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ANALYSIS OF ENERGY CONSUMPTION IN A COMBINED MICROWAVE–HOT AIR SPOUTED BED DRYING OF BIOMATERIAL: COFFEE BEANS

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In this study, an energy model based on the first law of thermodynamics is developed to evaluated energy efficiency and specific energy consumption. The influences of hot air temperature and initial weight of coffee beans on energy consumption are considered. Furthermore, a comparison between combined microwave–hot air spouted bed drying and hot air spouted bed drying methods on energy consumption is also investigated in detail. The results show that energy efficiency as well as energy consumption depends on hot air temperature, initial weight of coffee bean, and typical drying methods (combined microwave–hot air spouted bed and hot air spouted bed). The optimum drying condition is also achieved in this study.

Keywords specific energy consumption, energy efficiency, microwave energy

INTRODUCTION

Presently, the most important goal of industries, other than producing high-quality products for markets, is to increase productivity and reduce production cost. In general, several production processes of agricultural and industrial products are related with drying either by a natural method or using energy from other sources resulting in a low production rate or high-cost products. Microwave drying is one of the most interesting methods in terms of mechanisms and economics for heating and drying in various kinds of products. A combined microwave–hot air spouted bed (CMHS) drying method is a novel alternative method of drying and produces products of acceptable quality. It permits a shorter drying time and substantial improvement in the quality of dried materials in comparison to those dried with hot air and microwave drying methods. Other advantages include environmental friendliness at low temperatures, which not only overcomes the limitation of low thermal conductivity of the material but avoids the defect of internal cracking and interior burning caused by excessive heating in microwave drying, and its applicability within a wide range

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NOMENCLATURE

C_p	specific heat of the dielectric material (kJ/kg K)
c_m	material specific heat (kJ/kg K)
E	electromagnetic field intensity (V/cm)
D_p	penetration depth (m)
f	microwave frequency (Hz)
h	enthalpy (kJ/kg)
h_{fg}	latent heat of vaporization (kJ/kg_{water})
h_{fw}	enthalpy of water (kJ/kg)
h_m	enthalpy of material (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_a$	mass flow rate of dry air (kg/s)
$\dot{m}_w$	mass flow rate of water from the spouted bed (kg/s)
M_p	particle moisture content dry basis (kg_{water}/kg_{solid})
P_1	density of microwave power absorbed by dielectric material (kW/cm^3)
P_2	energy is required to heat up material (kW)
P_{in}	microwave power incident (microwave energy emitted from a microwave oscillator; kW)
$\dot{Q}_{evap}$	heat transfer rate due to water evaporation (kW)
$\dot{Q}_{loss}$	heat transfer rate to environment (kW)
$\dot{Q}_{MW}$	microwave energy (kW)
SEC	specific energy consumption (MJ/kg)
t	time (sec)
T	temperature (°C)
$\tan\delta$	loss tangent coefficient
W	weight of the dielectric material (kg)
W_b	weight of material before drying (kg)
W_d	weight of dry material (kg)
X	absolute humidity ($kg_{vapor}/kg_{dry\ air}$)

Greek Letters

ΔT	increment temperature (°C)
ε_0	permittivity of air (F/m)
ε_r'	relative dielectric constant
ε_r''	relative dielectric loss factor
η_e	energy efficiency (%)
η_m	microwave efficiency device (%)
υ	velocity of propagation (m/s)
ω	angular velocity of microwave (rad/s)

Subscripts

0	free space
1	inlet
2	outlet
a	air
ab	absorb
d	dry material
da	drying air
db	dry basis
fg	difference in property between saturated liquid and saturated vapor
g	gas
in	input
l	liquid water
m	material
o	standard state value
out	output
r	relative
s	solid
v	vapor
w	water

of herbal and food industries. It is also easily integrated into flexible, automated manufacturing systems. A CMHS drying method has been investigated as a potential method for obtaining high-quality dried foodstuffs, including fruits, vegetables, and herbs. The reasons for interest in the interaction of microwaves with porous materials have been reported in the recent literature [1–21]. An excellent review of the drying techniques in dielectric materials using microwave energy were presented in [1–5].

Rattanadecho et al. [6] developed a mathematic model and experimental test rig for microwave drying processing for described moisture migration and temperature gradient in unsaturated porous media. The temperature profiles and drying rate during microwave–fluidized bed drying of macaroni beads with various drying conditions were investigated in [7]. The heat and mass transfer model was developed to simulate microwave and spouted bed drying of hygroscopic porous material (diced apples) in [8]. The total gas–pressure equation was introduced to account for internal vapor generation during microwave drying. The governing equation for heat and mass transfer were simplified using a scaling technique and numerically solved with the finite-difference method. CMHS drying on the quality of dried lettuce cubes with initial moisture content was studied in [9], where the dielectric properties of lettuce were measured for the analysis. Response surface methodology was used to optimize the drying process conditions with chlorophyll content as the response value. Based on such properties as rehydration rate, chlorophyll content, color, drying time, and dielectric properties, the MWSB-dried products were compared with that from other drying technologies. A new model was proposed for thermodynamic analysis of a drying process based on the energy and exergy concept [10, 11]. An analysis of microwave energy consumption in heating and drying processes was performed in [12]. Specific energy consumption (SEC) in microwave drying of garlic cloves has been examined. A comparative study of SEC with two difference drying methods, namely microwave–hot air and hot air drying, has also been conducted. Other related studies present microwave energy and hot air heating processes, including the combined microwave and hot air drying of peeled longan [13]. The influence of moisture content on SEC was examined. In another important study [14], a comparison of SEC in cooking rice was presented among the microwave oven, electric rice cooker, and pressure cooker.

Investigations of energy efficiency of microwave drying of porous media have been performed since the late 1950s. Many authors [15–22] have emphasized the advantages of microwave drying over convective drying.

Although microwave drying of porous media has found some application in the dehydration of biomaterials and engineering products, more research and development was needed before the process was used on a large commercial scale. In particular, the effect of hot air temperature, initial weight of coffee beans, and typical drying methods (CMHS and hot air spouted bed [HASB]) on the drying kinetics should be quantitatively known, so that the drying system can be optimized from the cost and quality standpoints.

The main objective of this research is to examine the feasibility of using CMHS and HASB drying methods to dry coffee beans and to experimentally explore drying characteristics of coffee beans in different drying conditions, considering the hot air temperature and initial weight of coffee bean. The research results are beneficial in presenting a theory basis for further study and for industrial applications of a CMHS drying method of biomaterials in the future.

RELATED THEORIES

Microwave Heat Generation

Microwave heating involves heat dissipation and microwaves propagation, which cause the dipoles to vibrate and rotate. When the microwave energy from a microwave oscillator (P_{in}) is irradiated inside the microwave applicator, the dielectric material has a dielectric loss factor that absorbs the energy and is heated up. Internal heat generation then takes place. The basic equation calculating the density of microwave power absorbed by dielectric material (P_1) is given by [23]

$$P_1 = \omega \varepsilon_0 \varepsilon_r'' E^2 = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r' (\tan \delta) E^2, \tag{1}$$

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

From Eq. (1), 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; this means that increasing $\tan\delta$ of specimen, energy absorption, and heat generation are also increased. While $\tan\delta$ is small, the microwave will penetrate into a specimen without heat generation. However, the temperature increase depends on other factors, such as specific heat, size, and characteristic of the specimen.

As the material is unilaterally heated, it is found that when 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 [23]:

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

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. (2), 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 a 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 be absorbed. Furthermore, the dielectric properties of porous packed bed specimens typically show moderate lossiness, depending on the actual composition of the material. With a large amount of moisture content, greater potential for absorbing microwaves is revealed. 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 $W(g)$ 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 [24]:

$$P_2 = \frac{4.18 \cdot W \cdot C_p \cdot \Delta T}{t}, \tag{3}$$

where W is the weight of the dielectric material, C_p is the 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; such internal heat generation as shown in Eq. (1) takes place. In this case, the relation between P_{in} and P_2 is shown as [24]

$$P_{in} = P_2. \tag{4}$$

From a practical point of view, however, the transformation energy in the 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 [24]:

$$P_{in} = \frac{P_2}{\eta_m}, \tag{5}$$

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

Mass and Energy Balance Equation for Drying Process

For analyzing mass transfer in the drying process, the law of conservation of mass for the control volume is applied, as shown in Figure 1. The mass balance equation can be written as [24]

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2}. \tag{7}$$

Equation (7) 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 spouted bed leads to [24]

$$W_d \frac{dM_p}{dt} = \dot{m}_a (X_1 - X_2), \tag{8}$$

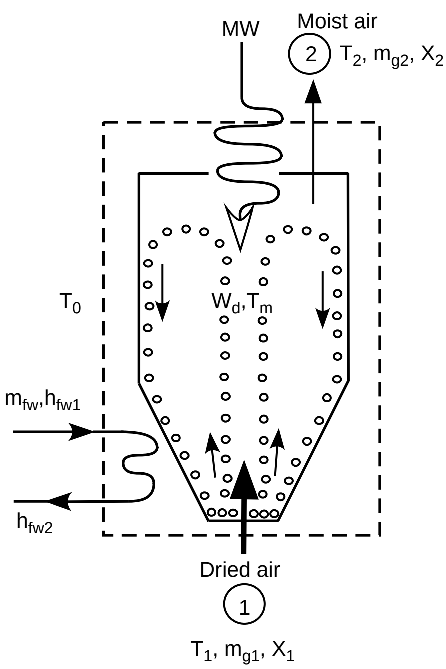

Figure 1. Physical control volume of CMHS drying process using energy analysis.

where W_d is weight of dry material, and M_p is particle moisture content, dry basis; this can be expressed as [24]

$$M_p = \frac{W_b - W_d}{W_d}, \tag{9}$$

where W_b is the weight of material before drying, $\dot{m}_a$ is the mass flow rate of dry air, and 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 the spouted bed and can be written as [24]

$$\dot{m}_w = \dot{m}_a(X_2 - X_1). \tag{10}$$

For analyzing energy transfer in the drying process, the first law of thermodynamics (the law of conservation of energy) is applied for the control volume, as shown in Figure 1. The significant heat transfer is due to the internal heat generation due to microwave energy and heat of evaporation between the porous structure 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

$$\frac{W_d(h_{m2} - h_{m1})}{\Delta t} = \dot{Q}_{evap} + \dot{m}_a(h_1 - h_2) + \dot{Q}_{MW} + \dot{Q}_{loss} + \dot{m}_{fw}(h_{fw1} - h_{fw2}), \tag{11}$$

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

The differences in specific enthalpy are as follows, assuming air as an ideal gas [24]:

$$h_{m1} - h_o = c_m(T_{m1} - T_o), \tag{12}$$

$$h_{m2} - h_o = c_m(T_{m2} - T_o). \tag{13}$$

The material enthalpy term of the energy rate balance can be expressed as [24]

$$h_{m2} - h_{m1} = c_m(T_{m2} - T_{m1}), \tag{14}$$

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 the mixture; thus the enthalpy of moist air is [24]

$$h = h_a + Xh_v, \tag{15}$$

$$h_{fw} = 0.1163 + 4.1861T. \tag{16}$$

The heat transfer rate due to phase change is [24]

$$\dot{Q}_{evap} = \dot{m}_w h_{fg}, \tag{17}$$

where h_{fg} is the latent heat of vaporization.

SEC and Energy Efficiency in Drying Process

The drying of biomaterial, a process of simultaneous heat and mass transfer, represents an energy-intensive operation of some industrial significance. The SEC is estimated in CMHS drying processes as a relationship between two values considering the total energy supplied to drying processes and the amount of water removed during drying. A CMHS drying process is conducted in the same drying conditions, keeping the microwave power output of 800 W at air velocity of 12 m/s. SEC is as follows:

$$SEC = \frac{\text{Total energy supplied in drying process}}{\text{Amount of moisture removed during drying}}, \frac{kJ}{kg}, \tag{18}$$

$$SEC = \frac{[P_{\text{in}} + \dot{m}_{da}(h_1 - h_0)]\Delta t}{\text{Amount of moisture removed during drying}}, \frac{kJ}{kg}. \tag{19}$$

The energy efficiency (η_e) for the drying process is described by

$$\eta_e = \frac{W_d[h_{fg}(M_{p1} - M_{p2}) + c_m(T_{m2} - T_{m1}) + \dot{m}_{fw}(h_{fw2} - h_{fw1})]}{\dot{m}_{da}(h_1 - h_o)\Delta t + \Delta t\dot{Q}_{MW}}, \tag{20}$$

where c_m is material-specific heat.

EXPERIMENTAL APPARATUS

An experimental stand for the lab-scale biomaterial drier using a CMHS drying method is shown in Figure 2. This drying method is modified from the work of [8]. The system consists of a microwave power source, multimode microwave cavity, hot air convective source, spouted bed, and water-dummy load. The microwave is generated by a one-feed magnetron with a maximum power of 800 W operating at a frequency of

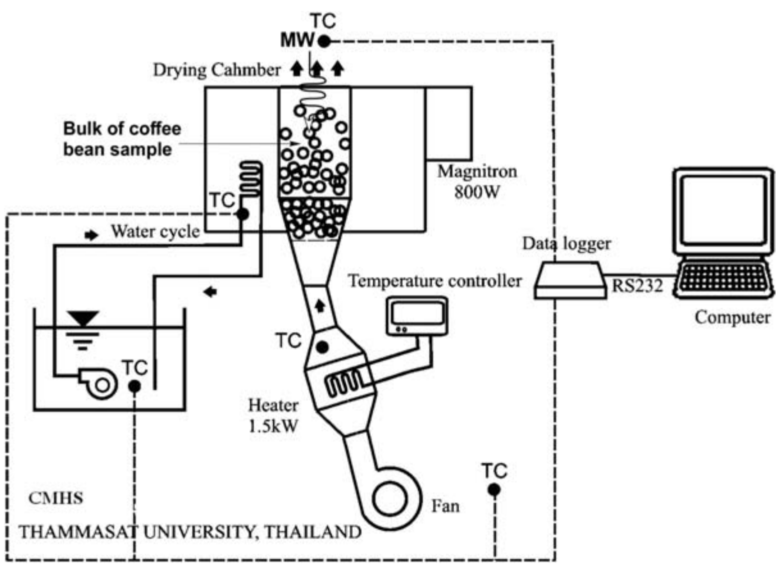

Figure 2. Schematic diagram of CMHS drying system.

Table 1. SEC under various drying conditions

Test condition	Drying methods	Weight of coffee bean (g)	Hot air temperature (°C)	SEC (MJ/kg)
Case 1	CMHS	200	50	114.046
Case 2	HASB	200	50	149.930
Case 3	CMHS	200	60	111.762
Case 4	HASB	200	60	136.697
Case 5	CMHS	200	70	105.892
Case 6	HASB	200	70	125.207
Case 7	CMHS	280	60	83.238
Case 8	HASB	280	60	104.302

2,450 MHz. The multimode microwave cavity had dimensions of 30 × 30 × 19 cm. The spouted bed installed in multimode microwave cavity is constructed with glass that cannot absorb waves. The bottom of the spouted bed is made from polypropylene meshes to hold the particulate samples and to provide a pass for the convective hot air. The spouted bed is supported by a metal sheet and a metal screen with holes small enough to cut off microwave leaking. The circulating water load system is installed to protect the magnetron from overheating, especially in the final stage of the drying process. In this study, the microwave power output from the generator is calibrated following the method recommended in [8] (International Microwave Power Institute). Inlet and outlet temperatures of the water load are measured by high-precision thermometers. At the bottom of multimode microwave cavity as well as the spouted bed, a blower is used to provide an air velocity of up to 12 m/s in the spouted bed. The ambient air is pre-heated by a 1.5-kW electric heater before entering the spouted bed. Experimentally, the samples to be dried can be circulated in the spouted bed with a designed terminal velocity to enhance the interaction between the microwave and dielectric load. In this study, the system can be operated in either a CMHS drying or pure HASB drying mode in each experiment under different drying conditions as listed in Table 1.

The moisture content (dry basis) and dry matter content are measured according to AOAC [26] standards using a laboratory scale system to an accuracy of 0.01 g. Optical Q2 fiber (LUXTRON Fluroptic Thermometer, model 790, accurate to ± 0.5°C) is employed Q3 for measuring the average temperature of the bulk load in the spouted bed. Optical fibers are used instead of conventional thermocouples because the latter absorb microwave energy and produce erroneous temperature indications. During the experimental (CMHS) drying processes, the uncertainty of data might come from the variations in humidity and room temperature. The uncertainty in drying kinetics is assumed to result from errors in the measured weight of the sample. The calculated drying kinetic uncertainties in all tests are less than 3%. The uncertainly in temperature is 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 are repeatedly carried out to obtain accurate data. A Multimeter™ Series Digital with PC interface is used to monitor Q4 the temperature inside the spouted bed. In CMHS, the leakage of microwaves is controlled below the U.S. Department of Health and Human Services standard of 5 mW/cm^2. The dielectric properties for coffee bean samples are measured at 25°C using a portable dielectric measurement (network analyzer) over a frequency band of 1.5 to 2.6 GHz to estimate microwave power absorbed in the dielectric load, as shown in Figure 3.

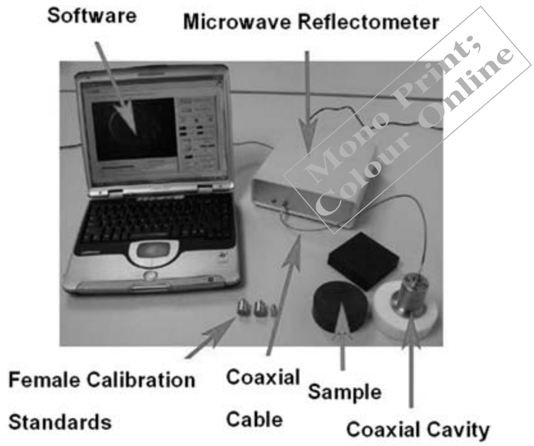

Figure 3. Portable dielectric measurement (network analyzer).

RESULTS AND DISCUSSION

Figures 4–6 show the temperature and moisture variations with respect to elapsed times with an initial weight coffee bean of 200 g, where the temperature is measured at the center of bulk load within the spouted bed. It should be noted that the energy efficiency seems to be very low in all testing conditions. This is because all testing conditions are done on a very small load (initial weight of coffee bean is 200 g/batch), which is much lower than the optimum designed load. Actually, the energy efficiency will be increased

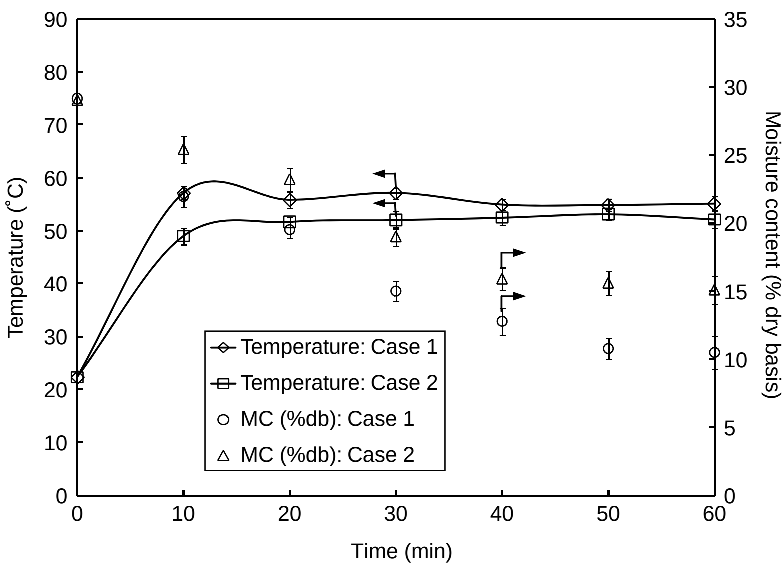

Figure 4. Temperature and moisture variations versus elapsed times with different drying methods ($W = 200$ g, $T_1 = 50$°C).

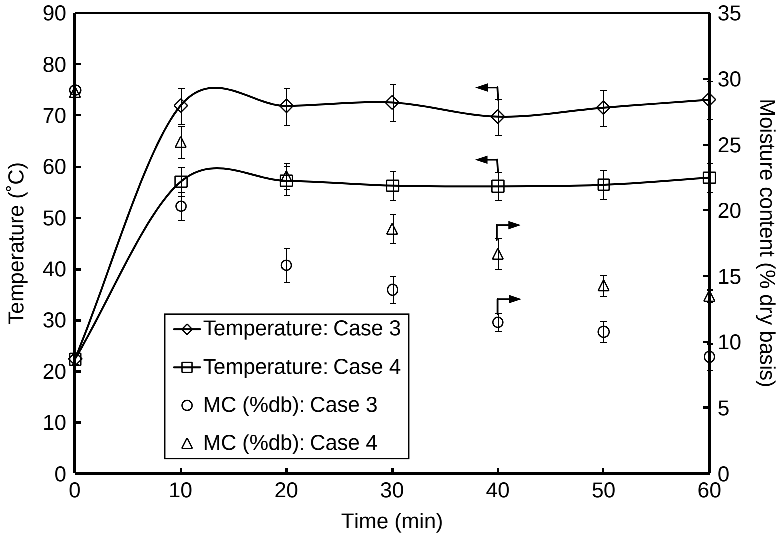

Figure 5. Temperature and moisture variations versus elapsed times with different drying methods ($W = 200$ g, $T_1 = 60$°C).

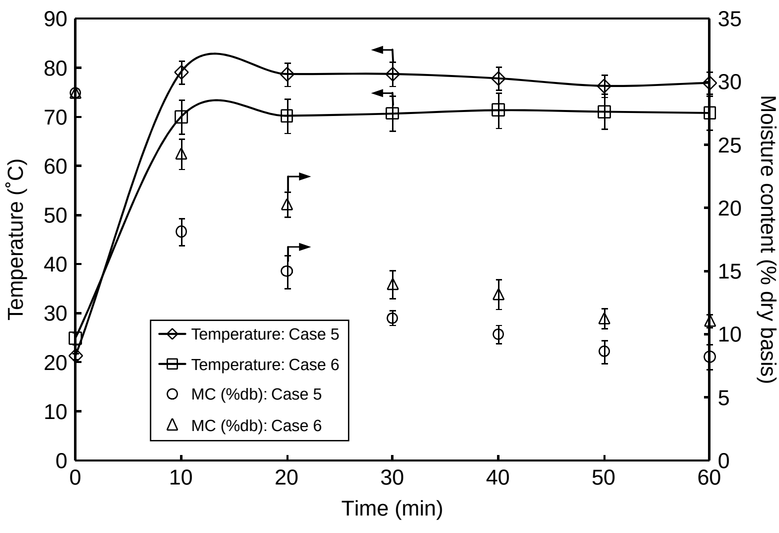

Figure 6. Temperature and moisture variations versus elapsed times with different drying methods ($W = 200$ g, $T_1 = 70$°C).

with an increasing load when it approaches optimum design load (about 30 kg for a full load in a rotary drum). This is because the increasing bulk of coffee beans corresponds to the highest rate of water evaporation using CMHS drying. In future work, the effects of initial weight on analyzing energy consumption demand as well as energy efficiency will 250
be investigated. It is found that in the CMHS at microwave power of 800 W in hot air temperatures of 50°C, 60°C, and 70°C, respectively, the moisture content inside the

spouted bed continuously decreases faster than that in all cases of the hot air temperature in the spouted bed drying (HASB) at 50°C, 60°C, and 70°C, respectively. This is because in the CMHS case, the bulk of this sample absorbed the largest amount of microwave energy. This phenomenon corresponds to the level of absorbed energy in the samples, as described in Eq. (1). It is observed the temperature profile within the spouted bed for both cases (CMHS and HASB) rises quickly in the early stages of the drying process (about 0–12 min); however, its rise slows down after this stage. It is evident from the figures that near the end stages of drying, the moisture content inside the spouted bed for both cases is continuously reduced. Additionally, in the CMHS case, 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 [6]. Thus, during this stage, microwave power should be under optimized control to reduce power consumption in the drying systems. Furthermore, in the CMHS case, the temperature profile within the spouted bed (Figures 4–6) corresponds to the moisture content profile, where the temperature continuously rises faster than that in the HASB case, and the temperature remains higher throughout all drying methods.

Figures 7–10 show the energy efficiency with respect to elapsed times. It seems that high energy efficiency occurs near the starting period about 0–10 min due to the high quantity of moisture content within coffee bean sample in the spouted bed; thus, the microwave power absorbed is effectively converted to internal heat generation in the spouted bed. Throughout the drying process, after the vapor within the spouted bed is progressing from the top of the spouted bed, the moisture content within the spouted bed quickly decreases, and the corresponding low quantity of absorbed waves decreases energy efficiency. The energy efficiency profile for both cases rises quickly in the early stages of the drying process (about 10 min); however, it continuously falls after this stage (about 10–60 min). It is evident from the figures that near the end stages of drying, as the moisture content inside the sample is reduced, the microwave power absorbed decreases. Although

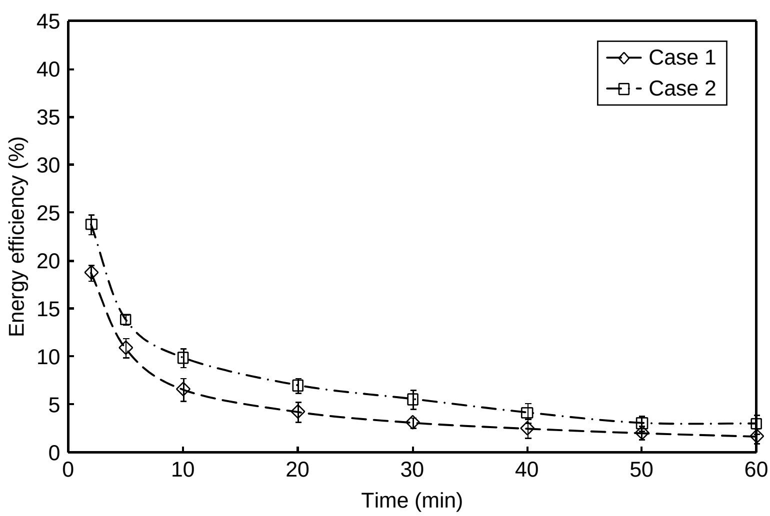

Figure 7. Energy efficiency versus elapsed times with different drying methods ($W = 200$ g, $T_1 = 50$°C).

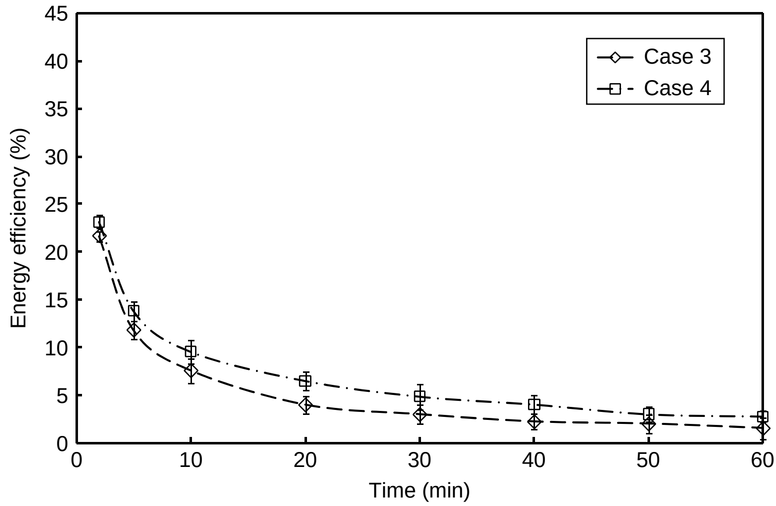

Figure 8. Energy efficiency versus elapsed times with different drying methods ($W = 200\,\text{g}$, $T_1 = 60°\text{C}$).

the process continuously feeds microwaves into the cavity with fixed microwave power supplied (800 W), it is noted that in this stage, most unused waves are directly absorbed by the water load (as shown in Figure 2). Further, since the microwave power supplied is fixed, the portion of useful microwave power for evaporating moisture inside the spouted bed is significantly reduced (Eq. (20)) due to the dried sample acting as a low lossy material, which explains why the energy efficiency profiles are decreased in this stage of the drying process. It can be observed from Figures 7–10 that the highest energy efficiency is presented in the HASB case throughout the drying method. This is because more waste energy is achieved in the CMHS case since the supplied energy sources are incoming from

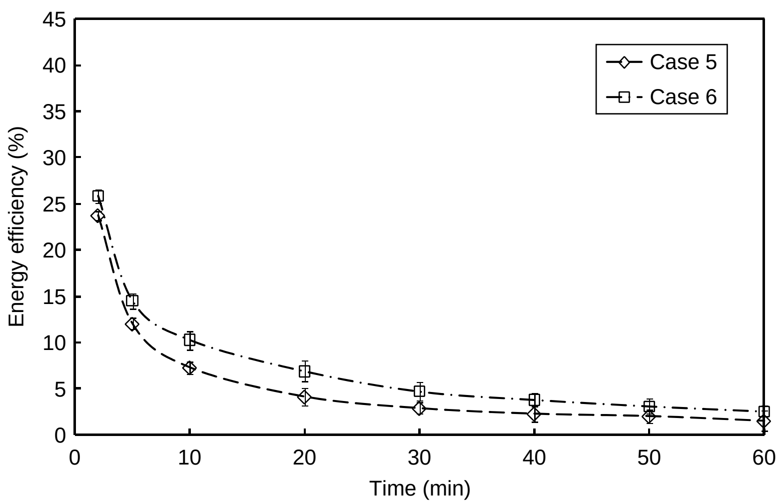

Figure 9. Energy efficiency versus elapsed times with different drying methods ($W = 200\,\text{g}$, $T_1 = 70°\text{C}$).

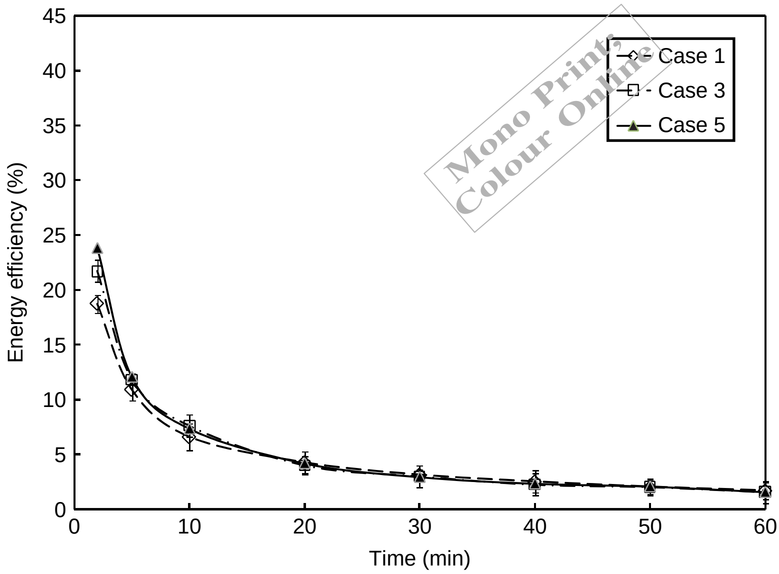

Figure 10. Energy efficiency at various hot air temperature with CMHS ($W = 200\,\mathrm{g}$).

the both modes, namely the microwave energy mode and hot air convective mode, during the drying process with a low initial weight of coffee bean. The next presentation will address the influences of the initial weight of coffee bean sample on the overall drying kinetics as well as the energy consumption rate.

Figure 11 shows the temperature and moisture variations with respect to elapsed time with an initial coffee bean weight of 280 g. A drying curve, exemplified by Figure 9,

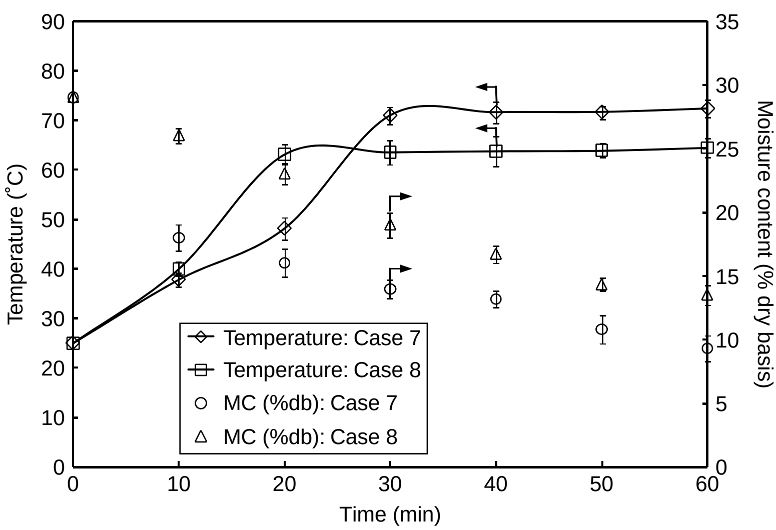

Figure 11. Temperature and moisture variations versus elapsed times with different drying methods ($W = 280\,\mathrm{g}$, $T_1 = 60°\mathrm{C}$).

exhibits the change in the temperature and moisture content of the sample with time under different drying conditions. In the HASB case, drying rates are more in the beginning of the drying process when the air stream easily evaporates moisture from the coffee bean. The moisture content exponentially decreased with the drying time, where substantial drying takes place in the constant drying period. The drying time required to reduce the moisture from initial moisture content of about 29% (db) to a desired moisture in the final product, approximately 14% (db), was 1 h with drying temperature of 62°C. The CMHS drying behavior of coffee beans followed the similar trend to that of the HASB case in that drying occurred mainly in the constant rate period.

It is found that drying rates are higher for the CMHS case. The accelerated drying rates may be attributed to internal heat generation and so-called liquid movement within the material when it is exposed to microwave energy. Generally, microwave power absorption by the sample depends on its moisture content. The moisture content of the coffee bean is relatively high during the early stage of drying, which resulted in higher absorption of the microwave power and led to an increased sample temperature. This results in a higher drying rate due to higher moisture diffusion. As the drying progressed, *i.e.*, falling rate period, microwave power is decreased due to the dried sample acting as the low lossy material during the end stage of drying [8], as explained in previous figures. Consequently, the energy efficiency is decreased in this stage of drying; this will be discussed again in Figure 12.

In Figure 12, the energy efficiency profiles for the sample in cases 7 and 8 are higher in the early stages of drying (about 0–5 min) and continuously drop after this period; this is in contrast to the previous drying case, where energy efficiency for the HASB case is always higher than the CMHS case with a low initial weight (200 g; Figures 7–10). In this case (280 g), the energy efficiency in the CMHS case is higher than HASB case, especially at the early stage of drying (constant drying period). This is because the majority of moisture content within coffee beans has been removed in this stage. After 20 min, the energy efficiency in the HASB case becomes a little bit higher than the CMHS case.

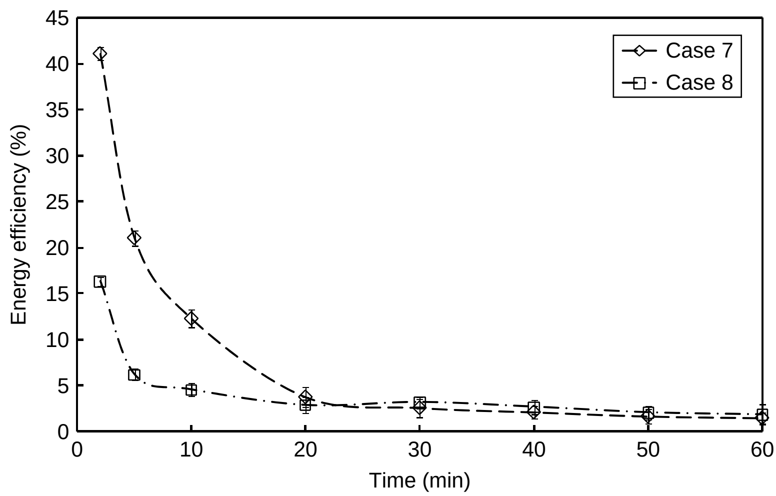

Figure 12. Energy efficiency versus elapsed times with different drying methods ($W = 280$ g, $T_1 = 60$°C).

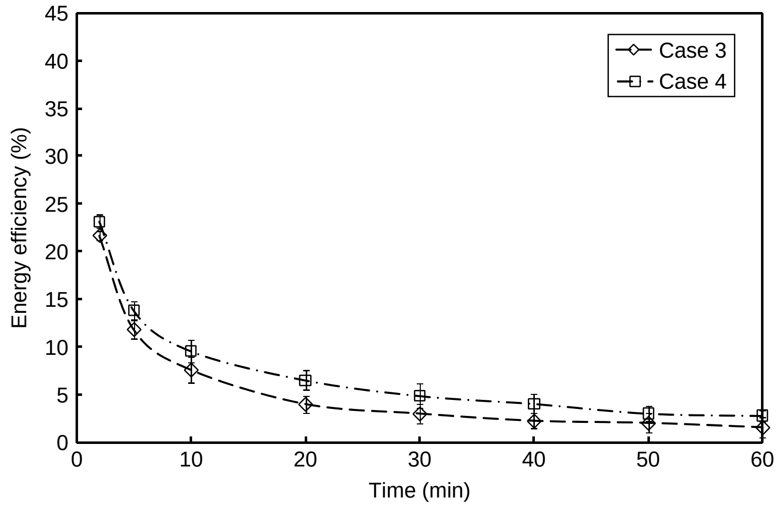

Figure 13. Energy efficiency at various initial coffee bean weights with CMHS ($T_1 = 60°C$).

However, no clear difference for both cases has been shown after a drying time of 20 min (Figure 13).

The experimental data are analyzed to obtain the SEC under different drying conditions as listed in Table 1. Figure 14, redrawn from Table 1, shows the variations of SEC as a function of different drying conditions during the CMHS and HASB coffee bean drying methods. The lowest value in all drying conditions regarding energy consumption is noted in case 7 (83.238 MJ/kg), whereas the highest value is noted in case 2 (149.930 MJ/kg). The lowest SEC is occurred in case 7 (83.238 MJ/kg), followed by case 8 (104.302 MJ/kg), case 5 (105.892 MJ/kg), case 3 (111.762 MJ/kg), case 1 (114.046 MJ/kg), case 6

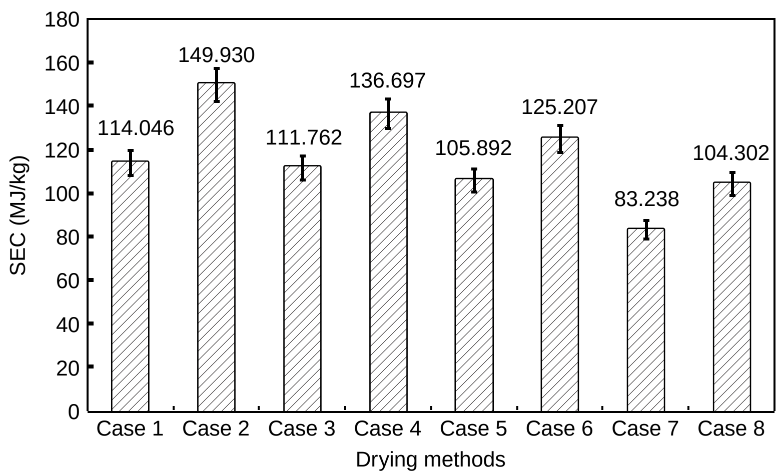

Figure 14. Variation in SEC for a different drying conditions (drying time = 60 min).

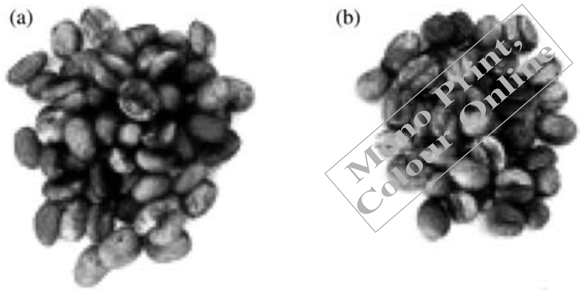

Figure 15. Color parameters of coffee beans before and after drying with CMHS (weight of coffee bean 280 g and hot air temperature of 60°C): (a) coffee beans before drying and (b) coffee beans after drying.

(125.207 MJ/kg), case 4 (136.697 MJ/kg), and case 2 (149.930 MJ/kg). To summarizes, the SEC for during the CMHS drying method is always lower than the HASB drying method considered at the (same) hot air temperature and coffee bean initial weight. This is because the CMHS drying method supplied microwave energy through the cavity, which leads to more volumetric heating inside the bulk of the coffee beans, resulting in a higher rate of water evaporation compared to the HASB drying method.

Figure 15 shows that the best color values are achieved during the CMHS drying method. Figures 15a and 15b show the rough color shades of the coffee beans before and after drying with the CMHS, respectively. It is observed that drying with CMHS gives better product quality in physical appearance. It should be mentioned again that the drying conditions at high initial coffee bean weight increase the drying rate and decrease the average temperature of the bulk load.

Leiker and Adamska [21] indicated that the energy consumption by using the CMHS can obviously save more than purely conventional drying with optimum drying conditions, i.e., initial weight of load and inlet hot air temperature. Nevertheless, this study attempted drying biomaterials to find essential factors for the assessment of energy consumption and biomaterials, and coffee beans have been used as the dried sample. This study confirms that the estimation of energy consumption in different drying conditions should be done to obtain the optimum drying point before expanding to a commercial-sized drying method.

CONCLUSIONS

The application of microwave energy for drying coffee beans is investigated. A CMHS drying method has been developed to regulate hot air temperature and initial coffee bean weight. Coffee beans are of uniform size and are used in the drying experiments, which are carried out in several drying conditions: at hot air temperatures of 50°C, 60°C, and 70°C; air velocities of 12 m/s; and a microwave power level of 800 W. CMHS drying is performed until the moisture content of the coffee bean reduced from the initial moisture content of 29% (db) to a level of approximately 10% (db). The energy efficiency and SEC related to drying kinetics involving all drying conditions are also estimated in drying kinetics. The quality attributes of the fresh and dehydrated coffee bean are evaluated for color shades. The process parameters for CMHS drying are optimized for the coffee bean using initial weight variable tests (200 and 280 g). The results reveal that the CMHS drying method with the drying conditions of hot air temperature of 60°C, air velocity of 12 m/s, and initial coffee bean weight of 280 g gave a good quality dehydrated coffee bean and involved low SEC in the drying method. Further, the quality of coffee beans dehydrated by the CMHS drying method is found to be superior to the HASB drying method.

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