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Analysis of Energy Consumption in Drying Process of Non-Hygroscopic Porous Packed Bed Using a Combined Multi-Feed Microwave-Convective Air and Continuous Belt System (CMCB)

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In this study, the analysis of energy consumption during the drying of non-hygroscopic porous packed bed by combined multi-feed microwave-convective air and continuous belt system (CMCB) was investigated experimentally. By using a combined multi-feed microwave-convective air and continuous belt system drier, the microwave power was generated by means of 12 compressed air-cooled magnetrons of 800 W each that give a maximum of 9.6 kW. The power setting could be adjusted individually in 800 W steps. Hot air with the maximum working temperature of 240°C was generated using 24 units of electric heater where the total power capacity is 10.8 kW. Most importantly, this work focused on the investigation of drying phenomena under industrialized microwave processing. In this analysis, the effects of the drying time, hot air temperature, porous structure (F-Bed and C-Bed), and location of magnetrons on overall drying kinetics and energy consumption were evaluated in detail. The results showed that the overall drying and energy consumption depend upon the porous structure, hot air temperature, and location of magnetrons. Furthermore, using the continuous microwave application technique had several advantages over the conventional method, such as shorter processing times, volumetric dissipation of energy throughout a product, and less energy consumption. The results presented here provided fundamental understanding for the drying process using a combined multi-feed microwave-convective air and continuous belt system in industrial size.

Keywords Continuous belt system; Microwave energy; Non-hygroscopic porous packed bed; Specific energy consumption

INTRODUCTION

During the past decade, there have been many successful examples of microwave application including the heating and drying of foods, heating and drying of ceramics, heating and curing of concrete, etc. The microwave heating process takes place inside the material, the penetrated depth of which governs how strongly the microwaves are absorbed. It is known that heat dissipated from the microwave energy depends on many parameters, such as configuration and structure of porous packed bed samples, microwave power level, microwave field distribution, the location of feed ports, and dielectric properties of porous packed bed samples. A number of analyses of the microwave heating process have appeared in the recent literature.[1–31] An excellent review of the drying techniques in porous material using microwave energy has been presented by Mujumdar,[1] Metaxas,[2] Datta and Anantheswaran,[3] and Schubert and Regier.[4]

The objective of drying is simply to remove water from the dried sample, i.e., porous packed bed without causing any damage. The process must be done both efficiently and economically. Water can leave the surface of the porous packed bed at a given rate depending on many parameters, such as microwave power level and air temperature, etc. In order to accomplish good drying of product, it requires a method that removes the water from the inside of the dried sample to the outside surface at the same rate as the evaporation of surface water.

The reasons for the interest in the interaction of microwaves with porous materials are reported by several investigators in the recent literature.[5–21] The microwave energy can lower the drying temperature in several porous materials by several hundred degrees, shorten drying times, reduce drying defects, provide greater throughput, increase energy efficiency because of the microwave source known as "magnetron", which is capable of very high power output; moreover, it has an efficiency to convert from electricity to microwave energy of 80%[22] and lessen floor-space requirements in comparison with conventional

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drying methods. It is also environmentally friendly and easily integrates into flexible, automated manufacturing systems. It appears that microwaves increase the heating efficiency by concentrating the heating process within porous material rather than in the cavity in which the porous material is placed.

Currently, the major concern of the drying process is increasing productivity while reducing energy cost. Conventional drying processes of porous material usually take a long time (1–6 hr). The major problem of conventional drying processes is long drying time, which results in increased energy consumption. Thus, there have been many attempts to enhance the rate of drying of porous material in order to decrease drying time as well as energy consumption.

For an analysis of microwave energy consumption in heating and drying processes, we refer to Sharma and Prasad;[23] this study examined specific energy consumption in microwave drying of garlic cloves. The comparative study of specific energy consumption with two different drying methods, namely microwave-hot air and hot air drying, was carried out. Other related papers present microwave energy and hot air heating processes. Varith et al.[24] studied the combined microwave and hot air drying of peeled longan. The influence of moisture content on specific energy consumption (SEC) was examined. The other important paper, written by Lakshmi et al.,[25] presented a comparison of SEC in cooking rice among the microwave oven, electric rice cooker, and pressure cooker.

Investigations of energy efficiency of microwave drying of porous material have been performed since the late 1950s. Many authors (Alibas,[26] Poli et al.,[27] Cheng et al.,[28] Holtz et al.,[29] Soysol et al.,[30] Leiker and Adamska,[31] and Prommas et al.[32]) have placed emphasis on the advantages of microwave drying over convective drying. Varith et al.[24] point out the suitability of combined microwave and hot drying of peeled longan. However, there still remain obstacles to be overcome in applying microwave drying technology to the drying industry. One of the difficulties is that the microwave power absorbed by moist porous material depends mainly on the moisture content and it is necessary to move the porous material for uniform power distribution with an on-off type microwave system at fixed power output.

Although a number of studies have been conducted to investigate a microwave heating process, most of them were carried out using a domestic or housing microwave oven and a single or multimode cavity with a non-movable material. Those studies showed that the result may be dependent on the method used to carry out the curing or heating process. The objective of this study is to demonstrate the applicability of microwave energy as an energy-saving when compared with drying processes, electrical consumption, and production-cost-reducing technology. The microwave drying of a non-hygroscopic porous packed bed in a combined multi-feed microwave-convective air and continuous belt system, where a series of 12 magnetrons, 800 W each with total power of 9.6 kW, were installed, was developed. The experimental results from this study could help to identify some of the potential problems during the practical design stage. This study was of great importance from the practical point of view because it showed the possibility of application of microwave heating-drying of porous materials on an industrial scale, especially in a continuous system.

EXPERIMENTAL PROCEDURE

Microwave-convective air drying was carried out using a combined multi-feed microwave-convective air and continuous belt system (CMCB) (Fig. 1(a)). The shape of the microwave cavity is rectangular with a cross-sectional area

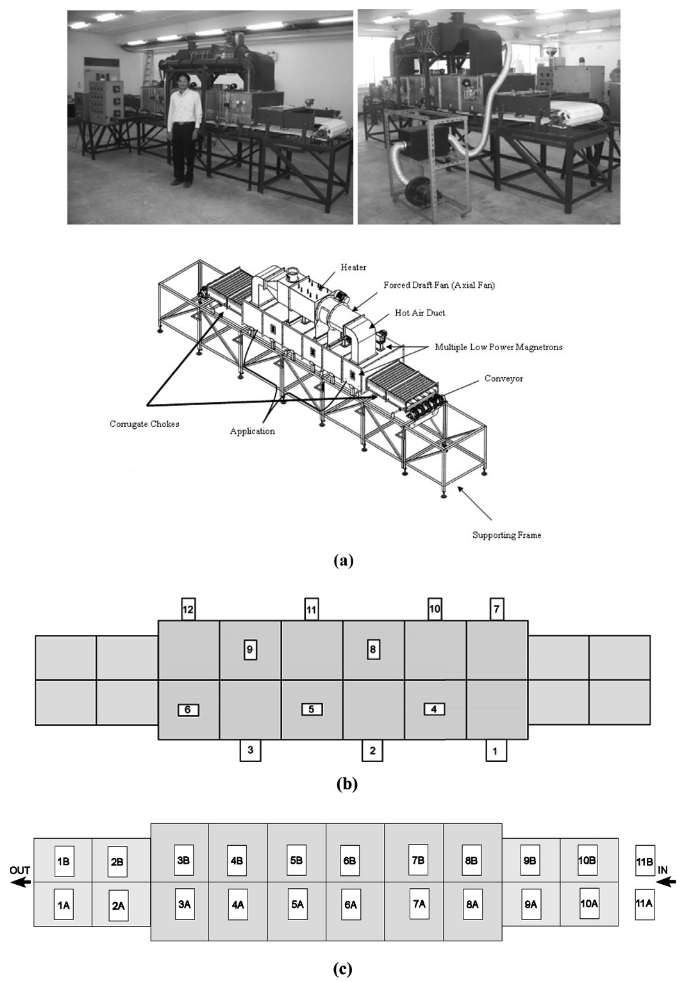

FIG. 1. Schematic diagram of experimental set-up. (a) A combined multi-feed microwave-convective air and continuous belt system; (b) Feed magnetrons positioned of 12 units and (c) Feed samples positioned of 22 packed beds.

of 90 cm × 45 cm × 270 cm. The drier was operated at a frequency of 2.45 GHz with maximum working temperature of 180°C. The microwave power was generated by means of 12 compressed air-cooled magnetrons. The maximum microwave capacity was 9.6 kW with a frequency of 2.45 GHz. The power setting could be adjusted individually in 800 W steps. In the continuous processing equipment, two open ends are essential, in which the material is to be heated up on the belt conveyer where it was put in and taken out. In this equipment, leakage of microwaves was prevented by the countermeasure in duplicate with a combination of mechanical blocking filter (corrugate choke) and microwave absorber zone filter was provided at each of the open ends. The microwave leakage was controlled under the DHHS (US Department of Health and Human Services) standard of 5 mW/cm^2. The multiple magnetrons (12 units) were installed in an asymmetrical position on the rectangular cavity (Fig. 1(b)). The microwave power was then directly supplied into the drier by using waveguides. An infrared thermometer (located at the opening ends) was used to measure the temperature of the specimens (accurate to ±0.5°C).

The magnetrons and transformers used in this system were cooled down by a fan. In the continuous heating/drying equipment, two open ends were essential to feed in and feed out the product, through which the material to be heated up on the belt conveyer was arranged in certain position, as shown in Fig. 1(c). The belt conveyor system consisted of a drive motor, a tension roller, and a belt conveyor. During the drying process, the conveyor speed was adjusted to 0.54 m/min (at the frequency 40 Hz) and the motor speed was controlled by the VSD control unit. Hot air was generated using the 24 units of electric heaters with the maximum capacity of 10.8 kW and the maximum working temperature of 240°C. The hot air was provided by blower fan with 0.4 kW power through the air duct into the cavity. The hot air temperature was measured using a thermocouple.

As shown in Fig. 2, the drying samples were in a non-hygroscopic porous packed bed, which was composed of glass beads and water ($S_0 = 1$). A sample container was made from polypropylene with a thickness of 2 mm (with dimension of 14.5 cm × 21 cm × 5 cm). The polypropylene did not absorb microwave energy. In this study, the voids occupied from a fraction up to 38 percent of the whole volume of packed beds. The samples were prepared in two configurations: a fine single-layered packed bed ($d = 0.15$ mm, $dp = 11.5$ mm) and a coarse single-layered packed bed ($d = 0.40$ mm, $dp = 11.5$ mm). The sample selected for the drying test was a non-hygroscopic porous packed bed with dimensions of 14.5 cm × 21 cm × 1.15 cm. The 22 porous packed beds had total weight of 11 kg, which had initial water saturation (S_0) of 1.0 and the initial temperature was equal to the ambient temperature.

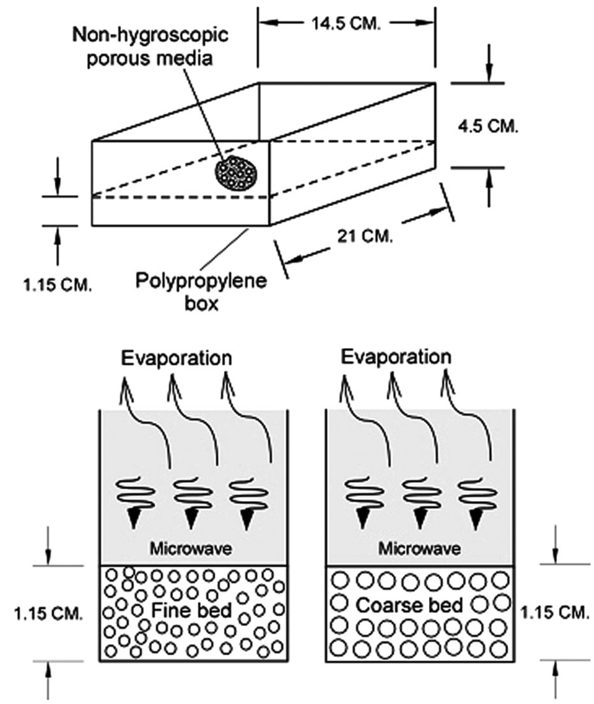

FIG. 2. Schematic of drying sample (porous packed bed).

The water saturation in the non-hygroscopic porous packed bed was defined as the fraction of the volume occupied by water to volume of the pores. It was obtained by weighing dry and wet mass of the sample. The water saturation formula can be described in the following from:[15]

$$S = \frac{M_p \cdot \rho_s \cdot (1 - \phi)}{\rho_w \cdot \phi \cdot 100} \tag{1}$$

where S is water saturation, ρ_s is density of solid, ρ_w is density of water, ϕ is porosity, and M_p is particle moisture content dry basis. During the experimental microwave drying processes, the uncertainty of our data might come from the variations in humidity and room temperature. The uncertainty in drying kinetics was assumed to result from errors in the measured weight of the sample. The calculated drying kinetic uncertainties in all tests were less than 3%. The uncertainty in temperature was assumed to result from errors in measured input power, ambient temperature, and ambient humidity. The calculated uncertainty associated with temperature was less than 2.85%. Three test runs were repeatedly carried out in order to obtain the accurate data.

RELATED THEORIES

Microwave Heat Generation

Microwave heating involves heat dissipation and microwave propagation which causes the dipoles to vibrate and rotate. When the microwave energy emitting from a microwave oscillator (P_{in}) is irradiated inside the microwave applicator, the dielectric material, which has a dielectric loss factor, absorbs the energy and is heated up. Then the internal heat generation takes place. The basic equation calculates the density of microwave power absorbed by dielectric material (P_1) is given by:[16]

$$P_1 = \omega\, \varepsilon_0\, \varepsilon_r''\, E^2 = 2\,\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r'(\tan\delta)E^2 \qquad (2)$$

where E is electromagnetic field intensity, f is microwave frequency, ω is angular velocity of microwave, ε_r' is relative dielectric constant, ε_0 is dielectric constant of air, and $\tan\delta$ is loss tangent coefficient.

From equation (2), P_1 is directly proportional to the frequency of the applied electric field, loss tangent coefficient, and root-mean-square value of the electric field. It means that an increase of $\tan\delta$ of specimen, energy absorption and heat generation are also increased. While $\tan\delta$ is smaller, microwave will penetrate into the specimen without heat generation. However, the temperature increase depends on other factors, such as specific heat, size, and characteristics of specimen.

When the material is heated unilaterally, it is found that as the dielectric constant and loss tangent coefficient vary, the penetration depth will be changed and the electric field within the dielectric material is altered. The penetration depth is used to denote the depth at which the power density has decreased to 37% of its initial value at the surface:[16]

$$D_p = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\left(\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1\right)}{2}}} = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\left(\sqrt{1+(\tan\delta)^2}-1\right)}{2}}} \qquad (3)$$

where D_P is penetration depth, ε_r'' is relative dielectric loss factor, and υ is microwave speed. The penetration depth of the microwave power is calculated according to Eq. (3), which shows how it depends on the dielectric properties of the material. It is noted that products with huge dimensions and high loss factors may occasionally be overheated to a considerably thick layer on the outer layer. To prevent such phenomenon, the power density must be chosen so that enough time is provided for the essential heat exchange between boundary and core. If the thickness of the material is less than the penetration depth, only a fraction of the supplied energy will become absorbed. Furthermore, the dielectric properties of porous material specimens typically show moderate loss depending on the actual composition of the material. With large amount of moisture content, it reveals a greater potential for absorbing microwaves. For typical porous packed bed specimens, a decrease in the moisture content typically decreases ε_r'', accompanied by a slight increment in D_p.

In the analysis, energy P_2 is required to heat up the dielectric material, which is placed in a microwave applicator. The temperature of material, initially (T_1), is raised to T_2. The energy (P_2) can be estimated by the following calorific equation:[16]

$$P_2 = \frac{4.18 \cdot W \cdot C_p \cdot \Delta T}{t} \qquad (4)$$

where W is weight of the dielectric material, C_p is specific heat of the dielectric material, ΔT is the increment of temperature ($T_2 - T_1$), and t is heating time.

Assuming an ideal condition, all of the oscillated microwave energy (P_{in}) is absorbed into the dielectric material, so internal heat generation as Eq. (2) takes place. In this case, the relation between P_{in} and P_2 is shown below:[16]

$$P_{in} = P_2 \qquad (5)$$

In a practical point of view, the transformation energy in the applicator exists due to Eq. (2), the rate of microwave energy absorbed by means of the dielectric loss factor of the sample, and Eq. (3) the energy loss in the microwave devices. Accordingly, by taking into account this transformation efficiency, the microwave oscillation output can be calculated by the following equations:[16]

$$P_{in} = \frac{P_2}{\eta_m} \qquad (6)$$

$$\eta_m = \frac{P_2}{P_{in}} \qquad (7)$$

where

$$P_2 = \frac{Q \cdot S_p \cdot C_P \cdot \Delta T \cdot 4.18}{60 \cdot \eta_m \cdot 10^3} \qquad (8)$$

where η_m is efficiency of microwave devices, Q is weight per meter of dielectric material (porous packed bed), S_p is a rate at which the dielectric material is put on the belt conveyer, C_P is specific heat of dielectric material, and ΔT is heat-up range of $T_1 - T_0$.

Mass and Energy Balance Equation for the Drying Process

The conservation of mass for the control volume of cavity is shown in Fig. 3. The mass balance equation can be written as:[33]

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2} \qquad (9)$$

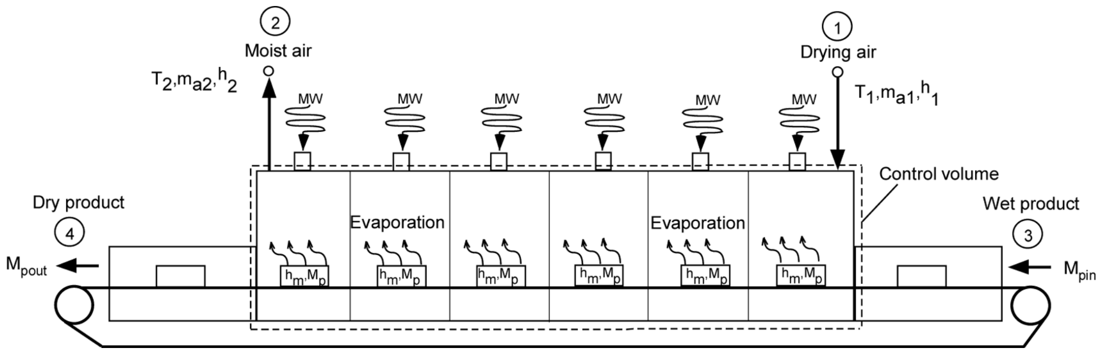

FIG. 3. Schematic of control volume representing drying process using a combined multi-feed microwave-convective air and continuous belt system (CMCB).

Here, Eq. (9) is the mass rate balance for the control volume where $\dot{m}_{g1}$ and $\dot{m}_{g2}$ denote the mass flow rate at inlet (1) and at exit (2), respectively. Similarly, a balance of water in air flowing through the drying cavity leads to:[33]

$$W_d \frac{dM_p}{dt} = \dot{m}_a(X_1 - X_2) \tag{10}$$

where W_d is weight of dry material and M_p is particle moisture content in dry basis. This can be expressed as:[33]

$$M_p = \frac{W_b - W_d}{W_d} \tag{11}$$

where W_b is weight of material before drying, $\dot{m}_a$ is the mass flow rate of dry air, X_1 and X_2 denote absolute humidity of inlet and exit air, respectively. The left-hand side of the mass balance equation, Eq. (10), is the mass flow rate of water in the air flowing from cavity. It can be written as:[33]

$$\dot{m}_w = \dot{m}_a(X_2 - X_1) \tag{12}$$

In the drying process, we apply the first law of thermodynamics (the conservation of energy) for the control volume as shown in Fig. 3. The significant heat transfer is due to the heat of evaporation between the solid and the drying air, and there is also heat rejection to the surroundings. The energy rate balance is simplified by ignoring kinetic and potential energies. Since the mass flow rate of the dry air and the mass of dry material within the control volume remain constant with time, the energy rate balance can be expressed as:

$$\frac{W_d(h_{m2} - h_{m1})}{\Delta t} = \dot{Q}_{evap} + \dot{m}_a(h_1 - h_2) + \dot{Q}_{MW} - \dot{Q}_{loss} \tag{13}$$

where $\dot{Q}_{evap}$ is heat transfer rate due to water evaporation, $\dot{Q}_{MW} = P_{in}$ is microwave energy, h_m is enthalpy of material, t is time, $\dot{m}_a$ is mass flow rate of dry air, h is enthalpy of dry air, and $\dot{Q}_{loss}$ is heat transfer rate to the environment.

Assuming air as an ideal gas, the differences in specific enthalpy are as follows:[33]

$$h_{m1} - h_o = c_m(T_{m1} - T_o) \tag{14}$$

$$h_{m2} - h_o = c_m(T_{m2} - T_o) \tag{15}$$

The enthalpy term of material in Eq. (13) can be written as:[33]

$$h_{m2} - h_{m1} = c_m(T_{m2} - T_{m1}) \tag{16}$$

where c_m represents the specific heat of the material. The enthalpy of moist air can be calculated by adding the contribution of each component as it exists in the mixture; thus the enthalpy of moist air is:[33]

$$h = h_a + Xh_v \tag{17}$$

The heat transfer rate due to phase change is:[33]

$$\dot{Q}_{evap} = \dot{m}_w h_{fg} \tag{18}$$

where h_{fg} is latent heat of vaporization.

Specific Energy Consumption and Energy Efficiency in Drying Process

The drying of a non-hygroscopic porous packed bed is a process of simultaneous heat and mass transfer. The specific energy consumption during the drying process using a combined multi-feed microwave-convective air and continuous belt system and convective drying processes was estimated. The drying conditions are total electrical power supplied in the drying process; convective air temperatures of 30, 50, and 70°C; convective air velocity of 0.5 m/s; total microwave power of 4.8 kW. The specific energy

TABLE 1
Drying time and electrical power under various drying conditions (C-bed)

Testing condition	Power of magnetrons (W)	Position of magnetrons	Air temperature (°C)	Drying time (min)	Electrical power (Kw-hr)	Cost (US$)*
Case 1	800 × 6	Side (1-10-2-11-3-12)	Ambient Air, 30	80	10.5	1.1
Case 2	800 × 6	Top (7-4-8-5-9-6)	Ambient Air, 30	70	8.9	0.91
Case 3	800 × 6	Side (1-10-2-11-3-12)	Hot Air 70	70	16	1.65
Case 4	800 × 6	Top (7-4-8-5-9-6)	Hot Air 70	70	13.5	1.39
Case 5	800 × 6	Side (1-10-2-11-3-12)	Hot Air 50	70	11.9	1.23
Case 6	800 × 6	Top (7-4-8-5-9-6)	Hot Air 50	70	11.8	1.22
Case 7	800 × 6	Screw (7-4-2-5-9-12)	Hot Air 50	70	12.2	1.26
Case 8	–	–	Hot Air 70	360	33	3.41

*Remark: Baht foreign exchange reference rates as at 15–27 January 2011 (Unit: Baht per 1 unit of U.S. dollar).

consumption (SEC) equation is represented by:

$$SEC = \frac{\text{Total electrical power supplied in drying process}}{\text{Amount of water removed during drying}}, \left[\frac{kW - hr}{kg}\right] \tag{19}$$

$$SEC = \frac{P_{total}}{\text{Amount of water removed during drying}}, \left[\frac{kJ}{kg}\right] \tag{20}$$

where P_{total} is a total electrical power supplied the in drying process; this term can be calculated from:

$$P_{total} = P_{mg} + P_{heater} + P_{exfan} + P_{blfan} + P_{cofan} + P_{con}, \quad [kW \times 3600s] \tag{21}$$

where P_{mg} is the electrical power supplied in the magnetron, P_{heater} is the electrical power supplied in the heater, P_{exfan} is the electrical power supplied in the exhaust fan, P_{blfan} is the electrical power supplied in the blower fan, P_{cofan} is the electrical power supplied in the cooling fans, and P_{con} is the electrical power supplied in the conveyor.

From,[33] the energy efficiency (η_e) for the drying process is defined as:

$$\eta_e = \frac{W_d[h_{fg}(M_{p1} - M_{p2}) + c_m(T_{m2} - T_{m1})]}{\dot{m}_{da}(h_1 - h_o)\Delta t + \Delta t \dot{Q}_{MW}} \tag{22}$$

RESULTS AND DISCUSSIONS

Experimental data are analyzed to obtain the drying kinetics for different drying cases and conditions as listed in Tables 1 and 2. The details of the analysis are as outlined in the following.

Drying Kinetics

Figures 4–7 show the temperature and moisture variations versus elapsed times for C-bed and F-bed with constant initial moisture content of 25% (dry basis). It is found that in the case of microwave–convective air drying

TABLE 2
Drying time and electrical power under various drying conditions (F-bed)

Testing condition	Power of magnetrons (W)	Position of magnetrons	Air temperature (°C)	Drying time (min)	Electrical power (Kw-hr)	Cost (US$)*
Case 1	800 × 6	Side (1-10-2-11-3-12)	Ambient Air, 30	90	11.4	1.17
Case 2	800 × 6	Top (7-4-8-5-9-6)	Ambient Air, 30	80	9.9	1.02
Case 3	800 × 6	Side (1-10-2-11-3-12)	Hot Air 70	80	15.7	1.64
Case 4	800 × 6	Top (7-4-8-5-9-6)	Hot Air 70	80	16	1.65
Case 5	800 × 6	Side (1-10-2-11-3-12)	Hot Air 50	80	12.6	1.3
Case 6	800 × 6	Top (7-4-8-5-9-6)	Hot Air 50	80	11.1	1.18
Case 7	800 × 6	Screw (7-4-2-5-9-12)	Hot Air 50	80	12.7	1.31
Case 8	–	–	Hot Air 70	420	35.5	3.67

*Remark: Baht foreign exchange reference rates as at 15–27 January 2011 (Unit: Baht per 1 unit of U.S. dollar).

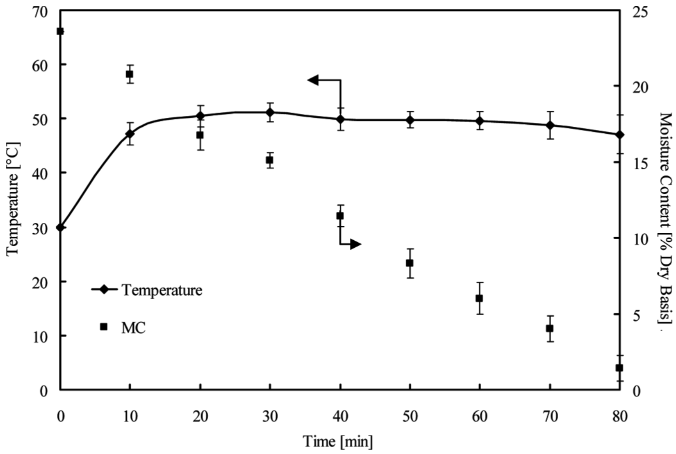

FIG. 4. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 30°C$) (C-bed, case 1).

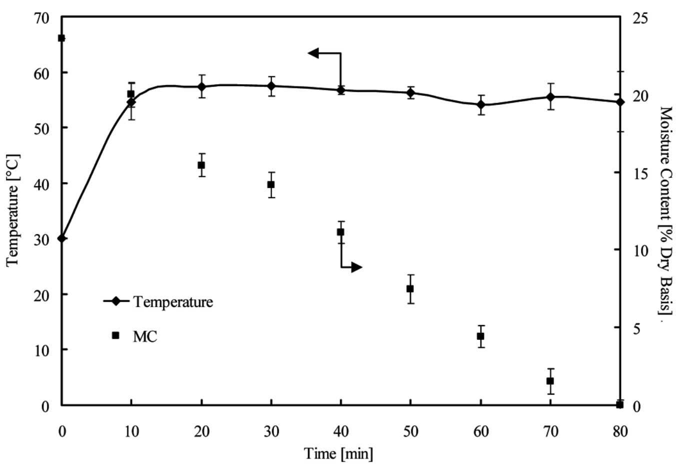

FIG. 5. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 30°C$) (case 2, C-bed).

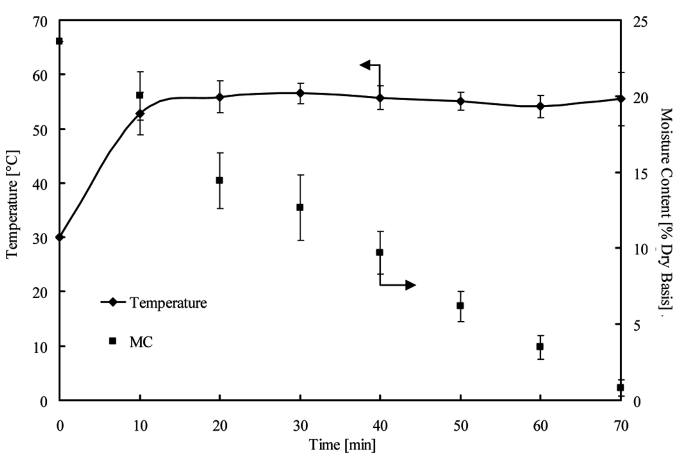

FIG. 6. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 70°C$) (case 4, C-bed).

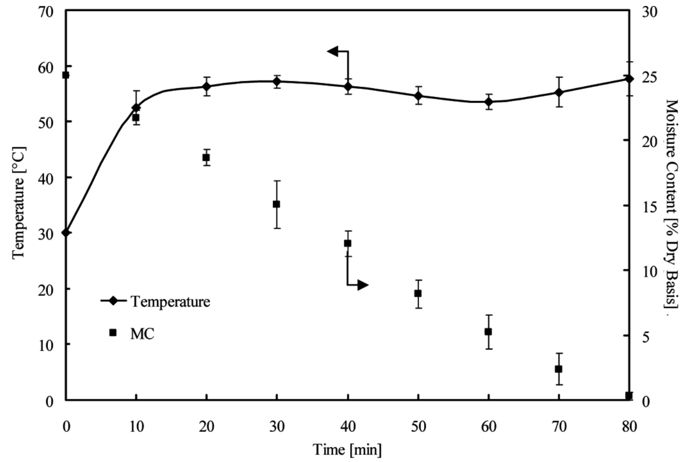

FIG. 7. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 70°C$) (case 4, F-bed).

(30 and 70°C) the moisture profile of the sample continuously decreases faster than the case of convective drying, as shown in Figs. 8 and 9. This phenomenon occurred in the case of convective drying (30 and 70°C) combined with microwave energy; thus the bulk of this sample absorbs the largest amount of microwave energy, which corresponds to the level of absorbed energy in samples as described in Eq. (2). Furthermore, when the process nearly reaches the end stage of drying, the moisture content inside the sample reduces and the absorption of microwave energy decreases.[15] Thus, during this period, microwave power should be optimized to control in order to reduce power consumption in the drying systems.

The temperature and moisture variations versus elapsed times are known as the parameters of the microwave power level 4.8 kW. During the first period of heating, most of the microwave energy supplied is used to heat the sample. The

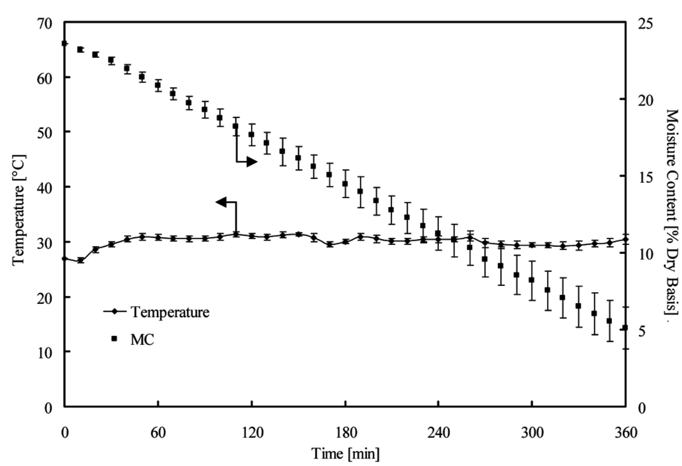

FIG. 8. Temperature and moisture variations versus elapsed times in case using convective drying ($T_1 = 70°C$) (case 8, C-bed).

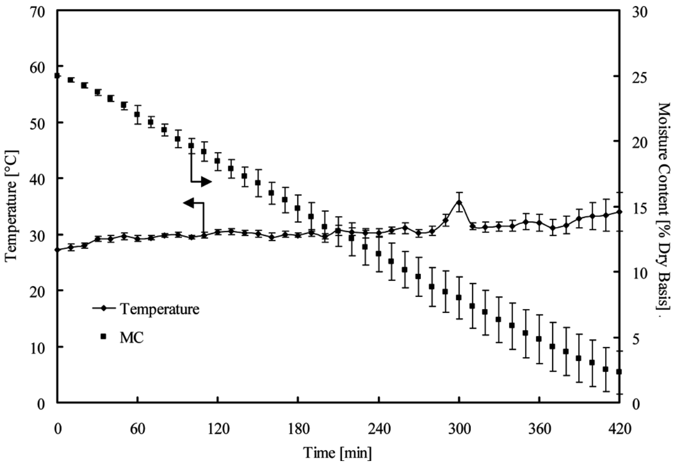

FIG. 9. Temperature and moisture variations versus elapsed times in case using convective drying ($T_1 = 70°C$) (case 8, F-bed).

temperature of the sample is raised rapidly up to 60°C in few minutes. It is found that the temperature increases in the narrow range after the convective air is applied since, at this period, the sample is filled with the moisture, which rapidly responses to the microwave energy at this frequency. Therefore, the major increasing of temperature comes from the microwave energy. However, undesired non-uniform heating patterns can be prevented either by changing the field configuration or by moving the product on a conveyer belt through the cavity where the microwave could be fed at several positions. In addition, considering the multiple magnetron system, the different directions of transmitted waves from different magnetrons make the uniformity of temperature inside the samples. This is because of its wave interference and the influence of the wave penetration capability, as shown in Eq. (2).

Figures 4–9 show the temperature and moisture variations versus elapsed times with respect to different drying methods. It can be observed from these figures that in a combined multi-feed microwave-convective air and continuous belt system, the sample is dried quickly without the residual moisture content in the sample due to the uniform heating. It is clear that the microwave-convective air drying times are drastically reduced compared to convective drying, from 420 min to less than 80 min. This investigation combined that microwave drying; i.e., microwave continuous belt drying can yield a considerable gain in drying time by a factor of ten or more. In the case of convective drying (Figs. 8 and 9), as the surface is dried while the interior is still wet, the dry layer offers a resistance to the heat transport, resulting in a reduction of the evaporation rate as well as drying rate, causing non-uniform heating.

As shown in Fig. 1(b), microwaves oscillated from the magnetron are fed into the cavity. The transmitted wave passes the wave guide (unit numbers 1–12) to heat up the non-hygroscopic porous packed bed. It is found in Figs. 5–7 that the feed magnetrons positioned on the top of the cavity show the influence of microwave power absorbed within the sample, and the temperature relation. Within the sample, the electric field attenuates owing to energy absorption, which is converted to the thermal energy, thus the sample temperature increases. However, the feed magnetrons positioned on the side of the cavity show a lower absorbed microwave power, as shown in Fig. 4. This is because of no direct wave irradiated on the sample; therefore, the influence of the absorbed energy converted to the sample temperature is lower. This phenomenon corresponds to the level of absorbed energy in samples, as explained earlier.

Figures 6 and 7 show the temperature variations and moisture content with respect to elapsed times at different testing conditions. It is found that at a microwave-convective air drying (30 and 70°C) the temperature profile of the sample continuously rises while the moisture content profile rapidly decreases. The electric field distribution in the cavity is uniform. The temperature and moisture content profiles are also depicted in Figs. 6 and 7. It is observed that the increase of temperature and the decrease of moisture content between packed beds A and B are uniform.

Electrical Energy Consumption and Drying Time

The electrical energy consumption during microwave-convective air drying and convective drying of a combined multi-feed microwave-convective air and continuous belt system is given in Figs. 10 and 11. When the two drying methods are compared in terms of electrical energy consumption, it is noted that the lowest electrical energy consumption is observed from the microwave-convective air drying method and this is followed by convective drying methods. The best result with regard to electrical energy

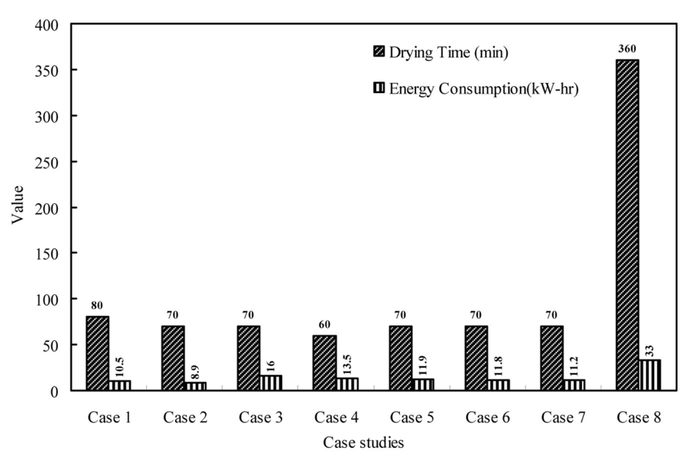

FIG. 10. Variations in drying time and electrical energy consumption in a different case (C-bed).

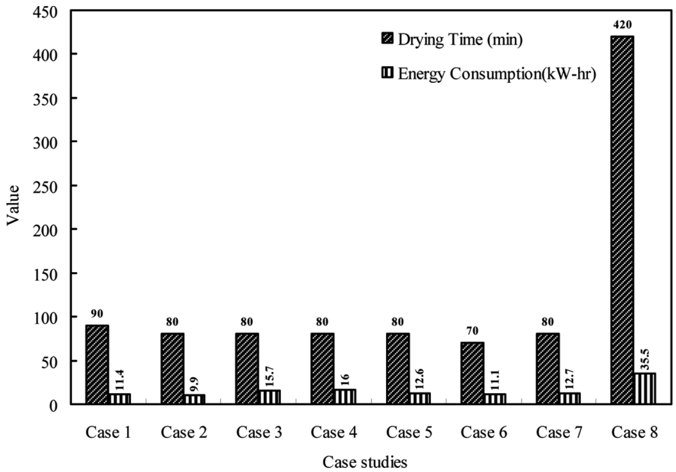

FIG. 11. Variations in drying time and electrical energy consumption in a different case (F-bed).

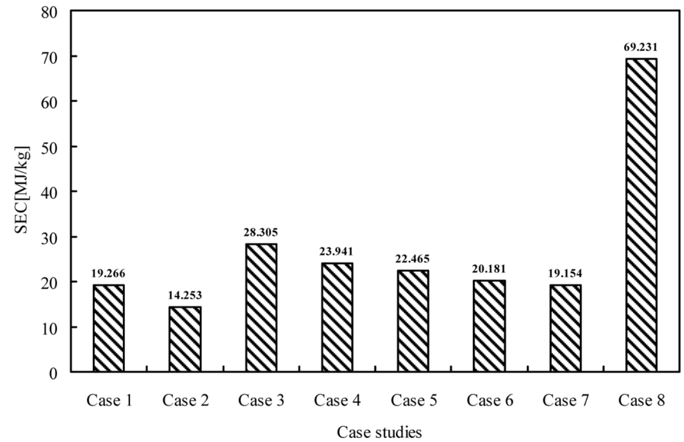

FIG. 12. Variations in specific energy consumption in a different case (C-bed).

consumption is obtained from a microwave power level of 4.8 kW among all drying methods. Electrical energy consumptions at this microwave power level are 8.9 kW-hr (case 2; C-bed) and 9.9 kW-hr (case 2; F-bed). The highest value in all drying methods regarding electrical energy consumption is noted in the convective drying process at temperature 70°C with of 33 kW-hr (case 8; C-bed) and 35.5 kW-hr (case 8; F-bed).

The drying time of convective drying along the drying process is given in Figs. 10 and 11. The highest value in all drying methods regarding the drying time is noted in the convective drying process operating at the temperature of 70°C with 360 minutes (case 8; C-bed) and 420 minutes (case 8; F-bed).

Analysis of Specific Energy Consumption (SEC)

Figures 12 and 13 show the specific energy consumption with the variation of the sample particles.

To obtain the experimental results, the microwave power level is set at 4.8 kW, and the thickness of the layers with C particles and F particles is fixed. Figures 12 and 13 show the specific energy consumption with the variation of the sample thickness. It can be seen in the first period of drying (around 0–120 min) that the packed bed can absorb a lot of microwave power due to the high moisture content, and thus the specific energy consumption is low in this period.

Microwave-convective air drying can be used to efficiently dry the sample. A non-hygroscopic porous packed bed dried using microwave energy required 5 times less specific energy consumption than the bed dried by a convective drying method at 70°C. Similar result are also observed in Figs. 12 and 13; the non-hygroscopic porous packed bed dried by microwave–convective air drying can be rapidly dried due to the uniform heating of the drying system as described in the previous section. The drying times of the microwave–convective air drying is less than 80 min, which is drastically reduced from the convective drying time of 420 min (Fig. 13). The results show that microwave drying can yield a considerable gain in drying time by a factor of two or more. In the case of convective drying, the surface is dried while the interior is still wet; the dry layer offers resistance to the heat transport, resulting in a reduction of the evaporation rate as well as drying rate and also causing high specific energy consumption.

The drying time of the drying trials is carried out by two different drying methods. No marked difference is found between the methods with and without hot air supplied in the cavity. Specific energy consumption depends on the power absorbed by the cavity and the drying time. In this study, the specific energy consumptions at microwave power levels of 4.8 kW are investigated. These short drying times may be due to a result of microwave power levels.

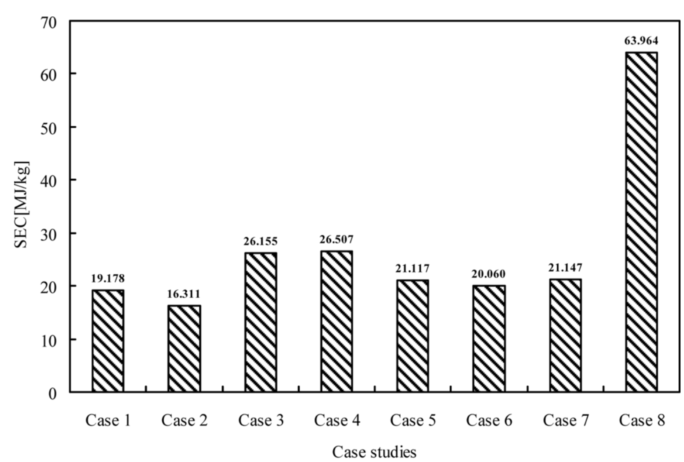

FIG. 13. Variations in specific energy consumption in a different case (F-bed).

However, for convective drying, the drying times are long because the convective heat transfer coefficient of the non-hygroscopic porous packed bed is low. The reduction of specific energy consumption observed during drying and the reduction of drying time is caused by the decrease in convective air levels. The specific energy consumptions of microwave-convective air drying at ambient temperature are 14.253 MJ/kg (case 2; C-bed) and 16.311 MJ/kg (case 2; F-bed), whereas the specific energy consumptions of convective drying at 70°C are 69.231 MJ/kg (case 2; C-bed) and 63.964 MJ/kg (case 2; F-bed). The specific energy consumptions of the combination drying (microwave–convective air drying) give similar trends at all drying processes. The reduction of specific energy consumption is achieved by decreasing the hot air temperature level supplied to cavity. Figures 12 and 13, respectively, show the comparison of specific energy consumption of different drying cases for C-bed and F-bed. The results show that the lowest specific energy consumption is found from the microwave–convective air drying method (ambient air), and followed by convective drying methods (Figs. 12 and 13).

Energy Efficiency

Figures 14 and 15 show the energy efficiency with respect to the drying time in different cases. It is found that the energy efficiency during drying of C-bed and F-bed at the starting period (0–15 min) is high due to the high quantity of moisture content in the non-hygroscopic porous packed bed, which leads to high value of dielectric loss factor; thus the wave absorption is more converted by the non-hygroscopic porous packed bed. The results are high energy efficiency after the vapor moves from the surface of the non-hygroscopic porous packed bed. This causes the moisture content to decrease quickly and the low quantity of absorbed waves because of the decreased energy consumption and decreased efficiency of absorbed microwave power, therefore the energy efficiency depends on the level of absorbed microwave power.

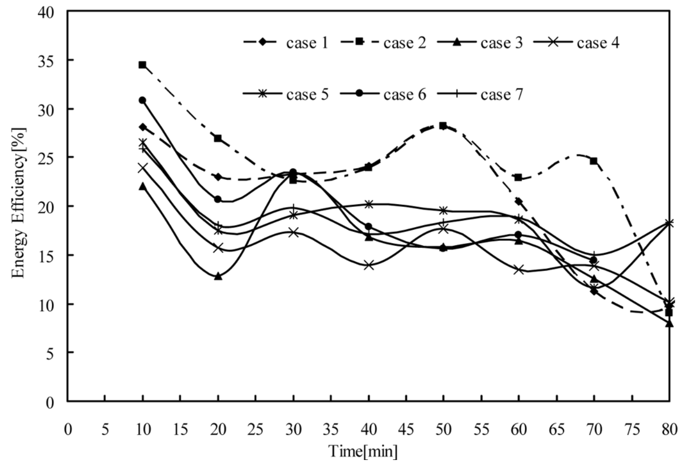

FIG. 15. Energy efficiency profiles with respect to elapsed time in a different case (F-bed).

In Fig. 14, the energy efficiency profile for the sample in the case of C-bed rises up quickly in the early stages of drying (between 10–15 min). However, the efficiency rises slowly after this stage (between 45–70 min). It is evident from the figure that the moisture content inside the sample reducing at the final stages of drying causes the decreases in the absorbed microwave power. Consequently, the energy efficiency profiles decrease in this stage of drying.

Figures 14 and 15 show the energy efficiency values during microwave-convective air drying of a combined multi-feed microwave-convective air and continuous belt system in case 1 and case 2 (C-bed and F-bed). It can be observed that when the drying methods are compared in

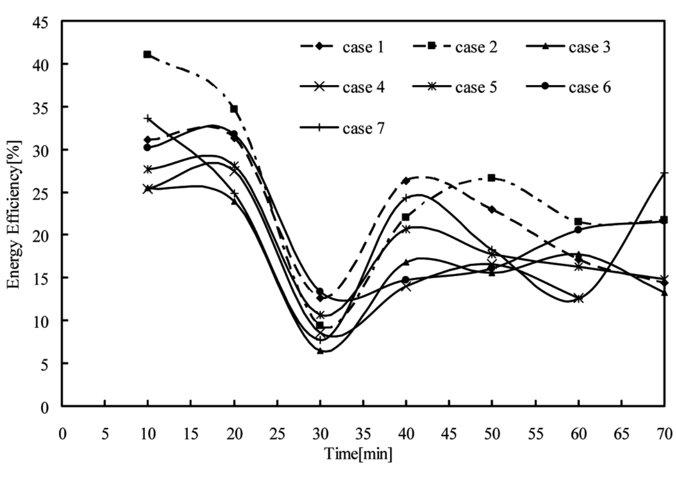

FIG. 14. Energy efficiency profiles with respect to elapsed time in a different case (C-bed).

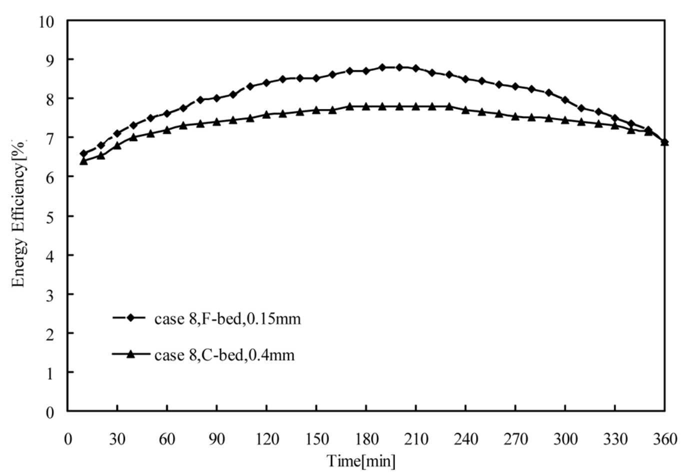

FIG. 16. Energy efficiency profiles with respect to elapsed time in case 8.

terms of energy efficiency, the highest energy efficiency is presented in case 1 and case 2 (Table 1 and Table 2: C-bed and F-bed). No marked difference is found between the supplied hot air into the cavity, since the drying time values obtained in the drying are also not different. The result shows that the microwave–convective air drying is not significant to decrease the drying time and to waste more energy consumption.

Figure 16 shows the energy efficiency with respect to the drying time. The low energy efficiency of convective drying is presented (case 8; C-bed and F-bed). Energy efficiency depends on the temperature in the cavity and the drying time. However, the drying times of convective drying, due to the convective heat transfer of the non-hygroscopic porous packed bed, are low.

Microwave technology is one of the most interesting heating methods because microwave processing requires lower energy consumption for the same or better results than conventional equipment. However, if we consider the capital and operating cost, it is found that microwave technology is capital-intensive and the economics of a particular application must be thoroughly examined before equipment is installed in industry.

CONCLUSIONS

A combined multi-feed microwave-convective air and continuous belt system permits quicker drying at lower temperature, resulting in a 30% reduction in energy consumption for what is normally an energy-intensive process. A non-hygroscopic porous packed bed dried using microwave energy required 5 times less specific energy consumption than the packed bed, which dried by a convective drying method at 70°C in a convective cavity. Moreover, this work depicts the technique that combined the conventional heating with the microwave heating and the continuous belt system. It shows the potential to reduce electrical energy consumption. If this technology is implemented to industry, it will decrease the production costs due to the lower electrical energy consumption.

Overall, when handling a combined multi-feed microwave-convective air and continuous belt system correctly, we can conclude that it will realize the following advantages over other drying systems:

1. Better heat distribution.
2. Faster product heating because the multiple magnetrons are placed around the rectangular cavity; this advantage corresponds to the better microwave power distribution, which can penetrate further into the multi-plane of the material.
3. Can immediately be ready for operation and control of heat capacity without delay.
4. Can continuously supply the material into the system.
5. The cavity is designed to prevent magnetron damage.
6. No heat storage losses.
7. Low specific energy consumption and high energy efficiency.

The next steps of the research related to this work will be done to develop the control system and optimal drying schedules for a combined multi-feed microwave-convective air and continuous belt system of hygroscopic porous material, especially biomaterial.

NOMENCLATURE

C_p	specific heat of the dielectric material (kJ/kg K)
c_m	material specific heat (kJ/kg K)
D_p	penetration depth (m)
d_p	depth of packed bed (mm)
E	electromagnetic field intensity (V/cm)
f	microwave frequency (Hz)
h	enthalpy (kJ/kg)
h_m	enthalpy of material (kJ/kg)
h_{fg}	latent heat of vaporization (kJ/kg_{water})
M_p	particle moisture content dry basis (kg_{water} / kg_{solid})
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_a$	mass flow rate of dry air (kg/s)
$\dot{m}_w$	mass flow rate of water in the air flowing from cavity (kg/s)
P_{in}	microwave energy emitted from a microwave oscillator (kW)
P_1	density of microwave power absorbed by dielectric material (kW/cm^3)
P_2	energy is required to heat up the dielectric material (kW)
P_{total}	total electrical power supplied in drying process (kJ)
P_{mg}	electrical power supplied in magnetron (kW-hr)
P_{heater}	electrical power supplied in heater (kW-hr)
P_{exfan}	electrical power supplied in exhaust fan (kW-hr)
P_{blfan}	electrical power supplied in blower fan (kW-hr)
P_{cofan}	electrical power supplied in cooling fans (kW-hr)
P_{con}	electrical power supplied in conveyor (kW-hr)
$\dot{Q}_{evap}$	heat transfer rate due to water evaporation (kW)
$\dot{Q}_{MW}$	microwave energy (kW)
$\dot{Q}_{loss}$	heat transfer rate to the environment (kW)
Q	weight per meter of dielectric material (non-hygroscopic porous packed bed) (g/m)
SEC	Specific Energy Consumption (kJ/kg)
S	water saturation
S_p	rate at which the dielectric material is put on the belt conveyer (m/min)
T	temperature (°C)
t	time (s)
tan δ	loss tangent coefficient (-)
W	weight of the dielectric material (kg)
W_d	weight of dry material (kg)

W_b	weight of material before drying (kg)
X	absolute humidity ($kg_{vapor}/kg_{dry\ air}$)

Greek Letters

ε_r''	relative dielectric loss factor
ε_r'	relative dielectric constant
ε_0	permittivity of air (F/m)
ΔT	increment temperature (°C)
η_e	energy efficiency (%)
η_m	efficiency of microwave device (%)
ρ_s	density of solid (glass bead) (kg/m^3)
ρ_w	density of water (kg/m^3)
ϕ	porosity (m^3/m^3)
υ	velocity of propagation (m/s)
ρ	density (kg/m^3)
ω	angular velocity of microwave (rad/s)

Subscripts

o	standard state value; surroundings; reference environment
1	inlet
2	outlet
a	air
b	before
da	drying air
d	dry material
fg	difference in property between saturated liquid and saturated vapor
g	gas
in	input
m	material
s	solid
w	water
total	total
mg	magnetron
heater	heater
exfan	exhaust fan
cofan	cooling fan
blfan	blower fan
con	conveyor

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