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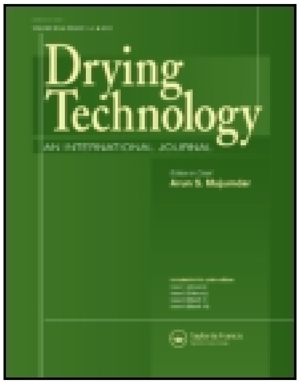

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Analysis of Energy Consumption in Drying Process of Biomaterials Using a Combined Unsymmetrical Double-Feed Microwave and Vacuum System (CUMV)—Case Study: Tea Leaves

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Analysis of Energy Consumption in Drying Process of Biomaterials Using a Combined Unsymmetrical Double-Feed Microwave and Vacuum System (CUMV)—Case Study: Tea Leaves

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An energy analysis of drying of biomaterials (tea leaves) was conducted on a combined unsymmetrical double-feed microwave and vacuum system (CUMV) to optimize the operating conditions and quality of the products. Tea leaves were dried from an initial moisture content of 172 to 7% (db). An energy consumption model based on the first law of thermodynamics was developed to evaluate energy efficiency. The influences of microwave power, vacuum pressure, and microwave operation modes on energy consumption were investigated in detail. The results showed that energy consumption as well as energy efficiency were strongly dependent on vacuum pressure and microwave power. Energy consumption and color parameters of the tea leaves were compared at different drying conditions. In particular, the experiments were carried out at different microwave powers (800 and 1,600 W) at a frequency of 2,450 MHz and different vacuum pressures (535 and 385 torr) to investigate the effects of these factors on the microwave–vacuum drying.

Keywords Energy efficiency; Microwave energy; Specific energy consumption; Vacuum pressure

INTRODUCTION

The most important thing in industry, in addition to producing high-quality products, is to increase productivity and reduce production cost. In general, several production processes for agricultural and industrial products are related to 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 for heating and drying materials.[1–6]

Microwave–vacuum (MV) drying is a novel alternative method of drying, producing products of acceptable quality. It permits a shorter drying time and a substantial improvement in the quality of dried materials compared to those dried with hot air and microwave drying methods. Other advantages include environmental friendliness at low temperature, which not only overcomes the limitation of low thermal conductivity of the material under vacuum due to the absence of drying medium but avoids defects such as internal cracking and interior burning caused by excessive heating in microwave drying. MV drying has been investigated as a potential method for obtaining high-quality dried foodstuffs, including fruits, vegetables, and grains.[7–14] Drouzas et al.[15] applied the MV technique to investigate the process of model fruit gel drying. They studied drying kinetics under different levels of pressure and microwave power. Sunjka et al.[16] dried cranberries using MV and microwave–hot air drying techniques and obtained a better quality product with MV drying. Alibas[17] studied the microwave, vacuum, and air drying characteristics of collard leaves. This author determined changes in the color values of the product after drying as well as the changes in the ascorbic acid (vitamin C) content of the product after drying and obtained the optimum drying method for the drying of collard. Wang et al.[18] studied corona discharge for stem lettuce cubes. Circular conduits of different diameters were used and compared with flat slab models at a high microwave frequency (2,450 MHz). Excellent reviews of the drying techniques in dielectric materials using microwave energy have been presented by Mujumdar,[19] Metaxas and Meridith,[20] Schubert and Regier,[21] Mejia-Meza et al.,[22] Setiady et al.,[23] Yaghmaee and Durance,[24] Jeni et al.,[25] Jindarat et al.,[26] Dincer and Sahin,[27] Sharma and Prasad,[28] Lakshmi et al.,[29] Alibas,[30] Holtz et al.,[31] Soysol et al.,[32] Leiker and Adamska,[33] Choicharoen et al.,[34] and Balbay and Şahin.[35]

Although combined MV drying has found some application in the dehydration of fruit juices, more research and development is necessary before the process can be used on a commercial scale. In particular, the effect of microwave power, vacuum pressure, and microwave operation modes on the drying kinetics should be known

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quantitatively, so that the drying system can be optimized from both cost and quality standpoints.

The main objective of this research is to examine the feasibility of using a combined unsymmetrical double-feed microwave and vacuum system (CUMV) to dry tea leaves and experimentally explore drying characteristics of tea leaves under different drying conditions, including microwave power, vacuum pressure, and microwave operation modes. The energy efficiency of development of the first law of thermodynamics is happen in heating process. At the same time, the research findings will provide a theoretical basis for further study and industrial application of combined microwave and vacuum technology in biomaterials drying.

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 is emitted from a microwave oscillator (P_{in}) and irradiated inside the microwave applicator, the dielectric material, which has a dielectric loss factor, absorbs the energy and is heated up. Then 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[26]

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

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 dielectric loss tangent coefficient.

From Eq. (1), 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. This means that as the $\tan\delta$ of specimen increases, energy absorption and heat generation are also increased. While $\tan\delta$ is small, microwaves will penetrate into the specimen without heat generation. However, the temperature increase depends on other factors, such as specific heat, size, and characteristics of the 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.[26]

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

where D_P is penetration depth; ε''_r is relative dielectric loss factor; and υ is the 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 large dimensions and high loss factors may occasionally be overheated to a considerably thick layer on the outer layer. To prevent such phenomena, the power density must be chosen so that enough time is provided for the essential heat exchange between the boundary and the 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 biomaterial specimens typically show moderate lossiness depending on the actual composition of the material. A high moisture content reveals a greater potential for absorbing microwaves. For typical specimens in a porous packed bed, 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 the material, T_1, is raised to T_2. The energy P_2 can be estimated by the following calorific equation:[26]

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

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 the heating time.

Assuming an ideal condition, all of the oscillated microwave energy (P_{in}) is absorbed into the dielectric material; internal heat generation as shown in Eq. (1) takes place. In this case, the relation between P_{in} and P_2 is shown below:[26]

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

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[26]:

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

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

Mass and Energy Balance Equations of the Drying Process

To analyze mass transfer in the drying process we applied the law of conservation of mass for the control volume as shown in Fig. 1. The mass balance equation can be written as:[26]

$$\frac{dm_{cv}}{dt} = m_{g1} - m_{g2} \tag{7}$$

Here, Eq. (7) is the mass rate balance for the control volume where m_{g1} and m_{g2} denote the mass flow rate at the inlet (1) and exit (2), respectively. Similarly, a balance of water in air flowing through the drying spouted bed leads to[26]

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

where W_d is the weight of the dry material and M_p is the particle moisture content (db); this can be expressed as[26]

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

where W_b is the weight of the material before drying; m_a is the mass flow rate of dry air; X_1 and X_2 denote the 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 CUMV and can be written as[26]

$$m_w = m_a(X_2 - X_1). \tag{10}$$

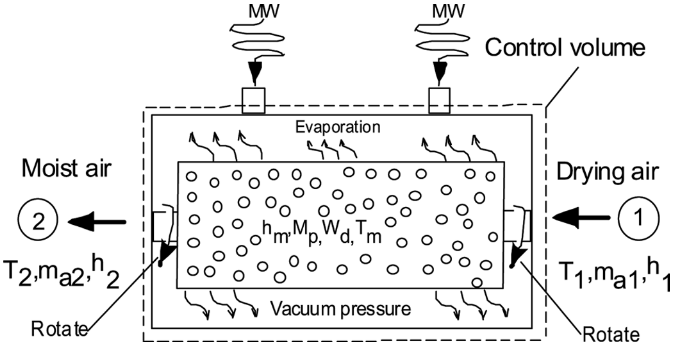

FIG. 1. Schematic of the control volume represented in the drying process using a combined unsymmetrical double-feed microwave and vacuum system (CUMV).

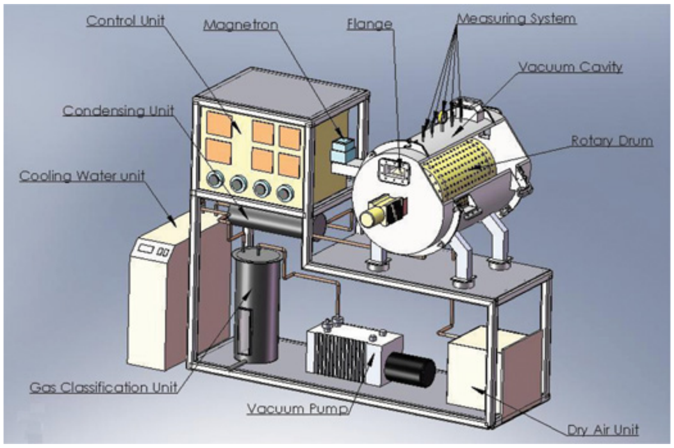

FIG. 2. Details of a combined unsymmetrical double-feed microwave and vacuum system (CUMV) (color figure available online).

To analyze energy transfer in the drying process, we applied the first law of thermodynamics (the law of conservation of energy) for the control volume as shown in Fig. 1. The significant heat transfer was due to the heat of evaporation between the solid and the drying air, and there was also heat rejection to the surroundings. The energy rate balance was simplified by ignoring kinetic and potential energies. Because 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

$$\frac{W_d(h_{m2} - h_{m1)}}{\Delta t} = Q_{\text{evap}} + m_a(h_1 - h_2) + Q_{MW} + Q_{\text{loss}}, \tag{11}$$

where Q_{evap} is heat transfer rate due to water evaporation; $Q_{MW} = P_{\text{in}}$ is the microwave energy; h_m is the enthalpy of the material; t is time; m_a is the mass flow rate of dry air; h is the enthalpy of dry air; and Q_{loss} is the heat transfer rate to the environment.

The differences in specific enthalpy are as follows, assuming air as an ideal gas:[26]

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

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

The material enthalpy term of the energy rate balance can be expressed as[26]

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

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 exist in the mixture; thus, the enthalpy of moist air is[26]

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

The heat transfer rate due to a phase change is[26]

$$Q_{\text{evap}} = m_w h_{fg}, \tag{16}$$

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

Specific Energy Consumption and Energy Efficiency of the Drying Process

The drying of biomaterial, a process of simultaneous heat and mass transfer, represents an energy-intensive operation of some industrial significance. The specific energy consumption is estimated, in CUMV drying processes, as a relationship between two values considering the total energy supplied to dry processes and amount of water removed during drying. A CUMV drying process is conducted in the same drying conditions, keeping the microwave power output at 800 and 1,600 W at an air velocity of 12 m/s. The specific energy consumption is as follows:

$$SEC = \frac{\text{Total energy supplied in drying process}}{\text{Amount of water removed during drying}}, \frac{\text{kJ}}{\text{kg}} \tag{17}$$

$$SEC = \frac{[P_{\text{in}} + m_{da}(h_1 - h_0)]\Delta t}{\text{Amount of water removed during drying}}, \frac{\text{kJ}}{\text{kg}} \tag{18}$$

The energy efficiency (η_e) for the drying process is represented by[26]

$$\eta_e = \frac{W_d[h_{fg}(M_{p1} - M_{p2}) + c_m(T_{m2} - T_{m1})]}{m_{da}(h_1 - h_o)\Delta t + \Delta t Q_{MW}}, \tag{19}$$

where c_m is the specific heat of the material.

MATERIAL AND METHODS

Materials

The experimental materials were tea leaves from a farm located in the northern part of Thailand that were stored at 10°C until the experiments. Three hours before drying, the bulk of tea leaves were left in the ambient air. The initial moisture content of the material was 172% (db). Three kilograms of tea leaves were applied with the CUMV.

Experimental Apparatus

An experimental stand for the commercialized tea leaves dryer using CUMV is shown in Fig. 3. The microwave power was generated by means of unsymmetrical double-feed magnetrons according to the design concept as shown in section 2 (two compressed air-cooled magnetrons of 800 W each for a maximum of 1.6 kW) operating at a frequency of 2,450 MHz. The microwave power setting could be adjusted individually in 800 W. The microwave was conveyed through a series of rectangular (11.0 × 5.5 cm) waveguides to a metallic vacuum cavity of 0.13 m^3 ($\pi \times 0.24^2 \times 0.72$ m) in which the materials to be dried can be rotated by a rotary drum in the cavity. The rotary drum has a maximum capacity of 30 kg (full load). The rotary drum installed in the multimode cavity was made of polypropylene with dimensions of approximately 30 cm radius and 50 cm length. The rotation speed of the rotary drum was controlled at about 10 rpm in order to enhance the interaction between microwave and the dielectric load. The maximum vacuum degree was about 50 torr.

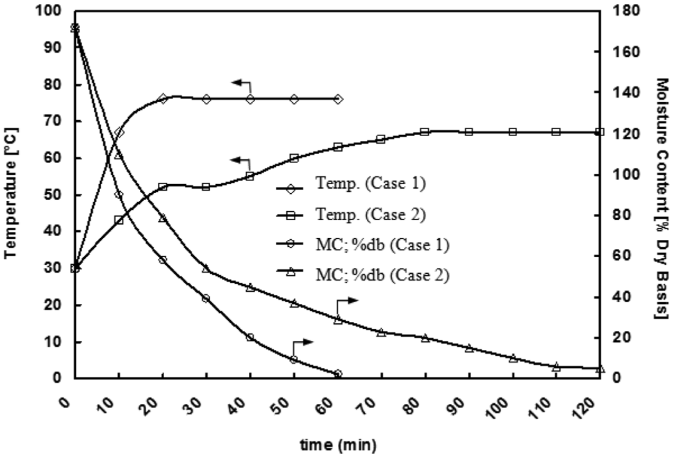

FIG. 3. Temperature and moisture variations versus elapsed times with respect to different drying conditions (microwave power 800 W, vacuum pressure 385 torr).

The CUMV drying experiments were carried out for two levels of microwave power (800 W: one magnetron turned on; 1,600 W: two magnetrons turned on) and two levels of vacuum pressure (385 and 535 torr). In this study, the system could be operated in either continuous or pulse mode. In the intermittent mode or pulsed microwave operation mode, the magnetron was alternately turned on and off for predetermined times. The pulsed microwave operation mode of 60 s on–60 s off was used in each experiment.

The moisture content (db) and dry matter content were measured according to the AOAC International standards,[36] using a laboratory scale with an accuracy of 0.01 g. Optical fiber (LUXTRON Fluoroptic Thermometer, model 790, Luxtron Corporation, Santa Clara, CA, USA; accuracy ±0.5°C) was employed to measure the average temperature of the bulk load in the cavity (the cavity temperature). Optical fibers were used instead of conventional thermocouples because the latter absorb microwave energy and produce erroneous temperature indications. An infrared camera was used to control the temperature in the cavity. An infrared camera (FLIR T200 Infrared Camera, Trek Equipment Corporation, USA) with a PC interface was used to monitor the temperature inside the cavity and to facilitate feedback control of the process.

An infrared camera was used to measure the surface temperature of the samples (accurate to ± 0.5°C). In the CUMV process, the leakage of microwaves was prevented by the countermeasure in double with a combination of mechanical blocking filter and microwave absorber zone filter to be provided at the both covers' ends. The microwave leakage was controlled below the U.S. Department of Health and Human Services (DHHS)[37] standard of 5 $\mathrm{mW/cm^2}$.

RESULTS AND DISCUSSION

Drying Kinetics

This section discusses the moisture content and average temperatures of a bulk load (cavity temperature) of tea leaves with respect to elapsed times and various drying conditions. Figures 3–6 show the tea leaf moisture content and average temperature of the bulk load (tea leaves) as influenced by applied microwave power, vacuum pressure, and microwave operation modes. Magnetron power as well as microwave operating mode had strong effects on the internal heat generation and drying rate of the dried samples.

Figures 3 and 4 show the cavity temperatures and tea leaf moisture content with respect to elapsed times at a microwave power of 800 W in case of continuous and pulsed operation modes. It is clear from the figure that the temperature profiles began to reach a steady-state plateau at approximately 20 and 50 min in continuous and pulsed microwave operation modes, respectively. For the continuous microwave operation mode, the cavity temperatures reached 75 and 77°C at vacuum pressures of 385 and 535 torr, respectively.

In the case of pulse microwave operation mode, the cavity temperatures reached 64 and 65°C at the vacuum pressures of 385 and 535 torr, respectively. Furthermore, for a microwave power of 1,600 W, the moisture content profiles of the bulk of tea leaves decreased faster than for a microwave power of 800 W, as shown in Figs. 3 and 4. The higher microwave power level as well as continuous microwave operation mode can increase the temperature and drying rate by providing more energy for water vaporization, thus accelerating moisture removal at higher temperature while the stronger vacuum pressure allows water to evaporate at lower temperature.

Figures 5 and 6 show the cavity temperature and tea leaf moisture content with respect to elapsed time at a microwave power of 1,600 W in case of continuous and pulsed operation modes. It is clear from the figures that the temperature profiles began to reach a steady state plateau at approximately 25 min; after this stage, the temperature remained constant. For the continuous microwave operation mode, the cavity temperatures reached 83 and 85°C at vacuum pressures of 385 and 535 torr, respectively. For the pulsed microwave operation mode, the cavity temperatures reached 64 and 66°C at vacuum pressures of 385 and 535 torr, respectively. The moisture content profiles for the bulk of tea leaves are also presented in both continuous and pulsed operation modes. It is clear from these curves that the moisture content profiles with respect to elapsed times were dependent on microwave operation mode and vacuum pressure. Furthermore, the total drying times were reduced substantially with changing the microwave operation modes compared to the variation in vacuum pressure level. In particular, in the case of continuous microwave operation mode where the supplied microwave energy continuously gives the more microwave energy absorbed rates, which leads to higher temperature and the moisture

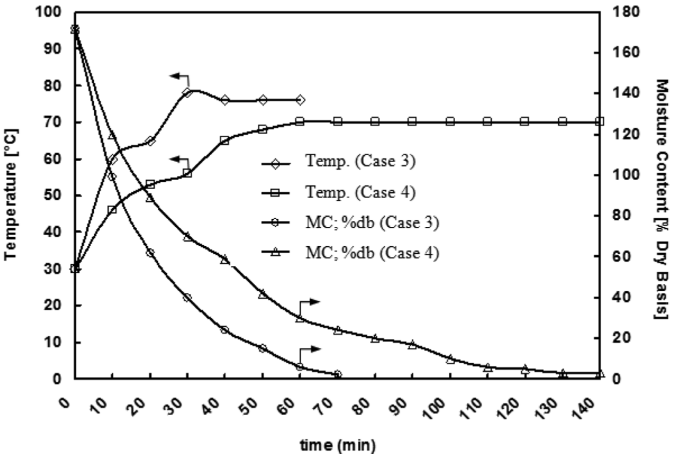

FIG. 4. Temperature and moisture variations versus elapsed times with respect to different drying conditions (microwave power 800 W, vacuum pressure 535 torr).

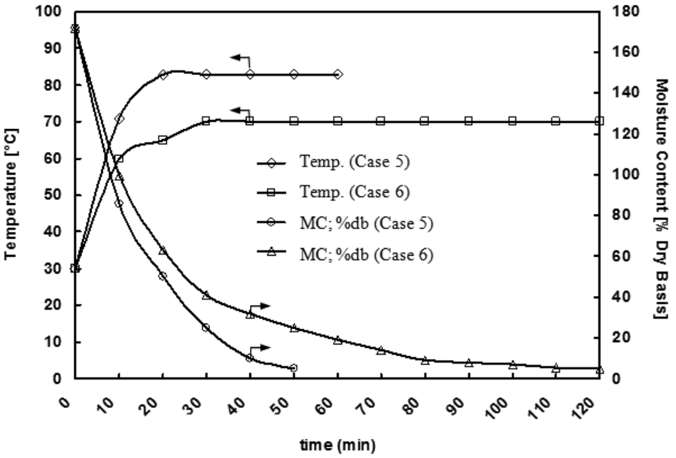

FIG. 5. Temperature and moisture variations versus elapsed times with respect to different drying conditions (microwave power 1,600 W, vacuum pressure 385 torr).

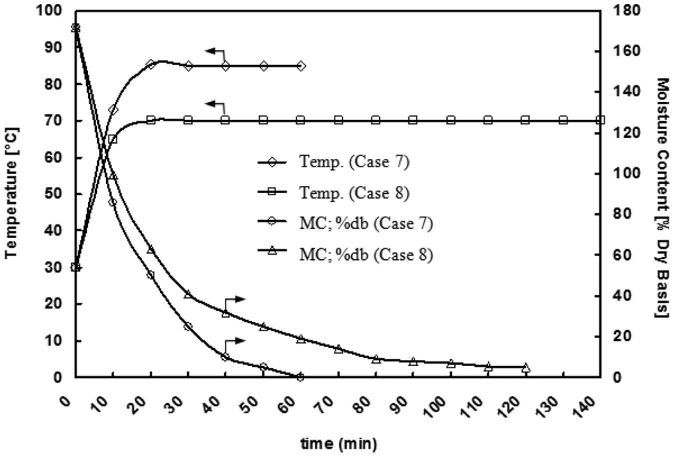

FIG. 6. Temperature and moisture variations versus elapsed times with respect to different drying conditions (microwave power 1,600 W, vacuum pressure 535 torr).

transfer rates within the dried samples. For continuous microwave operation mode at a microwave power of 1,600 W, the drying time for tea leaves was 50 min at a vacuum pressure of 385 torr, and the drying time was 60 min at a vacuum pressure of 535 torr. Nevertheless, the bulk of tea leaves considered as low-lossy dielectric materials, which corresponds to the lower microwave energy absorbed compared to other high-lossy dielectric materials (strawberries, beef, etc.) during CUMV.

Analysis of Specific Energy Consumption

Experimental data were analyzed to obtain the specific energy consumption under different drying conditions as listed in Table 1. Figure 7 shows the variations in specific energy consumption as a function of different drying conditions during CUMV drying of tea leaves. The lowest value in all drying conditions regarding energy consumption was noted in case 1 (6.85 MJ/kg), whereas the highest value noted was in case 8 (35.11 MJ/kg). The order of

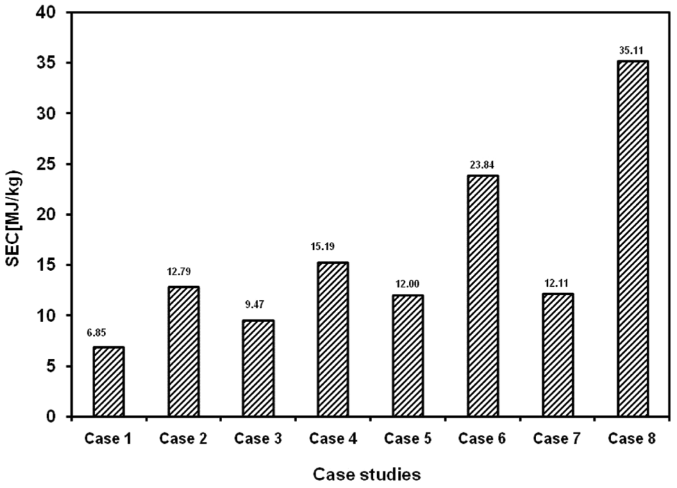

FIG. 7. Variations in specific energy consumption as a function of different drying conditions.

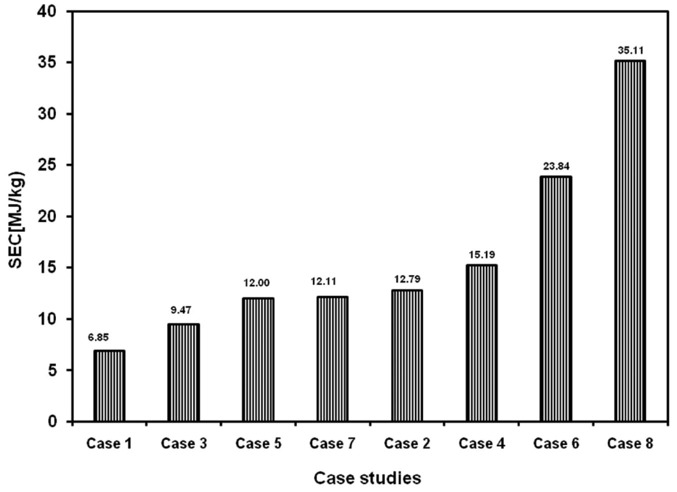

FIG. 8. Ordering of specific energy consumption for different drying conditions.

TABLE 1
Specific energy consumption under various drying conditions

Test condition	Microwave power (W)	Vacuum pressure (torr)	Microwave operation modes	Specific energy consumption (MJ/kg)
Case 1	800	385	Continuous	6.85
Case 2	800	385	Pulsed	12.79
Case 3	800	535	Continuous	9.47
Case 4	800	535	Pulsed	15.19
Case 5	1,600	385	Continuous	12.00
Case 6	1,600	385	Pulsed	23.84
Case 7	1,600	535	Continuous	12.11
Case 8	1,600	535	Pulsed	35.11

specific energy consumption for different drying conditions is shown in Fig. 8. The lowest specific energy consumption occurred in case 1 (6.85 MJ/kg), followed by case 3 (9.47 MJ/kg), case 5 (12.00 MJ/kg), case 7 (12.11 MJ/kg), case 2 (12.19 MJ/kg), case 4 (15.19 MJ/kg), case 6 (23.84 MJ/kg), and case 8 (35.11 MJ/kg). To summarize, the specific energy consumption for continuous microwave operation mode was always lower than that for pulsed microwave operation mode at the same microwave power and vacuum pressure. This is because the continuous microwave operation mode continuously supplied microwave energy through the cavity, which led to more microwave energy being absorbed in the bulk of tea leaves, resulting in a higher rate of water evaporation compared to pulsed microwave operation mode.

Energy Efficiency

The influence of microwave power, vacuum pressure, and microwave operation modes on energy efficiency (%) was investigated. The energy efficiency versus elapsed times with respect to different drying conditions of CUMV drying is illustrated in Figs. 9 and 10.

In Figs. 9 and 10, the energy efficiency profiles for all cases of CUMV drying increased quickly in the early stages of drying (about 0–10 min). However, the efficiency decreased rapidly after this stage (about 10–40 min). It is evident from the figures that the moisture content inside the bulk of tea leaves was substantially reduced in the early stages of drying. It is noted that bulk tea leaves have a low moisture content and act as a low dielectric material. During drying, this causes a decrease in the microwave energy absorbed. Consequently, the energy efficiency profiles decrease in this stage of drying. There is a difference between the energy efficiency of a microwave power of 800 W and a microwave power of 1,600 W using CUMV. Observations showed that the energy efficiency of a microwave power of 800 W (Fig. 9) was greater than that at a microwave power of 1,600 W in CUMV drying, as shown in Fig. 10. For the entering continuous microwave operation mode, the efficiency increased with a decrease in vacuum pressure (385 torr), as expected. This was because the stronger vacuum condition led to a higher rate of water evaporation inside the bulk tea leaves. This result of a higher rate of water evaporation corresponds to a higher energy efficiency, as shown in Fig. 9. Nevertheless, the trends of efficiency profiles in both figures displayed an unusual shape. This was due to the interaction between microwave and the dielectric sample (bulk of tea leaves) inside the rotary drum installed in the multimode cavity, which resulted in no control of the internal heat generation in the sample load.

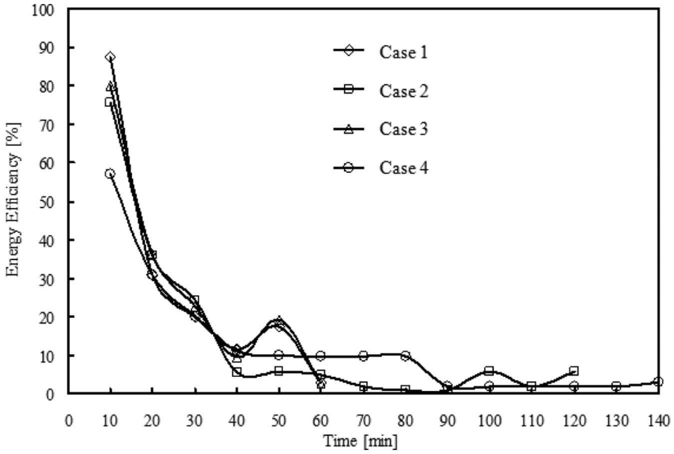

FIG. 9. Energy efficiency versus elapsed times with respect to different drying conditions (microwave power 800 W).

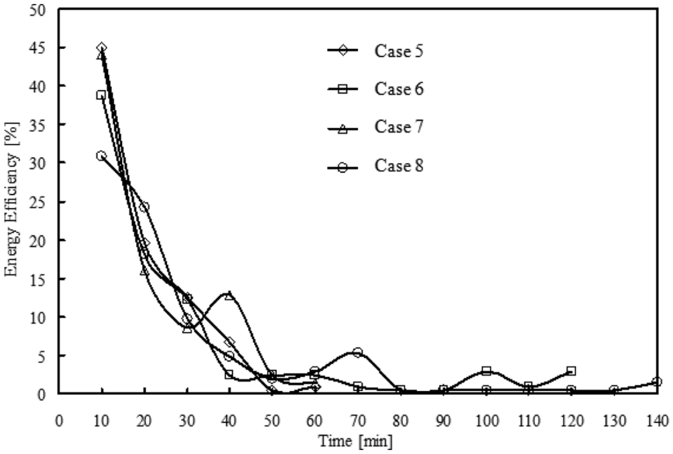

FIG. 10. Energy efficiency versus elapsed times with respect to different drying conditions (microwave power 1,600 W).

It should be noted that the energy efficiency was very low for all testing conditions. This was because all tests were performed on very small loads (initial weight of tea leaves was 3 kg/batch). Actually, the energy efficiency increased with increasing load when it approached the optimum design load (about 30 kg for a full load in the rotary drum). This was due to the increasing bulk of tea leaves corresponding to the highest rate of water evaporation using CUMV drying. In future work, the effects of initial weight on energy consumption as well as energy efficiency will be investigated.

Figure 11 shows that the best color values were achieved during continuous microwave drying. Figures 11a and 11b show the rough color shades of tea leaves dried with pulsed and continuous microwave operation modes, respectively. It can be observed that magnetron control affected the physical appearance of the tea leaves. It is clear from these figures that the pulsed microwave operation mode resulted in a better physical appearance than continuous microwave operation mode. As mentioned in previous work,[26] microwave energy consumption can save potentially more than

FIG. 11. Color parameter of the tea leaves dried in microwave operation mode (vacuum pressure of 385 torr, microwave power of 800 W): (a) pulsed microwave operation mode and (b) continuous microwave operation mode (color figure available online).

the purely conventional drying. Nevertheless, in this primary study aimed on drying of tea leaves, which has a lack of essential factors for assessment the energy consumption and biomaterials; that is, tea leaves has used in specific purpose in food or herb industries is produced in general purpose; therefore, estimate on energy consumption in biomaterials is suitable to perform.

CONCLUSIONS

The influence of drying conditions on the CUMV drying of tea leaves was evaluated based on the drying parameters, such as microwave power, vacuum pressure, and microwave operation modes with drying time. The results showed that energy consumption was dependent on our purpose parameters. Based on the experimental investigation and energy consumption analysis in CUMV drying, the following conclusions were drawn.

1. CUMV drying is more rapid in the continuous microwave operation mode than in the pulsed microwave operation mode.
2. The specific energy consumption values were relatively low in continuous microwave operation mode compared to those obtained for pulsed microwave operation mode. This was because the continuous microwave operation mode continuously supplied microwave energy through the cavity, which led to more microwave energy being absorbed in the bulk tea leaves, resulting in a higher rate of water evaporation compared to pulsed microwave operation mode. In contrast to the energy consumption results, the tea leaves dried with pulsed microwave operation mode had a better physical appearance than those obtained from continuous microwave operation mode.
3. The effects of microwave power, vacuum pressure, and microwave operation modes during CUMV drying on energy consumption as well as energy efficiency under different drying conditions were clarified.

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)
E	Electromagnetic field intensity (V/cm)
f	Microwave frequency (Hz)
h	Enthalpy (kJ/kg)
h_{fg}	Latent heat of vaporization (kJ/kg$_{\text{water}}$)
h_m	Enthalpy of material (kJ/kg)
M_p	Particle moisture content, db (kg$_{\text{water}}$/kg$_{\text{solid}}$)
m	Mass flow rate (kg/s)
m_a	Mass flow rate of dry air (kg/s)
m_{cv}	Mass rate balance for the control volume (kg/s)
m_w	Mass flow rate of water from the CUMV (kg/s)
P_{in}	Microwave power incident (kW)
P_1	Density of microwave power absorbed by dielectric material (kW/cm^3)
P_2	Energy required to heat up the dielectric material (kW)
Q_{evap}	Heat transfer rate due to water evaporation (kW)
Q_{loss}	Heat transfer rate to the environment (kW)
Q_{MW}	Microwave energy (kW)
SEC	Specific energy consumption (MJ/kg)
T	Temperature (°C)
ΔT	Increment temperature (°C)
t	Time (s)
$\tan\delta$	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$_{\text{vapor}}$/kg$_{\text{dryair}}$)

Greek Letters

ε'_r	Relative dielectric constant
ε''_r	Relative dielectric loss factor
ε_0	Permittivity of air (F/m)
η_e	Energy efficiency (%)
η_m	Microwave efficiency device (%)
υ	Velocity of propagation (m/s)
ω	Angular velocity of microwave (rad/s)

Subscripts

o	Surroundings; reference environment
a	Air
ab	Absorb
d	Dry material
da	Drying air
fg	Difference in property between saturated liquid and saturated vapor

g	Gas
in	Input
l	Liquid water
m	Material
out	Output
r	Relative
s	Solid
v	Vapor
w	Water
0	Free space
1	Inlet
2	Outlet

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