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MICROWAVE DRYING KINETICS OF HIGHLY-MOIST MUNICIPAL SOLID WASTE (MSW) PELLETS

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Abstract

The principal purpose of this study was to investigate the drying kinetics of highly-moist municipal solid waste (MSW) pellets using microwave irradiation. Each of MSW pellets used in this study was of cylindrical shape, 0.8-1.0 cm in diameter, 1.8-2.0 cm long, 1 g in weight, and with the initial moisture content of 50 wt.%. The experiments were carried out at the microwave powers of 300-800 W and the quantities of the MSW pellets of 15-30 g for the heating times ranging from 20 s to 20 min. It was found that the moisture content of the MSW pellets decreased with the heating time. The moisture removal time increased with a decrease in the microwave power and an increase in the quantity of the MSW pellets. The drying rate of the MSW pellets was low during the initial stage of the drying, then started to increase afterwards until reaching the peak, and subsequently entered the falling rate period. An increase in the microwave power resulted in an increase in the drying rate, whereas an increase in the quantity of the MSW pellets caused the drying rate to decrease. Among the drying models determined in this study, the Avhad and Marchetti model was the most suitable one for describing the drying behaviour of the MSW pellets. The activation energy of the microwave drying of the MSW pellets, determined using the modified Arrhenius relationship, was found to be 18.89 W/g.

Keywords: Municipal solid waste (MSW), Microwave irradiation, Drying kinetics, Activation energy

Introduction

As a consequence of rapid economic development and urbanisation, the generation of municipal solid waste (MSW) in several developing countries has increased dramatically. For example, in Thailand, the total annual generation of MSW in 2016 (2559 BE) was 27.06 million tonnes or nearly 75,000 tonnes a day [1]. This huge amount of MSW is a major challenge for governments of developing countries [2], as it can lead to human health, environmental, and social problems [3]. Thus, an effective MSW disposal method that can deal with a large amount of MSW at a reasonable cost and time is required. One of the promising MSW disposal techniques is the MSW incineration, as it can reduce a substantial amount, in both mass and volume, of MSW in timely fashion and also provide an option of energy recovery [4-5]. Problematically, however, due mainly to the poor MSW management and the lack of MSW handling facilities, MSW in Thailand contains a high amount of organic waste [3, 6], which, in turn, makes MSW highly moist. This high amount of moisture in MSW can render MSW incineration inefficient. Accordingly, MSW must be dried before being incinerated.

Conventionally, drying by thermal convection and conduction is employed to dry wet materials [7]. However, this conventional heating is considered slow and consumes a high amount of energy. [7]. On the contrary, microwave heating provides a quick and uniform drying of wet materials, as the drying materials are heated from the inside by microwave radiation (or electromagnetic wave) [7], which can lead to a great deal of energy savings [8].

Recently, considerable work has been carried out to investigate the microwave drying of several materials (*e.g.*, Refs [7-12]). However, the work on microwave drying of wet MSW, particularly in the aspect of drying kinetics, is rather scarce. Thus, the main objective of this study was to investigate the drying kinetics of highly-moist MSW. The drying behaviours of highly-moist MSW was considered; this included the determination of the suitable drying model to describe the drying characteristics of highly-moist MSW. The activation energy of the microwave drying of highly-moist MSW was also determined.

Materials and methods

The MSW samples used in this study were in the form of pellets, cylindrical shape, ~0.8-1.0 cm in diameter, ~1.8-2.0 cm long, and approximately 1 g in weight. The MSW pellets were made of 40 wt.% scrap paper, 30 wt.% sawdust, 20 wt.% corncob, and 10 wt.% plactic.

In each experiment, the MSW pellets, with the quantity ranging from 15-30 g, were put into a porcelain cup (11 cm diameter and 5 cm high). A pre-determined amount of water was carefully poured onto the MSW pellets to adjust the moisture content of the MSW pellets to 50 wt.%. The cup containing the wet MSW pellets was placed into a microwave oven (Samsung, ME711K Model). The microwave power and heating time were in the range of 300-800 W and 20 s to 20 min, respectively.

After the heating, the temperature of the resulting MSW pellets was measured using an infrared thermometer (Fluke, 66-IR Model). The cup containing the resulting MSW pellets was taken out of the microwave oven; placed in a desiccator, to allow the MSW pellets to cool down; weighed for the remaining mass; and analysed for the remaining moisture content, following ASTM D3173.

To study the drying behaviours of the MSW pellets, the moisture ratio (MR) of the resulting MSW pellets at the end of any heating time, defined as:

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \tag{1}$$

where
- M_t = the remaining moisture content of the MSW pellets at the end of any heating time
- M_0 = the initial moisture content of the MSW pellets
- M_e = the moisture content of the MSW pellets at equilibrium (*i.e.* after being heated for a long period of time)

were plotted against the corresponding heating time.

The drying rate (R), defined as:

$$R = -\frac{(MR_2 - MR_1)}{(t_2 - t_1)} \tag{2}$$

where MR_1 and MR_2 were the moisture ratios of the resulting MSW pellets at the end of heating times t_1 and t_2, respectively, was plotted against the average MR $\left(=\frac{MR_1 + MR_2}{2}\right)$ of the corresponding time interval (*i.e.* between t_1 and t_2). This plot is, in fact, the drying rate curve [13].

To determine the suitable drying model for describing the drying characteristics of the MSW pellets, the following drying models were examined:
- the Lewis model [14]:

$$MR = \exp(-kt) \tag{3}$$

where k is the Arrhenius constant and t is the heating time;
- the Henderson and Pabis model [14]:

$$MR = a\exp(-kt) \tag{4}$$

where a and k are the pre-exponential and Arrhenius constants, respectively, and t is the heating time;
- the Page model [14]:

$$MR = \exp(-kt^N) \tag{5}$$

where k and N are the Arrhenius constant and the constant of the model, respectively, and t is the heating time;

- the Avhad and Marchetti model [7]:

$$MR = a\exp\left(-kt^N\right) \tag{6}$$

where a, k, and N are the pre-exponential constant, the Arrhenius constant, and the constant of the model, respectively, and t is the heating time;

The model that yielded the value of R^2 (the coefficient of determination) closest to unity (1) was considered the most suitable drying model.

In order to obtain the activation energy (E_a) of the drying of MSW pellets used in this study, the resulting Arrhenius constant (k) obtained from the most suitable drying model was plotted against the mass to microwave power ratio $\left(\frac{m}{P}\right)$, according to the modified Arrhenius equation proposed by Dadali *et al* [12]:

$$k = k_0 \exp\left(-\frac{mE_a}{P}\right) \tag{7}$$

which can be modified to

$$\ln k = \ln k_0 - \frac{m}{P}E_a \tag{8}$$

where k_0, m, and P were the pre-exponential constant of the Arrhenius equation, total mass of the MSW pellets, and the microwave power, respectively. Note that the activation energy (E_a) is the slope the modified Arrhenius plot or the plot between $\ln k$ and $\frac{m}{P}$.

Results and discussion

The plot between the moisture ratio (MR) of the resulting MSW pellets (with the initial moisture content of 50 wt.%) and the heating time was as depicted in Figure 1. The solid lines in Figure 1 represented the *MR* calculated from the most suitable drying model (will be discussed in detail later). The plots of the moisture ratio (MR) against the heating time of the MSW pellets at other quantities (*i.e.* 15 and 30 g) were similar to that at 20 g.

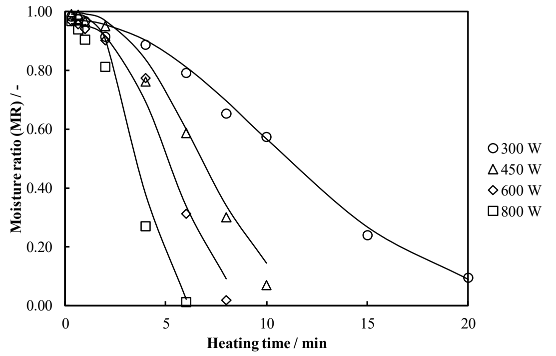

Figure 1 The moisture ratios (MR) at different heating times of the resulting MSW pellets (the initial moisture content was 50 wt.%) with the quantity of 20 g heated at the microwave powers of 300-800 W.

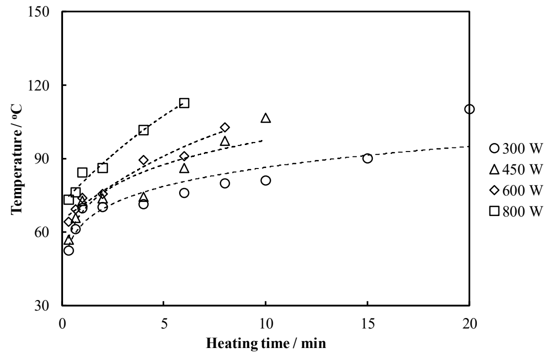

Figure 2 The temperatures at different heating times of the resulting MSW pellets (the initial moisture content was 50 wt.%) with the quantity of 20 g heated at the microwave powers of 300-800 W.

It was evident that the moisture content of the MSW pellets decreased with the heating time and that moisture was nearly completely removed from the MSW pellets. The moisture removal time (the time required for moisture to be completely removed from the MSW pellets) decreased with an increase in the microwave power. The moisture removal times for the microwave heating at 300, 450, 600, and 800 W were found to be more than 20 min, ~10 min, ~8 min, and ~6 min, respectively.

As the microwave power increased, the amount of energy provided to the MSW pellets increased, which could be observed by an increase in the temperature of the MSW pellets, illustrated in Figure 2, in which the temperature of the resulting MSW pellets increased with an increase in microwave power. Note that the dashed lines in Figure 2 represented the trend of the temperature for each microwave power. With an increase in the amount of energy from microwave irradiation, the moisture removal time decreased, as seen in Figure 1. It was important to note that the measured temperatures were lower than the actual ones by approximately 30-50 ºC, since the measurements of the temperatures using an infrared thermometer were slightly delayed, as the measurement had to wait until the door of the microwave oven had opened.

The results obtained in this study were in good agreement with those of the previous ones [11-12], in which the moisture removal time decreased as the microwave power increased.

The drying rate curves for the drying of MSW pellets with the quantity of 20 g heated at the microwave powers of 300-800 W were as shown in Figure 3.

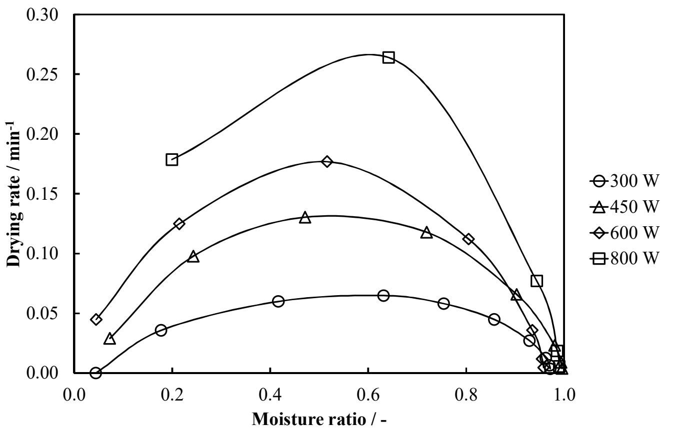

Figure 3 The drying rate curves of the MSW pellets (the initial moisture content was 50 wt.%) with the quantity of 20 g heated at the microwave powers of 300-800 W.

It was found that, for all microwave powers, the drying rates were low during the initial stage of drying (for the MR of ~1.0-0.8). The rate of drying increased between the MR of 0.8 and ~0.5-0.4, and decreased afterwards (after the MR of 0.5-0.4).

Initially, the MSW pellets contained a high amount of moisture (*i.e.* 50 wt.%). Hence, the temperature of the MSW pellets during the initial stage of drying was low, as depicted in Figure 2. As the heating process proceeds, the temperature of the MSW pellets increased, as also illustrated in Figure 2, thus resulting in an increase in the drying rate. When a certain amount of moisture had been driven off from the MSW pellets, the remaining amount of moisture in the MSW pellets became low. This low amount of moisture caused the drying rate to fall, and eventually approached zero when moisture was nearly completely removed from the MSW pellets.

These results were in accordance with those of the previous studies [8, 11-12], in which the dying rate of the drying sample was low during the early stage of drying, then started to increase until reaching the peak, and, eventually, entered the falling rate period.

The moisture ratios (MR) at the end of any heating time of the resulting MSW pellets with the quantities between 15 and 30 g heated at the microwave power of 600 W were as depicted in Figure 4. Note, once again, that the solid lines in Figure 4 were the values of the *MR* calculated from the drying model (will also be discussed in detail later). The plots of the moisture ratio (MR) against the heating time at other microwave powers were similar to that at 600 W.

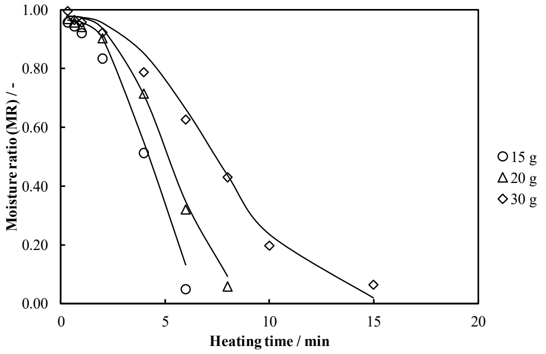

Figure 4 The moisture ratios (MR) at different heating times of the resulting MSW pellets (the initial moisture content was 50 wt.%) with the quantities of 15-30 g heated at the microwave power of 600 W.

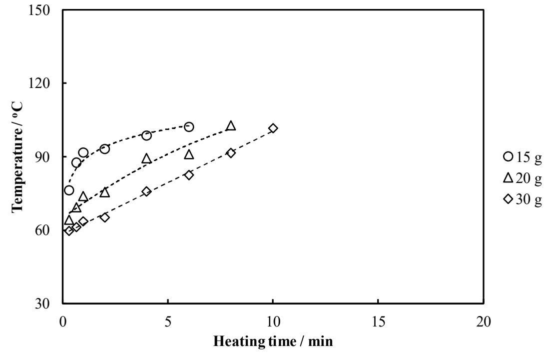

Figure 5 The temperatures at different heating times of the resulting MSW pellets (the initial moisture content was 50 wt.%) with the quantities of 15-30 g heated at the microwave power of 600 W.

Figure 4 indicated that an increase in the quantity of the MSW pellets resulted in a longer moisture removal time. The moisture removal times for the MSW pellets with the quantities of 15, 20, and 30 g heated at the microwave power of 600 W were found to be ~6, ~8, and ~15 min, respectively. These agreed with the results obtained from the previous studies [11-12], in which the moisture removal time increased with the quantity of the MSW pellets.

An increase in the quantity of the MSW pellets resulted in an increase in the amount of moisture required to be driven off from the MSW pellets. As moisture (or water) possesses a high heat capacity (or specific heat) [15], the MSW pellets containing a high amount of moisture behaves like a heat sink. Hence, energy obtained from microwave irradiation must firstly be employed to increase the temperature of the MSW pellets to the boiling point of water. Then, moisture could vaporise or was driven off from the MSW pellets. This explanation was justified since it was found from the plot of the temperature of the MSW pellets against the heating time, as shown in Figure 5 (note that the dashed lines in Figure 5 represented the trend of the temperature for each microwave power), that the temperature of the MSW pellets with a lower amount of quantity was higher that with a higher one.

With a higher temperature of the MSW pellets, the drying rate increased, as illustrated in Figure 6. This indicated that the drying rate of the MSW pellets with a lower amount of quantity was higher than that with a higher one. These findings were in accordance with those of the previous studies [11-12].

The behaviours of the dry rate curves were similar to those obtained previously in this study, in which the drying rates were low during the initial stage of drying, then increased until reaching the peak, and, subsequently, decreased afterwards. The explanation of these drying characteristics was similar to that described previously in this study.

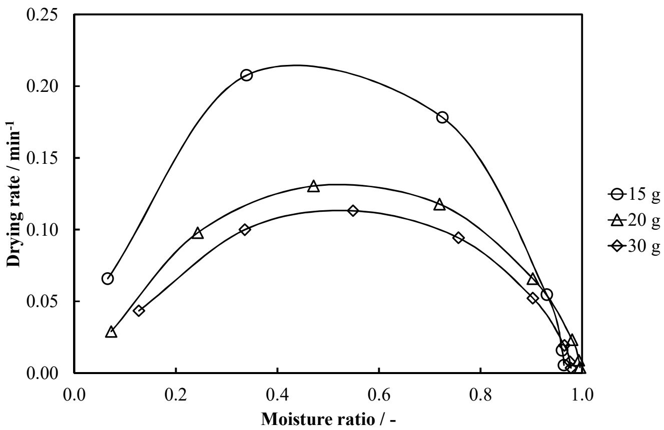

Figure 6 The drying rate curves of the MSW pellets (the initial moisture content was 50 wt.%) with the quantities of 15-30 g heated at the microwave power of 600 W.

From the experimental data obtained from the drying of MSW pellets as shown in Figures 1 and 4, the suitability of the proposed drying models (mentioned in the materials and methods section) was evaluated by fitting the models to all MR-heating time data. The model that was best fitted to the experimental data yielded the value of R^2 closest to unity (1).

The range of R^2 values (for all microwave powers and quantities) of each model was summarised in Table 1, in which the Avhad and Merchetti drying model provided the range of R^2 values closest unity (1). Accordingly, among the drying models considered in this study, the Avhad and Merchetti model was the most suitable one.

Table 1 The range of R^2 values of each drying model considered in this study

Model	Range of R^2 values
• Lewis	0.8087-0.9577
• Henderson and Pabis	0.8492-0.9701
• Page	0.8495-0.9961
• Avhad and Marchetti	0.9216-0.9995

The Arrhenius constants (k) obtained from the Avhad and Merchetti drying model were employed to determine the activation energy (E_a) of the drying of MSW pellets used in this study.

The modified Arrhenius plot of the drying of MSW pellets (the initial moisture content was 50 wt.%) with the quantities of 15-30 g heated at the microwave powers of 300-800 W is depicted in Figure 7.

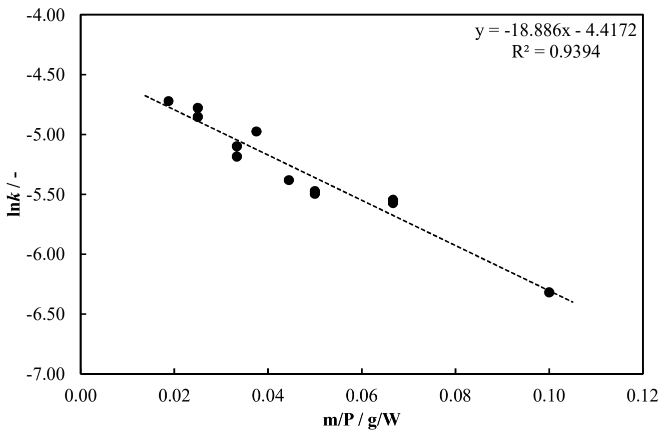

Figure 7 The modified Arrhenius plot of the drying of MSW pellets (the initial moisture content was 50 wt.%) with the quantities of 15-30 g heated at the microwave powers of 300-800 W

By considering the slope of the modified Arrhenius plot, the activation energy (E_a) of the drying of MSW pellets used in this study was found to be 18.89 W/g (with a reasonably high value of R^2 of 0.9394), which was in the same order of magnitude of those found in the previous studies. For instances, 10.91 W/g for the drying of low-rank sub-bituminous coal [7] and 77.05 W/g for the drying of Ximen lignite [8]. This indicated that the activation energy (E_a) of the MSW pellets obtained in this study was reasonably justified.

Conclusions

The findings obtained from the investigation of the drying kinetics of the highly-moist MSW pellets (50 wt.% moisture) using microwave irradiation could be summarised as follows

- The moisture content of the MSW pellets decreased with the heating time.
- The moisture removal time increased as the microwave power decreased, but decreased with an increase the quantity of the MSW pellets.
- The drying rate of the MSW pellets was low during the early stage of the drying, then increased afterwards until reaching the peak, and subsequently decreased in the final period of the drying.

- An increase in the microwave power caused the drying rate to increase. On the contrary, an increase in the quantity of the MSW pellets resulted in a decrease in the drying rate.
- The activation energy of the microwave drying of the MSW pellets, determined using the modified Arrhenius equation, was found to be 18.89 W/g.

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