

Thermal Characteristics of Microwave Reactor for Pyrolysis of Food Waste

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Published online: 30 July 2018

To cite this article: Anis, S. et al. (2018). Thermal characteristics of microwave reactor for pyrolysis of food waste. *J. Phys. Sci.*, 29(Supp. 2), 1–13, <https://doi.org/10.21315/jps2018.29.s2.1>

To link to this article: <https://doi.org/10.21315/jps2018.29.s2.1>

ABSTRACT: *Food waste generated from restaurants or food stalls needs to be processed correctly to minimise environmental pollution problems. One of the promising methods is pyrolysis process using low-power microwave energy reactor that can convert it into bio-oil. This process is strongly associated with the thermal heating process in a microwave reactor normally indicated by the reaction temperature, heating rate and the thermal efficiency. This work studies the thermal characteristics of microwave reactor during pyrolysis of food waste. A modified domestic microwave oven with a maximum output power of 418 W was used as the experimental reactor in this study. The samples with different moisture content (MC) of 11% and 24% were examined under various microwave power of 257 W, 362 W and 418 W for 1 h. The results showed that the thermal characteristics of microwave were influenced by the microwave powers and moisture contents of the food waste. High microwave power and low MC provide high reaction temperature, heating rate and thermal efficiency. Under investigated conditions, the optimum result was obtained at microwave power of 418 W and MC of 11% in which final temperature, heating rate and thermal efficiency of the pyrolysis process were 757°C, 12.1°C min⁻¹ and 53%, respectively. These results indicated that the modified microwave reactor is capable for pyrolysis of food waste even at relatively low microwave power.*

Keywords: Thermal characteristic, microwave reactor, pyrolysis, food waste, moisture content

1. INTRODUCTION

Billions of tons of waste, particularly municipal solid waste (MSW) are generated annually worldwide. The waste amount constantly increases in line with the high population growth and needs. Hoornweg and Bhada-Tata reported that about 1.3 billion tons MSW is produced every year and it is expected to rise to 2.2 billion tons by 2025.¹ Report by the Indonesia's Ministry of Environment shows that the amount of waste increased from around 64 million tons in 2015 to 65 million tons in Indonesia in 2016. Of these, 48% of the waste was generated from households. In addition, based on its composition, organic waste occupies 60% of the waste generated. Among the MSW, food waste is one of the prominent wastes generated from canteens, restaurants, kitchens of residential societies, food industries, etc.² Today, disposal of large amount of food waste has become a challenge. There is an urgent need for proper management, reuse or processing of food waste.

Chemically, food waste contains hydrocarbon materials such as lipids, carbohydrates, amino acids and other substances. Because of its high carbohydrate and lipid content, food waste contains more hydrogen and its H/C ratio is much higher than that of other biomasses.³ These materials can be converted into other forms of energy including gaseous, biodiesel, bioethanol, bio-oil, etc.⁴⁻⁷ Pyrolysis has been known as one of the effective methods for biomass processing. In this method, the biomass is thermally processed in the absence of air to produce products such as char, oil, combustible gases and valuable chemicals.⁸ So far, conventional heating sources such as electric and gas heater is the most used system by the researchers for biomass pyrolysis. Apart from the successful application of conventional heating, several recent literature works show that research activities on biomass pyrolysis in developing alternative energy resources under microwave heating have gained more attention. Biomass pyrolysis heated by microwave irradiation could be a more promising technique due to the unique feature of volumetric heating of materials. This feature could result in a more rapid heating process leading to significant energy and process time saving, yield improvement, fewer hazardous compounds generation and higher heating efficiency.^{9,10}

Studies on MSW and food waste pyrolysis using microwave reactor have been reported.^{8,11} In general, the main used parameters for assessing the yield of products obtained from microwave processing of waste include microwave power, addition of absorber and catalyst, as well as moisture content of the material. It should be noted that to obtain better result, the microwaves should be able to enter the materials and generate heat. On this basis, the processed material that exhibits good dielectric properties can be used directly as it can absorb microwave energy and then convert it into heat. Nevertheless, materials have different responses to

microwave heating which indicate that the dielectric properties of the materials vary widely.¹²

Although research on the processing of food waste using microwave heating has been done as described, the research mainly focuses on the production of liquid or gaseous fuels. In fact, there are many other important parameters that need to be investigated in detail in order to improve the performance of a microwave reactor. One of the crucial parameters is thermal characteristics of microwave reactor associated with the materials to be processed. Therefore, in this work, thermal characteristics of microwave reactor for pyrolysis of food waste in terms of temperature evolution, heating rate and thermal efficiency are investigated. With the aim to obtain optimal conditions and achievable technical performance, several parameters including microwave power, irradiation time and moisture content (MC) of food waste were studied.

2. EXPERIMENTAL

2.1 Materials

The food waste used in this study consisted of a mixture of rice, vegetables and meats which was obtained from some bins of nearby restaurant. It was then separated into two parts. The first part was used as received while the other part was dried in the sun for a day before use. With these treatments, both samples had MC of 24% and 11%, respectively.

2.2 Experimental Apparatus

Figure 1 shows the schematic diagram of the experimental apparatus. It mainly consists of a microwave reactor and a cooling system as previously reported.¹³ A refractory reactor with a size of 84 mm inner diameter and 125 mm length was installed vertically in the microwave chamber and designed as a fixed bed reactor. The reactor had a thermocouple positioned at the centre of the reactor and contained food waste to be processed. Commercial microwave oven with a frequency of 2.45 GHz was modified to allow pyrolysis processes. The microwave oven has an input and a maximum output power of 450 W and 700 W, respectively. To monitor the temperature of the microwave cavity, a thermocouple was also applied. In order to avoid damage of the microwave unit, the temperature of microwave cavity should be kept below 200°C. In this work, temperatures of the reactor and microwave cavity were measured using a 3 mm outer diameter 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. The cooling system consisted of a double pipe condenser and a liquid collector of 250 ml glass bottle. Teflon and copper pipes with a size of 9.5 mm inner diameter were used for transporting volatile substance from refractory reactor to liquid collector generated during pyrolysis process.

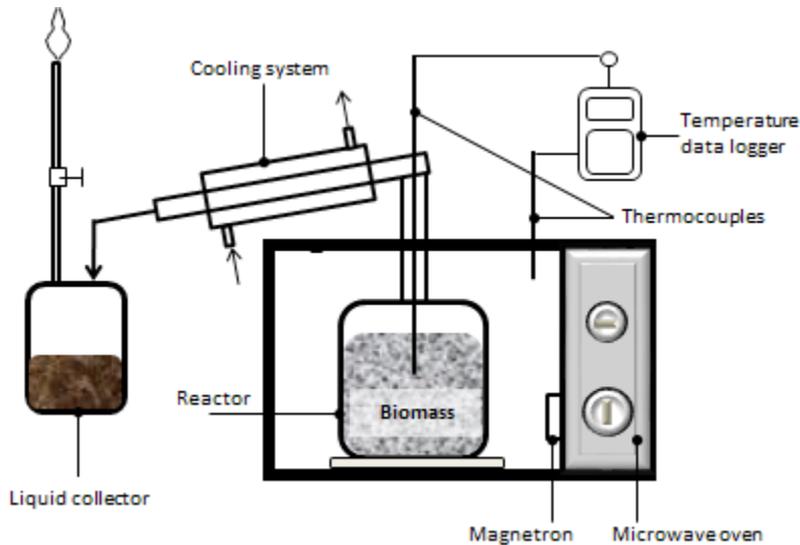


Figure 1: Schematic diagram of the experimental apparatus.

2.3 Thermal Heating Experiment

Various parameters including microwave power and moisture content of food waste were employed to study thermal characteristic of microwave reactor in terms of temperature evolution, heating rate and thermal efficiency. There were three levels of microwave power, i.e., medium (257 W), medium-high (362 W) and high power (418 W), and two levels of moisture content (11% and 24%) applied in the experiments. In each experimental test, the amount of food waste treated within the reactor was kept constant at 300 g and tested for 60 min of irradiation time. During the experiment, temperatures of the reactor and microwave cavity were recorded every 30 s. 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, thermal efficiency (η_T) and absorbed microwave power (P_{abs}) were calculated based on the equations in the following.¹³

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

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

where P_{MW} is the chosen microwave power (W), m is the mass of material (kg), C_p is the heat capacity of material ($\text{J kg}^{-1} \text{K}^{-1}$), 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 ($\text{W m}^{-2} \text{K}^{-1}$), A is the area of the object (m^2), ε is the emissivity of material, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4}$), and \bar{T} is the average temperature within the microwave reactor (K).

3. RESULTS AND DISCUSSION

3.1 Effect of Microwave Power

In order to evaluate the effect of microwave power on the thermal characteristics of microwave reactor consisting of temperature profile, heating rate and thermal efficiency, a series of studies were performed. Figure 2 shows temperature profile of microwave reactor at three different microwave powers during thermal decomposition of food waste with MC of 24%. As indicated in the figure, the reactor temperature is highly influenced by the microwave power. It increases with the increase of microwave power. The highest temperature was obtained at 418 W, which was the highest microwave power applied in this study. After 1 h of irradiation time, reactor temperature of 265°C, 442°C and 552°C could be reached using microwave power of 257 W, 362 W and 418 W, respectively. These results showed that the absorbed microwave power by the material inside reactor increased as the incident microwave power increased, therefore the temperature within the reactor would also increase. The results were in line with previous works which reported that the absorbed microwave power is highly influenced by the electric field.^{13–15} It should be noted that at maximum microwave power, the 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).

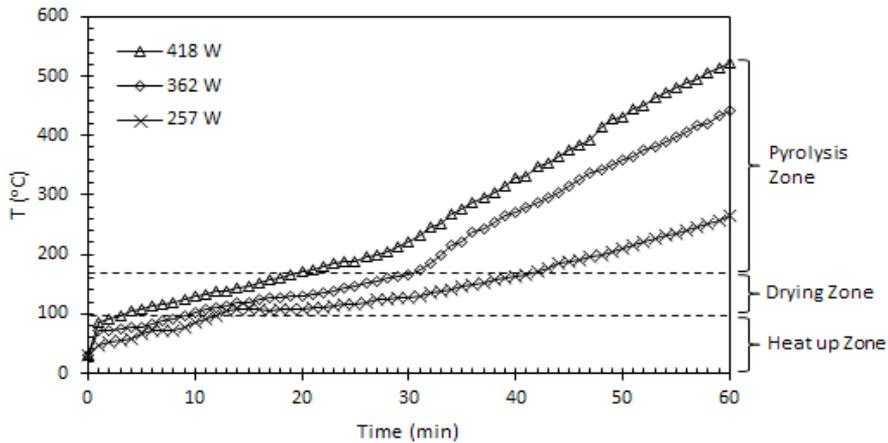


Figure 2: Temperature profile of microwave reactor at various microwave powers for food waste with 24% MC during 60 min of irradiation time.

Figure 2 also shows three heating zones during thermal process of food waste indicated by the reactor temperatures evolution. The first is heat-up zone where the reactor temperatures increased rapidly up to around 100°C particularly for microwave power of 362 W and 418 W. The high MC of food waste that absorbs microwave power energy well is considered as the main factor affecting reactor temperatures. The second is drying zone where reactor temperatures increased slowly up to about 170°C due to evaporation of water within the samples. The last is pyrolysis zone in which volatile materials were released. In this zone, thermal decomposition of organic materials into other products including carbon-rich solid products (bio-char), condensable (liquid) products and non-condensable (gaseous) products are formed. In this zone, the high increase of temperature during thermal process could be due to the formation of bio-char that absorbs microwave energy and converts it into heat. The literature showed that bio-char is one of good absorber materials in microwave processing.¹⁶

Figure 3 shows the heating rate of microwave reactor for food waste with MC of 24% at various microwave powers. It was evaluated every 5 min of irradiation time. In general, heating rate reduced gradually up to a specific irradiation time for all microwave power applied. After that time, heating rate increased slightly for microwave power of 362 W and 418 W whereas for lower microwave power of 257 W, heating rate seemed to be constant. It can be observed that the highest heating rates were reached in the first 5 min of irradiation, i.e., 7°C min⁻¹, 9.4°C min⁻¹ and 15.8°C min⁻¹ for 257 W, 362 W and 418 W, respectively. At irradiation time of 60 min, the heating rates were only 3.92°C min⁻¹, 6.87°C min⁻¹ and

8.2°C min⁻¹, respectively. Similar observation was also reported in other studies.^{13–15} 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.

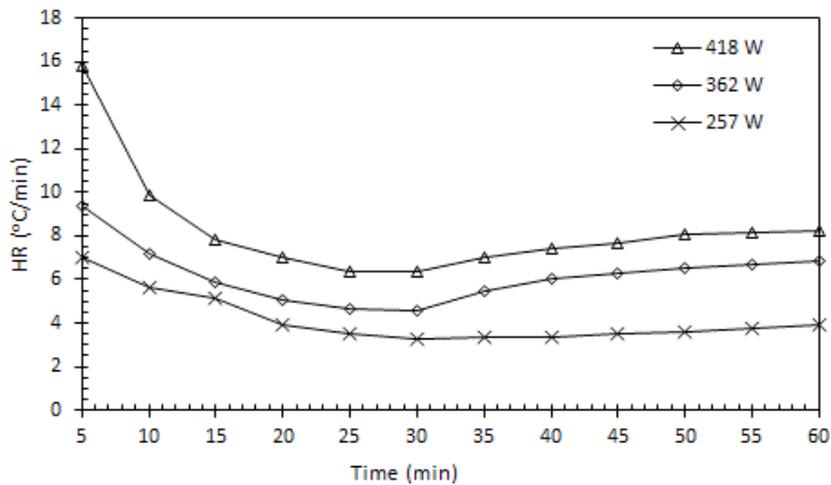


Figure 3: Heating rate of microwave reactor for food waste with 24% MC at various microwave powers.

Figure 4 shows thermal efficiency of microwave reactor at various microwave powers during thermal decomposition of food waste with MC of 24%. It was also evaluated every 5 min of irradiation time. As in the case of heating rate, below 30 min of irradiation, thermal efficiency generally decreased significantly for all microwave power applied, then increased due to the formation of carbon-rich solid products. High microwave powers provided better thermal efficiency. It can be observed from the figure that in the first 5 min of irradiation, thermal efficiencies were 30.82%, 29.07% and 41.79% for 257 W, 362 W and 418 W, respectively. While, at irradiation time of 30 min, thermal efficiencies were only 16.37%, 16% and 19.21%, respectively, showing the reduction of thermal efficiencies of about 49% on average. This condition occurred due to drying process of food waste where the absorbed microwave energy is mainly utilised for water evaporation rather than for heating process.¹⁷

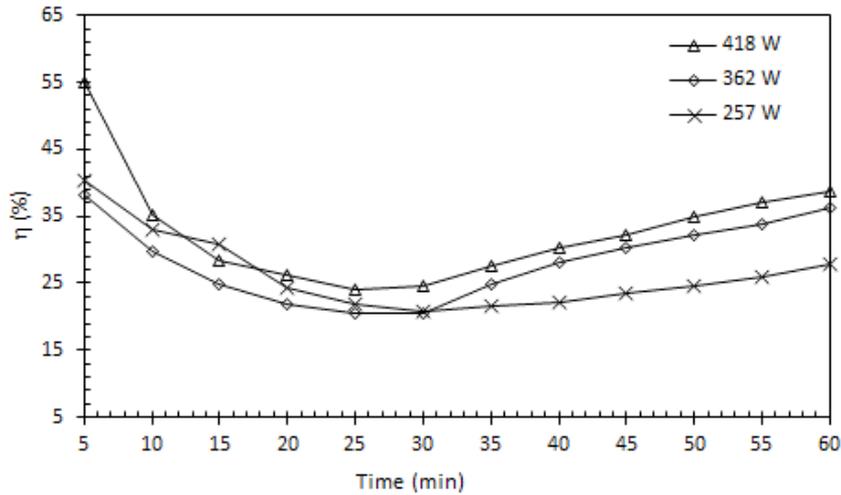


Figure 4: Thermal efficiency of microwave reactor for food waste with 24% MC at various microwave powers.

3.2 Effect of MC

Effect of food waste MC on the reactor temperature, heating rate and thermal efficiency was tested at a fixed microwave power of 418 W for 60 min of irradiation. Figure 5 shows temperature evolution as a function of irradiation time at MC of 11% and 24%. The figure indicates that moisture content significantly affects reactor temperature. After 60 min of irradiation, reactor temperature reached 757°C and 522°C for MC of 11% and 24%, respectively. This result suggested that lower MC of food waste provided rapid increase of reactor temperature during thermal process. It could be observed from the figure that reactor temperature of about 170°C could be reached in short irradiation time of 1 min only for MC of 11%. In contrast, for MC of 24%, longer irradiation time of about 20 min was needed that could be attributed to water evaporation. The low water content is preferable in microwave heating of material.¹⁷ Nevertheless, beyond 170°C, the increase in reactor temperature was relatively similar for both 11% and 24% although the obtained maximum temperatures are different. This condition showed that formation of carbon-rich solid products played a major role in microwave thermal heating process. This result is in line with previous studies that the absorbed microwave power increased with the increase of amount of absorber material due to formation of carbon-rich solid products.^{16,18}

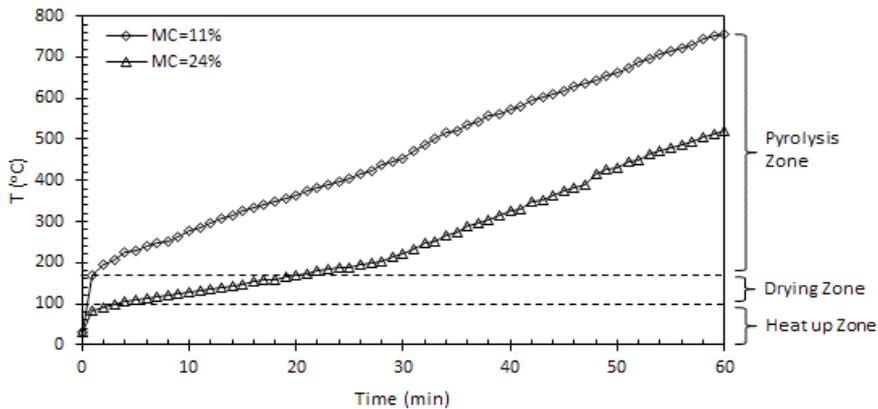


Figure 5: Temperature profile as a function of irradiation time at various MC.

Studies on the effect of food waste MC on the reactor temperature also show three heating zones including heat up, drying and pyrolysis zones as shown in Figure 5. Nevertheless, special interest for lower MC of 11% due to rapid increase of temperature during heating process, only two heating zones could be observed, i.e., heat up/drying zone and pyrolysis zone. This result showed that material with low MC allows quick evaporation of water that contributes to reduction of energy consumption for heating processes.

The heating rate for two different food waste MC is presented in Figure 6. In general, heating rate decreased up to a certain irradiation time before becoming constant. The decrease of heating rate corresponds to reduction of water content contained in the sample during the process. It can be observed from the figure that heating rates of the microwave reactor with MC of 11% was much higher than that of the system with MC of 24%. It can be evaluated that during 60 min of irradiation, the average heating rates were around $12.12^{\circ}\text{C min}^{-1}$ and $8.2^{\circ}\text{C min}^{-1}$ for food waste MC of 11% and 24%, respectively. The high heating rates of the system with low MC not only provide high reactor temperature but also reduce the required heating time as depicted earlier in Figure 5. For example, reactor temperature of 250°C could be attained in 8 min with food waste MC of 11% whereas it needed about 33 min for MC of 24%.

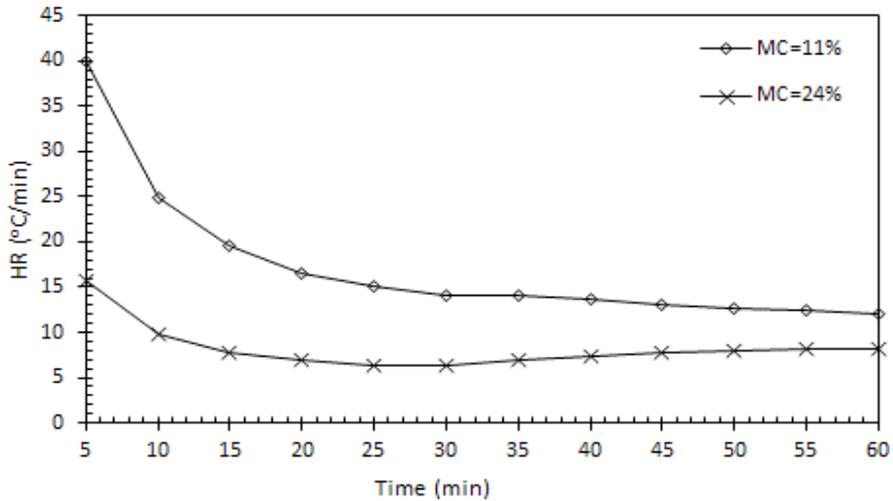


Figure 6: Heating rate at various food waste MC.

Thermal efficiency as a function of irradiation time for food waste MC of 11% and 24% can be observed in Figure 7. In general, thermal efficiency decreased significantly during 25 min of irradiation before linearly increased. In this condition, the calculation results showed that the thermal efficiency of the system with MC of 11% decreased from 84.23% after 5 min to about 46.86% at final irradiation time studied. While for food waste MC of 24%, it was 41.79% to 31.51%, respectively. These results showed that in the range of irradiation time investigated, the food waste with low MC have higher thermal efficiency of microwave reactor compared to the other. It should be noted that the thermal efficiency of microwave reactor is influenced by various factors such as initial and final temperatures, irradiation time, heat capacity, etc., as given in Equations 1 and 2. In this case, the first two parameters are considered the main factors contributing to the high thermal efficiency of the sample with MC of 11%.

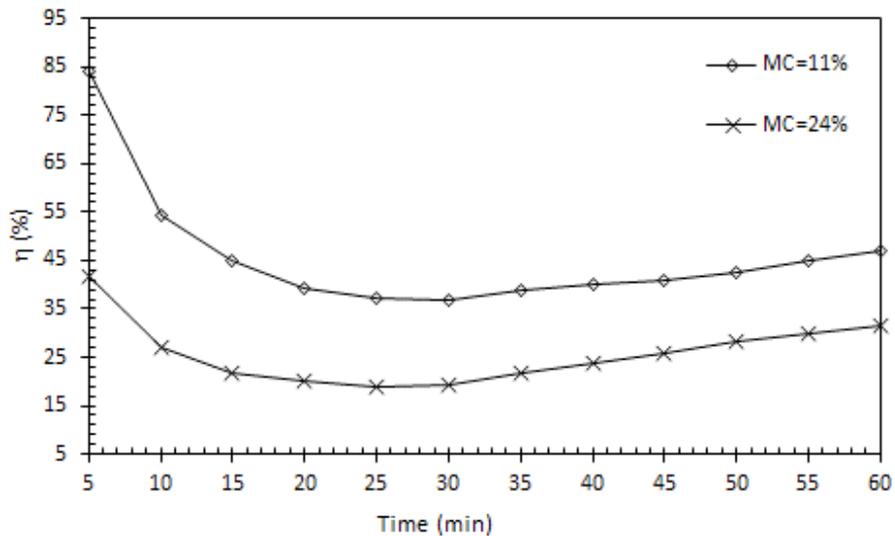


Figure 7: Thermal efficiency at various food waste MC.

4. CONCLUSION

Thermal characteristics of microwave reactor for pyrolysis of food waste has been investigated. The results showed that the microwave power and moisture content of food waste were found to be the main factors affecting reactor temperature, heating rate and thermal efficiency. System with higher microwave power and lower MC were preferred for processing of food waste under microwave irradiation. Microwave power of 418 W and MC of 11% provided higher temperature, heating rate and thermal efficiency. As a whole, pyrolysis of food waste by using microwave reactor is highly potential to produce alternative fuel for power generation and transportation.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the research grant 1.1.7/PPK.4.5/2016 awarded by the Faculty of Engineering, Universitas Negeri Semarang, Indonesia to carry out this work.

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