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An Experimental Study on the Effect of Closed-Steam Pressure as a Thermal Core on the Combustion Characteristics of Used Oil in a Pool Combustion System

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A B S T R A C T

Used oil can be used as an alternative fuel; however, its combustion characteristics must be controlled to ensure flame stability. This study evaluates the effects of closed-system steam pressure, which serves as the thermal core, on flame temperature, thermal core temperature, burning rate, and flame stability in a pool combustion system. We conducted experimental tests at three steam pressure levels (1.0, 1.5, and 2.0 bar), using an initial used-oil mass of 120 g for the burning-rate measurements. Each temperature measurement was performed in triplicate. The results showed that increasing steam pressure increased the average flame temperature from 395.67 °C at 1.0 bar to 416.00 °C at 1.5 bar and 502.67 °C at 2.0 bar. The thermal core temperature also increased from 100.17 °C to 111.80 °C and 129.03 °C, respectively. The burning rate increased from 7.38 to 8.10 and 9.02 g/min, while the combustion time required to burn 120 g of used oil decreased from 16.25 to 14.8 and 13.3 min. Based on observational assessments, flame stability improved from poor at 1.0 bar to stable at 1.5 bar and highly stable at 2.0 bar. However, a loud, jet-like roaring sound was observed at the highest pressure. These findings indicate that a steam pressure of 2.0 bar provided the best performance among the tested conditions in terms of flame temperature, thermal core temperature, and burning rate, although the accompanying noise should be considered in further system optimization.

Contribution to Sustainable Development Goals (SDGs):
SDG 7: Affordable and Clean Energy
SDG 11: Sustainable Cities and Communities
SDG 12: Responsible Consumption and Production

1. INTRODUCTION

1.1. Research Background

The increasing demand for energy and the challenges associated with waste management have encouraged the development of technologies that utilize waste as an alternative energy source. One type of waste with fuel potential is used lubricating oil. Used oil still contains hydrocarbon compounds with energy content, making it suitable for combustion applications, provided that its characteristics and operating conditions are properly considered [1–4]. Utilizing used oil as a fuel may also help reduce the volume of waste oil that could otherwise pose adverse environmental impacts.

Several studies have investigated the development of used-oil-fired stoves and burners. Pratama et al. [1] developed a used-oil-fired stove (burner) and demonstrated the feasibility of using used oil as a fuel in a combustion system. Ramadhan and Basyirun [2] reported that air pressure affects the combustion temperature of used oil. Meanwhile, Hidayat and Basyirun [3]

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found that the type of used oil can influence fuel consumption time and maximum combustion temperature.

Further developments in used-oil-fired stoves have focused on modifications to air supply systems and burner design. Putra et al. [4] developed an economical used-oil-fired stove, while Wahyudi et al. [7] demonstrated that the number of burner holes and air velocity influence combustion performance. These findings indicate that air supply conditions and combustion system configuration strongly influence the combustion characteristics of used oil.

In addition to variations in air supply, the use of steam in combustion systems has also been investigated. Mafruddin et al. [5] examined the effects of airflow rate and the number of steam holes on the performance of a used-oil-fired stove. Their findings indicate that controlling air and steam supply conditions can affect combustion characteristics. Furthermore, studies on the pretreatment of used oil have shown that fuel characteristics prior to combustion can influence its potential utilization as an alternative fuel [8].

In a *pool combustion* system, liquid fuel is contained in a vessel, and combustion occurs above the fuel surface. One of the key characteristics of this system is the *burning rate*, defined as the rate at which fuel mass decreases due to evaporation and combustion. Studies on *pool fires* have identified the burning rate, flame temperature, flame geometry, and heat transfer as important parameters for characterizing the combustion behavior of liquid fuels [11–13].

Chen et al. [11] explained that *various heat transfer and fluid-flow mechanisms govern pool fire dynamics* during combustion. Ditch et al. [12] also demonstrated a relationship between *pool fire* characteristics and the burning rate. Meanwhile, Chatris et al. [13] conducted an experimental investigation into the burning rates of hydrocarbon pool fires. Collectively, these studies indicate that heat transfer from the flame back to the fuel surface is an important factor in sustaining the combustion process [11–15].

The heat transferred from the flame back to the fuel surface is known as *heat feedback*. This heat increases the fuel surface temperature, thereby promoting evaporation. The resulting fuel vapor mixes with air and undergoes combustion in the flame region. Consequently, the thermal conditions surrounding the fuel surface are directly related to the system's ability to sustain the combustion process [13–15].

This *heat-feedback concept forms the basis for* the *thermal core* employed in the present study. The thermal core is positioned within the flame region to absorb heat from combustion and retain thermal energy in the combustion zone. Unlike a blower, which operates by increasing the air supply, the thermal core is designed to utilize heat storage and heat transfer mechanisms to influence the thermal conditions of the combustion system.

The application of *internal heat recirculation* in waste-oil combustion has been investigated by Zhao et al. [16]. Their study demonstrated that internal heat management can be incorporated into waste-oil combustion systems, influencing combustion performance and emission characteristics. Research on the use of reprocessed used lubricating oil as a fuel has also highlighted the importance of controlling combustion behavior and emissions to support its effective utilization as an alternative energy source [17].

Previous studies on used-oil combustion have primarily focused on variations in air pressure, burner design, the number of air inlets, and fuel supply regulation [1–10]. Meanwhile, research on *pool fires* has extensively examined burning rate, heat feedback, temperature, and flame characteristics [11–15, 18–20]. However, the use of a closed-system, steam-based thermal core positioned within the flame region, with steam pressure as the primary experimental variable, remains underexplored. In particular, the influence of steam pressure on the thermal behavior and combustion characteristics of used oil in a *pool combustion* system requires further experimental investigation.

Therefore, this study aims to experimentally investigate how closed-system steam pressure, with the steam system functioning as a thermal core, affects the combustion characteristics of used oil in a *pool combustion* system. The investigation focuses on the relationships between steam pressure (1.0, 1.5, and 2.0 bar), flame temperature, thermal core temperature, burning rate, and flame stability. The findings are expected to provide insights into the role of steam pressure in modifying the thermal conditions and combustion performance of used-oil-fired systems.

1.2. Literature Review

1.2.1. Combustion Characteristics of Used Oil

Used lubricating oil has the potential to serve as an alternative energy source; however, its application as a fuel requires careful control of combustion conditions and evaluation of emissions. Fuel properties, air supply, temperature, and burner configuration influence combustion characteristics. Therefore, a high flame temperature alone is insufficient to establish combustion efficiency or demonstrate low emissions.

Firiski et al. [21] investigated a used-oil-fired stove employing water vapor pressure and reported that nozzle configuration influenced the time required to boil water. Their findings indicate that combustion system design can affect the energy utilization performance of used oil. However, their study focused on the number of nozzle holes, whereas the present study investigates the effects of closed-system steam pressure, with the steam system functioning as a *thermal core* within the flame region. This approach provides a different perspective on improving the thermal characteristics of used-oil combustion by examining the role of steam pressure rather than nozzle configuration.

1.2.2. Combustion Characteristics of the Pool Combustion System

Pool combustion refers to the combustion process occurring above the surface of a liquid fuel pool. The fuel absorbs heat from the flame and the surrounding combustion environment, undergoes heating and vaporization, and subsequently reacts with oxygen in the flame zone. The interactions among fuel vaporization, heat transfer, and air supply play important roles in determining the burning rate and flame characteristics.

Chen et al. [11] explained that the burning rate, flame structure, air entrainment, radiation, and heat transfer in pool fires are interrelated. Heat feedback from the flame to the fuel surface is a key mechanism influencing fuel vaporization and flame development. These findings provide a theoretical basis for investigating the relationship between flame temperature and burning rate in used-oil pool combustion systems.

Zhang et al. [22] reported that the burning rate of pool fires is influenced by fuel type, fuel temperature, ambient conditions, and heat and mass transfer mechanisms. Accordingly, variations in the burning rate under different steam pressure conditions should be interpreted in the context of the overall thermal behavior of the system rather than attributed to steam pressure alone. This consideration is particularly relevant to the present study, in which closed-system steam pressure is varied to investigate its influence on flame temperature, thermal core temperature, and burning rate in a used-oil pool combustion system.

1.2.3. The Role of the Thermal Core

In this study, the thermal core is a sealed, steam-containing component positioned within the central flame zone to influence thermal conditions during combustion. Conceptually, this component may act as a thermal element that absorbs, stores, and transfers heat, depending on its operating conditions. However, the amount of heat absorbed or released cannot be determined solely from the thermal core temperature. To quantify these thermal processes, additional measurements such as heat flux, temperature distribution, and temperature variation over time are required.

The literature on pool fires indicates that heat feedback to the fuel surface can occur through radiation, convection, and conduction, with their respective contributions depending on fuel properties and combustion configuration. Therefore, treat the thermal core's effects on flame temperature and burning rate as experimental hypotheses and evaluate them through systematic measurements, rather than as established mechanisms based solely on an observed temperature increase. This approach provides a more rigorous basis for assessing the role of a sealed steam-based thermal core in modifying the combustion characteristics of used oil.

2. MATERIALS AND METHODS

2.1. Research Type and Experimental Design

This study employed an experimental approach to investigate the effects of closed-system steam pressure, with the steam-containing component serving as a *thermal core*, on the combustion characteristics of used oil in a *pool combustion* system. The experiments varied the steam pressure within the thermal core and monitored changes in flame temperature, thermal core temperature, burning rate, and flame stability.

The experimental design comprised three steam pressure levels: 1.0, 1.5, and 2.0 bar. Each pressure condition was tested in triplicate to obtain repeated measurements and improve the reliability of the experimental results. The collected data were used to calculate the mean values of the measured parameters and compare the combustion characteristics across the three pressure conditions.

2.2. Experimental Apparatus and Materials

The primary apparatus used in this study was a purpose-built *pool combustion* system designed to burn used lubricating oil. The system incorporated a sealed, steam-filled component that functioned as a thermal core and was positioned within the combustion zone. The experimental apparatus was equipped with instruments to regulate or monitor steam pressure and measure temperature during combustion.

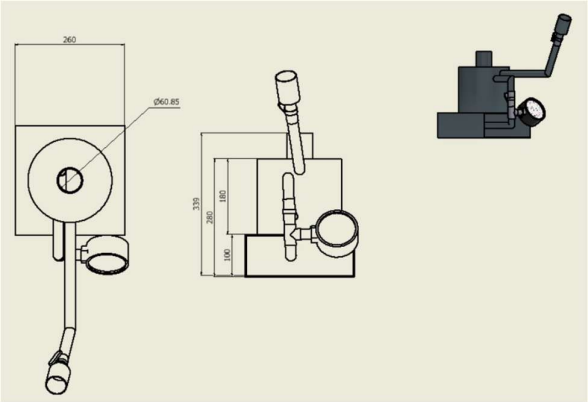


Figure 1. Design of the Used-Oil-Fired Stove

2.3. Experimental Procedure

The experimental procedure consisted of the following steps:
Apparatus Preparation. The *pool combustion* apparatus, thermal core, temperature sensors, pressure gauge, weighing scale, and stopwatch were prepared before testing.

1. System Inspection. We inspected all connections, measuring instruments, and pressure system components before ignition. Testing was conducted only after the apparatus had been verified as safe for operation.
2. Fuel Preparation. The used oil was weighed to the predetermined initial mass. For burning-rate measurements, an initial fuel mass of 120 g was used for each steam pressure condition.
3. Steam Pressure Adjustment. The steam pressure was set to the specified experimental levels of 1.0, 1.5, and 2.0 bar. The actual operating pressure was monitored using a pressure gauge.
4. Combustion Testing. The used oil was ignited in the *pool combustion* apparatus. During combustion, temperature sensors at the designated measurement locations measured the flame temperature and thermal core temperature.
5. Combustion Time and Flame Stability Recording. The combustion duration was recorded to determine the burning rate. Flame behavior was also observed to identify misfires, sudden flame extinction, variations in flame stability, and any noise generated during combustion.
6. Experimental Replication. Each steam pressure condition was tested three times. We recorded the measurements from each replicate and used them to calculate the mean values.
7. Data Processing and Analysis. All experimental measurements were organized into tables and quantitatively analyzed. The results were subsequently compared to identify trends in the effects of steam pressure on the combustion characteristics of used oil.

2.4. Data Processing and Analysis

The experimental data were analyzed quantitatively by calculating the mean temperatures and burning rates. Flame stability was evaluated descriptively based on observations recorded during the combustion tests.

2.4.1. Calculation of Mean Temperature

The mean temperature for each pressure condition was calculated using the following equation:

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$$\dot{T} = \frac{\sum_{i=1}^{n}(T_i)}{n}$$

where:
$\dot{T}$ = Mean Temperature (°C)
T_i = Measured temperature at the i-th measurement (°C)
n = Number of Measurement Replicates

2.4.2. Calculation of the Burning Rate

The burning rate was calculated as the mass of fuel consumed divided by the combustion duration, using the following equation:

$$\dot{m} = \frac{m}{t}$$

where:
$\dot{m}$ = Burning Rate (g/min)
m = Mass of Oil Consumed (g)
t = Combustion Duration (min)

2.5. Comparative Analysis of the Effects of Steam Pressure

The results obtained from the three steam pressure conditions were compared using tables and graphs illustrating the relationships between steam pressure and flame temperature, thermal core temperature, and burning rate. The analysis was conducted to identify trends in the combustion parameters as steam pressure increased.



Figure 2. Used-Oil-Fired Stove

3. RESULT AND DISCUSSION

3.1. Flame Temperature

Table 1 presents the flame temperature measurements obtained from three experimental replicates.

Table 1. Flame Temperature

Steam Pressure (bar)	Measurement 1 (°C)	Measurement 2 (°C)	Measurement 3 (°C)
1.0	395	405	387
1.5	419	421	409
2.0	517	504	487

The average flame temperature increased from 395.67 °C at 1.0 bar to 416.00 °C at 1.5 bar and 502.67 °C at 2.0 bar. The increase was approximately 5.14% between 1.0 and 1.5 bar and 27.05% between 1.0 and 2.0 bar. These results indicate a positive relationship between the steam pressure in the thermal core and the flame temperature within the investigated pressure range. One possible explanation is that steam pressure is associated with the core's thermal condition and heat distribution within the flame zone. However, because these mechanisms were not directly measured, this explanation should be regarded as a plausible interpretation rather than evidence of a causal relationship. Previous studies on pool fires have reported that flame temperature and burning rate are closely associated with heat feedback and flow conditions around the fuel surface [8–13]. The relationship between steam pressure and average flame temperature is illustrated in the following figure.

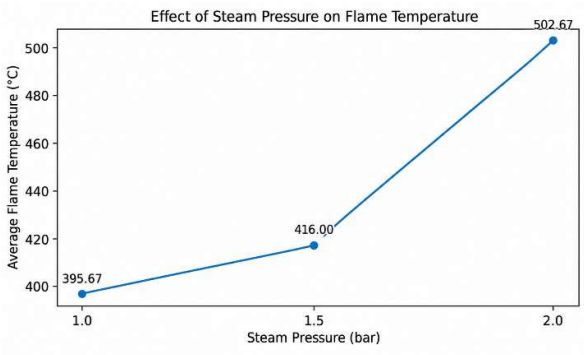


Figure 3. Effect of Steam Pressure on the Average Flame Temperature

As steam pressure increased from 1.0 to 1.5 bar, the average flame temperature rose by 20.33 °C, or approximately 5.14%. Meanwhile, increasing the pressure from 1.5 to 2.0 bar increased the temperature by 86.67 °C, or approximately 20.83%. Overall, increasing the steam pressure from 1.0 to 2.0 bar raised the average flame temperature by 107.00 °C, or approximately 27.04%.

The differences in temperature increments indicate that the relationship between steam pressure and flame temperature was not strictly linear within the investigated pressure range. The temperature increase was substantially greater when the pressure rose from 1.5 to 2.0 bar than when it increased from 1.0 to 1.5 bar. This observation suggests that flame temperature may respond differently to changes in steam pressure across the tested operating conditions. However, further experiments at additional pressure levels are needed to establish this relationship more conclusively.

3.2. Thermal Core Temperature

Table 2 presents the thermal core temperature measurements obtained from three experimental trials. As steam pressure increased from 1.0 to 1.5 bar, the average thermal core temperature rose by 11.63 °C, or approximately 11.61%. Meanwhile, increasing the pressure from 1.5 to 2.0 bar increased the temperature by 17.23 °C, or approximately 15.41%. Overall, increasing the steam pressure from 1.0 to 2.0 bar raised the average thermal core temperature by 28.86 °C, or approximately 28.81%.

Table 2. Thermal Core Temperature Data

Steam Pressure (bar)	Measurement 1 (°C)	Measurement 2 (°C)	Measurement 3 (°C)
1.0	98.4	99.7	102.4
1.5	108.7	110.5	116.2
2.0	133.2	124.5	129.4

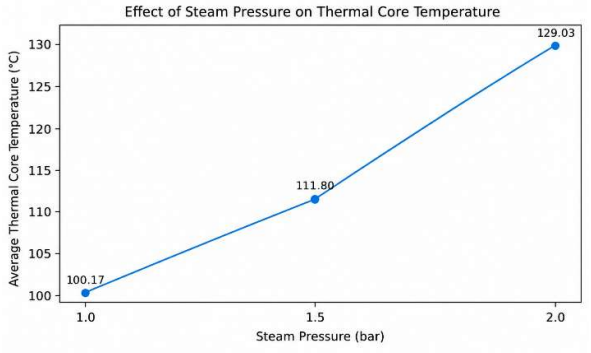


Figure 4. Effect of Steam Pressure on the Average Thermal Core Temperature

The greater temperature increase observed within the 1.5–2.0 bar pressure range indicates that the temperature response did not follow a perfectly linear trend with increasing steam pressure. Nevertheless, the graph represents only three pressure levels and is therefore insufficient to establish a definitive mathematical relationship or identify the underlying causal mechanisms.

From a thermal perspective, the increase in thermal core temperature may indicate that the component receives heat from the combustion environment. As a sealed component positioned within the flame zone, the thermal core may absorb and conduct heat during combustion. Variations in steam pressure may be associated with changes in the thermodynamic conditions inside the component and in heat transfer between the flame and the thermal core. However, further investigation through measurements of actual steam pressure, temperature evolution over time, and heat transfer characteristics is needed to confirm these potential causal relationships.

A comparison with the flame temperature data shows that the thermal core temperature increased concurrently with the average flame temperature. At a steam pressure of 2.0 bar, for example, the average thermal core temperature reached 129.03 °C, while the average flame temperature reached 502.67 °C. This pattern suggests a potential association between the thermal conditions of the thermal core and those of the combustion zone. However, the available data do not demonstrate that an increase in thermal core temperature directly causes an increase in flame temperature.

Overall, a steam pressure of 2.0 bar produced the highest average thermal core temperature among the tested conditions. These findings support the hypothesis that steam pressure variations are associated with changes in the thermal state of the thermal core during waste-oil combustion.

3.3. Burning Rate and Waste-Oil Consumption Time

Table 3 presents the calculated burning rates and waste-oil consumption times obtained under the different steam pressure conditions.

Table 3. Burning Rate of Waste Oil

Steam Pressure (bar)	Waste Oil Mass (g)	Combustion Time (min)	Burning Rate (g/min)
1.0	120	16.25	7.38
1.5	120	14.8	8.10
2.0	120	13.3	9.02

At the same initial fuel mass, the burning rate increased from 7.38 g/min at 1.0 bar to 8.10 g/min at 1.5 bar and 9.02 g/min at 2.0 bar. The burning rate increased by approximately 22.22% as the steam pressure rose from 1.0 to 2.0 bar. Concurrently, the time required to consume 120 g of waste oil decreased from 16.25 to 13.3 min, representing a reduction of approximately 18.15%. These findings are consistent with the higher average flame temperature observed at a steam pressure of 2.0 bar. In general, increased heat feedback can enhance fuel vaporization and increase the burning rate in pool fires [8, 10, 11].

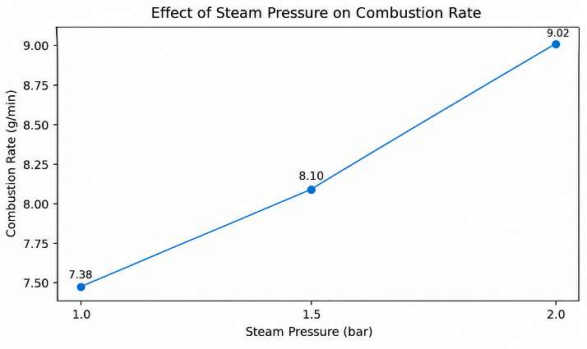


Figure 5. Effect of Steam Pressure on the Burning Rate of Waste Oil

The increased burning rate indicates that waste oil combusted faster at higher steam pressures. This trend is consistent with the previously reported flame and thermal core temperature measurements, both of which increased with increasing steam pressure. At 2.0 bar, the average flame temperature reached 502.67 °C, the average thermal core temperature reached 129.03 °C, and the burning rate was highest at 9.02 g/min.

Theoretically, an increase in temperature within the combustion zone may enhance heat transfer to the waste-oil surface. This condition could accelerate fuel heating and the vaporization of its constituent fractions, thereby increasing the availability of fuel vapor for reaction with oxygen. In the investigated system, the thermal core is hypothesized to influence heat distribution and thermal energy storage within the combustion zone. However, further measurements of heat flux, fuel-surface temperature, and transient thermal behavior are required to verify this proposed mechanism.

3.4. Flame Stability

Table 4 presents the observed flame stability under different steam pressure conditions during combustion. The table indicates improved flame stability as steam pressure increased from 1.0 to 1.5 and 2.0 bar. At 1.0 bar, misfires and sudden flame extinction indicated relatively unstable operation. At 1.5 bar, the flame was stable, whereas at 2.0 bar, it was highly stable.

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Table 4. Qualitative Assessment of Flame Stability

Steam Pressure	Flame Stability Observations
1.0 bar	Poor; frequent misfires and sudden flame extinction were observed
1.5 bar	Stable; temperature and pressure were reported to remain relatively constant
2.0 bar	Highly stable; however, a loud, jet-like roaring sound was observed

However, the loud jet-like roaring sound observed at 2.0 bar represents an operational characteristic that warrants further investigation and should not be overlooked.

4. CONCLUSION

The experimental results showed that increasing the closed-steam pressure from 1.0 to 2.0 bar increased flame temperature, thermal core temperature, and waste-oil burning rate. The average flame temperature increased from 395.67 °C at 1.0 bar to 416.00 °C at 1.5 bar and 502.67 °C at 2.0 bar. Meanwhile, the average thermal core temperature increased from 100.17 °C to 111.80 °C and 129.03 °C, respectively. The burning rate also increased from 7.38 g/min to 8.10 g/min and 9.02 g/min, respectively. In terms of flame stability, combustion at 1.0 bar was less stable, with frequent misfires and sudden flame extinction. At 1.5 bar, the flame was stable, whereas at 2.0 bar, the flame was highly stable but accompanied by a loud, jet-like roaring sound. Therefore, 2.0 bar produced the highest temperatures and burning rate among the tested conditions, while 1.5 bar provided stable combustion without the reported roaring sound. However, further investigation is required to determine the optimum operating pressure and evaluate operational safety.

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