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Thermal Characteristics Analysis of Microwaves Reactor for Pyrolysis of Used Cooking Oil

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Abstract. The research is objected to develop microwave reactor for pyrolysis of used cooking oil. The effect of microwave power as well as addition of char as absorber towards its thermal characteristic were investigated. Domestic microwave was modified and used to test the thermal characteristic of used cooking oil in the terms of temperature evolution, heating rate, and thermal efficiency. The samples were examined under various microwave power of 347W, 399W, 572W and 642W for 25 minutes of irradiation time. The char loading was tested in the level of 0, 50, and 100 g. Microwave reactor consists of microwave unit with a maximum power of 642W, a ceramic reactor, and a condenser equipped with temperature measurement system was successfully developed. It was found that microwave power and addition of absorber significantly influenced the thermal characteristic of microwave reactor. Under investigated condition, the optimum result was obtained at microwave power of 642W and 100 g of char. The condition was able to provide temperature of 480°C, heating rate of 18.2°C/min and thermal efficiency of 53% that is suitable to pyrolyze used cooking oil.

INTRODUCTION

Nowadays, research activities on the application of microwave heating for biofuels production have gained more and more attention in developing alternative energy resources to substitute the fossil fuels. The high interest in using microwave technology is due to it solves the limitations of conventional heating by the unique feature of volumetric heating of materials. This feature can result in more rapid heating process leading to energy and process time saving significantly, improve process yield, generation of fewer hazardous compounds, and higher heating efficiency [1, 2].

One of the implementation of microwave heating is microwave-assisted pyrolysis (MAP) that is able to treat various kinds of waste and converted into other forms of fuel including solid, liquid, and gaseous hydrocarbons. For heat to be generated within the materials during MAP processes, the microwaves should be able to enter the materials and generate heat. On this basis, microwave irradiation can be used directly to heat materials if they exhibit good dielectric properties that can absorb microwave energy. However, materials have different responses to microwave heating and not all materials have high dielectric properties [3]. In common, materials can be classified into three principal groups, i.e., conductor, insulator, and absorber that reflect, transmit, and absorb the microwave energy, respectively. Materials such as fused quartz, ceramics, glasses, and plastics are always treated as insulator/transparent materials due to their low dielectric properties. Metals and alloys are always considered as conductor/reflective materials, whereas water, polar solvent, activated carbon and silicon carbide are considered as microwave absorbers due to their high dielectric properties.

In a number of reported literatures, treatment of various types of biomass under MAP process has been successfully demonstrated [1, 4, 5]. Plastic wastes [6, 7], automotive shredded residue [8], oil shales [9], and waste engine oil [10] have also been treated under MAP process. In general, these materials are transparent to microwave energy or have poor dielectric properties that need addition of absorber material such as carbon materials in order to allow the process

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can take place properly. In addition, waste cooking oil (WCO) or used cooking oil (UCO) has also been used as a feedstock to produce biodiesel in a microwave reactor [11, 12]. However, like the other oils, UCO is also a non-polar substance that can be regarded as transparent material to microwave energy, making it difficult to be processed in a microwave reactor. For this reason, in the available literature so far, microwave-assisted transesterification (MAT), instead of MAP, with the aid of polar substances has been applied by some researchers.

Based on the above description, although studies on the treatment of various types of waste using microwave heating, in particular the wastes that are clearly unable to absorb and convert microwave energy into heat have been performed, but most of these studies focused on the production of liquid biofuels or gaseous. In fact, there are many other important characteristics that need to be in detail investigated in order to improve the performance of microwave reactor. One is the thermal characteristics of microwave reactor associated with substances to be processed.

Therefore, in this study, thermal heating characteristics of the developed microwave reactor for pyrolysis of used cooking oil (UCO) are investigated. This study is very important to assess the performance of the developed microwave reactor in term 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 wood char loading were tested.

MATERIALS AND METHODS

Materials

Used cooking oil (UCO) was collected from some local restaurants in Semarang, Indonesia. Before used, the UCO was heated at 100°C for 30 minutes in order to remove water content. After cooling to room temperature, the UCO was filtered using filter paper to separate the solid particles. Commercial wood char was used as an absorber material to increase the reactor temperature. It was crushed to obtain char particles with a size of 0.5 cm cube.

Experimental Apparatus

A schematic diagram of the experimental apparatus is presented in Fig. 1. It consists of two main units: microwave reactor and cooling system. Microwave reactor includes a modified microwave oven and a ceramic reactor containing UCO with or without wood char. The modified microwave oven has a frequency of 2.45 GHz corresponding to wavelength of 12.23 cm. The maximum output power of the microwave oven was 750 W. The ceramic reactor with 84 mm i.d. and 125 mm length was installed vertically in the microwave chamber and designed as a fixed bed reactor. It contains a temperature detector (K-type thermocouple) at the center of the reactor. To monitor microwave cavity temperature, a J-type thermocouple was also used. The microwave cavity temperature should be kept below 200ºC to avoid damage of the microwave unit. Cooling system consists of a condenser and a liquid collector of 250 mL glass bottle. For channeling volatile material produced during the process from ceramic reactor to liquid collector, Teflon and copper pipe with a size of 9.5 mm i.d was used.

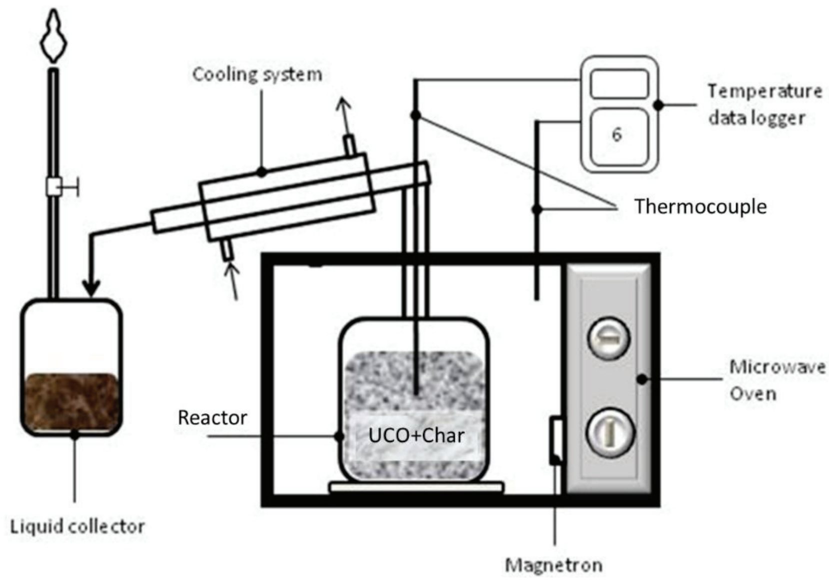

FIGURE 1. Schematic diagram of the experimental apparatus

Thermal Heating Experiment

Thermal characteristic of microwave reactor in terms of temperature evolution, heating rate, and thermal efficiency were investigated under various microwave powers and amount of wood char as absorber material. Four levels of microwave power i.e. low (347 W), medium (399 W), medium-high (572 W), and high (642W) and three level of wood char loading (0, 50, and 100 g) were applied in the experiments. In each experimental run, the amount of UCO was kept constant of 200 mL and tested for 25 minutes of irradiation time. During the experiment, temperatures within the reactor and microwave cavity were recorded every 30 seconds. Temperature was measured using a 3 mm o.d. K-type stainless steel sheathed thermocouple that satisfies measurement of temperature in electromagnetic field. Grounding of the metallic sheath to the chamber is required to avoid arcing. After the designated irradiation time, the microwave oven was automatically switched off. Then, the system was allowed to cool to ambient temperature. This procedure was repeated for each set of conditions investigated.

In this work, heating rate was evaluated based on initial temperature (T_1) and final temperature (T_2) reached in 25 minutes of irradiation time (t). For thermal efficiency (η_T), it was calculated based on the equation below:

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

where P_{MW} is the chosen microwave power and P_{abs} is the absorbed microwave power that can be determined as follows:

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

where m is the mass of material (kg), c_p is the heat capacity of material (J/kg.K), h is the convective heat transfer coefficient (W/m^2.K), A is the area of the object (m^2), ε is the emissivity of material, σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2.K^4), and $\bar{T}$ is the average temperature of microwave reactor (K).

RESULTS AND DISCUSSION

Effect of Microwave Power

A series of studies were conducted in order to evaluate the effect of microwave power on thermal characteristic of microwave reactor characterized by the temperature profile, heating rate, and thermal efficiency. In this study, the microwave power were varied from 347 W to 642 W, whereas the amount of UCO was fixed at 200 mL without addition of wood char. Fig. 2 shows the temperature profile of four microwave powers for 25 minutes of irradiation.

As indicated in the figure, reactor temperature increased with the increase of microwave power. The highest temperature was obtained at 642 W. After 25 minutes of irradiation, reactor temperature reached 70^oC, 97^oC, 158^oC, and 187^oC for 342 W, 399 W, 572 W, and 642 W, respectively. These results show that the absorbed microwave power by the material inside reactor increases as the incident microwave power increases, therefore temperature within the reactor will also increase. This is because at maximum microwave power of 642 W, material in the reactor was exposed continuously by the high intensity microwave energy (continuous mode). While at low 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 [2, 13]. Nevertheless, the obtained final reactor temperature has not yet reached the minimum pyrolysis temperature of 325^oC for UCO [11]. This confirms that UCO cannot absorb microwave energy well so that it can be categorized as a non-absorber material in microwave processing.

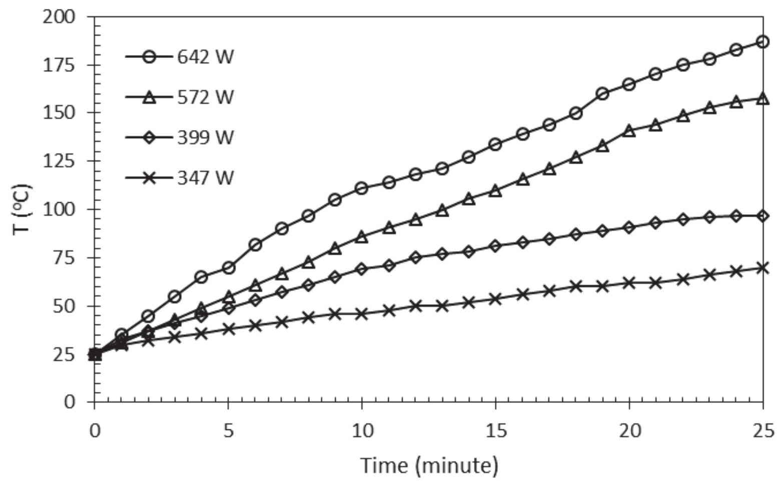

FIGURE 2. Temperature profile as a function of irradiation time at various microwave powers

Figure 3 shows the heating rate at various microwave powers. It was evaluated after 5, 10, 15, 20, and 25 minutes of irradiation time. It can be observed that for microwave power of 642 W, the heating rate reduced gradually during 25 minutes of irradiation. In contrast, for lower microwave powers of 347 W, 399 W, and 572 W, lower heating rates were also observed. Generally, the highest heating rates were reached in the first 5 minutes of irradiation i.e. 2.6^oC/min, 4.8^oC/min, 6^oC/min, and 9^oC/min for 347 W, 399 W, 572 W, and 642 W, respectively. While, at irradiation time of 25 minutes, the heating rates were only 1.8^oC/min, 2.88^oC/min, 5.32^oC/min, and 6.48^oC/min, respectively. Similar tendency was also informed by other studies [13, 14]. The reduction of heating rate is due to the penetration depth of microwave power changes 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 are primarily dependent on the temperature.

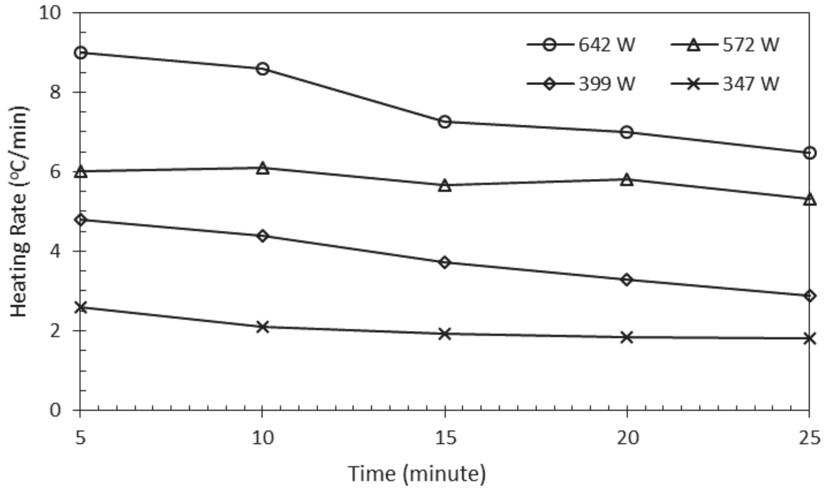

FIGURE 3. Heating rate at various microwave powers

Figure 4 shows the thermal efficiency at various microwave powers. It was also evaluated after 5, 10, 15, 20, and 25 minutes of irradiation time. In general, thermal efficiency did not change significantly during this process. The thermal efficiency increased by only about 1 to 3% after 25 minutes of irradiation. For instance, at 642 W, thermal efficiency was about 12.57% after 5 minutes and became to 15.34% after 25 minutes of irradiation. This low thermal efficiency is a strong indication that UCO is not a good material to absorb microwave energy as previously revealed. Therefore, additional absorber material such as char is highly required in order to increase the reactor temperature so that later the microwave reactor can be used for pyrolysis of UCO.

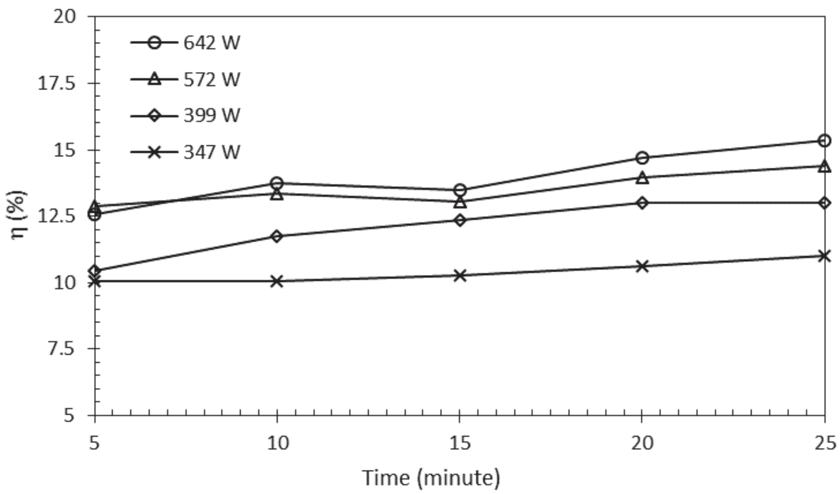

FIGURE 4. Thermal efficiency at various microwave powers

Effect of Wood Char Loading

Effect of wood char loading on reactor temperature, heating rate, and thermal efficiency was examined at a fixed microwave power of 642 W for 25 minutes of irradiation. Fig. 5 shows temperature profile as a function of irradiation time at various wood char loading. The figure indicated that addition of wood char significantly affects reactor temperature. By addition of 50 g and 100 g of wood char, reactor temperatures increased considerably. After 25 minutes of irradiation, reactor temperature reached 419ºC and 480ºC, respectively. It could be observed that the increase in temperature is relatively similar for both 50 g and 100g up to irradiation time of 20 minutes. Beyond that, the reactor temperature increased significantly for 100 g of wood char as absorber material. These results indicate that the more amount of absorber in the reactor, the higher the absorbed microwave power therefore the reactor temperature is also higher. This result is in line with an earlier study that the absorbed microwave power increases as the volume of the absorber material increases [15].

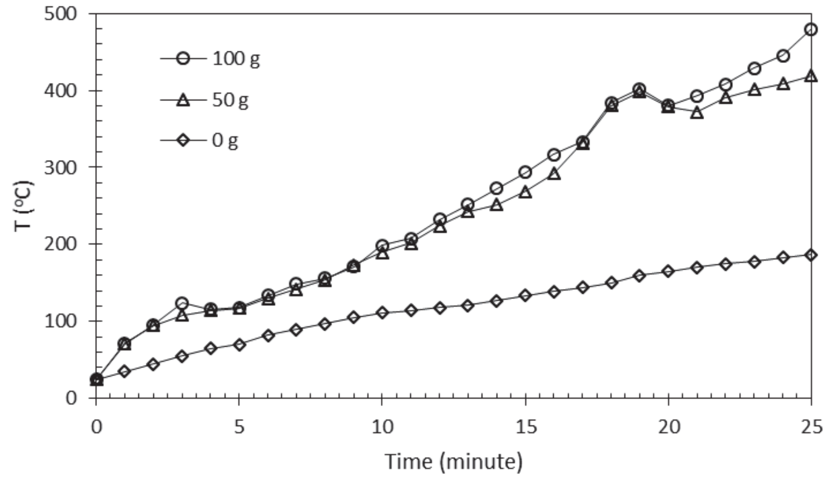

FIGURE 5. Temperature profile as a function of irradiation time at various wood char loading

Figure 5 also shows that reactor temperatures suddenly rose dramatically at irradiation time interval of 17-19 minutes for both 50 g and 100 g of wood char. This phenomenon occurs because when the pyrolysis temperature approached about 325ºC, UCO in the reactor started to evaporate and partially transformed from liquid to vapor phase. In this condition, the contact between thermocouple probes with liquid UCO may be disturbed by gas bubbles formed in the oil, as a result, the measured temperature fluctuated.

The heating rate at various wood char loading is presented in Fig. 6. As can be seen from the figure that heating rates of the system with the presence of wood char were much higher than that of the system without wood char within the reactor. Moreover, the heating rates produced by addition of 50 g and 100 g of wood char were relatively constant compared to the case without the use of absorber. It can be evaluated that during 25 minutes of irradiation, the average heating rates were around 18ºC/min and 17ºC/min for 100 g and 50 g of wood char loading, respectively, whereas only around 8ºC/min on average for without wood char loading (0 g). The high heating rates of the system with the presence of wood char not only provide high reactor temperature but also reduce the required heating time as depicted earlier in Fig. 5. For example, reactor temperature of 150ºC could be attained in 7 minutes with 100 g of wood char whereas it needed 18 minutes for the case without wood char.

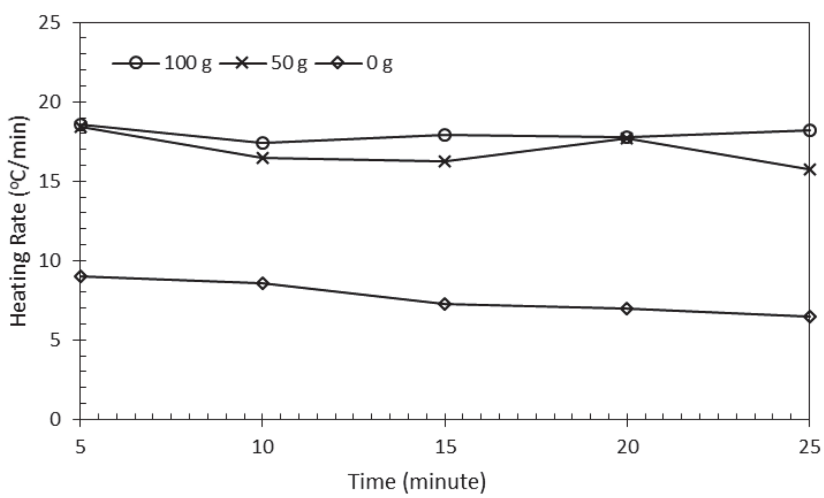

FIGURE 6. Heating rate at various wood char loading

Thermal efficiency at various wood char loading can be observed in Fig. 7. In the range of irradiation time investigated, the presence of wood char as absorber material is capable to enhance thermal efficiency of microwave reactor. Thermal efficiency increased significantly during 25 minutes of irradiation particularly for 100 g of wood char loading. In this condition, the calculation results show that thermal efficiency increased from 23% after 5 minutes to more than 50% at final irradiation time studied. From this result, it can be concluded that the exponential increase of thermal efficiency of microwave reactor could be attributed to the high absorbed microwave power by the increased of wood char loading.

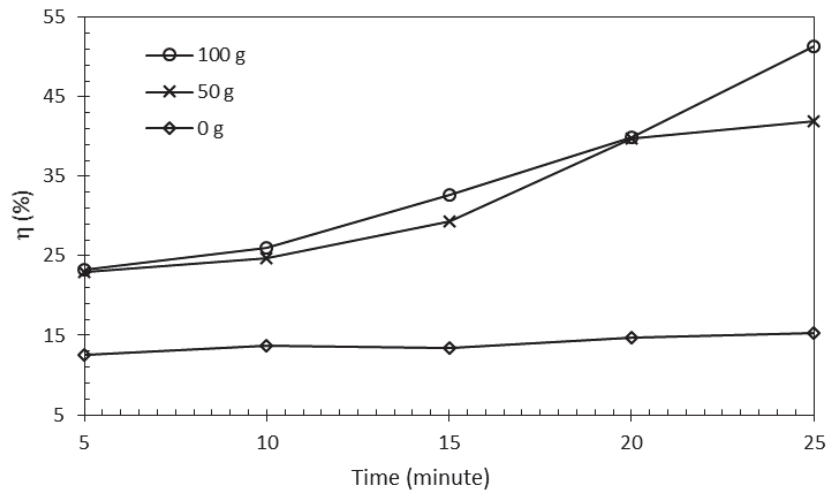

FIGURE 7. Thermal efficiency at various wood char loading

CONCLUSIONS

Thermal characteristic of the developed microwave reactor for pyrolysis of used cooking oil (UCO) has been investigated. The results showed that it was difficult to pyrolyze UCO under microwave energy without the presence of absorber material as it has low capacity in absorbing microwave energy. Microwave power and wood char loading were found to be the main parameters affecting reactor temperature, heating rate, and thermal efficiency. The higher the microwave power and wood char loading, the higher the temperature, the heating rate, and the thermal efficiency. These parameters were not only able to raise the temperature of the reactor but also accelerate the heating process. As a whole, the developed microwave reactor is eligible to be used for pyrolysis of used cooking oil.

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