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Study of Thermal Heating of Waste Engine Oil in a Microwave Pyrolysis Reactor

Moh. Arif Budianto, Samsudin Anis* and Wirawan Sumbodo

Department of Mechanical Engineering, Universitas Negeri Semarang, Kampus Sekaran, Gunungpati, Semarang 50229 Indonesia

*Corresponding author: samsudin_anis@mail.unnes.ac.id

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ABSTRACT: *The purpose of this study is to investigate the effect of microwave power and irradiation time, as well as the effect of types of absorber on thermal characteristics of microwave reactor during pyrolysis of waste engine oil. This study is needed to provide basic knowledge into the fundamentals of microwave heating process for pyrolysis of waste engine oil. In this work, a domestic microwave oven with a maximum output power of 418 W was modified and used as the experimental reactor. Two types of absorber, i.e., wood char and coconut shell char were also employed to enhance reaction temperature. The char loading was tested in the level of 75 g. The samples were examined under various microwave power of 257 W, 362 W and 418 W for 60 min of irradiation. Microwave power and irradiation time significantly affect thermal characteristics of microwave reactor. The higher the microwave power, the higher the reactor temperature, heating rate and thermal efficiency. Coconut shell char provided better results compared to wood char as absorbers. Reactor temperature, heating rate and thermal efficiency of 639°C, 10.05°C min^{-1} and 25.53%, respectively could be obtained with the use of 75 g coconut shell char at 418 W microwave power. It can be concluded that waste engine oil can only be processed in microwave pyrolysis reactor with the aid of an absorber material.*

Keywords: Thermal heating, microwave, pyrolysis, waste engine oil, coconut shell char

1. INTRODUCTION

Rapid industrial development in the world has resulted in the increase of fuel consumption. Currently, fossil-based fuels are the most widely used fuels.

Besides in industries, fossil-based fuels as the major source of energy are also used in various human activities. The high fossil-based fuel consumption contributes to the reduction of world's oil reserves. In addition, the use of fossil-based fuels continuously has been identified as a major cause of air pollution and global warming.

To overcome the energy crisis due to the depletion of fossil energy reserves and environmental issues, ideas for treating various types of wastes as a source of energy have been explored. One of the types of waste that can be used as a fuel is waste engine oil (WEO). So far, WEO has been used as fuel in cement and lime kilns, in brick works and metallurgical furnaces, as well as for co-firing in a boiler.[1–3] Chemically, WEO contains hydrocarbon materials including aliphatic, aromatic and olefinic hydrocarbons. The hydrocarbon structure of the WEO has been estimated to be 98.9% aliphatic hydrocarbons, 0.94% aromatic hydrocarbons and 0.08% olefinic hydrocarbons.[4] It was reported that WEO is one of the most abundant residual pollutants produced in the world, reaching 24 million metric tonnes per year, most of which is disposed through landfill or in water.[5,6] The high volume of WEO can actually be converted into valuable fuel products such as diesel and gasoline through chemical or thermochemical methods, without disposing it into the environment.[7–9] In addition, utilisation of fuel products from WEO treatment by using diesel or gasoline engines not only reduces the fossil-based fuels consumption but also protects the environment from toxic and hazardous chemicals.[6] It should be noted that pyrolysis has become one of the preferred methods to convert WEO into more useful fuel products in the form of liquid (diesel and gasoline), gases or solid fuels.[5,9–12]

Nowadays, research activities on wastes pyrolysis with the aid of microwave heating to produce fuels as alternative energy resources have gained more attention. The interest in using microwave technology is due to the unique feature of volumetric heating of materials which can significantly save processing time, improve process yields, produce fewer harmful compounds and provide higher heating efficiency.[13,14] With regard to the advantages of microwave heating, treatment of various types of wastes under microwave heating has been successfully demonstrated, not only for lignocellulose biomass but also for automotive shredded residue, oil shales and waste automotive engine oil.[13,15–20] Essentially, oil-based materials are transparent to microwave energy making it difficult to be heated in a microwave reactor. Therefore, to allow heating process running well, researchers used absorbers such as carbon materials that can absorb microwave energy to generate sufficient thermal energy.

Based on the above description, although studies on the treatment of various types of wastes in particular waste oils using microwave heating have been performed, the studies focused only on the production and characterisation of pyrolysis oils and gases. In fact, there are many other important parameters need to be investigated in detail to improve the performance of microwave reactors. One such parameter is the thermal characteristics of the microwave reactor associated with the material to be processed. Therefore, this study is focused on thermal characteristics of microwave reactor during processing of WEO. This study is very important to assess the technical performance of the microwave reactor in terms of temperature evolution, heating rates and thermal efficiencies. With the aim to obtain optimal conditions and achievable technical performance, various parameters including microwave power, irradiation time and types of absorber were studied.

2. EXPERIMENTAL

2.1 Materials

WEO was collected from some local motorcycle workshops in Semarang, Indonesia. Before used, the WEO was heated at 100°C for 30 min in order to remove water content. After cooling to room temperature, the WEO was filtered using filter paper to separate the solid particles. Commercial wood char and coconut shell char were also employed as absorber materials to increase the reactor temperature. They were crushed to obtain char particles with a size of 0.5 cm cube.

2.2 Experimental Apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. It consists of microwave reactor unit, cooling unit and controlling unit. Microwave reactor unit includes a microwave oven and a ceramic reactor containing a temperature detector (K-type thermocouple) at the centre of the reactor and WEO with and without char. The microwave oven has a frequency of 2.45 GHz with a maximum output power of 450 W. The ceramic reactor with 84 mm inside diameter (ID) and 125 mm length designed as a fixed bed reactor was vertically installed in the microwave chamber. A J-type thermocouple was also used to monitor microwave cavity temperature. The microwave cavity temperature should be kept below 200°C to avoid damage of the microwave unit. Cooling system consisted of a condenser, a water pump and a liquid collector of 250 ml glass bottle. Teflon and copper pipe with a size of 9.5 mm ID were used for transporting volatile materials produced during the process from ceramic reactor to liquid collector. Reactor and cavity temperatures were monitored and controlled using thermometer controllers.

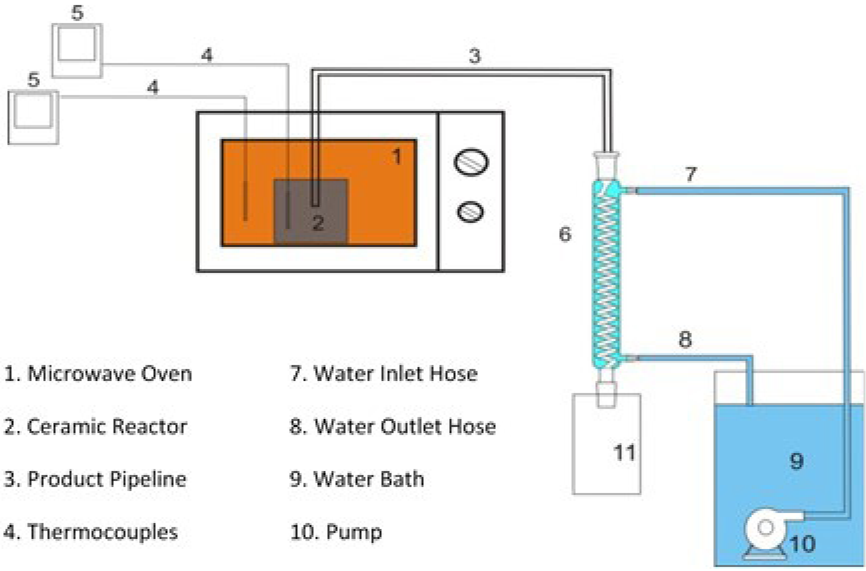

Figure 1: Schematic diagram of the experimental apparatus.

2.3 Thermal Heating Experiment

Thermal heating experiments were performed to evaluate thermal characteristic of microwave reactor in terms of temperature evolution, heating rate and thermal efficiency. In each experimental run, the amount of WEO was kept constant at 200 ml and tested for 60 min of irradiation time. It was tested at three levels of microwave powers (257 W, 362 W and 418 W) and using three kinds of absorbers (without/no char, wood char and coconut shell char). The change of microwave reactor and cavity temperatures were recorded every 60 s. After the designated irradiation time, the microwave oven was automatically switched off. The system was allowed to cool to ambient temperature. This procedure was repeated for each set of conditions studied. With these parameters, a total of 300 data was collected during the experiments.

In this work, the obtained data were used to evaluate heating rate (HR) and thermal efficiency (η_T). The below equations were used to calculate thermal efficiency and absorbed microwave power (P_{abs}).[21]

$$\eta_T = \frac{P_{abs}}{P_{MW}} \times 100\% \quad (1)$$

$$P_{abs} = \left[mc_p \left(\frac{T_2 - T_1}{t} \right) \right] + [hA(T_2 - T_1)] + [\varepsilon \sigma A \overline{T}^4] \quad (2)$$

where P_{MW} is the chosen microwave power (W), m is the mass of material (kg), C_p is the heat capacity of material (J kg^{-1} K^{-1}), T_1 and T_2 are the initial and final temperatures (K) respectively, t is the irradiation time (s), h is the convective heat transfer coefficient (W m^{-2} K^{-1}), A is the area of the object (m^2), ε is the emissivity of material, σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), and $\overline{T}$ is the average temperature within the microwave reactor (K).

3. RESULTS AND DISCUSSION

3.1 Effect of Microwave Power

A series of experiments were performed to evaluate the effect of microwave power on thermal characteristic of microwave reactor indicated by the temperature profile, heating rate and thermal efficiency. In this study, the amount of WEO was fixed at 200 ml whereas the microwave powers were varied from 257 W to 418 W without addition of char as absorber. Figure 2 shows the reactor temperature evolution during 60 min of irradiation for each microwave powers applied. It could be observed that reactor temperature increased with the increase of microwave power. The highest temperature was obtained at 418 W in which after 60 min of irradiation, reactor temperature reached 269°C. These results showed that when the incident microwave power increases, the absorbed microwave power by the material inside reactor will also increase which leads to an increase in reactor temperature. Another reason is at maximum applied microwave power of 418 W, material in the reactor was exposed continuously by the high intensity of microwave energy (continuous mode), while at lower microwave power, the material was only exposed periodically by microwave energy (pulse mode). The results were in compliance with previous studies that the absorbed microwave power is strongly affected by the electric field.[21,22]

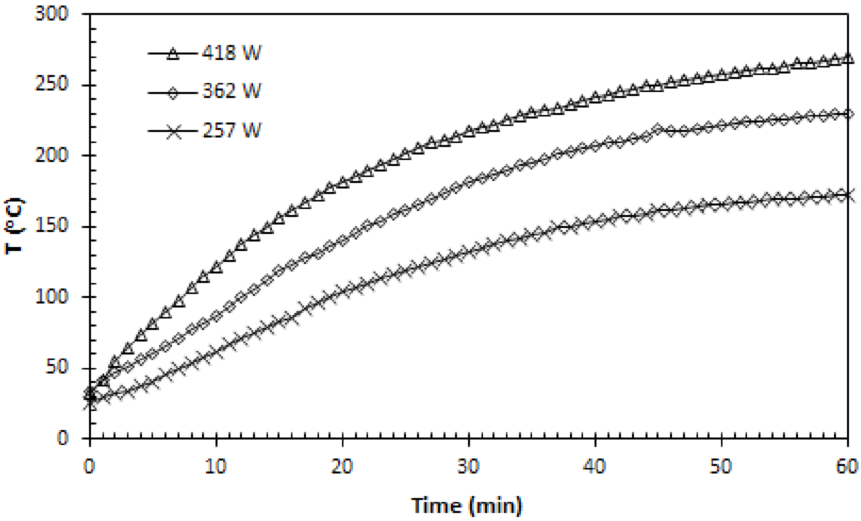

Figure 2: Reactor temperature profile as a function of irradiation time at various microwave powers.

Based on the results, although the highest temperature could be achieved at the highest microwave power applied, the obtained final reactor temperature has not yet reached the minimum pyrolysis temperature of 500°C for WEO.[20] In addition, previous study found that optimum yield of liquid from pyrolysis of WEO could be obtained at 550°C.[19] It confirmed that WEO cannot absorb microwave energy well so that it can be categorised as a non-absorber material in microwave processing.

Figure 3 shows the heating rate at various microwave powers. It was evaluated every 5 min of irradiation time. It can be observed that for microwave power of 418 W, the heating rate reduced gradually during 60 min of irradiation. Similar tendency was also reported by other studies.[21–23] For microwave powers of 257 W and 362 W, initially the heating rate increased slightly up to a specific irradiation time before decreasing. The reduction of heating rate is caused by the change of penetration depth of microwave power during processing. It will decrease when the material temperature rises. This change was strongly associated with relative values of dielectric constant and loss factor of material. These variables primarily depend on the temperature.[24,25]

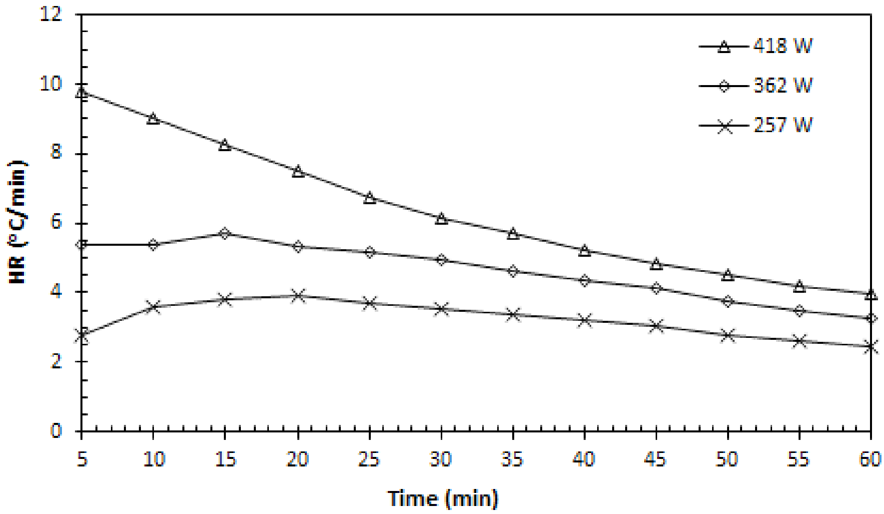

Figure 3: Heating rate at various microwave powers.

Figure 4 shows the thermal efficiency at various microwave powers that was also evaluated every 5 min of irradiation time. As shown in the figure, the highest microwave power used in this study (418 W) has better thermal efficiency compared to lower microwave powers although it experiences decreasing values during 60 min of irradiation. For instance, thermal efficiency was about 8.11% after 5 min and became to 6.63% after 60 min of irradiation. In contrast with 418 W, the obtained thermal efficiencies for 257 W and 362 W seemed to increase up to 20 min of irradiation. Beyond the time, thermal efficiency tended to constant. The low thermal efficiency for all microwave powers applied is a strong indication that WEO is not a good absorber material as previously revealed. Therefore, additional absorber material such as char is highly required to increase the reactor temperature so that the modified microwave reactor can be used for pyrolysis of WEO.

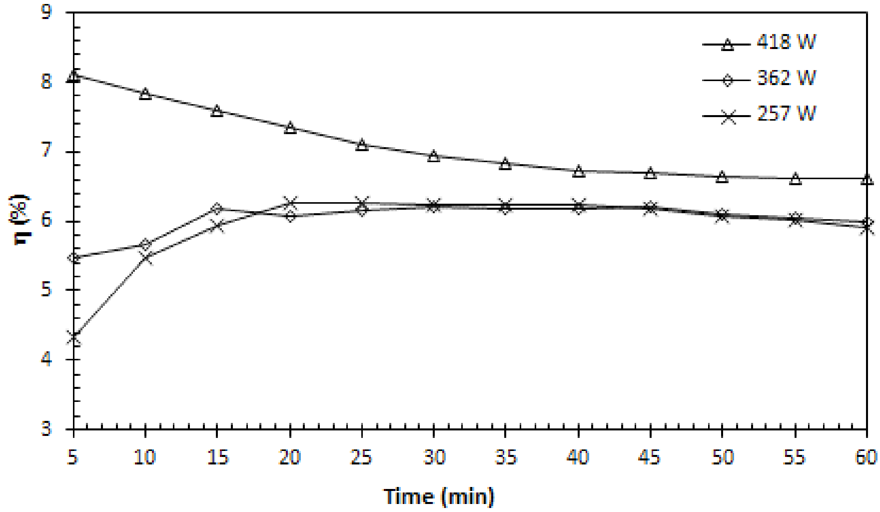

Figure 4: Thermal efficiency at various microwave powers.

3.2 Effect of Types of Absorber

Effect of types of absorber on reactor temperature, heating rate and thermal efficiency was examined at a fixed microwave power of 418 W and at a constant amount of absorber of 75 g for 60 min of irradiation time. Figure 5 shows temperature profile as a function of irradiation time for various types of absorber. The figure indicates that the use of absorbers significantly affected reactor temperature. By using wood char and coconut shell char, reactor temperatures increased considerably. After 60 min of irradiation, reactor temperature of 566°C and 639°C could be reached, respectively. The figure also evinced that the two char absorbers provided relatively different temperature profiles during processing. The use of coconut shell char not only provided high reactor temperature but also caused rapid increase in temperature. The literature showed that char derived from coconut shell has higher loss tangent value compared to wood-based char.[13,26,27] The higher loss tangent of materials, the higher the absorbed microwave power is, and therefore the reactor temperature is also higher.

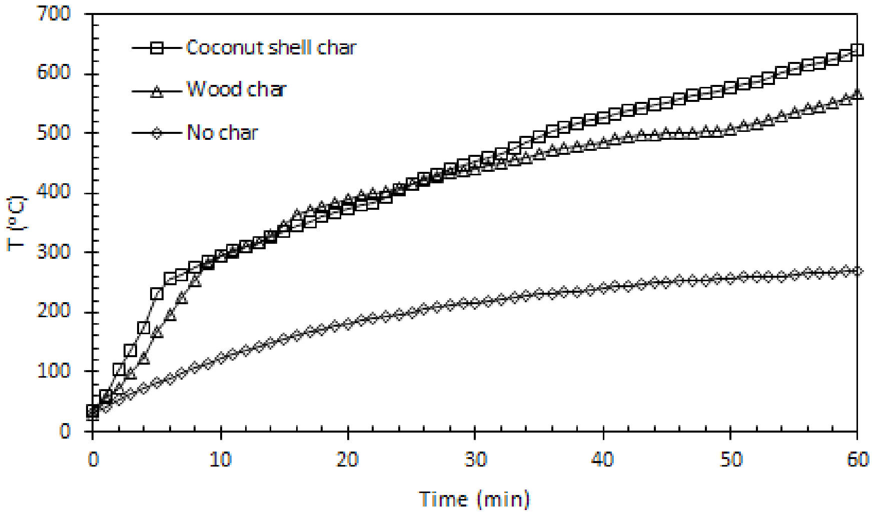

Figure 5: Reactor temperature profile as a function of irradiation time for various types of absorber.

Figure 5 also shows that the reactor temperatures suddenly rose dramatically at specific irradiation times after minimum temperature pyrolysis of 500°C was reached for both coconut shell char and wood char. This phenomenon occurred because when the pyrolysis temperature approached about 500°C, WEO in the reactor started to evaporate and partially transformed from liquid into vapour phase. In this condition, the contact between thermocouple probes with liquid WEO may be disturbed by gas bubbles formed in the oil, and as a result, the measured temperature fluctuated especially for the case of wood char as an absorber.

The heating rate for various types of absorber is presented in Figure 6. As can be seen from the figure that the systems with char as absorber provided higher heating rates than the system without char. Generally, the highest heating rates were reached in 5 min of irradiation time, i.e., 9.8°C min^{-1}, 27.6°C min^{-1} and 38.8°C min^{-1} for without/no char, wood char and coconut shell char, respectively. Meanwhile, at irradiation time of 60 min, the heating rates were only 3.95°C min^{-1}, 8.95°C min^{-1} and 10.05°C min^{-1}, respectively. The high heating rates of the system with the presence of coconut shell char not only provided high reactor temperature but also reduced the required heating time as depicted earlier in Figure 5. For example, reactor temperature of 500°C could be attained in 35 min with the use of coconut shell char whereas it needed about 45 min for the case of wood char.

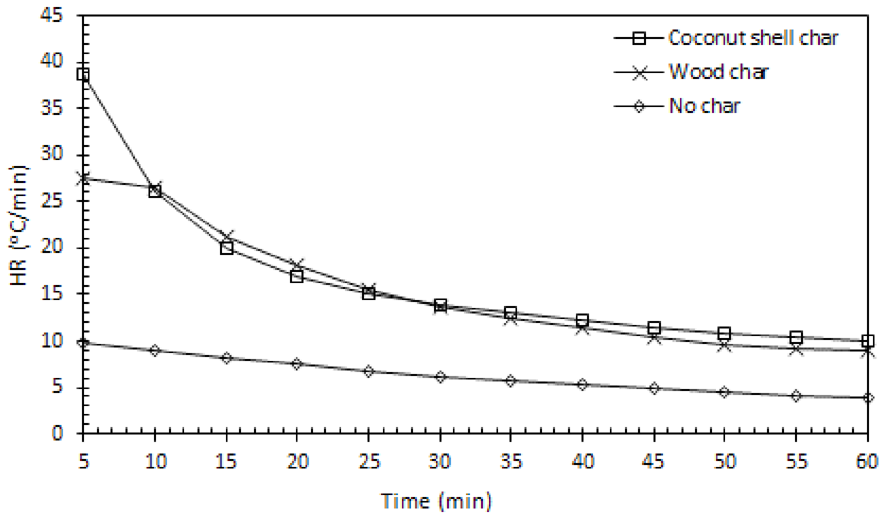

Figure 6: Heating rate for various types of absorber.

Thermal efficiency for various types of absorber can be observed in Figure 7. In the range of irradiation time investigated, the presence of coconut shell char and wood char as absorber materials was capable to enhance thermal efficiency of microwave reactor. Thermal efficiency decreased initially for irradiation time below 25 min and then increased significantly up to 60 min of irradiation. The increase of thermal efficiency of coconut shell char was much higher than that of wood char. In this condition, the calculation results show that thermal efficiency increased from 18.67% after 25 min to more than 25.5% at final irradiation time studied for coconut shell char. While for wood char, it was 18.61% after 25 min to about 22% at final irradiation time. From this result, it can be concluded that the high thermal efficiency of microwave reactor with coconut shell char as an absorber could be attributed due to better dielectric properties that can absorb and convert microwave energy into heat.[13,26]

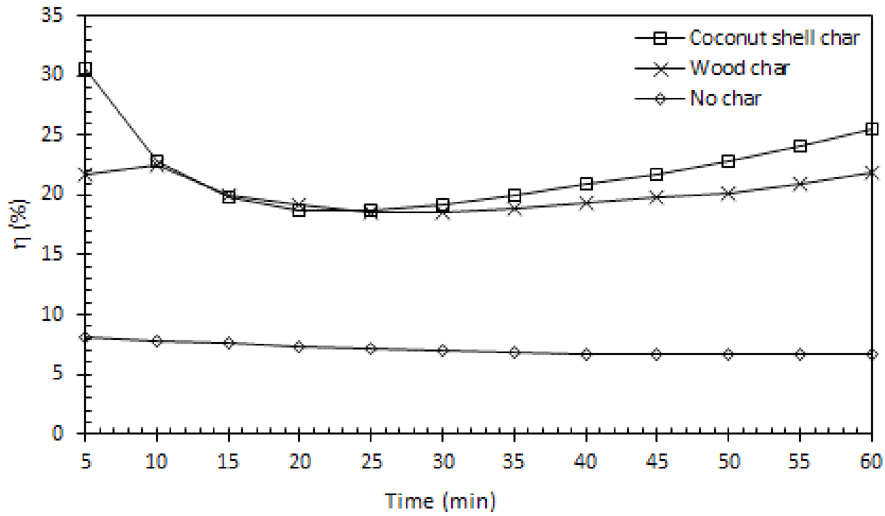

Figure 7: Thermal efficiency of various types of absorber.

4. CONCLUSION

Thermal heating of WEO under microwave irradiation has been investigated. The results showed that the presence of absorber material that has good capacity in absorbing microwave energy is crucial in pyrolysis of WEO under microwave energy. Microwave power and type of char were found to be the main factors influencing reactor temperature, heating rate and thermal efficiency. The higher the microwave power, the higher the temperature, the heating rate and the thermal efficiency are. This study also found that the use of coconut shell char provided better thermal characteristic compared to wood char. Under conditions investigated, reactor temperature of 550°C could be obtained after 45 min of irradiation with the use of 75 g coconut shell char at microwave power of 418 W. As a whole, the developed microwave reactor is eligible to be applied for pyrolysis of WEO.

5. ACKNOWLEDGEMENTS

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