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Energy and exergy analyses 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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ABSTRACT

This paper is concerned with the energy and exergy analyses in the drying process of non-hygroscopic porous packed bed by combined multi-feed microwave-convective air and continuous belt system (CMCB). 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 magnetron on overall drying kinetics and energy utilization ratio (EUR) were evaluated in detail. The results showed that 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 with higher energy utilization and less exergy efficiency in drying process. The results presented here provided fundamental understanding for drying process using CMCB in industrial size.

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1. Introduction

Microwave and convection heating may be applied simultaneously or at different times. It has been proven that combination drying is an effective way particularly when microwaves are introduced in the final stages of drying to reduce the product moisture below 20% [1]. Microwave application can be effectively utilized in the falling rate period where hot-air drying is too slow affecting the quality of the dried product with over exposure to hot-air conditions. Application of microwave or combination drying technique for potato [2], apple and mushroom [3–4], raisins [5–6], blueberries [7] and banana [8] has been successfully experimented. These researchers also noted the improvement in the end product quality along with the reduction of total drying time compared to hot-air only drying. This technique combines the capability of microwaves to heat the product internally (depending on the dielectric properties and interaction of the material with electromagnetic energy) and enables faster removal of the surface moisture due to conventional heating of the surroundings.

Various materials that undergo drying in industrial production require different approach to this process [9]. In many cases, the time of drying becomes important because of the production rate. In another case, the time is less important but the quality of the products, that is, their appearance and good mechanical state or the biological value in the case of food or medicine products are relevant. In all cases, important is the minimization of the energy use as drying is a big energy consuming process. To fulfill these requirements, one has to look for special methods of drying among others for the combined methods in which different sources of energy supply are used.

When drying with dielectric heating it is usual to combine hot air with the system, particularly with microwave systems. This is because it usually improves the efficiency and the economics of the drying process [10]. Hot air is, by itself, relatively efficient at removing free water at or near the surface, whereas the unique pumping action of dielectric heating provides an efficient way of removing internal free water as well as bound water. By combining these properly, it is possible to draw on the benefits of each and maximize efficiency and keep the costs of drying down. Note that drying with microwaves or dielectrics alone can be very expensive in terms of both equipment and operating costs.

The traditional thermodynamics method of assessing processes involving the physical or chemical processing of materials with accompanying transfer and transformation of energy is by the completion of an energy balance which is based on the first law of thermodynamics. The first law analysis is used to reduce heat losses or enhance heat recovery. Meanwhile, it gives no information on the degradation of the useful energy that occurs within the process equipment [11]. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential change [12]. Exergy is defined as the maximum work, which can be produced by a system or a flow of matter or energy and it comes to equilibrium with a

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specified reference environment (dead state) [13]. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes [14].

The features of exergy are identified to highlight its importance in a wide range of applications [15]. Exergy analysis has been increasingly as a useful tool in the design, assessment, optimization and improvement of energy systems. It can be applied on both system and component levels. Exergy analysis leads to a better understanding of the influence of thermodynamics phenomena on effective process, comparison of the importance of different thermodynamics factors, and the determination of the most effective ways of improving the process [16]. As regards the exergy analyses of drying processes, some work has been carried out in recent years. Kanoglua and et al. [17] analyzed a thermodynamics aspect of the fluidized bed drying process of large particles for optimizing the input and output conditions by using energy and exergy models. The effects of the hydrodynamic and thermodynamics conditions were also analyzed such as inlet air temperature, fluidization velocity and initial moisture content on EUR and exergy efficiency. Syahrul and et al. [18] and Dincer [19] used a model to analyze exergy losses of a air drying process. Their work demonstrated that the usefulness of exergy analysis in thermodynamics assessments of drying processes and providence the performances and efficiencies of these processes. Akpinar et al. [20–21] studied energy and exergy of the drying of red pepper slices in a convective type dryer, with potato slices in a cyclone type dryer and pumpkin slices in a cyclone type dryer. The type and magnitude of exergy losses during drying was calculated. Colak [22] performed an exergy analysis of thin layer drying of green olive in a tray dryer. In Colak's study the effects of the drying air temperature, the mass flow rate of drying air and olives on the system performance were discussed. Ceylan et al. [23] carried out energy and exergy analyses during the drying of two types of timber.

However, few works has been reported on the energy and exergy analysis in combined microwave-convective drying process of porous media. The drying of porous media has been interested by many researchers and become complex, coupled, and multiphase processes with a wide range of applications in industry. In addition, as a result of high cost of energy, an operation with a high potential for optimizing with respect to energy savings has been realized. For many years, it has been studied experimentally for measuring drying kinetics on the macro-scale.

Typical applications of non-uniform material include the tertiary oil recovery process, geothermal analysis, asphalt concrete pavements process and preservation process of food stuffs. Therefore, knowledge of heat and mass transfer that occurs during convective drying of porous materials is necessary to provide a basis for fundamental understanding of convective drying of non-uniform materials.

The fore mentioned works concerned mainly with, energy and exergy analyses of drying process. Normally, most of materials in the drying process are porous materials. In the recent works the authors were mention about porous materials structure, with are concern with energy and exergy analyses of drying process.

The objectives of this work are to evaluate (i) the exergy losses of two operations porous packed bed, (ii) the distributions of the exergy losses and exergy input of the different drying operations and (iii) the influences of operating parameters on exergy losses. The knowledge gained will provide an understanding in porous media and the parameters which can help to reduce EUR and exergy losses.

2. Experimental setup

Microwave-convective air drying was carried out using a CMCB (Fig. 1(a)).The shape of microwave cavity was rectangular with a cross sectional area 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 were essential, through which the material to be heated up on the belt conveyer was put in and taken out. In this equipment, leakage of microwaves was prevented by the countermeasure in double 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 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 arranged in certain position, as shown, as 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 could be controlled by the varied speed drive (vsd) of control unit. Hot air was generated using the 24 unit of electric heaters with the maximum capacity of 10.8 kW and the maximum working temperature of 240 °C. The hot air was supplied by blower fan with 0.4 kW power through the air duct into the cavity. The hot-air temperature was measured by using thermocouples.

As shown in Fig. 2, the drying samples were non-hygroscopic porous packed bed, which composed of glass beads and water (saturated porous packed bed, $s_0 = 1$). 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 single-layered packed bed ($d = 0.15$ mm, $d = 0.40$ mm, and $d_p = 11.5$ mm). The sample selected for 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 the initial water saturation (s_0) of 1.0 and the initial temperature was equal to the ambient temperature.

The water saturations in the non-hygroscopic porous packed bed were defined as the fraction of the volume occupied by water to volume of the pores. They were obtained by weighing dry and wet mass of the sample. The water saturation formula can be described in the following form [24]:

$$s' = \frac{M_p \cdot \rho_s \cdot (1-\varphi)}{\rho_w \cdot \varphi \cdot 100} \quad (1)$$

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 the experimental data might be generated by the variations of humidity, room temperature and human errors. The uncertainty in drying kinetics was assumed to be a result of errors in the measured weight of the sample. The calculated drying kinetic uncertainties in all tests were less than 3%. The uncertainly in temperature was assumed to be a result of errors in measured input power, ambient temperature and ambient humidity. The calculated uncertainty associated with temperature was less than 2.85%.The different drying cases were then carried out in each test run (see details in Table (1)).

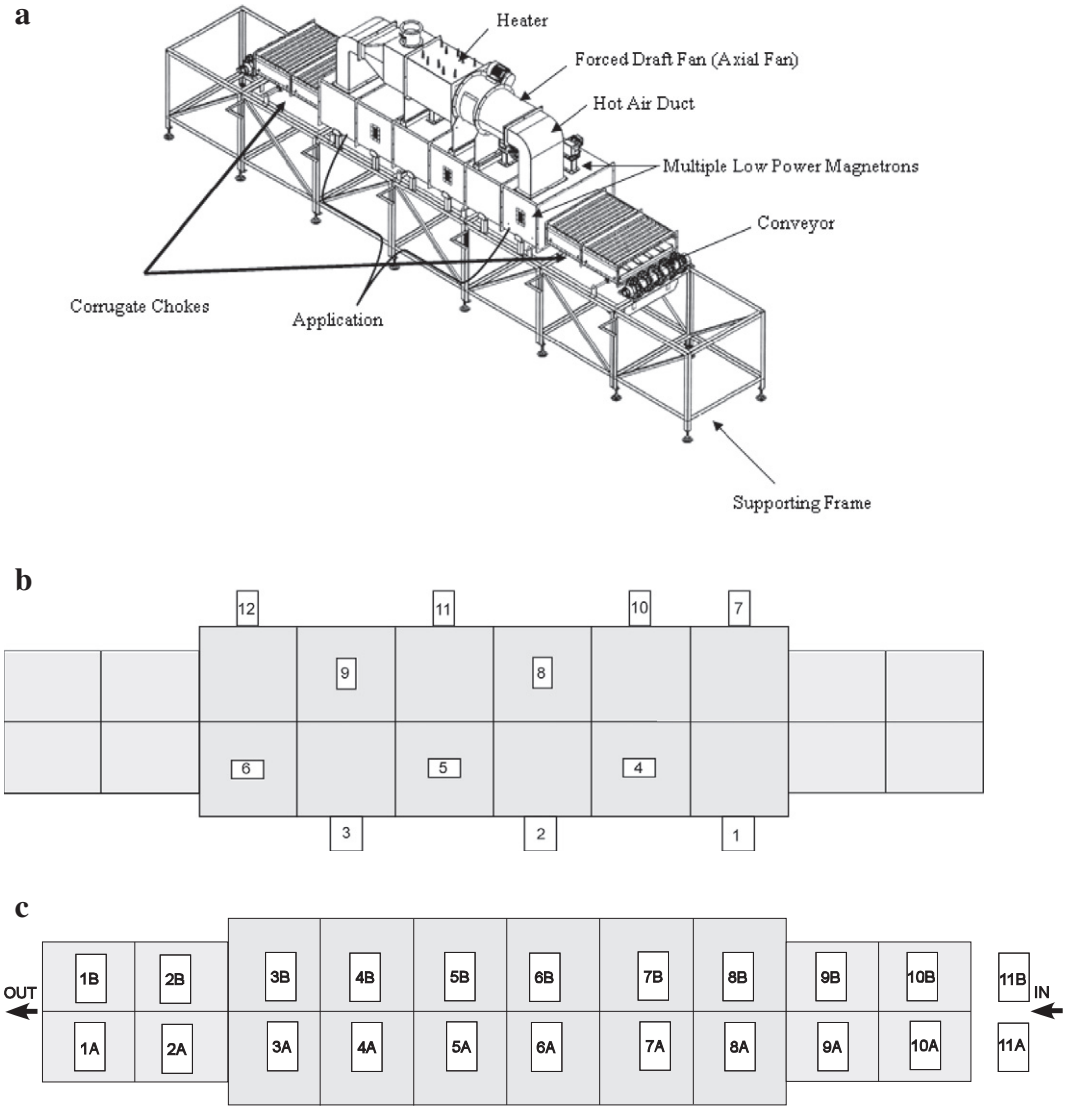

Fig. 1. Schematic diagram of experimental set up. (a) A combined multi-feed microwave-convective air and continuous belt system. (b) Feeds magnetrons positioned of 12 units. (c) Feeds samples positioned of 22 packed beds.

3. Microwave heat generation

Microwave heating involves heat dissipation and microwaves propagation which causes the dipoles to vibrate and rotate. When the microwave energy emitted 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 for calculation of the density of microwave power absorbed by dielectric material (P_1) is given by [25]:

$$P_1 = \omega\ \varepsilon_0\ \varepsilon_r''\ E^2 = 2\ \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r'(\tan\delta)E^2 \tag{2}$$

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 dielectric loss tangent coefficient.

From Eq. (2), P_1 is directly proportional to the frequency of the applied electric field and dielectric loss tangent coefficient and root-mean-square value of the electric field. It means that during an increasing of $\tan\delta$ of specimen, energy absorption and heat generation are also increased. While $\tan\delta$ is small, microwave will penetrate into specimen without heat generation. However, the temperature increase depends on other factors such as specific heat, size and characteristic 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 will be altered. The penetration depth is used to denote the depth at which the power density decreased to 37% of its initial value at the surface [25].

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

Where D_P is penetration depth; ε''_r is relative dielectric loss factor and v 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

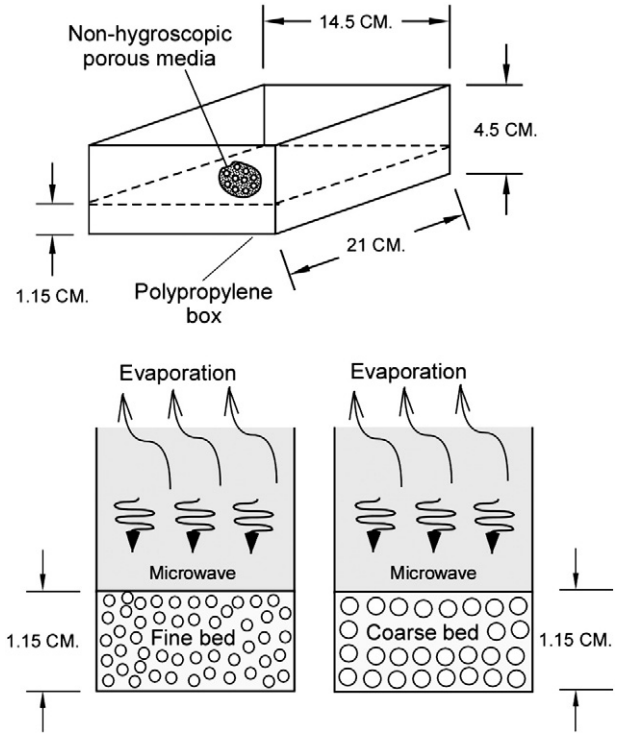

Fig. 2. Schematic of drying sample (porous packed bed).

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 be absorbed. Furthermore, the dielectric properties of porous packed bed specimens typically show moderate looseness 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'', accompanied by a slight increment in D_p.

In the analysis, energy P_2 is required to heat up the dielectric material W (g) placed in a microwave applicator. The initial temperature of material T_1, is raised to T_2. The energy P_2 can be estimated by the following calorific equation [25].

$$P_2 = \frac{4.18 \cdot W \cdot C_p \cdot \Delta T}{t} \tag{4}$$

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.

Table 1
Drying conditions of porous packed bed (C-bed and F-bed).

Drying condition	Power of magnetron (W)	Magnetrons operation	Air temperature (°C)	Drying time (min)	
				C-Bed	F-Bed
Case 1	800×6	Side (1-10-2-11-3-12)	Ambient air, 30	80	90
Case 2	800×6	Top (7-4-8-5-9-6)	Ambient air, 30	70	80
Case 3	800×6	Side (1-10-2-11-3-12)	Hot air 70	70	80
Case 4	800×6	Top (7-4-8-5-9-6)	Hot air 70	70	80
Case 5	800×6	Side (1-10-2-11-3-12)	Hot air 50	70	80
Case 6	800×6	Top (7-4-8-5-9-6)	Hot air 50	70	80
Case 7	800×6	Screw (7-4-2-5-9-12)	Hot air 50	70	80
Case 8	–	–	Hot air 70	360	420

Assuming an ideal condition, all of the oscillated microwave energy (P_{in}) is absorbed into the dielectric material; such internal heat generation as shown in Eq. (2) takes place. In this case, the relation between P_{in} and P_2 is shown below [25]:

$$P_{in} = P_2 \tag{5}$$

In a practical point of view; however, the transformation energy in applicator exists due to (1) the rate of microwave energy absorbed by means of the dielectric loss factor of the sample and (2) the energy loss in the microwave devices. Accordingly, by taking this transformation efficiency into account, the microwave oscillation output can be calculated by the following equations [25]:

$$P_{in} = \frac{P_2}{\eta_m} \tag{6}$$

$$\eta_m = \frac{P_2}{P_{in}} \tag{7}$$

Where

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

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 $T_1 - T_0$.

4. Energy analyses

For analyzing mass transfer in drying process we applied the low of conservation of mass for the control volume as shown in Fig. 3. The mass balance equation can be written as [18]:

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

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 exit at (2) respectively. Similarly, a balance of water in air flowing through the drying cavity leads to [18]:

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

Where W_d is weight of dry material and M_p is particle moisture content, dry basis; this can be expressed as [18]:

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

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 Eq. (10), is the mass flow rate of water in the air flowing from cavity and can be written as [18]:

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

For analyzing energy transfer in drying process, we applied the First Law of Thermodynamics (the law of 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.

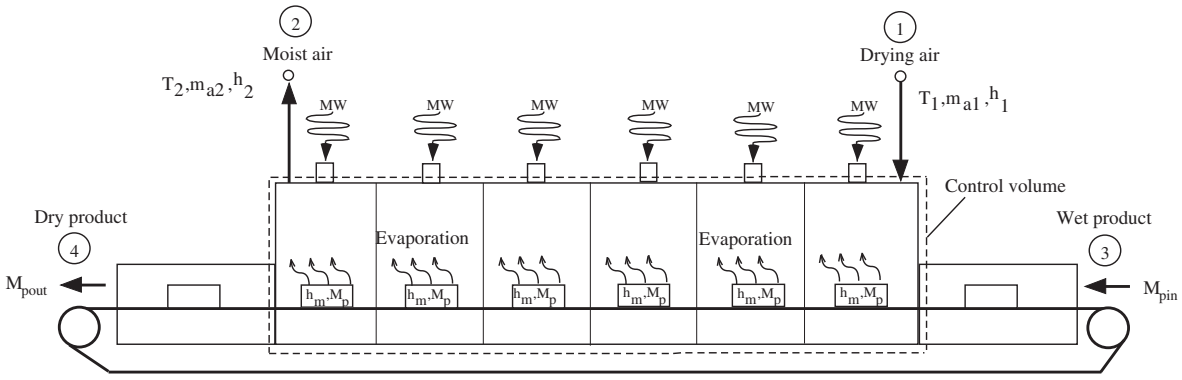

Fig. 3. Schematic of control volume representing drying of process using a combined multi-feed microwave-convective air and continuous belt system (CMCB).

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.

The differences in specific enthalpy are as follows, assuming air as an ideal gas [18]:

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

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

The material enthalpy term of the energy rate balance can be expressed as [18]:

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

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 exits in the mixture; thus the enthalpy of moist air is [18]:

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

The heat transfer rate due to phase change is [18]:

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

where h_{fg} is latent heat of vaporization.

The EUR for the drying chamber can be obtained using the following expression [18]:

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

5. Exergy analyses

The second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal systems. As known, exergy analysis evaluates the available energy at different points in a system. Exergy is a measurement of the quality or grade of energy and it can be destroyed in the thermal system [26-27]. The second law states that part of the exergy entering a thermal system with fuel, electricity, flowing streams of matter, or other sources is destroyed within the system due to irreversibilities. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems. In the scope of the second law analysis of thermodynamics, total exergy of inflow, outflow and losses of the drying chamber were estimated. The basic procedure for exergy analysis of the chamber is to determine the exergy values at steady-state points and the reason of exergy variation for the process. The exergy values are calculated by using the characteristics of the working medium from a first law energy balance. For this purpose, the mathematical formulations used to carry out the exergy balance are as show below Ahern [28].

$$\begin{aligned} Exergy = {} & \underset{\text{internal energy}}{(u-u_\infty)} - \underset{\text{entropy}}{T_\infty(s-s_\infty)} + \underset{\text{work}}{\frac{P_\infty}{J}(v-v_\infty)} + \underset{\text{momentum}}{\frac{V^2}{2gJ}} + \underset{\text{gravity}}{(z-z_\infty)\frac{g}{g_cJ}} \\ & + \underset{\text{chemical}}{\sum_c(\mu_c-\mu_\infty)N_c} + \underset{\text{radiation}}{E_iA_iF_i\left(3T^4-T_\infty{}^4-4T_\infty T^3\right)} + \underset{\text{emission}}{\cdots\cdots\cdots} \end{aligned} \tag{11}$$

The subscript ∞ denotes the reference conditions. In the exergy analyses of many systems, only some of the terms shown in Eq. (11) are used but not all. Since exergy is energy available from any source, it can be developed using electrical current flow, magnetic fields, and diffusion flow of materials. One common simplification is to substitute enthalpy for the internal energy and *PV* terms that are applicable for steady-flow systems. Eq. (11) is often used under conditions where the gravitational and momentum terms are neglected. In addition to these, the pressure changes in the system are also neglected because of $v \cong v_\infty$, hence Eq. (11) is reduced as:

$$Exergy = \bar{c}_p\left[(T-T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \tag{12}$$

The inflow and outflow of exergy can be found using the above expression depending on the inlet and outlet temperatures of the drying chamber. Hence, the exergy loss is determined as:

$$\begin{aligned} &\text{Exergy loss} = \text{Exergy inflow} - \text{Exergy outflow} \\ &\textstyle\sum Ex_L = \sum Ex_i - \sum Ex_o \end{aligned} \tag{13}$$

The exergy inflow for the chamber is stated as below

$$Ex_{dci} = Ex_{pbi} = \bar{c}_{p_{da}}\left[(T_{dci}-T_\infty) - T_\infty \ln\frac{T_{dci}}{T_\infty}\right] + Ex_{microwave} \tag{14}$$

The exergy outflow for the drying chamber is stated as:

$$Ex_{dco} = Ex_{pbo} = \bar{c}_{pda}\left[(T_{dco} - T_\infty) - T_\infty \ln\frac{T_{dco}}{T_\infty}\right] \quad (15)$$

The exergetic efficiency can be defined as the ratio of the product exergy to exergy inflow for the chamber as outlined below [29]:

$$Exergy\ \ Efficiency = \frac{Exergy\ \inf low - Exergy\ \ loss}{Exergy\ \inf low} \quad (16)$$

$$\eta_{Ex} = 1 - \frac{Ex_L}{Ex_i} \quad (17)$$

For half a century, through the continuous research on microwave-drying technology, the advantages of intensive drying resulting in shorter drying time, energy efficiency, superior product quality, environment protection, etc. had well been documented through factually hundreds of research papers. With the development of microwave-drying technology, the microwave-drying equipment has also been upgraded at various levels.

6. Results and discussions

Experimental data were analyzed to obtain the drying kinetics for different drying cases and conditions as listed in Table 1.The details of analysis are as below.

6.1. Drying kinetics

Microwave-drying exploits the phenomenon of internal heat generation in wet materials placed in a high-frequency electromagnetic field. Advantageously, in microwave drying the temperature gradient, pressure gradient and the moisture concentration gradient have the same direction, which promotes water removal with no crust formation owing to evaporative cooling.

Figs. 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 (30 and 70 °C) the moisture profile of the sample continuously decreases faster than that in the case of convective drying as shown in Figs. 8 and 9. This is because in the case of microwave-convective drying (30 and 70 °C), the bulk of this sample absorbs the largest amount of microwave energy. This phenomenon 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 is reduced and hence the absorption of microwave energy decreases [15]. Thus, during this period, microwave power should be optimized control in order to reduce power consumption in the drying systems.

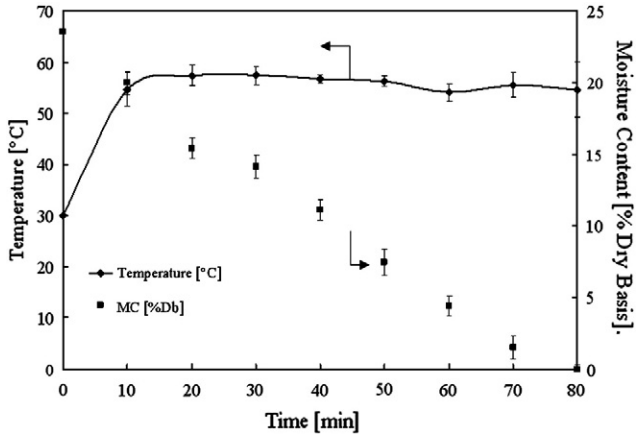

Fig. 5. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 30$ °C) (case 2, C-bed).

The temperature and moisture variations versus elapsed times are known as a parameter of the microwave position and fixed the microwave power (4.8 kW). During the very first period of heating, most of the microwave energy supplied is used to heat the sample. The temperature of sample is raised rapidly up to 60 °C in a few minutes. It is found that only minor temperature differences are observed when convective air is applied. This is because of an undesired non-uniform heating pattern which can be prevented either by changing the field configuration or by moving the product on a conveyer belt through the cavity where microwave could be fed at several positions. Besides, considering the multiple magnetron system, the different directions of transmitted wave from different magnetron 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).

Figs. 4–9 show the temperature and moisture variations versus elapsed times with respect for different drying methods. It can be observed from Figs. 4–7 that for a CMCB, the sample is dried quickly without the residual moisture content in the sample due to the uniform heating. It is clear that drying of 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 case of convective drying (Figs. 8 and 9), as the surface is dried while the

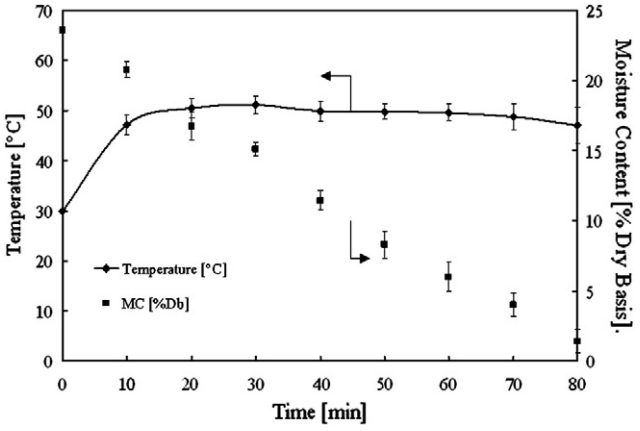

Fig. 4. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 30$ °C) (case 1,C-bed).

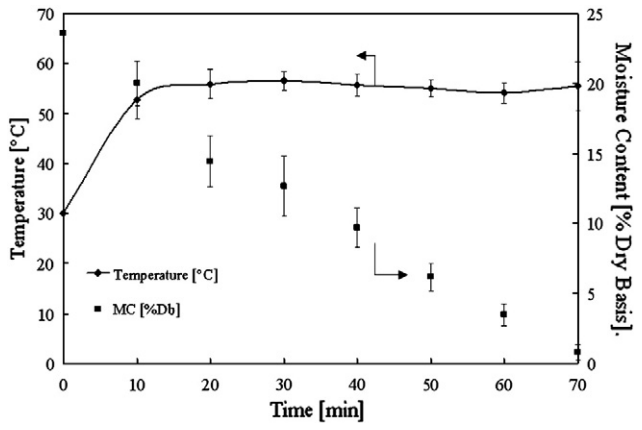

Fig. 6. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 70$ °C) (case 4, C-bed).

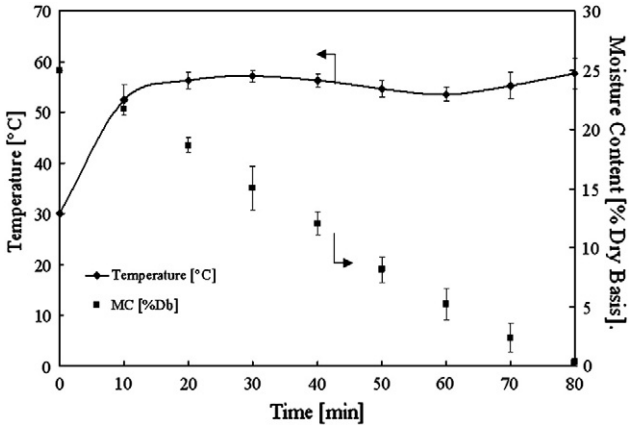

Fig. 7. Temperature and moisture variations versus elapsed times in case drying using CMCB ($T_1 = 70$ °C) (case 4, F-bed).

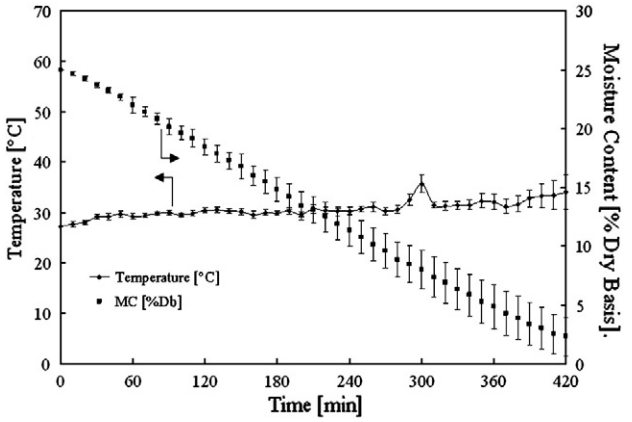

Fig. 9. Temperature and moisture variations versus elapsed times in case using a convective drying ($T_1 = 70$ °C) (case 8, F-bed).

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) microwave oscillated from the magnetron are radiated into the cavity. The transmitted wave passes wave guide (the unit numbers 1–12) to heat up the non-hygroscopic porous packed bed. It is found that the feed magnetron positioned on top shows the influence of microwave power absorbed within the sample; the influence is high and related to temperature profile as shown in Figs. 5–7. Within the sample, the electric field attenuates owing to energy absorption. Thereafter the absorbed energy is converted to the thermal energy, which increases the sample temperature. However, the feed magnetrons positioned on side shows the lower absorbed microwave power as shown in Fig. 4. This is because of no direct irradiated wave 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 above.

Figs. 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 samples continuously rises while the moisture content profile rapidly decreases with respect to elapsed time.

In practice, it is not always effective to improve the uniformity of microwave-heating by solely increasing the uniformity of an electromagnetic field because the internal temperature distribution in the material is affected not only by the electromagnetic field pattern in the microwave cavity that changes with the material load and the ongoing drying, but also by the material shape, size, dielectric properties and other factors. Therefore, the random displacement of the material during drying can lessen the dependence on the electromagnetic field distribution, because the time/space averaged microwave energy absorption can be considered of the same probability.

6.2. Energy and exergy analysis

Figs. 10 and 11 show the EUR 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 (0–20 min) is height due to the high value of dielectric loss factor, thus show the most of microwave energy can be absorbed by non-hygroscopic porous packed bed. Furthermore, near the end stage of drying process as the moisture content inside the sample is reduced, this decreases the microwave energy absorbed. Thus, equilibrium is reached between microwave drying and convective losses by lowering sample temperature. Consequently, the EUR profiles decreases in this stage of drying.

It can be observed from Figs. 10 and 11 that the EUR in case of C-bed (Fig. 10) is totally higher than case of F-bed (Fig. 11). This is because in case of C-bed the sample dries quickly throughout where the vapor diffusion plays an important role on moisture migration. Additionally, it is evident from the figure that the EUR profile mostly displays irregular shapes. In particular, the bulk of this sample that receives the largest amount of microwave energy absorbed. It would correlate to microwave energy absorbed which depends on the changing of the configuration of electromagnetic field in the sample due to the variation of moisture content. No marked difference is founded for the case of different hot-air temperatures, since the

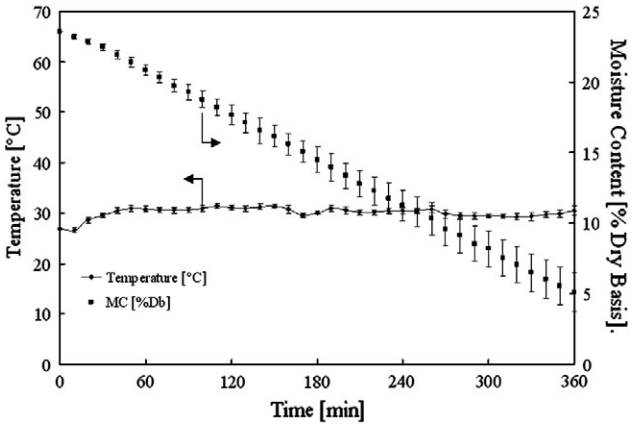

Fig. 8. Temperature and moisture variations versus elapsed times in case using a convective drying ($T_1 = 70$ °C) (case 8, C-bed).

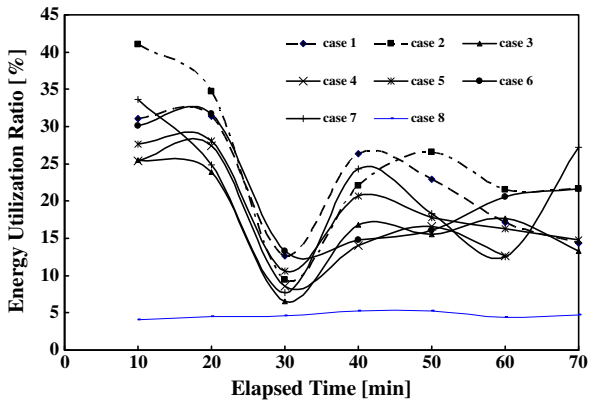

Fig. 10. EUR profiles with respect to elapsed time in different cases (C-bed).

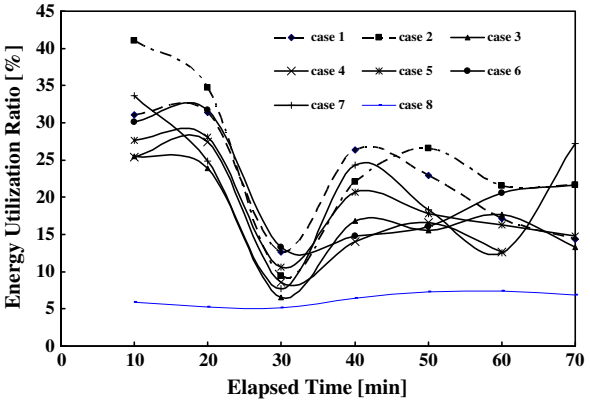

Fig. 11. EUR profiles with respect to elapsed time in different cases (F-bed).

microwave energy is the majority part of supplied energy. It is noted that the EUR in case of convective drying (case 8) is always lower than that case of CMCB. This is because the pure convective drying gives the less thermal efficiency, as explained in previous subsection.

Figs. 12 and 13 show the variations of the exergetic efficiency in the drying chamber as a function of drying time. The exergetic efficiency for different case is calculated by using Eq. (17) based on the inflow, outflow and loss of exergy. The exergetic efficiencies of the trays and the chamber decreased depending on the experimental conditions in the beginning of the drying process, and then increased almost continued with the increase of drying time. It was realized that the exergy losses at the point is small where the exergetic efficiency is high due to the discontinuity of the drying process in the system. However, the exergetic efficiency of the porous packed bed C-bed is higher than the porous packed bed F-bed and the drying chamber. Moreover, the exergetic efficiency is inversely proportional to EUR through the drying process, That values are depend on the drying time, hot-air temperature, porous structure (F-Bed and C-Bed) and location of magnetron.

7. Conclusion

Heating uniformity is a great challenge to the industrial application of microwave drying, especially of food products. Here, the process measurement and control are the process options to ensure more uniform heating. The modular design of a microwave dryer, for instance, is also of practical interest as several microwave emitters arranged in series over the product being transported by the conveyor can easily be configured.

The experimental analysis presented in this paper describes many important interactions within non-hygroscopic porous packed bed during CMCB. The following paragraph summarizes the conclusions of this study.

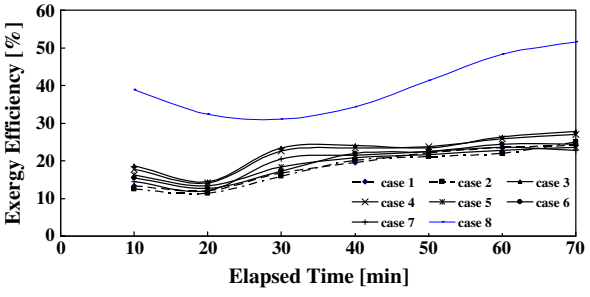

Fig. 12. Exergy efficiency profiles with respect to elapsed time in different case (C-bed).

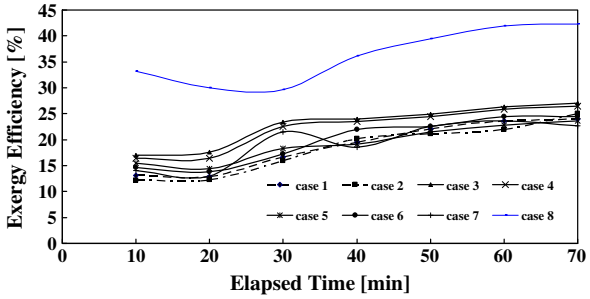

Fig. 13. Exergy efficiency profiles with respect to elapsed time in different case (F-bed).

The effects of particle sizes, hot-air temperature and location of magnetron on the overall drying kinetics are clarified. The drying rate in the F-bed is slightly higher than that of the C-bed. This is because the higher capillary pressure for the F-bed results in to maintain a wetted drying surface for a longer period of time. The F-bed displays the drying curve which differentiates it from the others. It has a shorter drying time due to the strong effect of capillary action.

Energy and exergy of the drying process of the non-hygroscopic porous packed bed are analyzed. It can be concluded that energy utilization ratio and exergy efficiency also depend on particle sizes, hot-air temperature and location of magnetron.

Acknowledgments

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