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# Optimizing energy harvesting from waste motor oil through steam reforming: A path to efficient combustion and emissions reduction

**Budi Waluyo**[1] *, **Bambang Pujiarto**[2], **Nofa Ardana**[3], **An'nisa Solihah**[3], **Muhammad Latifur Rochman**[1], **Ahmad Tresno Adi**[1]

[1] Department of Mechanical Engineering, Universitas Muhammadiyah Magelang, Magelang 56172, **Indonesia**
[2] Department of Information Technology, Universitas Muhammadiyah Magelang, Magelang 56172, **Indonesia**
[3] Department of Automotive Engineering, Universitas Muhammadiyah Magelang, Magelang 56172, **Indonesia**
✉ budi.mech@unimma.ac.id

This article contributes to:

7 AFFORDABLE AND CLEAN ENERGY
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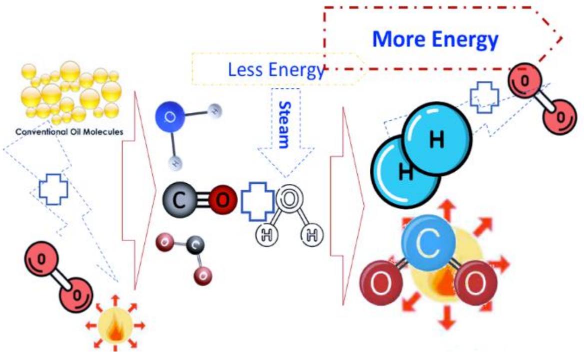

**Highlights:**

- Steam injection effectively transforms carbon monoxide emissions into hydrogen and carbon dioxide.
- Steam injection serves as a corrective measure for addressing incomplete combustion of Waste Motor Oil.
- The inclusion of a reservoir in the steam pipeline is essential for stabilizing the steam injection rate.

## Abstract

Waste Motor Oil (WMO) is a hazardous waste material with the potential to contaminate water, soil, and the atmosphere. The management and engineering of WMO have become imperative in modern society for both resource utilization and environmental protection. Maximizing the energy content of WMO poses a significant challenge for researchers, to solve environmentally friendly solutions. Direct combustion of WMO often results in incomplete combustion and elevated CO emissions. Therefore, this research aims to optimize the harnessing of WMO's energy potential through a furnace equipped with steam injection. The steam is generated by utilizing the heat energy produced during the WMO heating process. Our study demonstrates that steam injection in the WMO furnace is an effective method for maximizing energy content while simultaneously reducing CO emissions.

**Keywords:** Waste Motor Oil; Energy harvesting; Steam reforming; Emissions reduction

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## 1. Introduction

Global energy consumption continues to be primarily reliant on fossil energy sources, such as oil, natural gas, and coal [1]–[3]. This presents a multifaceted challenge and threat to the sustainability of the global energy sector. The supply of fossil energy resources is declining, prices are steadily rising, and the environmental repercussions of their use pose a significant concern for the sustainability of the eart [4]. Moreover, economic growth remains chained to the fossil energy sector, while the proportion of available new and renewable energy sources remains insufficient to meet the surging demand [5]. In response, researchers in the energy field are focusing on the development and utilization of alternative fuels, both as blends with conventional fossil fuels and as stand-alone replacements [6], [7].

One of the most significant contributors to waste oil products on a global scale is Waste Motor Oil (WMO). With global lubricating oil consumption reaching 24 million tons in 2014 and surging to

48 million tons by 2019 [8], [9], the gradual degradation of lubricating oil over time and its transition into waste oil pose substantial challenges for the resource recycling industry. This issue extends to environmental concerns, as WMO is categorized as hazardous waste with the potential to contaminate water, soil, and the atmosphere [10], [11]. Therefore, the management and engineering of WMO have become crucial in the perspective of both waste resource utilization and environmental safeguarding.

Management strategies to utilize WMO often employ physical or chemical reaction methods. Yet, as the volume of WMO waste continues to increase, and the worldwide energy crisis persists as an unresolved problems [12], innovative solutions are imperative. Microorganisms have garnered attention for their potential in breaking down fossil hydrocarbon waste, including WMO. Nevertheless, this approach entails lengthy decomposition times and does not tap into the energy potential of WMO [13]. An alternative approach requires introducing WMO into the pyrolysis process of waste polyethylene (PE) and waste polypropylene (PP) to enhance the quality of the resulting liquid product [14], but this method remains relatively inefficient in harnessing the full energy potential of WMO.

Removal of contaminants from WMO has been investigated with the addition of strong acids, such as acetic, hydrochloric, and sulfuric acids, to increase the absorption ability of nanosized clay powders [15]. However, strong acid treatments are ecologically unsafe and present adverse impacts, making them less favorable for widespread implementation. Additionally, the use of recycled lubricating oil from processes involving strong acids can lead to atmospheric pollution, further worsening concerns related to occupational health and safety [16]. Pyrolysis of WMO using microwave heating exhibits promising results, yielding lubricating oil with quality equivalent to fresh lubricating oil [17], [18].

Analysis using the Fourier Transform Infrared Spectroscopy (FTIR) method has revealed that WMO contains hydrocarbon compounds and their oxides, presenting a valuable potential as an alternative energy source due to its hydrocarbon content, high energy content, and widespread availability [19], [20]. The reuse of WMO through appropriate thermochemical and combustion methods can unlock its optimal energy potential, further reducing the dependency on fossil fuels [21]. Recent research indicates that WMO cracking employing a biochar catalyst from biomass residue yields hydrocarbon chains between $C_{10}$ - $C_{27}$, similar to those found in commercial diesel fuel [22].

This comprehensive review of past research demonstrates the potential for WMO to serve as an environmentally friendly energy source, particularly in the thermochemical processes. The high energy content of WMO positions it as an ideal candidate for application in steam reforming (SR) reactions [20]. Traditional combustion of WMO with longer molecular chains often leads to incomplete combustion and produces carbon monoxide. In contrast, steam presents the opportunity to reform carbon monoxide into hydrogen, boasting an energy content nearly three times that of fossil fuels for vehicular use [23]. The key chemical reaction for the reforming of carbon monoxide into hydrogen through the reaction with water vapor is defined by Equation (1) [24].

$$CO(g) + H_2O(g) \rightarrow H_2(g) + CO_2(g) \tag{1}$$

Therefore, this study introduces a novel energy-harvesting concept based on circular economics. WMO is combusted in a heating furnace, which concurrently heats water to produce water vapor. This vapor is subsequently utilized to reform carbon monoxide resulting from WMO combustion. The hydrogen generated, located within the combustion temperature range, ignites immediately, yielding enhanced combustion energy, as illustrated in **Figure 1**.

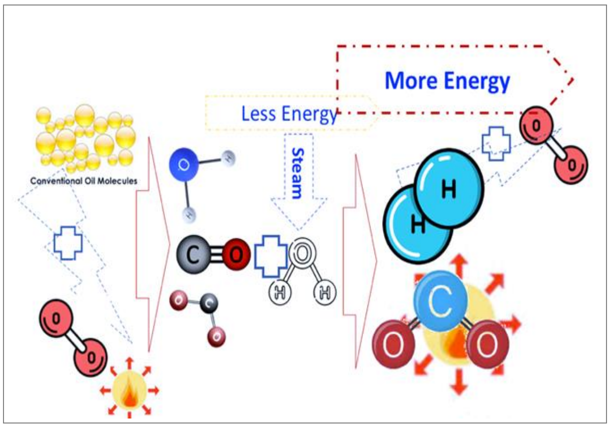

**Figure 1.** The innovative approach of harnessing energy from Waste Motor Oil (WMO) combustion through carbon monoxide steam reform

# 2. Methods

## 2.1. Materials

Waste Motor Oil (WMO) sourced from Shell 10W/40 was used for the experiments. This WMO was obtained from a petrol engine after it had traveled 5,000 kilometers. To ensure that dissolved carbon particles do not interfere with the combustion results, the WMO flows through a filtering process utilizing a 200-mesh filter. Viscosity 10W/40 was selected as the test material, representing the lubricating oil most used in present-day motor vehicles. To facilitate the initial combustion process, a 5% gasoline blend was added to 100 mL of WMO. Once ignited, pure WMO was introduced into the burner system after the 5% WMO-gasoline blend reached its desired flame temperature. Distilled pure water was employed as the raw material for steam. Water was selected as the working fluid for steam due to its cost-effectiveness and low evaporation enthalpy, which stands at 334 $kJ\cdot kg^{-1}$ [25]. This low evaporation enthalpy contributes to more efficient steam generation.

## 2.2. Experiment Setup

This study utilized a WMO heating furnace with a 200 mL capacity, while the water vapor chamber had a volume of 43,290 $cm^3$. The steam flowed into the pipe of 6 mm diameter. A dryer tube was introduced into the steam chamber to ensure the delivery of dry steam to the base of the furnace's fire chimney. At the end of the pipe, a 1 mm diameter nozzle was affixed and positioned at the base of the fire chimney to generate a high rate of steam. This high steam rate was necessary to create a suction effect, drawing in combustion air from outside the heating furnace. The steam distribution pipe crossed the WMO combustion chamber, enhancing the steam's enthalpy before exiting through the nozzle. A depiction of the research setup is illustrated in **Figure 2**. For data collection, a K-type thermocouple, an airflow sensor (LM-8010), a hydrogen sensor (MQ-9 Module), and a CO sensor (MQ-7 Module) were placed at the fire pipe's end. These sensors recorded temperature, hydrogen, and CO emissions resulting from WMO combustion, both before and after steam injection into the base of the heating furnace fire funnel. Temperature and CO emission readings were transferred to a data acquisition system and then forwarded to a PC equipped with DAQ Master for analysis.

This study was conducted under standard ambient conditions, with a temperature of 28 °C and a pressure of 1 atmosphere (1 atm). The initial ignition of the Waste Motor Oil (WMO) was initiated using a butane-fueled torch. Specifically, a 100 mL sample of the 5% v/v WMO-gasoline blend was placed on a steel torch within the heating furnace. Ignition was initiated using the torch until the steel fibers began glowering. Subsequently, pure WMO was introduced into the heating furnace from a dedicated reservoir. Data collection prior to steam injection took place after the WMO flame had stabilized for a duration of 20 seconds, all while the water within the system had not yet reached its boiling point. In contrast, data collection following steam injection occurred once the water had boiled and a consistent stream of steam had been generated for a continuous 20-second period. These accurately controlled experimental conditions ensured that the data obtained was representative of the stable and consistent combustion processes, both prior to and post-steam injection, facilitating a comprehensive analysis of the effects of steam on the combustion of WMO.

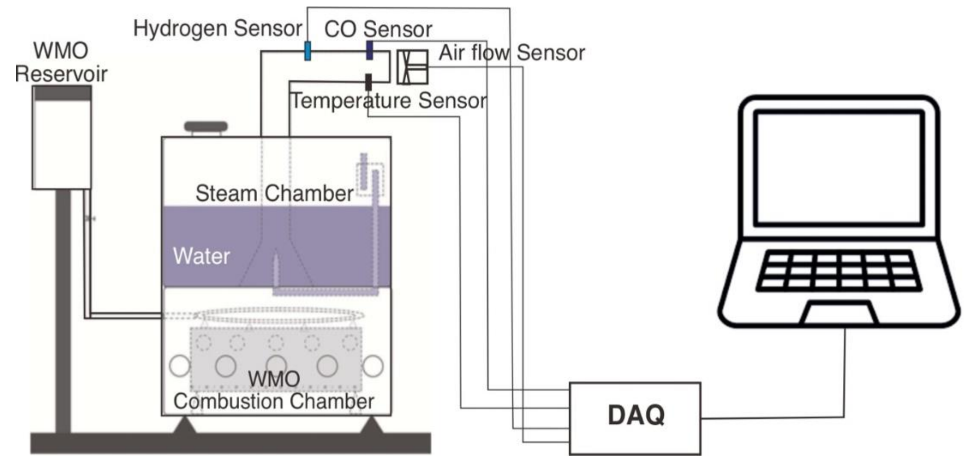

**Figure 2.** Experiment setup

# 3. Results and Discussion

## 3.1. Carbon Monoxide Emissions

The study assessed carbon monoxide (CO) emissions before and after the steam reforming process, aiming to determine the reduction in CO emissions resulting from CO reformation via steam generated in the Waste Motor Oil (WMO) furnace. CO emissions were monitored using the MQ-7 module connected to a data acquisition system (DAQ) and read in real-time on a PC. Before steam reforming, the MQ-7 sensor reading for CO emissions showed a value of 77. The profile of CO emissions, presented in **Figure 3**, demonstrated CO levels ranging from 2.05 to 2.21 before reforming and 1.06 to 1.19 after reforming. This observation revealed a significant decrease in CO emissions when steam was introduced, indicating the conversion of some CO emissions into hydrogen. A clear trend of increasing steam rates was observed, leading to a higher population of CO molecules that were reformed into hydrogen.

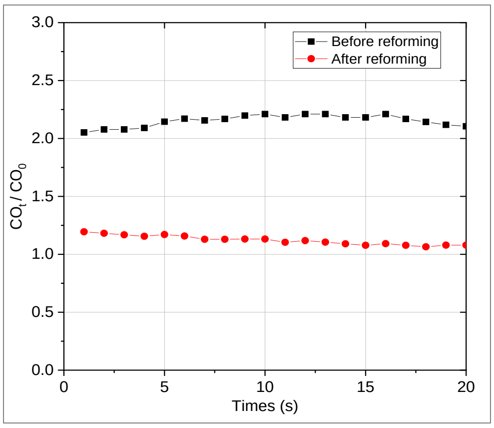

**Figure 3.** Carbon monoxide emissions

## 3.2. Hydrogen Production

Observations of hydrogen gas production were conducted to evaluate unburned hydrogen remaining after WMO combustion following steam reforming. A MQ-9 sensor was used for hydrogen measurement. Prior to measurement, the MQ-9 sensor showed an initial value of 69. The presentation of hydrogen production results is presented as a relative (non-dimensional) value, which represents the ratio of hydrogen measurements after steam reforming to CO emissions.

**Figure 4** illustrated the fluctuating hydrogen yield recorded over 20 seconds. These fluctuations were showed to variations in the steam production rate, which exhibited a non-continuous pattern over time. The findings obtained by using video to JPG software to edit the flame video following the WMO combustion reforming process clearly demonstrate flame fluctuations, visually depicted in **Figure 5**. The energy generated from burning WMO is illustrated by the resultant flame. The rate of steam production is correlated to the energy input into the steam chamber.

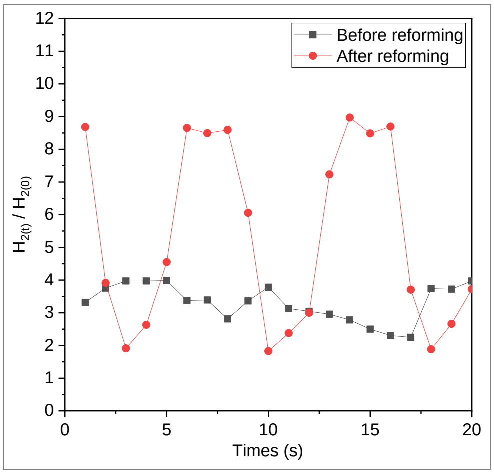

**Figure 4.** Hydrogen production

**Figure 5.** The results of cutting the video of the flame after the WMO combustion reforming process

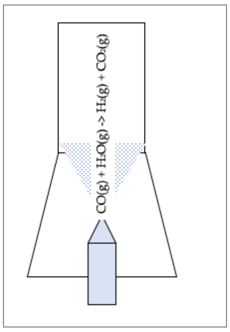

**Figure 6.** The conversion of CO to hydrogen process

This discontinuity in steam rate was associated with the intermittent supply of water vapor, generated from the heat produced during WMO combustion in the burner furnace. Further stability in steam rates could be achieved through the addition of a steam reservoir before the nozzle in the distribution pipe, reducing fluctuation in steam rates. Enhanced steam rate stability would optimize the CO-to-hydrogen reforming process within the WMO burner furnace. The conversion of CO emissions into hydrogen takes place after the thermal reformation of steam / H2O(g) as Equation (1), transpiring above the steam nozzle at the level of the fire funnel, demonstrated in **Figure 6**.

### 3.3. Energy Combustion

The study implemented an airflow sensor (LM-8010) to measure the velocity of hot air generated by the WMO furnace. This enabled the calculation of the mass rate ($\dot{m}$) of hot air produced by multiplying velocity ($v$) by density ($\rho$), where the density of hot air is temperature dependent. The rate of heat energy produced was computed using the equation $\dot{E}_{heat} = \dot{m}.C_p.(\Delta T)$, where $\Delta T$ represents the temperature difference between the hot air resulting from WMO combustion and the environmental temperature. Furthermore, the rate of kinetic energy was calculated through the equation $\dot{E}_{kinetic} = \frac{1}{2}\dot{m}v^2$.

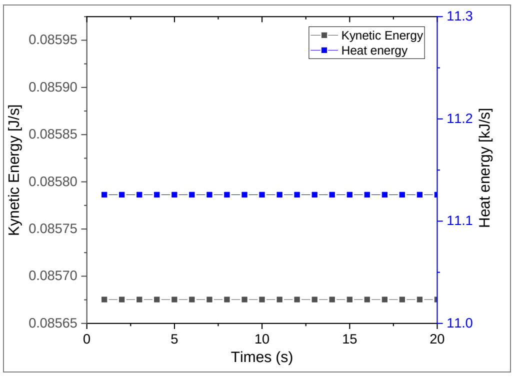

**Figure 7.** Observation of kinetic and heat energy from WMO combustion

**Figure 7** illustrated observations of heat and kinetic energy rates over 20 seconds after steam reforming. Heat energy rates notably exceeded kinetic energy rates. The rate of kinetic energy correlated with the steam produced during the water boiling process, which, as steam exited the nozzle, induced a vacuum effect, drawing in fresh external air and facilitating more complete combustion. Meanwhile, a higher rate of heat energy resulted from harnessing the combustion energy of hydrogen derived from CO reform by steam injection at the base of the fire chimney. This high heat energy rate is related to the decrease in CO emissions observed in **Figure 3**.

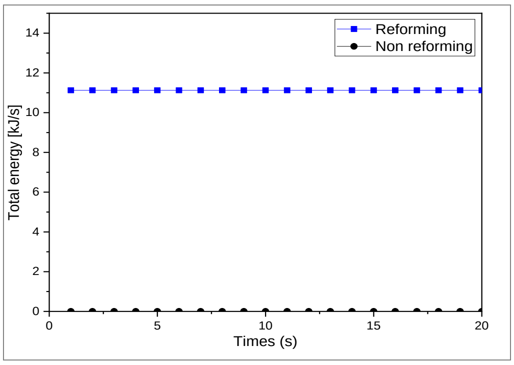

**Figure 8.** Observation of kinetic and heat energy from WMO combustion

Then, **Figure 8** shows the total energy rate from WMO combustion with steam reform, combining heat and kinetic energy. The proportion of kinetic energy produced was relatively small, approximately 0.8% of the heat energy rate. Harvesting heat energy through WMO combustion with steam reform led to a substantial energy surplus compared to combustion without steam reform. This system demonstrated the potential to replace conventional WMO burners with electric blowers while significantly reducing harmful CO emissions and yielding higher energy rates. Finally, the study's results highlight the transformational potential of steam reforming in waste-to-energy solutions. Future research could explore the scalability and practical applications of this technology, further refining process parameters to maximize efficiency and emissions reduction. In conclusion, the integration of steam reforming demonstrates the possibility of converting hazardous waste, such as WMO, into an environmentally friendly and efficient energy resource with significant reductions in emissions.

## 4. Conclusion

The research focused on obtaining energy from Waste Motor Oil (WMO) using steam reforming, demonstrating a considerable improvement in the combustion process. This method offers a cleaner and more efficient approach compared to conventional combustion, effectively transforming hazardous carbon monoxide (CO) emissions into hydrogen and carbon dioxide. Maintaining a consistent steam flow at the nozzle is important for optimal efficiency, necessitating to addition of a steam reservoir to the steam pipe nozzle. This study reveals the substantial potential of utilizing WMO through steam reforming to address incomplete combustion and CO emissions while increasing heat energy output. Implementing this innovative technology holds the promise of cleaner energy solutions and better environmental outcomes. Future research should focus on refining and upscaling this approach for practical applications, paving the way for a more sustainable and efficient energy scene.

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## Authors' Declaration

**Authors' contributions and responsibilities** - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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**Availability of data and materials** - All data is available from the authors.

**Competing interests** - The authors declare no competing interest.

**Additional information** – No additional information from the authors.

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