate that the following conclusions may be made by adjusting the FGR % while keeping the thermal load, equivalency ratio, swirl number, and air-to-fuel mass ratio at 40, 0.4, 0.5, and 21 kW, respectively.

- By increasing FGR percentage the high-temperature zones are eliminated and pushed outside along the axial centerline of the combustor tube and upstream towards the burner head.
- By raising FGR percentage from 0 to 20 %, the L_f/L is reduced by around 43.3% and the flame widens.
- At the end of the combustor, there is an increase in CO and CO_2 emissions but a decrease in O_2 and NO concentrations when the FGR percentage is increased from 0 % to 20 %.
- The Q_w/Q_{in} is reduced by around 45 % when the FGR percentage is raised from 0 to 20 %.
- The maximum NO concentration value coincides with the scenario of normal combustion.

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