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An Experimental Study of Combustion Characteristics and Thermal Efficiency of LPG using an Industrial Burner

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ABSTRACT

This research focuses on studying the combustion characteristics of LPG gas using an industrial gas burner, the NU-WAY model STG120/2 S1L 95 from Sweden. A combustion chamber has a cylindrical shape with a length of 185 cm, an internal diameter of 40 cm. Water jackets with a thickness of 5 cm were assembled covering the combustion chamber. To evaluate the thermal efficiency of the system, temperature inlet and outlet of cooling water were measured under steady state. Properties of exhaust gas were measured using flue gas analyzer (Testo350). The results show that the equivalence ratio (ER) significantly affects the flame characteristics, flame temperature, and thermal efficiency. At ER=1, the flame is the longest and light blue, indicating complete combustion and the highest thermal efficiency. At ER=1.1, the flame remains long but has a lower temperature due to insufficient air, resulting in incomplete combustion and reduced energy release. This study helps understand the flame characteristics and combustion efficiency under different conditions, which is crucial for improving efficiency and reducing harmful gas emissions in industrial processes. Additionally, the findings can be applied in the design and control of industrial thermal equipment.

1. Introduction

The energy problem is getting worse due to rising human energy use and the slow depletion of conventional energy sources like coal and oil. In addition, conventional energy sources have a host of negative effects, including acid rain, greenhouse gas emissions, and environmental degradation. To lessen the problems associated with existing energy sources and steer clear of its drawbacks, it is essential to establish some green alternative energy sources. The environmental degradation crisis

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and depletion caused by fossil fuels have prompted the development of clean and renewable energy over the past several decades [1]. Chemical and particulate emissions produced by the combustion of fossil fuels pose a threat to human health. The Paris Agreement's long-term objective [2], COP2, is to limit the average global temperature increase to less than 2°C above pre-industrial levels [3, 4]. This objective requires significantly reducing greenhouse gas emissions from the energy production sectors [5-7]. Since the early 2000s, wind and solar power have been developed to produce clean, low-carbon energy [8, 9], while both are intermittent.

As demonstrated in Table 1, LPG has many suitable properties that make it one of the most widely used fuels in homes, businesses, and transportation. It also offers many benefits to users, including complete combustion during use, which results in low emissions and soot production and safety [10-12]. Due to these factors, LPG is in great demand; in 2014, the United States and Japan consumed around 86,700 and 28,700 tons of LPG each day, respectively, while more than 85% of domestic fuel in India came from LPG [13]. The World LPG Association projects that the expansion of the economy will result in a compound annual growth rate of 3.5% in LPG usage in the global industry between 2022 and 2027. With a 45% market share, Asia Pacific leads the world, followed by North America with a 25% share. In these regions, LPG is utilized for both e-commerce and power generation. With a 20% market share, Europe comes in third place for LPG use in cooking and heating [14]. The United Nations Environment Programme (UNEP) reported that worldwide LPG emissions contributed 1.3 Gt CO_2 in 2020, or 3% of greenhouse gas emissions. primarily from the production (15%) and combustion of LPG (85%). About 100 Mt of CO are emitted by the LPG business; 80 percent come from combustion and 20 percent are produced. Adoption of best practices and technology might reduce LPG CO_2 emissions to 1.2 Gt, preventing global warming by 0.1 °C by 2050 [15]. In Thailand, the monthly usage of LPG for households is roughly 185,000 tons, while the monthly consumption for industries is roughly 57,000 tons [16]. The amount of LPG used generally tends to rise quickly. Despite being launched as a sustainable energy alternative to LPG, biomethane's energy and flame temperature are lower than those of LPG [17], hence both need to be improved.

Thus, it is crucial to study the best way to burn LPG in order to increase efficiency. The purpose of this research is to use experimentation to examine the LPG combustion characteristics, including temperature and flame characteristics, thermal efficiency, and exhaust gas analyze using an industrial burner.

Table1
Overview of LPG properties [18]

Properties	Range of use
Stoichiometric ratio (air–fuel ratio)	15.5:1 by mass, 23.9:1 by volume
Low heating value (LHV)	28.06 MJ/L
Utilized phase	Vapor
Flame propagation speed	0.5 m/s
Autoignition temperature	405–407 °C

2. Methodology
2.1 Experimental setup

Figure 1 - 3 depict the experimental setup and industrial burner used to study gaseous fuel combustion. A combustion chamber has a cylindrical shape with a length of 185 cm, an internal diameter of 40 cm, and an external diameter of 50 cm. The primary elements of this experimental

setup consist of an industrial gas burner NU-WAY model STG120/2 S1L 95 (Sweden) as shown in Figure 3, an air and fuel supply system, a U-type manometer, a pressure regulator, and a stainless steel combustion chamber with water jackets as a flowing water system with nine channels to evaluate thermal efficiency of combustion. Each channel has a flow meter to measure the water flow rate and the temperature of the inlet and outlet water with thermocouples. This experimental setup was designed following the work of Ahmed Mahfouz et al. [19].

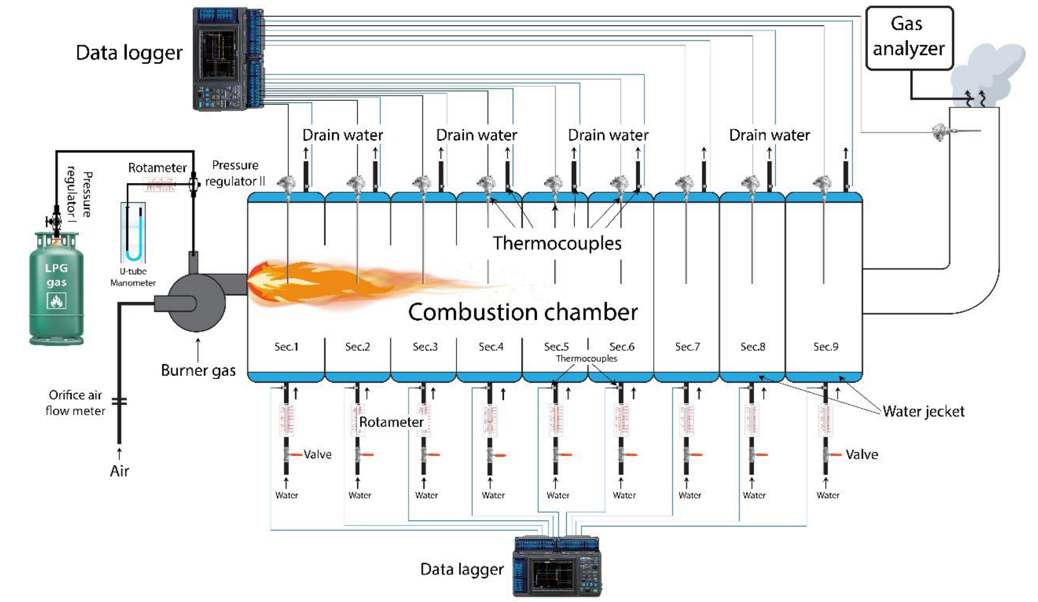

Fig.1. An experimental setup diagram for the investigation of gaseous fuels

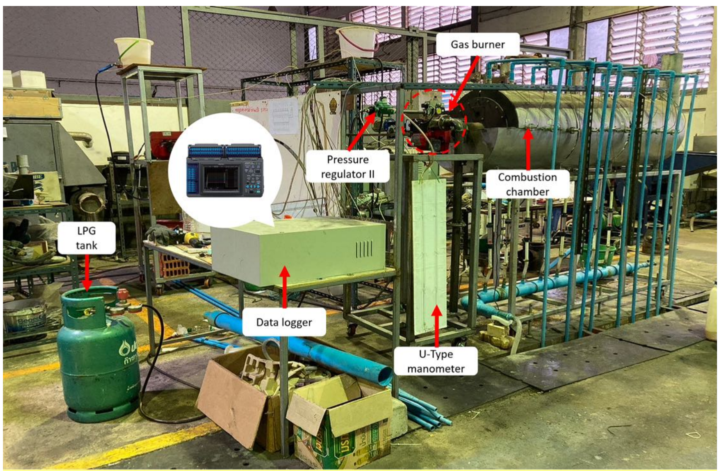

Fig. 2. A photo of combustion chamber

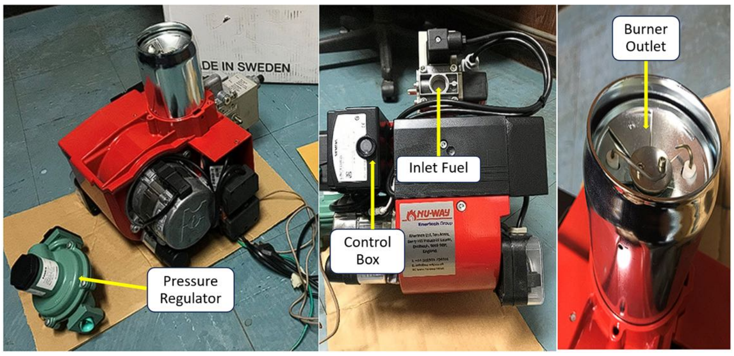

Fig. 3. Industrial gas burner NU-WAY model STG120/2 (Sweden)

2.2 Experimental parameters and thermal efficiency calculation

The equivalence ratio (ER) in this study is dependent on the mass flow rate of fuel and air. It is adjusted to be in the range of ER=0.7-1.1 by maintaining a constant mass flow rate of fuel and modifying the air mass flow rate. Table 2 shows the specifics of the fuel and air parameters. The temperature of the water in the inlet and outlet is monitored by thermocouples installed at each of the nine channels in the inlet and outlet pipes, with the water flow rate being adjusted to 240 LPH during the experiment. An arm of thermocouples that are positioned in the combustion chamber and extends into the chamber's centerline is used to measure the flame temperature. The temperature data was recorded every minute using a Hioki LR8400-20 (Japan).

Table 2
The details of fuel and air calculation

ER	(AF)actual	$\dot{m}_{air}$ (kg/s)	$\dot{m}_{fuel}$ (kg/s)	Velocity air (m/s)	Velocity fuel (m/s)
0.7	22.22667	0.025725316	0.001157407	17.56518	1.85373
0.8	19.44834	0.022509652	0.001157407	15.36953	1.85373
0.9	17.28741	0.020008579	0.001157407	13.66180	1.85373
1	15.55867	0.018007721	0.001157407	12.29562	1.85373
1.1	14.14425	0.016370656	0.001157407	11.17784	1.85373

A flue gas analyzer (TESTO 350) is used to measure the flue gas. The range in which the experiment will be carried out is ER = 0.7 -1.1. In order to calculate the effectiveness of providing heat energy to the cooling system, LPG gas would be burned in the combustion chamber according to the thermal efficiency calculated by the following equation [19], [20]:

$$\eta = \frac{M_w \times C_{pw}(T_{wo} - T_{wi})}{M_f \times C.V_f}$$

Where;

η Thermal efficiency
M_w Mass flow rate of water, kg/s.
C_{pw} Specific heat at constant water pressure, kJ/kg. K.
T_{wo} Temperature outlet of water, K.
T_{wi} Temperature inlet of water, K.
M_f Mass flow rate of fuel, kg/s.
$C.V_f$ Heating value of fuel, kJ/kg.

3. Results

3.1 Flame Characteristics

Figure 4 shows the characteristics of flames from LPG fuel combustion using an industrial gas burner. The flame characteristics were captured using a digital camera. The results show that the flame characteristics like jet discharging from inlet and flowing to outlet of combustion chamber. The equivalence ratio is a crucial variable affecting the flame characteristics, representing the mixture of air and fuel in the combustion process. At ER=0.7, the flame is dark blue and short, indicating combustion with less fuel than air, and the flame density occurs only at the burner head. At ER=0.8, the flame starts to lengthen and becomes lighter blue. At ER=0.9, the flame becomes longer and the blue color start to fade. At ER=1, the flame is the longest and light blue, indicating complete combustion (stoichiometric mixture). The flame at ER=1.1 is the longest but has a lower temperature than ER=1 due to excess air, leading to reduce energy release. The increased air help disperse heat better but lowers the flame temperature and lengthens the flame. Air contains 79% nitrogen, which acts as an inert component in the combustion reaction. Therefore, reducing the air also reduces the nitrogen.

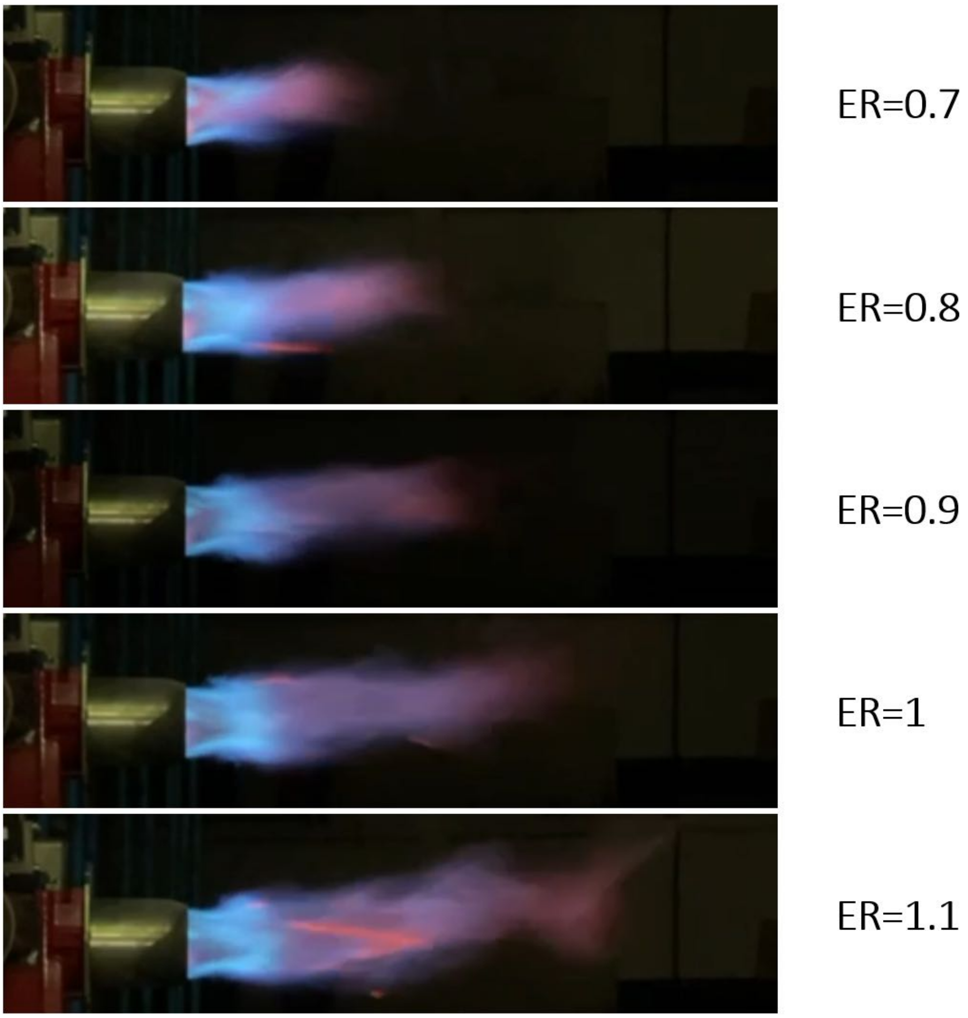

Fig. 4. Flame characteristics of the experiment

3.2 Flame temperature

The temperature of LPG fuel combustion at the centerline of combustion chamber is shown in Figure 5. For all ERs, the trends of temperature are high at the outlet of the burner and decrease suddenly in position of 1.5 – 3. This high temperature range is a flaming zone as shown previously in Figure 4. The trends of temperature decrease gradually in position of 3 – 6 and become nearly constant in position of 6 – 3. This lower temperature range is a flue gas zone which has no chemical reaction. Because of complete combustion and the identical air-fuel ratio, it is evident that ER=1 has the highest temperature at positions 1.5 to 6 in graph. At ER=1.1, the temperature at all positions is lower than the case of ER=1 (Accept at Position 1.5). As a result, as previously mentioned, excess air will reduce the flame temperature, which is useful for industrial heating equipment design and control.

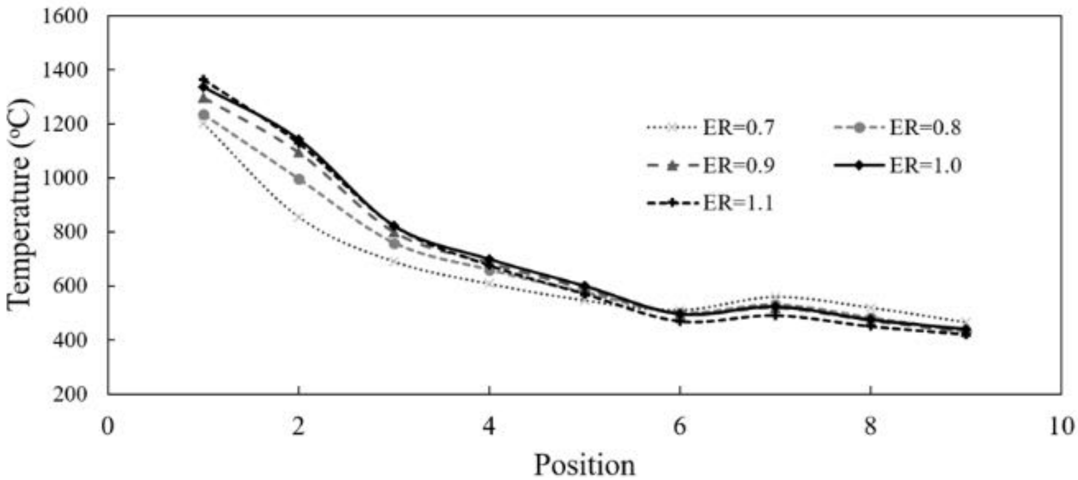

Fig. 5. Temperature along the centerline of combustion chamber (0 position is the outlet of burner)

3.3 Thermal efficiency

According to the experimental results as shown in Figure 6, the thermal efficiency tends to increase continuously in the ER=0.7-1 range until it reaches ER=1, at which point it reduces in the ER=1.1 range. This behavior corresponds to the flame temperature along the combustion chamber's centerline as previously shown in Figure 5. The flame temperature reaches its highest point at ER=1. Therefore, the equivalence ratio is an important variable in changing the thermal efficiency. The air contains 79% nitrogen, therefore as the ratio of air increases, the thermal efficiency decreases. Thus, increasing the nitrogen will also include adding air. As previously indicated, nitrogen is considered as a retardant for the combustion reaction. Also, complete combustion and efficient heat a dispersion inside the combustion chamber results in the highest thermal efficiency when the air-fuel ratio is equal.

In this research, the experimental results from the study by Ahmed Mahfouz et al. [20] were compared. It was observed that the maximum thermal efficiency at an ER below 1 was due to the use of diesel oil, which is liquid phase. Therefore, combustion required air to facilitate atomization. However, in this research, LPG, which is in a gaseous phase, was used, resulting in more complete combustion with less air required, as shown in Figure 6.

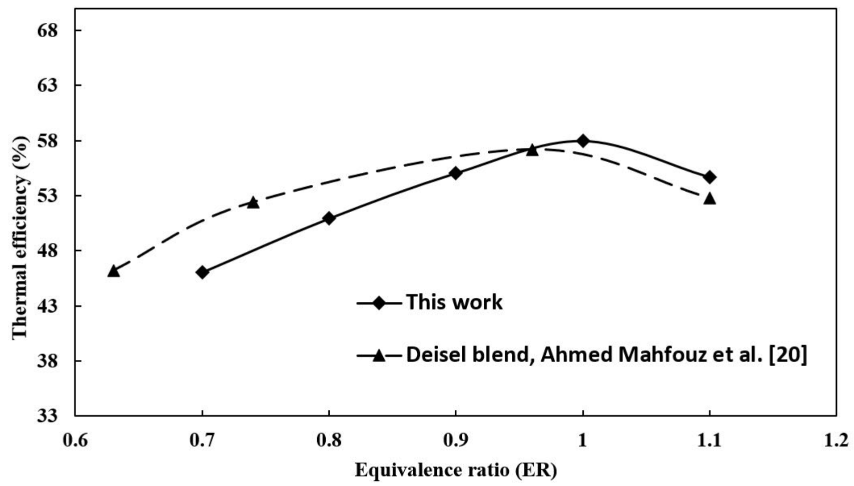

Fig. 6. The thermal efficiency of LPG combustion from this study compared to Diesel blend combustion (Ahmed Mahfouz et al. [20])

3.4 Properties of exhaust gas

In this research, the properties of exhaust gases are shown in Figure 7. From Figure 7(a), which shows the concentration of oxygen (O_2) versus the equivalence ratio (ER), it can be seen that oxygen is at its lowest at ER=1. This is because an equivalence ratio of 1 means there is enough oxygen to completely combust the fuel without any excess oxygen or fuel. This condition is known as complete combustion, resulting in the lowest oxygen concentration at this point. At ER=0.7, there is excess oxygen compared to the amount of fuel, leading to remaining residual oxygen in the exhaust gases.

From Figure 7(b), at ER=1, the fuel and oxygen ratio are perfectly balanced, leading to complete combustion, which produces the highest amount of carbon dioxide (CO_2). At ER less than 1, the combustion temperature is lower, reducing CO_2 formation due to incomplete combustion and insufficient temperature for high CO_2 production.

From Figure 7(c), which shows the concentration of carbon monoxide (CO) versus the equivalence ratio (ER), it can be seen that at ER=1, combustion is most complete due to sufficient oxygen for complete fuel combustion, resulting in the lowest CO levels. At ER less than 1, there is excess oxygen compared to the amount of fuel, leading to incomplete combustion and higher CO levels. At ER greater than 1, there is excess fuel compared to the amount of oxygen, leading to incomplete combustion and higher CO levels due to unburned fuel.

From Figure 7(d), at ER=1, combustion occurs most completely, resulting in a higher combustion chamber temperature. This high temperature is a significant factor in the formation of NO_x, as nitrogen and oxygen in the air react at high temperatures. Complete combustion leads to high temperatures and sufficient oxygen for NO_x formation. At ER less than 1, there is excess oxygen compared to the amount of fuel, leading to incomplete combustion and lower combustion temperatures, which reduce NO_x formation.

This information helps to understand the impact of changing the equivalence ratio on the production of various gases during LPG combustion. It is important for improving the combustion process to reduce the emission of harmful gases.

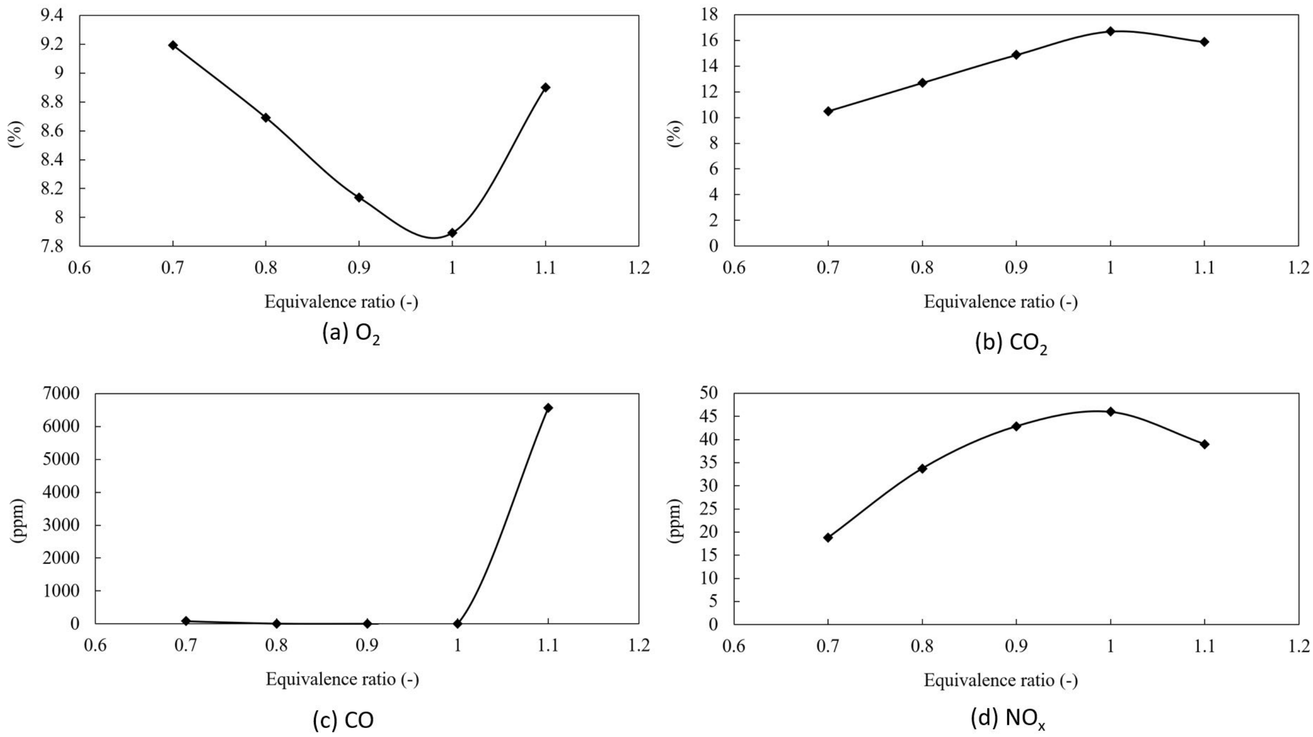

Fig. 7 The properties of exhaust gases from LPG combustion at ER=0.7 to 1.1

4. Conclusions

From the study of the combustion of LPG fuel with an industrial gas burner, the main findings outlined as follows:

(1) At ER=1, the flame is the longest and has a light blue color, indicating complete combustion (optimal air-fuel ratio). At ER=1.1, the flame is still long but has a lower temperature due to excess air, leading to incomplete combustion and reduced energy release.

(2) The highest temperature is at ER=1 due to complete combustion and the optimal air-fuel ratio. The temperature decreases with excess air because nitrogen in the air acts as a combustion inhibitor.

(3) The highest thermal efficiency is at ER=1 and decreases at ER=1.1 due to incomplete combustion and poor heat distribution.

(4) At ER=1, combustion is most complete, resulting in the highest CO_2 production and the lowest CO production. At ER>1, combustion is incomplete, leading to higher CO production.

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