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Performance evaluation of a steam-assisted incinerator using used oil fuels for diaper waste treatment under natural convection

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Abstract

Incinerators offer an effective solution for waste processing by maintaining high combustion temperatures in a well-insulated and enclosed chamber. The combustion process using an incinerator has the ability to convert waste into steam gas and ash that can be utilized. The advantage of the incineration process is its ability to reduce the volume of waste significantly, with a reduction rate of more than 65%. In this research, a water steam stove was fueled by liquid waste, namely used motor oil and used cooking oil. It was tested for its performance in burning diaper waste under natural convection. The stove used has a height of 370 cm, a nozzle diameter of 2 cm, and a water vapor flow rate of 0.75 kg/hour. This study aimed to evaluate the thermal efficiency of the incinerator and analyze the influence of natural convection, fuel type, and the number of air holes on combustion performance. Experimental results showed that using eight air holes produced optimal results. Combustion with used motor oil reached the highest temperature of 397°C, burned for 65 minutes, and left 0.68 kg of ash residue. In comparison, used cooking oil reached 381°C, burned for 89 minutes, and left 0.95 kg of ash. The difference in fuel boiling points and viscosity significantly affected combustion efficiency. The highest thermal efficiency was 87% when using used motor oil, compared to 35% for used cooking oil. These findings suggest that used motor oil is a more effective and efficient fuel for diaper waste incineration in naturally ventilated systems.

Keywords:

Incinerator, water steam stove, used oil fuel, diaper waste, combustion, natural convection.

Nomenclature:

- η : Efficiency, %
- m : Mass, kg
- C_p : Specific heat capacity, J/kg·K
- T : Temperature, K
- V_{fuel} : Volume of fuel, m³
- HHV_{fuel} : High Heating Value of Fuel, J/kg
- t : Time, t
- CR : Combustion Rate, mm/s

1 Introduction

Incinerator is a waste processing system that uses chemical transformation, where waste is chemically converted through a combustion or integration process [1-2]. This combustion process changes materials that were originally solid into gas, and vapor, and

also has solid results after combustion that is converted, accompanied by the release of heat energy [3-4].

The advantage of the incineration process is its ability to significantly reduce waste volume, with a reduction rate of more than 65%. Incinerator technology is a waste processing method that is carried out through a high-temperature and integrated combustion process [5-6]. Incinerator operations are relatively easy and safe because the emissions produced by the incinerator are very environmentally friendly [7-10].

Oil is a residue from other petroleum products. Some examples of these waste products include residual fuel oil, diesel fuel oil, road oil, spray oil, coke, asphalt, and others. In general, there are two types of used oil, namely industrial used oil (light industrial oil) and black oil [11-13]. Industrial used oil tends to be cleaner and easier to clean with simple treatments, for example, using filters and heating. Black oil comes from automotive lubrication; so far, the use of used oil has not been maximized by the community, especially as fuel. So, using a used oil stove can utilize waste from used oil as fuel for combustion, so as not to pollute the environment [14-17].

A steam stove with used oil fuel produces an orange flame with a temperature of 1127°C at a pressure of 3.5 bar [18-19]. The water stored in the stove is heated by the used oil fuel itself, thus providing high steam pressure that can replace the function of the blower. This high-pressure water vapor then exits through the nozzle, thereby providing fuel speed to burn at a high-temperature value; in this case, it is very suitable for burning waste in incinerators [20].

Used oil is oil that has been used for a certain period of time so that it can no longer function optimally. Used oil still has a calorific value, which indicates the amount of heat or calories produced when a particular fuel is burned with air or oxygen. Used oil is included in the category of hazardous and toxic materials because it contains chemicals that can be harmful. Oil has the potential as an energy source like petroleum, but burning it directly is not easy. Unlike gasoline or diesel, oil is more difficult to burn and cannot achieve effective combustion like conventional fuels. Therefore, to use used oil as fuel, special techniques are required. One method is to heat the oil to almost the flash point. Another way is to mix the oil with a more flammable substance and then burn the mixture, so that the temperature increases and allows the oil to burn well [22-24]. Other differences are also shown in the chemical formulas they have, namely, used oil with the chemical formula C₂₂H₄₆ and used cooking oil C₁₉H₃₆, which were tested using gas chromatography and mass spectroscopy equipment. The differences in these chemical formulas can be used as calculations to find the ideal air-fuel ratio value, so that the temperature value can play an important role in ideal combustion (Table 1).

Table 1. Properties of used oil and used cooking oil [21]

Properties	Used oil	Used cooking oil
Density	825.7 kg/m ³	936 kg/m ³
Viscosity	6.1 mm ² /s	15.921 mm ² /s
Calorific value	39.316 MJ/kg	37 MJ/kg

Diapers are equipment that acts as a container for metabolic waste such as urine and feces made of polymers that have high absorption capacity. These highly absorbent polymers are polyacrylate and cellulose. The polymer contained in diapers is sodium polyacrylate. While the cellulose used is 19 wool materials that are useful as intermediaries between the skin and sodium polyacrylate [25-26]. The diaper part is made of superabsorbent polymer which has a high ability to absorb liquids, 100 times its size but still in a minimal size. The superabsorbent polymer in diapers consists of polyethylene as the outermost part, a hydrophobic polypropylene layer, a hydrophilic layer, cellulose, moisturizing lotions, aroma lotions, and sometimes contains an indicator of the level of wetness. The inside of the diaper with the outer skin of the diaper which generally consists of plastic that is difficult to decompose [27].

2 Research methods/materials and methods

2.1 Methodology and implementation

The research method in this title has a variation of the number of holes 4, 6, and 8 with a diameter of 63 mm. The fuel used is used motor oil and used cooking oil. Diaper waste with urine and feces content with a mass of 30 kg is taken from the final disposal site. Measurement and calculation values include combustion temperature, ash residue, combustion time, and thermal efficiency. The incinerator has a combustion capacity of 30 kg of waste which utilizes heating from a steam-pressure stove with a temperature above 1100°C. The installation of 3 thermocouples is placed in the combustion zone inside the incinerator or parallel to the natural air inlet. These 3 thermocouple points are used to measure the average value of the combustion temperature. The application of the research implementation flow is depicted in Fig. 1.

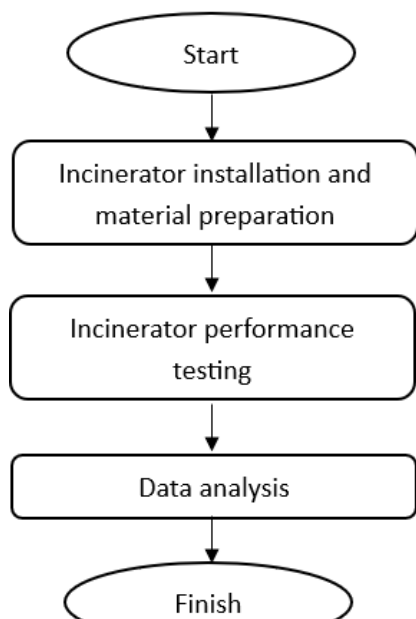


Fig. 1. Research method.

2.2 Incinerator

An incinerator is a tool or system used to burn garbage or waste until it turns into ash, gas, and other residues to reduce the volume and weight of waste, and destroying hazardous substances contained therein. The function of an incinerator is to significantly reduce the volume and weight of waste and produce ash and gas that are easier to handle and dispose of. With the specifications of the incinerator height of 2 meters, and a diameter of 1.1, so that it can accommodate up to 30 kg of waste. A water steam stove is placed under the incinerator, with the aim of vertical combustion. The Fig. 2 of the incinerator that will be used and Table 2 explain the specifications of the incinerator.

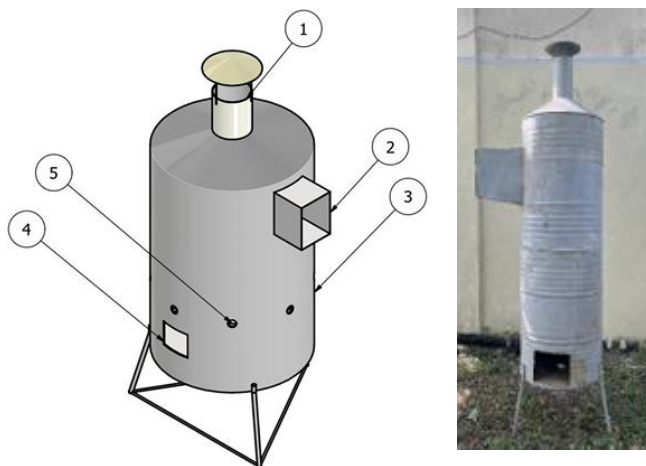


Fig. 2. Incinerator.

Table 2. Tool specifications

No.	Part name	Material
1	Smoke funnel	Iron
2	Feeder	Iron
3	Reactor tube	Iron
4	Ash container	Iron
5	air convection hole	Iron

The addition of air to the incinerator with natural convection is done by adding holes on the side of the incinerator in the combustion zone with variations in the number of convection air holes, namely 4, 6, and 8 holes, with each hole diameter of 63 mm. The position of the natural convection air holes is made evenly on the incinerator wall, according to the number of convection air holes. Other dimensional information is shown in Fig. 3.

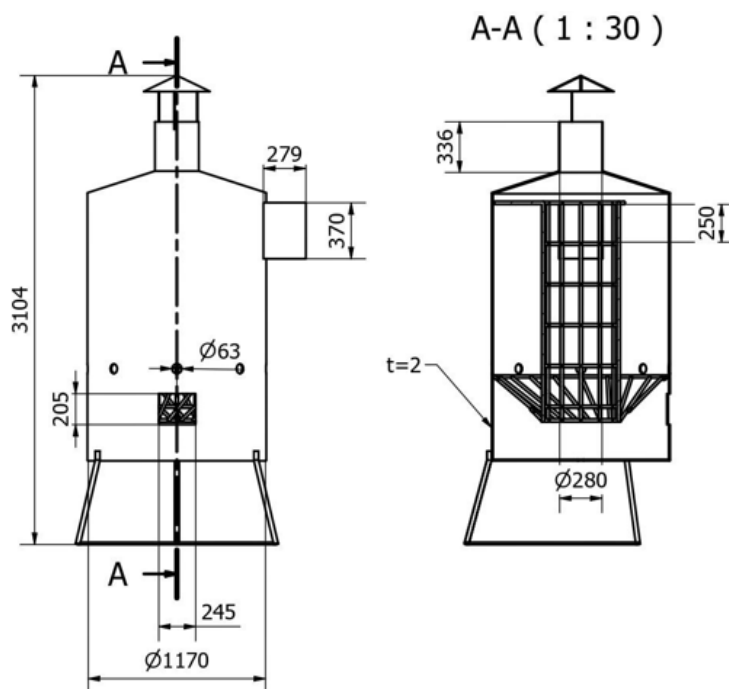


Fig. 3. Incinerator size dimensions.

2.3 Water steam stove

The water steam stove in Fig. 4 is a tool used to produce a fire source whose use can be controlled directly [28]. The stove has fuel as an energy source to produce fire. The type of stove used in this study is a stove with liquid residue waste fuel, namely, used oil and used cooking oil. The specifications of the stove are 370 cm high, 2 cm nozzle diameter, 50 cm high, with a water vapor flow rate of 75 kg/hour

The stove manufacturing process uses iron pipes and stainless-steel pipes on the chimney and all pipe connections use welding. The Fig. 4 is a pressurized steam stove with used oil and used cooking oil fuel. Information on the specifications of the steam stove can be explained in Table 3.

Table 3. Water steam stove specifications

No.	Part Name	Material
1	Chimney	Stainless steel
2	Boiler	Iron
3	Faucet	Copper
4	Maximum water limit hole	Iron
5	Water funnel	Iron

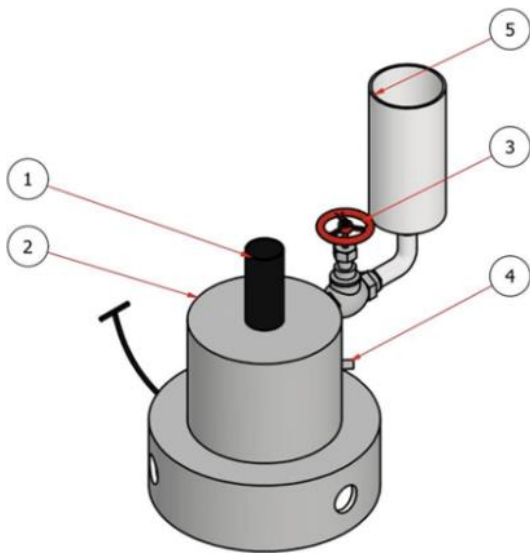


Fig. 4. Water steam stove.

2.4 Thermal efficiency

Thermal efficiency is a value that indicates how well a device converts heat energy into other energy, such as mechanical energy or electrical energy. This value always ranges between input and output, with the output being perfectly efficient. However, since the first law of thermodynamics states that energy cannot be created or destroyed, no thermal device can achieve 100% efficiency. This is due to factors such as friction, heat loss, and limitations of the thermodynamic cycle used. Thermal efficiency is the ratio between the heat obtained by a system and the heat energy provided by the fuel (Eq. 1). This occurs due to the process of heat diffusion (energy transfer) [29].

$$\eta_{th} = \frac{m_{diapers} \cdot C_{p_{diaper}} \cdot \Delta T}{V_{fuel} \cdot HHV_{fuel} \cdot t} \quad (1)$$

Combustion efficiency is used to determine how much heat is produced by a tool (incinerator) against a given input, in reducing waste. A percentage is a measure that is generally used for efficiency results. The formula used to find the level of incinerator performance efficiency is as Eq. 2 [30].

$$\eta = \frac{m_{in} - m_{out}}{m_{in}} \cdot 100\% \quad (2)$$

2.5 Combustion rate

Combustion rate is a test method by weighing the mass of diapers that enter the incinerator until they are completely burned, against the time required (Eq. 3). The results of the end of the burning, then weighing the ash mass. The ignition time is measured with a stopwatch, and the mass of the diapers is weighed using a digital scale. The burning rate reflects the speed of the combustion process of the material over a certain period of time until the material is completely burned out. In other words, the higher the burning rate value, the faster the burned material is completely burned out [30].

$$CR = \frac{m_{in}}{t} \quad (3)$$

3 Results and discussion

3.1 Temperature value testing

Data collection in this study was carried out by experimenting with the effect of air holes on the incinerator using natural convection. The temperature value was obtained by measuring the flame in the incinerator using a digital thermocouple, with the data collection process carried out using a test sensor placed into the incinerator during combustion, and then the value of each variation



of the air hole was identified. The Fig. 5 is the results of the data and temperature values.

The combination of each variation quite affects the test results on the temperature value. The temperature value data with testing using used oil fuel variations gets a higher temperature value, while using used cooking oil gets a lower value.

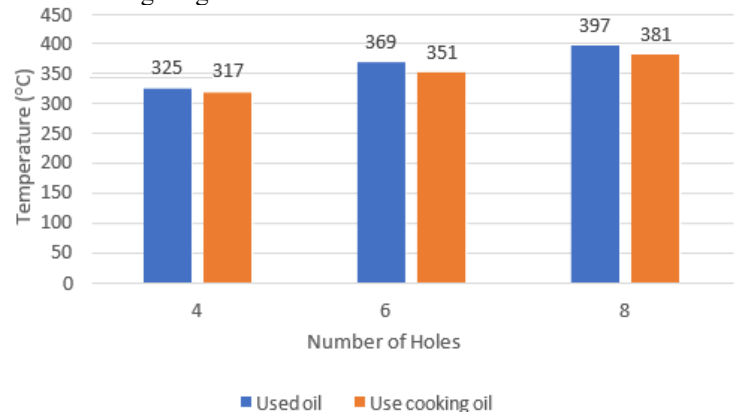


Fig. 5. Graph of temperature values against the number of holes in the incinerator.

This is because the density value of used oil is lower than used cooking oil. The low-density value causes the fuel evaporation rate to increase; in this case, the heat source generated from fuel with low density causes high temperatures. The source of fire generated by used oil is higher than using used cooking oil, therefore the increasing number of convection holes causes the heat value generated to also be high. In previous research on used oil stoves with a drip system, it can be proven that preheating fuel can reduce the density value and is easier to burn, thus causing the combustion rate to increase along with the increasing combustion temperature value [2].

3.2 Combustion time testing

Data collection in this study was carried out by testing the effect of variations in the number of air holes on combustion in an incinerator using natural convection. The combustion time value was obtained by measuring the flame in the incinerator using a stopwatch with the data collection process. The purpose of collecting data on the duration of combustion is to determine how fast the incinerator takes to reduce waste and then record the time of each type of variation in the number of air holes (Fig. 6).

Variations in the number of air inlet holes with natural convection have a significant effect on the test results on the duration of combustion. The data on the duration of combustion with tests using variations of used oil fuels obtained a faster combustion time, while using used cooking oil obtained a slower combustion time.

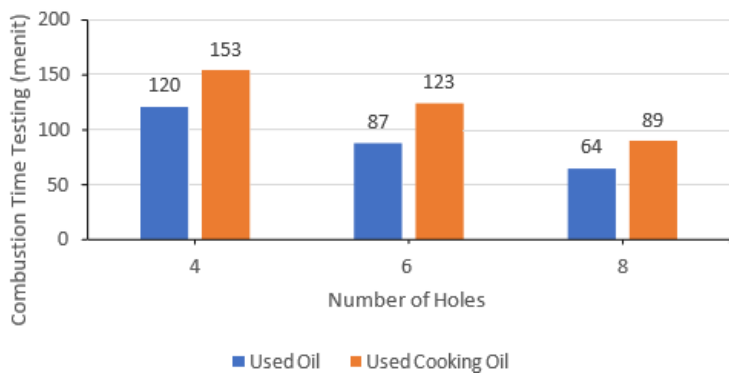


Fig. 6. Graph of combustion time testing values against the number of holes in the incinerator.

This is because the speed of fuel consumption to burn is dominated by used oil fuel, while used cooking oil requires a longer time because the speed of fuel consumption tends to be slower. The effect of high density will affect the rate of fuel evaporation and result in a decrease in temperature value and an increase in burning time. In Eq. 1 regarding thermal efficiency, it is explained that the high-temperature value produced by the fuel and the fast combustion time will increase the efficiency value. The increase in the burning speed carried out previously on medical waste was also proven by the presence of an incoming air supply which can affect the burning duration and temperature value [5].

3.3 Combustion ash residue testing

Testing the ash value against the variation in the number of air convection holes can be determined by measuring the mass of ash from the combustion. The ash value of combustion is obtained through the results of burning diaper waste, with the data collection process carried out to find out how much ash is produced during combustion, and then the highest results from each are identified. The less ash produced, the incinerator's ability to burn can be a measure of its best performance for burning diapers (Fig. 7).

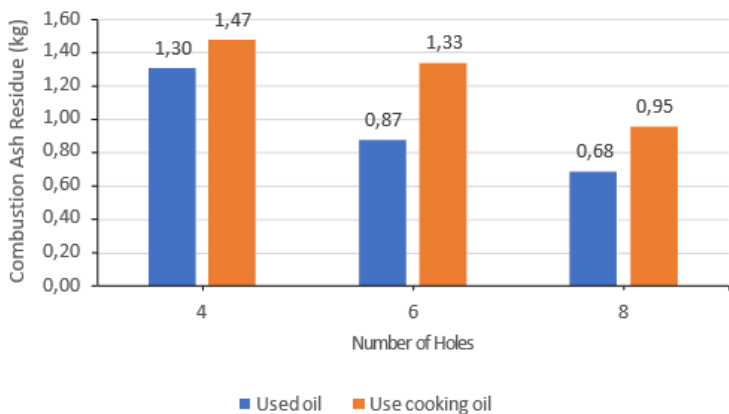


Fig. 7. Graph of combustion ash residue testing values against the number of holes in the incinerator.

The effect of air intake from each variation is quite significant, from the results of the test of the number of holes against combustion ash. Data on the amount of combustion ash on used oil fuel gets a smaller amount of combustion ash, while using used cooking oil gets a higher value. This is because the source of the fire produced by used oil is higher than using used cooking oil, thus affecting the results of combustion ash from this test. At the time of combustion, it can be seen that the size of the fire is more significant in used oil fuel than in used cooking oil. The difference in the size of the fire can cause light ash from combustion to fly into the environment and also get trapped in the incinerator cover [20].

3.4 Analysis of variance

The results of Table 4, Table 5, and Table 6, are the fuel variables on temperature values, combustion time, and combustion ash residue

have a P value of <0.001 (<0.05), so it can be concluded that the fuel has a significant difference in the test results or the results of the fuel significantly affect the number of air holes. It is known that the air hole value has a P value of <0.001 (<0.05), so it can be concluded that there is a significant difference in temperature values, combustion time, and combustion ash residue based on the number of air holes or air holes significantly affect the combustion results. Based on the existing data, it can be concluded that the fuel has a significant effect on the temperature value, combustion time, and combustion ash residue on the number of air holes has a significant effect when viewed through a statistical approach.

3.5 Thermal efficiency

Combustion efficiency is often associated with the optimal combustion rate, but in reality, combustion efficiency is produced by the ratio of fuel used and ideal air. The thermal efficiency value of the diaper waste incinerator using used oil and used cooking oil fuels is as shown in Fig. 8.

Table 4. Two-way Anova temperature values

Source	DF	Adj SS	Adj MS	F-value	P-value
Fuel	1	1042.7	1042.72	4.75	0.005
Number of holes	2	13986.8	6993.39	81.87	<0.001
Fuel*Number of holes	2	136.8	68.39	0.31	0.738
Error	12	2633.3	219.44		
Total	17	17799.6			

Table 5. Two-way Anova combustion time

Source	DF	Adj SS	Adj MS	F-value	P-value
Fuel	1	4293.6	4293.56	572.47	<0.001
Number of holes	2	10805.4	5402.72	720.36	<0.001
Fuel*Number of holes	2	106.8	53.39	7.12	0.009
Error	12	90.0	7.50		
Total	17	15295.8			

Table 6. Two-way Anova combustion ash residue

Source	DF	Adj SS	Adj MS	F-value	P-value
Fuel	1	0.40500	0.405000	45.56	<0.001
Number of holes	2	0.96333	0.481667	54.19	<0.001
Fuel*Number of holes	2	0.07000	0.035000	3.94	0.048
Error	12	0.10667	0.008889		
Total	17	1.54500			

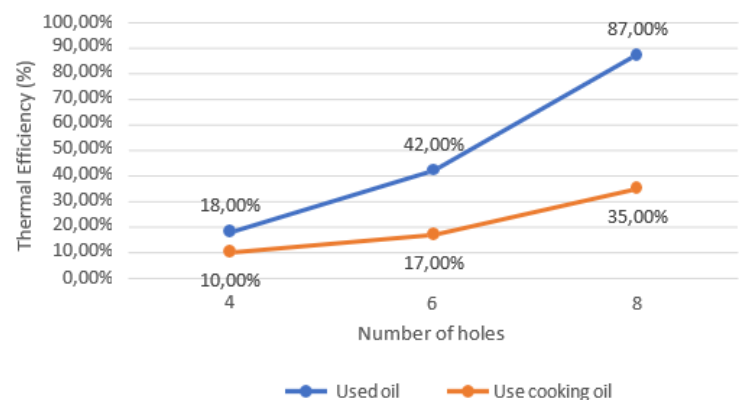


Fig. 8. Graph of thermal efficiency values against the number of holes in the incinerator.

The highest thermal efficiency value of the incinerator with 8 holes gets a value of 87% using used oil fuel, if using used cooking oil with the same number of holes, namely 8, then the thermal efficiency value is 35%. Conversely, if using 4 holes using used cooking oil, the thermal efficiency value is 18%, while if using used cooking oil with 4 air holes, it is 10%. This condition occurs because the air requirement is fairly good for the incinerator combustion process. The addition of 8 air holes increases the amount of heat received by the incinerator, thereby increasing the amount of heat

absorbed. The increase in the amount of heat is due to the sufficient air supply through natural convection, this condition has a good effect on the fuel molecules if they meet with sufficient air. In previous research, the addition of compressed air can increase the performance of the incinerator by 37 percent, this is also comparable to the natural air intake which can also increase the performance of the incinerator, but the efficiency value is below the forced air convection [17].

4 Conclusions

The results of this study demonstrate that natural convection incineration using a water steam stove is more effective when fueled by used motor oil compared to used cooking oil, primarily due to differences in viscosity and boiling points. Using motor oil as the fuel with eight air holes yielded the best combustion results, achieving a peak temperature of 397°C, a combustion time of 65 minutes, and only 0.68 kg of residual ash. In contrast, used cooking oil resulted in a lower temperature (381°C), longer combustion time (89 minutes), and higher ash residue (0.95 kg). The highest thermal efficiency of 87% was achieved with used motor oil, whereas used cooking oil only reached 35%, indicating the superior performance of used motor oil for efficient incineration under natural convection. These findings offer practical insights for optimizing incinerator design and fuel selection in waste treatment applications. Enhancing the inlet air temperature could further improve the thermal efficiency of the system.

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