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An Investigation of the Effect of Propylene Gas Flame on Emissions and Temperature Distribution of a Preheated Metal Plate

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Abstract: This study investigates the effect of the propylene gas flame on the emissions and temperature distribution of the metal plate during the preheating process. Experimental tests were carried out using a preheating system with a cylindrical chamber for emissions measurement and a metal plate placed near the torch head. Emissions were measured using a gas analyzer, while the temperature distribution of the metal plate was measured using an infrared thermal camera and thermocouples. The findings reveal that the emissions decrease as the equivalence ratio is increased as it approaches a ratio of 1. However, when the appropriate equivalence ratio is reached, NO_x emissions will rise and then gradually fall. The peak temperature of propane fuel is higher than that of other fuels because of the concentrated flame. Propane fuel can achieve a peak temperature of 347.65 °C, surpassing both propylene fuel (275.45 °C) and acetylene fuel (335.45 °C). Using a propylene gas flame results in a reduction in emissions of carbon monoxide and nitrogen oxides compared to a propane flame. But, acetylene fuel produces the most NO_x emissions, reaching 450.79 ppm for the experimental conditions. Additionally, the temperature distribution of the preheated metal plate was more uniform with the propylene gas flame, indicating improved heat transfer. However, the peak temperature of the metal plate was slightly lower when using the propylene gas flame.

Keywords: propylene gas flame; equivalence ratio; preheated metal plate; emissions; temperature distribution

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1. Introduction

Preheating is a technique that involves providing heat to a metal plate and is frequently used in industrial processes, including preheating metal before welding and glass manufacturing [1,2]. The use of gas flames for the heating and processing of metals is a widely adopted industrial practice. Propylene gas, in particular, is known for its high energy density, which makes it a popular choice for many industrial applications. However, the use of propylene gas flames in metal processing can have significant environmental impacts, such as the release of harmful emissions into the atmosphere. To address this issue, there is a growing need to better understand the effects of propylene gas flames on the temperature distribution and emissions when heating metal plates [3]. The ratio of the distance between the burner head and the metal plate to the nozzle diameter, the Reynolds number, and the equivalence ratio are a few factors that have a substantial impact on the heat transfer properties of flame. Out of these factors, the equivalence ratio has a very significant effect on the heat transfer of the flame [4].

Numerous studies have been carried out on the heat transfer properties of different flames using analytical and numerical simulation techniques, including computational fluid dynamics (CFD) [4–6]. Liu et al. [7] and Zhen et al. [8] examined how a premixed hydrogen–liquefied petroleum gas (LPG) flame's heat transmission properties changed with hydrogen concentration. According to their findings, relatively high hydrogen concentrations caused a rise in combustion temperature and NO_x production but a decrease in

CO emission. Additionally, they evaluated that the LPG-H_2 and CH_4-H_2 mixes showed improved flame heat transfer with the addition of hydrogen. For a particular hydrogen concentration, the CH_4-H_2 mixture had a higher rate of heat transfer than LPG-H_2.

Several studies have investigated the impact of gas flames on emissions and temperature distributions in metal processing. For instance, Kandilli et al. [9] investigated the effect of natural gas flames on the thermal and environmental performance of a metallic honeycomb monolith. The study found that the use of natural gas flames led to significant emissions of CO, NO_x, and PM. Another study by Wang et al. [10] investigated the effect of propane gas flames on the thermal and environmental performance of a rotary kiln. The study found that the use of propane gas flames resulted in high emissions of CO and NO_x. A study by Zulkefli et al. [11] investigated the effects of LPG flames on the emission of NO_x and CO from a stainless-steel plate. The study found that the emission of NO_x and CO increased with increasing flame temperature, and the emissions were more significant at the edge of the flame than in the center. Another study by Yao-Yao Wang et al. [12] investigated the impact of preheating on the surface quality and corrosion resistance of 316L stainless steel plates that were cut by laser. The authors conducted experiments where the stainless-steel plates were preheated to different temperatures before being cut with a laser. They then analyzed the surface qualities and corrosion resistances of the plates. The study found that preheating the plates to a specific temperature range resulted in improved surface quality and corrosion resistance. The study conducted by Bader A. Alfarraj et al. [13] investigated the emissions and performance of conventional liquefied petroleum gas (LPG) cookstove burners. The results showed that the emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM) were found to be higher than the limits set by regulatory agencies. The study also found that the performance of the burners was affected by multiple factors, including the LPG pressure, air–fuel ratio, and burner diameter.

In the context of propylene gas flames, several studies have investigated their impact on emissions and temperature distribution. For example, A.T. Hartlieb et al. [14] investigated the impact of a quartz nozzle on the structure and temperature of a propene flame. Their results indicate that the nozzle can enhance mixing and improve the homogeneity of the flame, leading to a reduction in the required flame temperature. Specifically, the use of the nozzle results in a shift towards fuel-lean combustion, which reduces the temperature in the flame front and promotes complete combustion. The findings suggest that the use of a sampling quartz nozzle could be a viable strategy for controlling the temperature and improving the efficiency of low-pressure propylene (propene) flames. Krishna C. Kalvakala et al. [15] investigated the effects of oxygen enrichment and fuel unsaturation on soot and NO_x emissions in different flames, including propene. The study found that increasing the oxygen concentration in the combustion air led to a decrease in soot emissions in propene flames. However, the increase in oxygen concentration also led to an increase in NO_x emissions in propene flames. Additionally, the study found that fuel unsaturation, such as in propene, led to higher soot emissions compared to saturated fuels like propane. Overall, the results suggest that the combustion of propene can lead to significant emissions of both soot and NO_x, which should be considered in developing effective emission reduction strategies.

While these studies provide insights into the effects of gas flames on metal surfaces [16–20], further research is needed to investigate the specific effects of propylene gas flames on the temperature distribution and emissions of metal plates. Moreover, the impact of the heat transfer characteristics on temperature distribution and thermal efficiency during combustion with a specific focus on NO_x emissions have been extensively studied to date. However, none of the studies have highlighted the effect of the equivalence ratio on the temperature distribution and NO_x emissions.

The current study aims to address this gap by investigating the interaction between propylene gas flames and metal plates and exploring the effects of the flame on temperature distribution and associated emissions. In summary, previous research has investigated the

effects of gas flames on metal surfaces, including heat transfer characteristics, emissions, and surface quality [21–25]. However, there is a need for further research to investigate the specific effects of propylene gas flames on the temperature distribution and emissions of flame in heating metal plates, which is the focus of the current study. The findings of this research could contribute to the widespread adoption and use of propylene gas flames.

2. Methodology

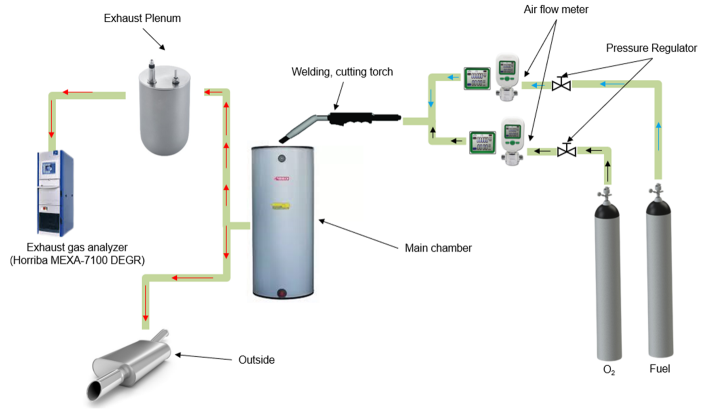
2.1. Experiment Setup

The schematic designs for the exhaust gas measurement system and the experimental setup are shown in Figure 1a,b, respectively. The experimental system consists of 7 components. The feed tanks supply the air and fuel to the torch, and the airflow meters are used to manage the flow rate of the fuel mixture. The torch is employed to burn fuel inside the main chamber, and an exhaust gas chamber is added to maintain the homogeneity of the exhaust gas and enhance the measurement accuracy. The signal from the exhaust gas temperature sensor is analyzed using an exhaust gas analyzer (Horiba MEXA-7100 DEGR). The experiments were performed in a well-ventilated laboratory environment with the torch system placed on a laboratory bench. The gas pressure, flow rate, and torch-to-workpiece distance were adjusted as required. The torch was connected to a regulator, which controlled the pressure of the fuel mixture gas, and it was mounted on a stand to ensure stability during the experiments. The fuel was stored in a feed tank and delivered to the torch system through a flexible hose. The air and fuel pressure were measured using a pressure gauge installed on the regulator, and the gas flow rate was measured using a flow meter installed on the flexible hose. The gas pressure and flow rate were adjusted using the regulator to achieve the desired operating conditions. The tests were conducted under steady-state conditions at near-room temperature conditions of approximately 27 °C.

The experiment setup and schematic design for the preheating procedure are shown in Figure 1c,d, respectively. The metal plate's total width, length, and thickness were 0.5 m, 0.5 m, and 0.03 m, respectively. The distance (d) between the torch outlet and the metal plate was 0.06 m. The gas torch combined fuel and air to facilitate combustion. After leaving the exits of the gas torch, the mixture of fuel and air was ignited, generating a combustion flame for preheating the metal plate. The operating conditions were optimized to achieve the best performance of the torch system using LPG as fuel. The optimal gas pressure and flow rate were determined based on the statistical analysis of the data. The torch-to-metal plate distance was also optimized for optimal performance. The temperature distribution on the reverse side of the metal plate was measured using a TVS-200EX infrared camera, as shown in Figure 1d. To compensate for the lower sensitivity of the infrared camera, an additional thermocouple sensor connected to a Midi logger 840 was employed for temperature measurements. To measure the temperature distribution of a metal plate during the preheating process, 9 thermocouples were positioned on the rear of the plate in three lines. The upper line's temperature was measured using Ch1, 2, and 3, the middle line's temperature was obtained using Ch4, 5, and 6, and the lower line's temperature was measured using Ch7, 8, and 9. The calibration of the equipment is shown in Table 1.

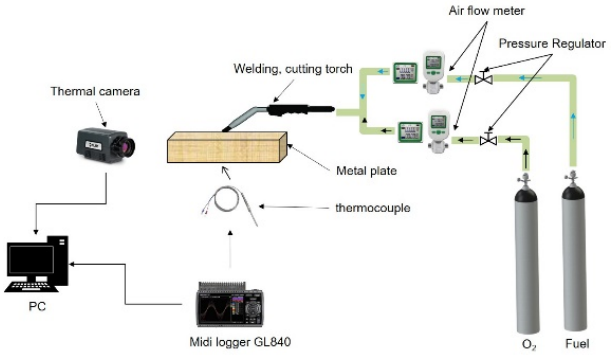
Table 1. Calibration of equipment.

No	Equipment	Producer	Specification
1	Horiba MEXA-7100 DEGR	HORRIBA	CO (0-50 ppm)
			HC (0-10 ppm)
			CO_2 (0-10 ppm)
			NO_x (0-10 ppm)
2	TVS-200EX infrared camera	HANDY	±2%
3	Midi logger GL840	GRAPHTEC	±1.5%

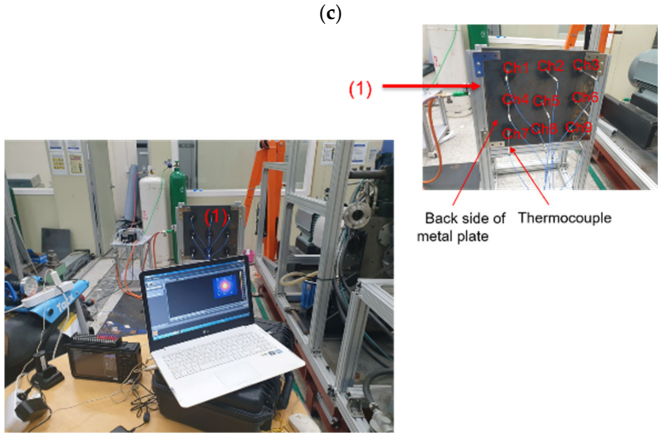


(**a**)

(**b**)



(**c**)



(**d**)

Figure 1. Experimental setup for the torch system. Schematic (**a**) and detail (**b**) setup for exhaust gas measurement, schematic (**c**) and detail (**d**) setup for preheating process.

2.2. Fuel Properties

Propylene gas, a hydrocarbon gas with the chemical formula C_3H_6, is a colorless and flammable gas. It has a high energy density and burns cleanly, making it a popular choice for heating, cutting, and welding. Propylene gas has a lower heating value than natural gas, but it can be used as a substitute for natural gas in many applications. Propylene gas has a high flash point and low volatility, which makes it relatively safe to handle and store.

Propane gas with the chemical formula C_3H_8, lacking the carbon double bond of propene, is a hydrocarbon gas that is commonly used as a fuel for heating and powering vehicles. It is a colorless, odorless gas that is typically stored in pressurized tanks as a liquid. Propane gas has a higher vapor pressure than propylene gas, making it easier to store and transport. Additionally, propane gas has a low flammability range and can be safely used in enclosed spaces with adequate ventilation. It produces relatively low emissions of pollutants.

Acetylene gas is a hydrocarbon with the chemical formula C_2H_2. It has a high energy density and burns with a high-temperature flame, making it suitable for applications that require high heat. However, acetylene gas also has high flammability, which requires special handling and storage precautions. It also has a narrow flammability range and is sensitive to shock and friction. Acetylene gas produces high emissions of pollutants.

In summary, propylene gas, propane gas, and acetylene gas are all useful hydrocarbon fuels with different fuel properties. Propane gas has the highest heating value. Propylene gas has high-energy fuels, while acetylene gas has the highest flame temperature. Detailed information on the properties of these fuels is presented in Table 2.

Table 2. Fuel properties.

Property	Propane	Propylene	Acetylene
Chemical formula	C_3H_8	C_3H_6	C_2H_2
Liquid density (kg/m^3)	509	609	1097
Calorific value (MJ/kg)	46.34	43.9	49.9
Boiling poing (°C)	−42	−47.7	−84.7
Autoignition temperature (°C)	510	438	305
Flame temperature (°C)	1980	2924	3160
Flame speed (m/s)	0.4	0.5	0.15
Stoichiometric air/fuel	15.8	14.5	13.3
Equivalent AFR	15.5	14.7	10.3

The air–fuel equivalence ratio is the ratio of actual air–fuel ratio (AFR) to stoichiometric air–fuel ratio (AFR). An equivalence ratio of 1.0 corresponds to the stoichiometric air–fuel ratio, while rich air–fuel mixtures have an equivalence ratio of <1.0, and lean mixtures have an equivalence ratio of >1.0. There is a direct relationship between equivalence ratio and air–fuel ratio (AFR).

$$AFR = \frac{m_{air}}{m_{fuel}} \quad (1)$$

where

m_{air}: mass of air.
m_{fuel}: mass of fuel.

$$\varnothing = \frac{AFR}{AFR_{stoich}} \quad (2)$$

where

AFR: actual AFR.

AFR_{stoich}: stoichiometric AFR.

3. Result and Discussion

3.1. The Effect of the Equivalence Ratio on Emission Exhaust Gas

The graph presented in Figure 2 provides a visual representation of the relationship between equivalence ratio and total hydrocarbon (THC) emissions. The data indicate that as the equivalence ratio increases, there is a noticeable reduction in THC emissions when the ratio is below 1. This can be attributed to the presence of excess oxygen in the combustion chamber, which facilitates the combustion process and promotes the oxidation of unburned hydrocarbon molecules.

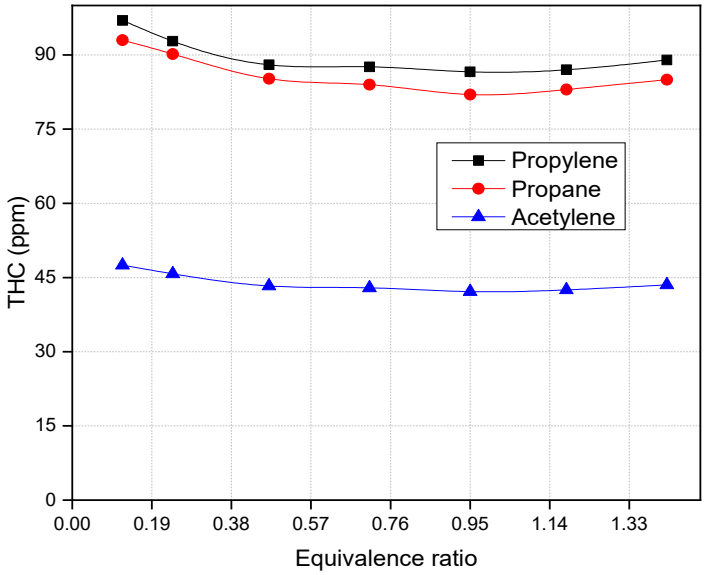


Figure 2. The effect of the equivalence ratio on THC emissions.

However, an interesting observation is made when the equivalence ratio surpasses 1. In this scenario, the THC emissions show a slight increase. This phenomenon can be attributed to the conditions of lean combustion, where the mixture becomes fuel-lean, and there is an insufficient amount of oxygen available for complete combustion. As a result, the combustion process becomes sluggish, leading to an extended combustion time. These factors contribute to the rise in THC emissions.

Furthermore, it is noteworthy that propylene fuel exhibits higher THC emissions compared to propane and acetylene fuels. This can be attributed to the unique combustion characteristics of propylene. The flame rate of propylene is relatively higher, resulting in a shorter burning time. However, this shorter duration may lead to incomplete combustion, where some hydrocarbon molecules are not fully oxidized. As a consequence, propylene fuel emits a greater amount of THCs. These findings align with the fuel properties discussed in Section 2.2, which highlight the combustion behavior and characteristics of the different fuels.

Figure 3 depicts the effect of the equivalence ratio on CO_2 emissions. The findings demonstrate that the carbon dioxide (CO_2) emission decreases as the equivalence ratio values increase. The impact of the equivalence ratio on CO_2 emissions is relatively minimal compared to other emissions. CO_2 is primarily determined by the carbon content in the fuel rather than the equivalence ratio. However, extremely high equivalence ratios can lead to incomplete combustion and increased CO_2 emissions. Aside from that, propane emits significantly more CO_2 than other gases. The fuel is completely burned, leaving behind only carbon dioxide (CO_2) and water. It is evident that propane fuel burns more completely than propylene and acetylene fuel because of its molecular structure and combustion characteristics. Propane gas has a relatively simple chemical structure, which makes it

easier to burn completely in the presence of oxygen. Propane gas also has a narrower flammability range, enabling better control and optimization of conditions for achieving complete combustion.

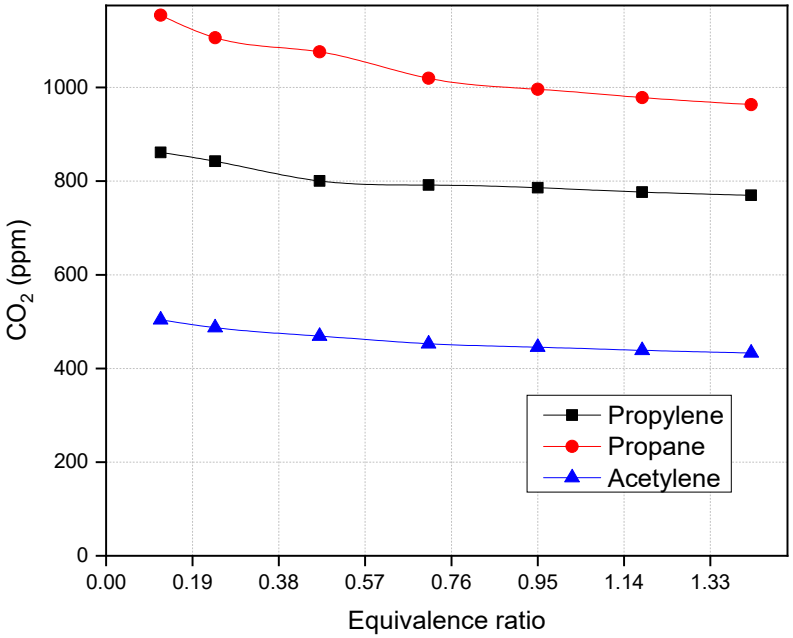


Figure 3. The effect of the equivalence ratio on CO_2 emissions.

Figure 4 depicts the influence of the equivalence ratio on CO emission. The results demonstrate that lowering the equivalence ratio increases CO emissions. It is understandable that increases in CO emission with a decrease in the equivalence ratio were brought on by a drop in the oxygen concentration. Furthermore, because THC emissions rise with lambda (air/fuel) when the relative air–fuel ratio is larger than 1, the presence of unburned hydrocarbons in the reaction zone slows CO oxidation, as seen in Figure 4. Therefore, CO emissions increase during times of oxygen scarcity, implied by the single oxygen atom in the carbon monoxide structure. Furthermore, acetylene creates far less CO than propylene and propane fuel because of its unique combustion properties and the stoichiometry of its combustion reaction. The stoichiometric ratio for acetylene combustion is much lower than for propylene and propane. This means that a smaller amount of air is needed to combust a given amount of acetylene relative to the other fuels. Furthermore, the combustion reaction of acetylene is highly exothermic, meaning that it releases a large amount of heat when it reacts with oxygen. This high heat release helps to ensure that complete combustion occurs, reducing the formation of harmful byproducts like CO.

Figure 5 shows the impact of the equivalence ratio on NO_x emissions. According to the figure, a drop in the equivalence ratio resulted in a sharp decrease in NO_x in most of these experiments. The main contributor to NO_x generation is the reduction in NO_x at an equivalent oxygen concentration. Additionally, at fuel-lean conditions, the availability of oxygen is relatively higher compared to the fuel, resulting in lower peak flame temperatures. This leads to a reduction in the formation of NO_x, as lower temperatures inhibit the reaction between nitrogen and oxygen. Conversely, under fuel-rich conditions, the excess fuel generates higher peak flame temperatures, thereby promoting the formation of NO_x.

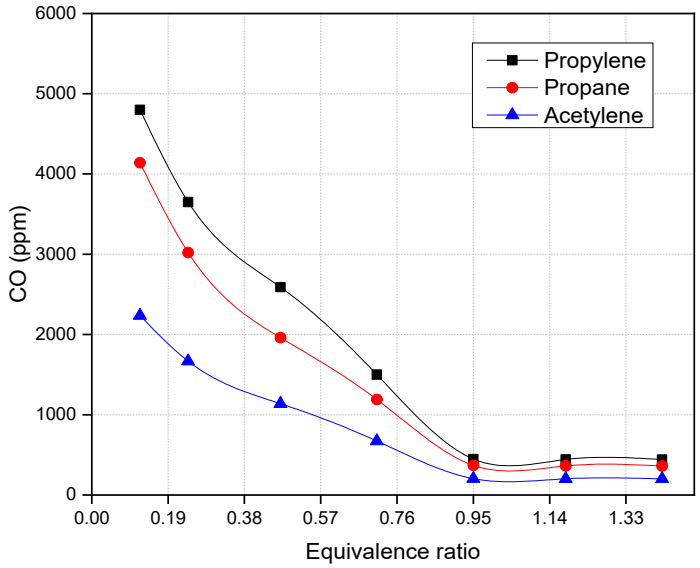


Figure 4. The effect of the equivalence ratio on CO emissions.

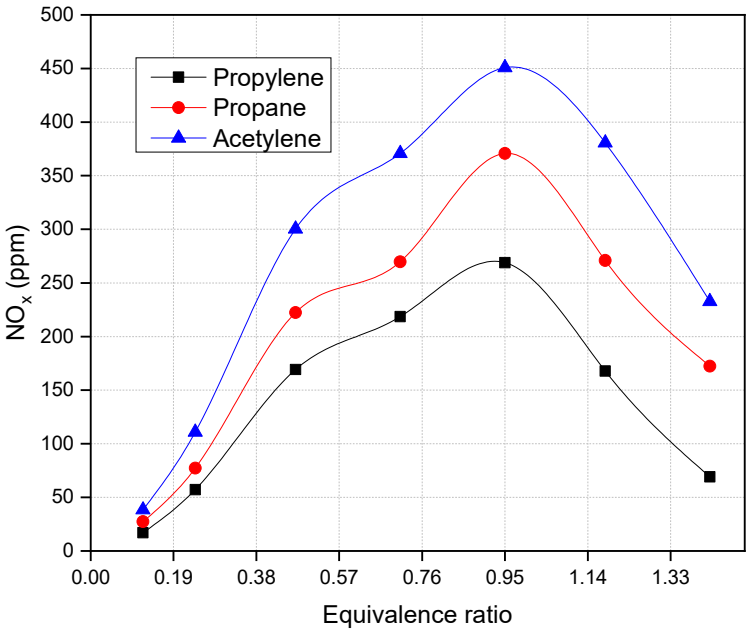


Figure 5. The effect of the equivalence ratio on NO_x emissions.

Furthermore, it is noteworthy that acetylene exhibits the highest NO_x emission value. This can be attributed to the significant heat generated during acetylene combustion, resulting in an increase in chamber temperature, which in turn promotes the formation of NO_x emissions. This is predictable because the N_2 bond is stronger than the O_2 bond, and the N_2 bond requires more energy to break. One factor that contributes to the high NO_x emissions of acetylene is its combustion temperature. Acetylene has a relatively low ignition temperature and a high flame temperature, which leads to rapid combustion and high temperatures. Moreover, acetylene has a triple bond between its carbon atoms, which makes it highly reactive, leading to the creation of an oxygen-rich flame zone, which favors the formation of NO_x emissions.

3.2. Comparison of Temperature Distributions on a Metal Plate

Figure 6a–c depict the temperature contours from the gas torch outlets to the metal plate of propane, propylene, and acetylene, respectively. As shown in Figure 6a–c, the heat

transfer rate of propylene fuel is greater than that of propane fuel. However, the central point of propane fuel has a higher temperature, indicating the flame of the propane fuel is more focused.

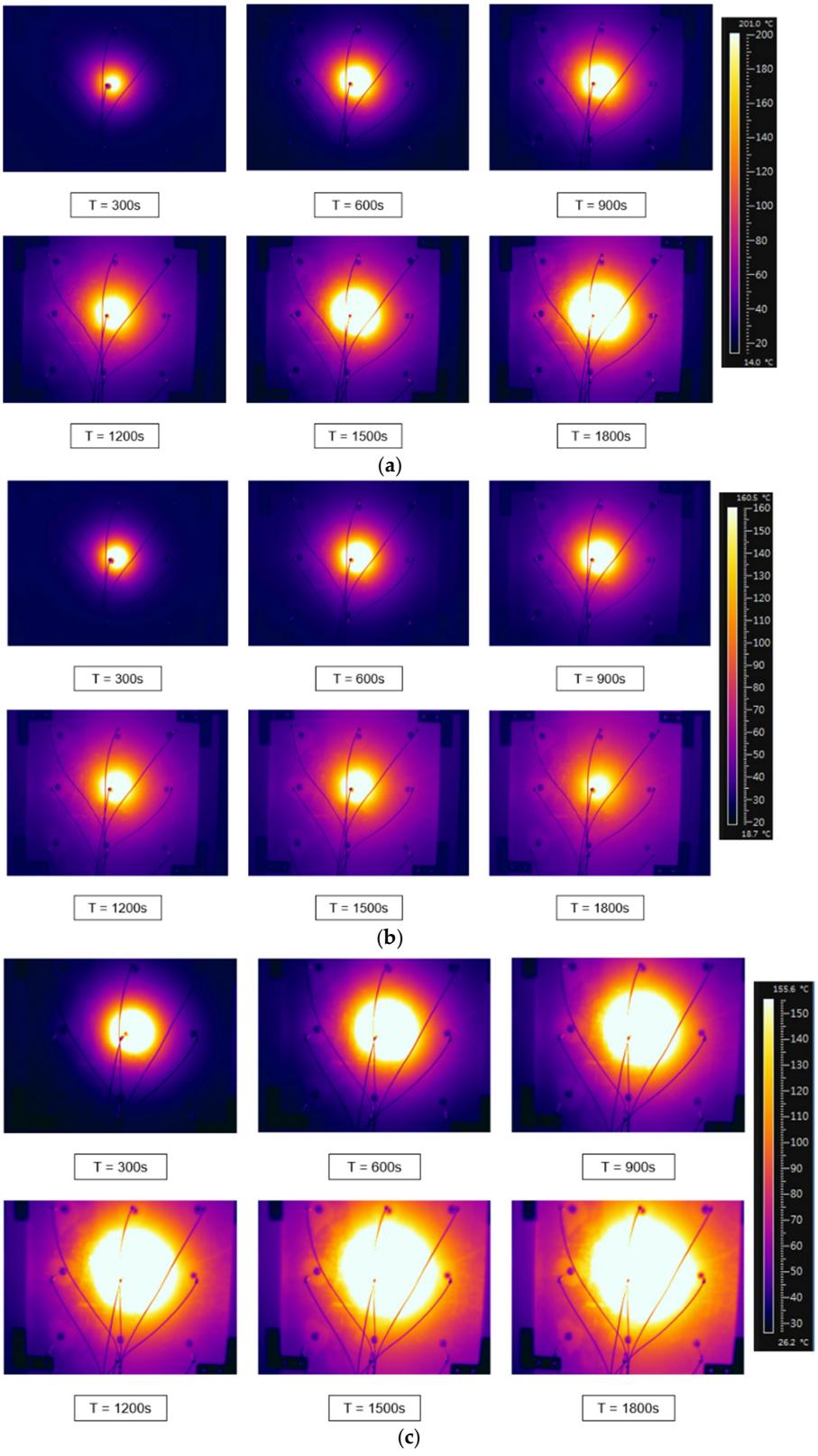


Figure 6. The temperature contours from the gas torch outlets to the metal plate: (**a**) propane flame, (**b**) propylene fuel, and (**c**) acetylene fuel.

Additionally, propylene fuel is considered safer due to its more uniform temperature distribution compared to propane fuel. Propane fuel has a higher flame temperature than propylene fuel, which can lead to localized hotspots during combustion. These hotspots can result in uneven heating of the material being heated, causing thermal stresses and deformation of the material. Additionally, the localized hotspots can increase the risk of ignition or fire if the hotspots exceed the ignition temperature of the material or surrounding environment. In contrast, propylene fuel has a lower flame temperature than propane fuel, which leads to a more uniform temperature distribution during combustion. This uniform temperature distribution reduces the risk of localized hotspots and thermal stresses on the heated material. Furthermore, a more uniform temperature distribution also means that the overall temperature of the heated material can be kept lower, which can reduce the risk of ignition or fire.

Figure 7a–c present the temperature distributions of propylene, propane, and acetylene fuels, respectively, as a function of time. These distributions provide valuable insights into the thermal behavior and characteristics of each fuel throughout the experimental duration.

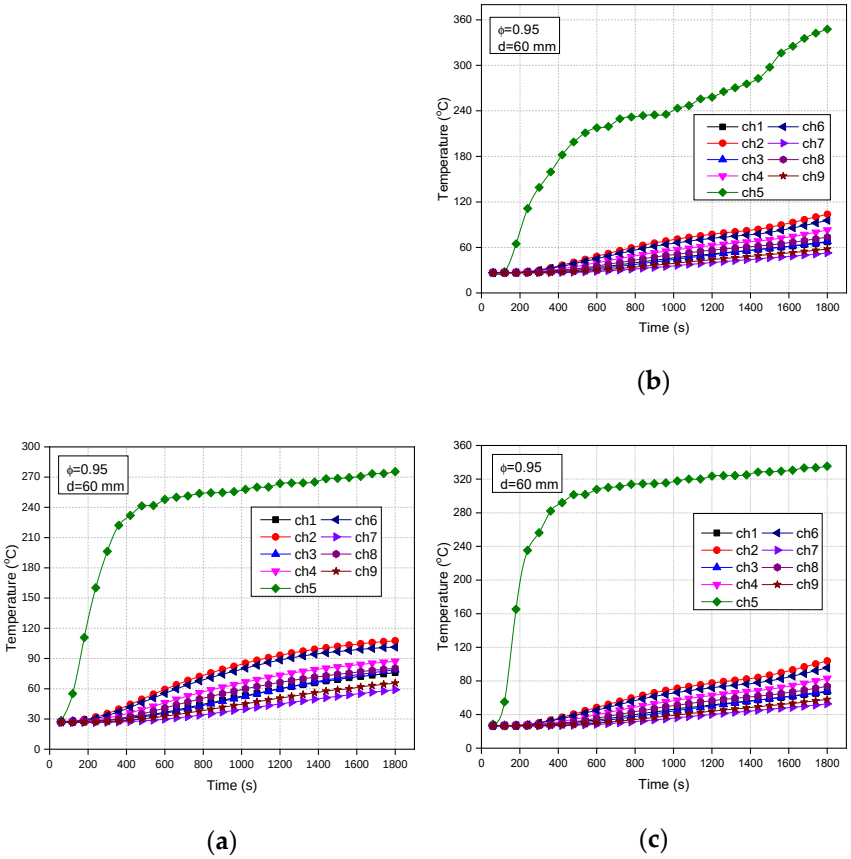


Figure 7. The temperature distribution as a function of time: (**a**) propylene fuel, (**b**) propane fuel, and (**c**) acetylene fuel.

The temperature distribution of propylene fuel, as depicted in Figure 7a, exhibits an interesting pattern. At the central point, the temperature experiences a rapid rise from its initial value, reaching 222.15 °C within 360 s. As time progresses, the temperature gradually approaches a steady-state value, indicating a more stable thermal condition. At the end of the experiment (1800 s), the maximum temperature recorded at the central point of the propylene fuel is 275.45 °C. This finding suggests that propylene fuel has a relatively fast response in terms of temperature increase and achieves a moderate maximum temperature.

In Figure 7b, the temperature distribution of propane fuel is showcased. The central point temperature of the propane fuel gradually increases from the starting temperature and reaches 211.05 °C after 540 s. However, unlike propylene fuel, the temperature profile

of propane fuel does not stabilize and continues to exhibit fluctuations beyond the experimental timeframe. This indicates the potential for a further rise in temperature or variability. Impressively, the central point of the propane fuel records a maximum temperature of 347.65 °C at 1800 s, indicating a higher peak temperature compared to propylene fuel.

Figure 7c illustrates the temperature distribution of acetylene fuel. Similar to propylene fuel, the central point temperature of acetylene fuel experiences a rapid initial increase. Within 480 s, the temperature rises quickly from the starting temperature to 301.45 °C. As the experiment progresses, the temperature of the acetylene fuel gradually stabilizes and approaches a steady-state value. At 1800 s, the central point of the acetylene fuel reaches a maximum temperature of 335.45 °C, indicating a relatively high peak temperature.

The observed temperature distributions highlight the distinct characteristics of each fuel gas. Propylene fuel demonstrates a rapid but stable temperature increase, propane fuel exhibits a gradually rising temperature with potential fluctuations, and acetylene fuel showcases a rapid initial increase followed by a relatively stable temperature profile.

Figures 8 and 9 compare the temperatures and temperature increase rates of the three fuels at the middle point. The graphs show that the temperature of acetylene fuel increases at a higher rate than for propene, but the temperature of propane fuel increases faster than other fuels. After a period of burning, the temperature of propylene and acetylene fuel stabilizes, while the temperature of propane continues to rise. Furthermore, the peak temperatures of propane and acetylene fuels are higher than that of propylene fuel due to the concentrated flame. Moreover, acetylene's atomic structure has a triple bond, and propylene's atomic structure has a double bond, which allows it to easily react with oxygen and create heat rapidly, but propane generates more heat due to its high latent heat of vaporization. On the other hand, propane has a lower flame temperature compared to acetylene. Despite this, propane's combustion process is more complete, resulting in a higher energy output per unit mass of fuel. This leads to a more rapid increase in temperature relative to propylene and acetylene.

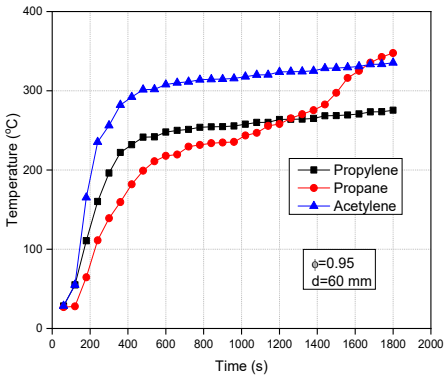


Figure 8. A comparison of temperatures at center points using three fuels.

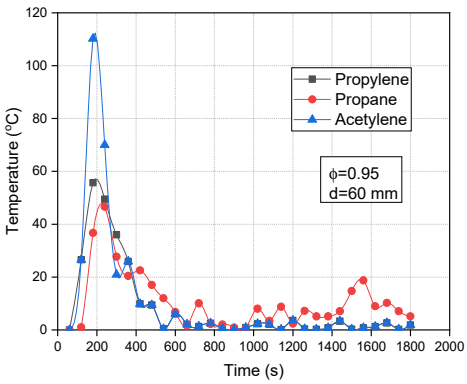


Figure 9. A comparison of the change in temperature rates at the center points using the three fuels.

4. Conclusion

In this study, we used an experimental strategy to overcome some of the shortcomings of previous experimental optimization approaches. We carefully researched the equivalence ratio, which has sensitive impacts on exhaust gases such as NO_x, CO, CO_2, and THC, as well as the temperature distribution when heating a metal plate. The ideal equivalence ratio was also found. When the equivalence ratio is at its ideal value, the torch system performs better. While this is not true for NO_x emissions, as the equivalence ratio of three fuels increases and reaches 1.0, the CO, CO_2, and THC emissions decrease. The combustion parameters of three fuels are optimized at an equivalence ratio of 0.95.

Analyzing the temperature profiles of the different fuels, distinct patterns emerged. Acetylene fuel demonstrated a rapid increase in temperature, surpassing the other fuels. In contrast, the temperature increase for the other fuels was gradual and fluctuating, with the potential for further escalation. Notably, the central point of propane fuel recorded the highest temperature of 347.65 °C at 1800 s, exceeding both propylene fuel (275.45 °C) and acetylene fuel (335.45 °C). Furthermore, except for the center point of the propylene fuel, the temperature was consistently higher compared to the other analyzed fuels. This denotes that, as the flame of propane and acetylene fuels are more concentrated, the flame of propylene fuel spreads over a wider area.

Using a propylene gas flame can lead to a reduction in emissions of carbon monoxide and nitrogen oxides compared to the propane flame. Additionally, the temperature distribution of the preheated metal plate was more uniform with the propylene gas flame, indicating improved heat transfer. These findings highlight the potential benefits of employing propylene gas as a fuel source in preheating systems. Its adoption could enhance energy efficiency, promote environmental sustainability through reduced emissions, and facilitate the production of sustainable chemicals. Moreover, the utilization of propylene gas has the potential to optimize energy consumption in various industrial processes.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Ch	Channel
ppm	Parts per million
THC	Total hydrocarbon
Lambda	Air–fuel ratio
Ø	Equivalence ratio

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