Chemical Engineering and Processing 49 (2010) 389–395

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Design and analysis of the commercialized drier processing using a combined unsymmetrical double-feed microwave and vacuum system (case study: tea leaves)

Kusturee Jeni, Mudtapha Yapa, Phadungsak Rattanadecho*

Research Center of Microwave Utilization in Engineering (R.C.M.E.), Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani 12120, Thailand

ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form 4 March 2010
Accepted 5 March 2010
Available online 15 March 2010

Keywords:
Microwave vacuum drying
Tea leaves
Heat and mass transfer
Quality

ABSTRACT

Combined microwave (MW) and vacuum drying of biomaterials has a promising potential for high-quality dehydrated products. A better knowledge of the drying kinetics of biomaterial products could improve the design and operation of efficient dehydration systems. The experiments were carried out on commercialized biomaterials drier using a combined unsymmetrical double-feed microwave and vacuum system. Three kilograms of tea leaves were applied with the microwave power of 800 (single-feed magnetron) and 1600 W (unsymmetrical double-feed magnetrons) operating at 2450 MHz frequency. Rotation rates of the rotary drum were held constant at 10 rpm. Vacuum pressure was controlled at the constant pressure of 385 Torr and 535 Torr, respectively. In this study, the system can be operated either in continuous or pulse mode in each experiments. Experiments show that in the case of high power level and continuous operating mode causes greater damage to the structure of tea leaves sample. Microwave drying with pulse operating mode at 385 Torr ensured the shortest drying time and the best overall quality of dried tea leaves, and thus was chosen as the most appropriate technique for tea leaves drying.

1. Introduction

Nowadays, the most important thing in industries, except for producing the high quality products to the markets, is to increase productivity and to reduce production cost. In general, several production processes of 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 a high cost products. Microwave drying is one of the most interesting methods in term of mechanisms and economics for heating and drying in various kinds of product [1–8].

Microwave–vacuum (MV) drying is a novel alternative method of drying, allowing to obtain products of acceptable quality. It permits a shorter drying time and a substantial improvement in the quality of dried materials, in relation to those dried with hot air and microwave drying methods. Furthermore, other advantages including environmental friendliness at low temperature, which not only over-comes the limitation of low thermal conductivity of the material under vacuum due to the absence of drying medium, but also avoids the defect of internal crack and interior burning caused by excessive heating in microwave drying, and acquires a wide range of application on the pharmaceutical and food industries. Microwave–vacuum drying has been investigated as a potential method for obtaining high-quality dried foodstuffs, including fruits, vegetables and grains [9–16]. Drouzas et al. [17] applied the vacuum–microwave 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. [18] dried cranberries using vacuum–microwave and microwave–hot air drying techniques, and demonstrated better quality of the product obtained with vacuum–microwave drying.

An excellent review of the drying techniques in dielectric materials using microwave energy has been presented by Schiffmann [19], Metaxas and Meridith [20] and Datta and Anantheswaran [21].

Although combined MW–vacuum drying has found some application in the dehydration of fruit juices, more research and development is needed before the process is used in large commercial scale. In particular, the effect of vacuum and MW power on the drying kinetics should be known quantitatively, so that the drying system can be optimized from the cost and quality standpoints.

The main objective of this research was to examine the feasibility of using MW–vacuum drier to dry biomaterials, i.e., tea leaves and experimentally explore drying characteristics of tea leaves in different drying conditions, including microwave radiation time, microwave power level, vacuum level and typical microwave feeding process. At the same time, the research results would be

* Corresponding author. Tel.: +66 2564 3001 9; fax: +66 2564 3010.
E-mail address: ratphadu@engr.tu.ac.th (P. Rattanadecho).

0255-2701/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cep.2010.03.003

beneficial to present a theory basis for further study and industrial application of a combined microwave and vacuum technology in biomaterials in the future.

2. Design of unsymmetrical double-feed magnetrons in multi-mode cavity

It is well known that the uneven field distribution creates the hot and cold spots. Hot spot could contribute to the phenomena of runaway. For food products, cold spots are unwelcome as they allow bacteria to thrive if the temperature is not sufficient high enough to kill them, which could cause food poisoning [22]. This reason explains why a more uniform heating is generally desirable. In the past, many researchers have devised ways of improving the electric field as well as heating distribution with varying the degrees of success by changing either the source, the microwave feeding system, shape of cavity or the environment surrounding the load. Some base their ideas on empty cavities, which in a practical situation are meaningless [23,24]. In analysis, electromagnetic waves in the cavity were simulated to design the microwave–vacuum system. The distributions of electric field strength and mode generation were investigated in the simulation. COMSOL software was used for constructing domain meshes while Finite Element Method was used to solve the problems. Generated resonant modes inside the multimode cavity, where the reflections from the walls of cavity constructively reinforce each other to produce a standing wave, were calculated by determining the number of half-wavelengths in each of the principal directions [21]. The quality factor (Q-factor) and the maximum electric field strength (E_{max}) were calculated by using the equations found in [20]. The time-average complex power flow through a defined closed surface is calculated from Poynting's theorem [4] when a microwave source is connected to the cavity.

In this study, the idea of using the multiple sources is presented. This idea is providing certain advantages such as lower inventory of spare parts and less maintenance downtime, the method has the added benefit of creating a good uniformity. However, when it comes to improving the electric field as well as heating uniformity and low cross-coupling using multiple feeds, the obvious question to ask is where and how to position the feeds. The disadvantage with multiple feeds is the mutual coupling that exists if they are improperly fed. The feed positioning requires an understanding and knowledge of the electric and magnetic field directions. As described above, the simulation is needed to determine the positioning of feeds in cavity [24].

The principle behind the design of feed multimode cavities for improved heating and low cross-coupling can be demonstrated here in various cases. With the details of calculations omitted, the simulation results in various cases will be summarized in Fig. 1 with single-feed cavity and double-feed cavity having different orientation, i.e. symmetrical double-feed and unsymmetrical double-feed magnetrons.

Fig. 1a shows the simulation of electric field arrow plot of single-feed wall on which the TE10 waveguide is to be connected and microwave power of 800 W is applied. It is observed that a single source and feed will certainly create patchy regions of field maxima and minima. Fig. 1b and c shows the simulation of electric field arrow plot in case of symmetrical double-feeds magnetrons and unsymmetrical double-feeds magnetrons on simultaneously, respectively, assuming that the double feeds provide double the amount of power.

The simulation results show that it is the excitation of similar modes in symmetrical double-feeds magnetrons that increases the cross-coupling which leads to uneven field distribution. The reason for high coupling between feeds that because they are symmetrically positioned on the cavity wall and therefore excite the same mode. The reduction of this coupling is done by using the unsymmetrical feeds placement where each port excites a different set of modes. The conclusion drawn from these results is that the electric field uniformity is better with double-feeds sources as compared to one-feed source. Furthermore, a better energy spread throughout the entire cavity is obtained with the unsymmetrical placed sources with each one exciting discrete modes. Therefore, the

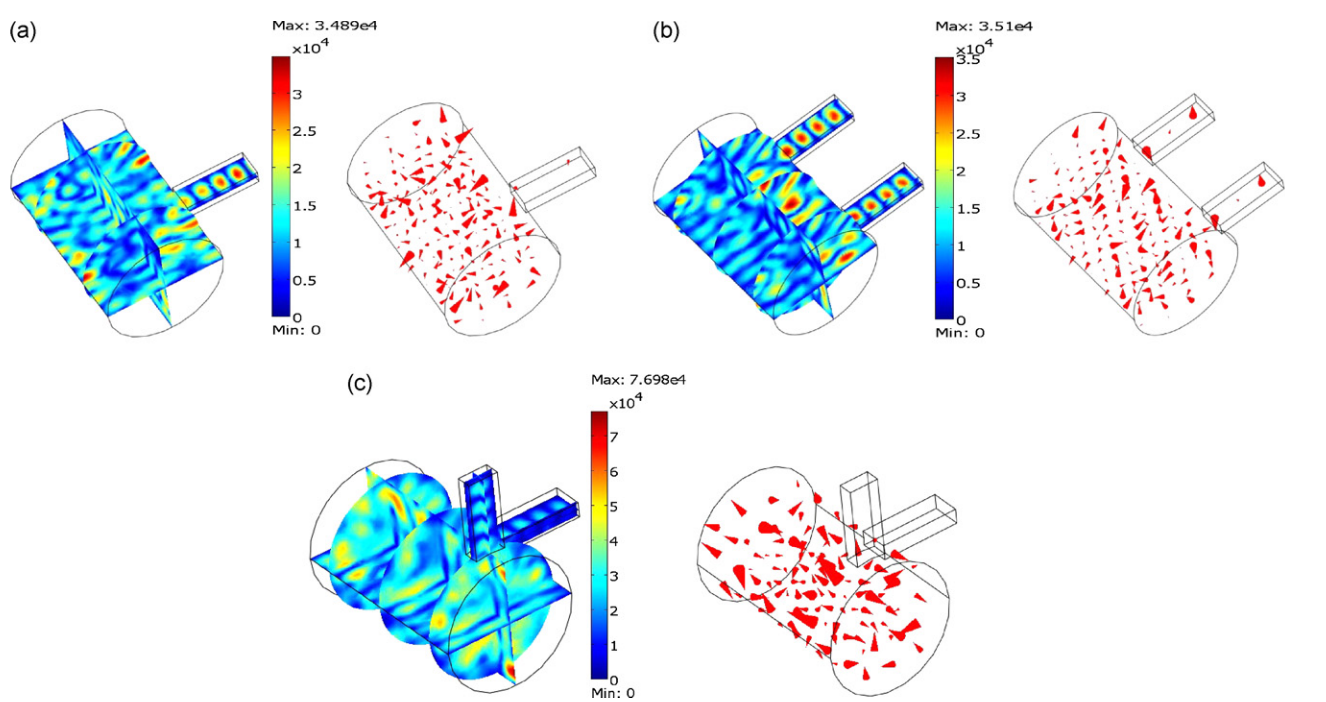

Fig. 1. The simulation of electric filed distribution (V/m) in multimode cavity (Slice Plot Type and Arrow Plot Type). (a) Simulated electric field distribution and arrow plot in multimode cavity with one-feed single magnetron. (b) Simulated electric field distribution and arrow plot in multimode cavity with symmetrical double-feed two magnetrons. (c) Simulated electric field distribution and arrow plot in multimode cavity with unsymmetrical double-feed two magnetrons.

concept designed by using unsymmetrical double-feed sources was performed in this study.

3. Materials and methods

3.1. Materials

The experimental materials comprised tea leaves from a farm located North Part of Thailand, stored at 10 °C until sample preparation. Three hours before drying the bulk of tea leaves were placed at ambient air temperature. The initial moisture content of material was 172% (dry basis). All tea leaves used for drying were from the same batch.

3.2. Experimental program

An experimental stand for the commercialized biomaterials drier using a combined unsymmetrical double-feeds microwave and vacuum system was shown in Fig. 2a. The microwave power was generated by means of unsymmetrical double-feeds mag-

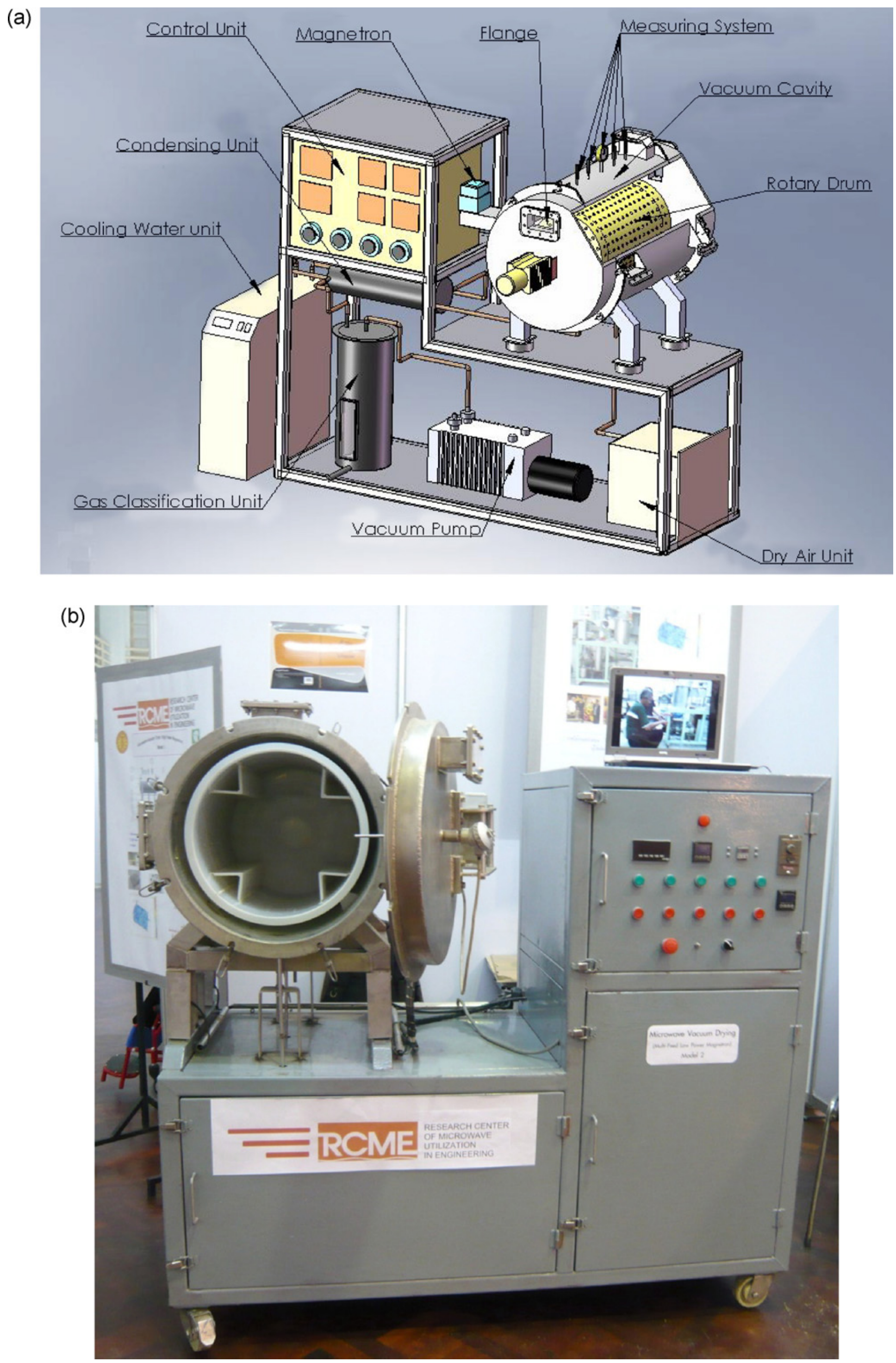

Fig. 2. The commercialized biomaterials drier. (a) Detail of the system. (b) MW drying experiments were carried out at the Research Center of Microwave Utilization in Engineering (R.C.M.E.) Department of Mechanical Engineering, Faculty of Engineering, Thammasat University.

netrons according to design concept as shown in Section 2 (2 compressed air-cooled magnetrons of 800 W each for a maximum of 1.6 kW) operating at a frequency of 2450 MHz. The power setting could be adjusted individually in 800 W steps. The microwave was conveyed through a series of rectangular (11.0 cm × 5.5 cm) wave guides to a metallic vacuum cavity of 0.13 m^3 (¶ × 0.24^2 × 0.72 m) in which the materials to be dried can be rotated by rotary drum in the cavity. The rotary drum was made of polypropylene with dimensions approximately of 30 cm radius and 50 cm length and the rotation speed of the rotary drum was controlled about 10 rpm in order to enhanced the interaction between microwave and dielectric load. The maximum vacuum degree was about 50 Torr. The Microwave–vacuum drying experiments were carried out for two levels of microwave power (800 W-one magnetron turned on and 1600 W-two magnetrons turned on) and two levels of vacuum pressure (535 Torr and 385 Torr). In this study, the system can be operated either in continuous or pulse mode in each experiment. In the intermittent mode or pulsed microwave operating mode, the magnetron was alternately turned on and off for pre-determined set times. The pulsed microwave operating mode of 60 s on/60 s off was performed in each experiment.

The moisture content (dry basis) and dry matter content were measured according to the AOAC (1995) standards [25], using a laboratory scale system to an accuracy of 0.01 g. Optical fiber (LUXTRON Fluroptic Thermometer, model 790, accurate to ±0.5 °C) was employed for measuring the averaged temperature of bulk load in cavity. 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 the cavity. A Multimeter^{TM} Series Digital with PC interface was used to monitor the temperature inside the cavity and to facilitate feedback control of process. An infrared camera was used to measure the surface temperature of the samples (accurate to ±0.5 °C).

In MW–vacuum 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 each at the both covers end. The microwave leakage was controlled below the DHHS (US Department of Health and Human Services) standard of 5 mW/cm^2.

The dielectric properties for tea leaves samples were measured at 25 °C using a portable dielectric measurement (Network Analyzer) over a frequency band of 1.5 GHz to 2.6 GHz as shown in Fig. 2b. The portable dielectric measurement kit allows for measurements of the complex permittivity over a wide range of solid, semi-solid, granular and liquid materials. It performs all of the necessary control functions, treatment of the microwave signals, calculation, data processing, and results representation. The software controls the microwave reflectometer to measure the complex reflection coefficient of the material under test (MUT). Then it detects the cavity resonant frequency and quality factor and converts the information into the complex permittivity of the MUT. Finally, the measurement results are displayed in a variety of graphical formats, or saved to disk.

4. Results and discussion

According to the electric field simulation of the drier cavity, a single feed magnetron will certainly create patchy regions of field maxima and minima. The using of multiple sources is presented to create a good uniform electric field. The simulated result is that it is the excitation of similar modes in symmetrical double-feeds magnetrons that increases the cross-coupling which leads to uneven field distribution. The reason for high coupling between feeds is because they are symmetrically positioned on the cavity wall and therefore excite the same mode. The reduced this coupling is done by using the unsymmetrical feeds placement where each port excites a different set of modes. The conclusion drawn from these results is that the electric field uniformity is better with double-feeds sources as compared to one-feed source. Furthermore, a better energy spread throughout the entire cavity is obtained with the unsymmetrical placed sources with each one exciting discrete modes.

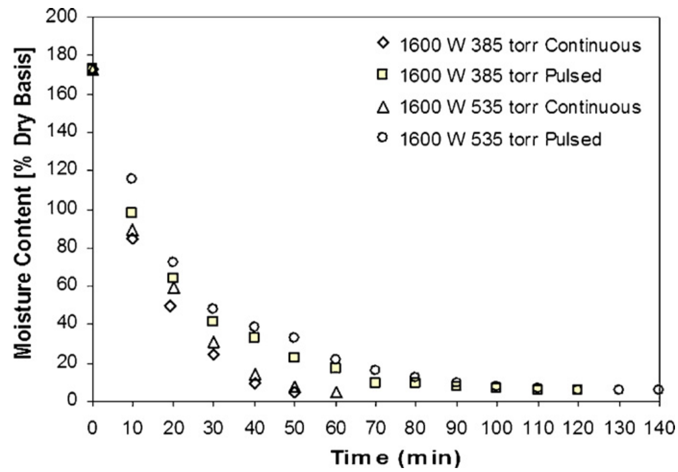

Fig. 3. Variations of moisture content with drying time using continuous microwave operating mode and pulsed microwave operating mode at 1600 W magnetron power.

The experiments were carried out on commercialized biomaterials drier using a combined unsymmetrical double-feed microwave and vacuum system. Three kilograms of tea leaves were applied with the microwave power of 800 (single-feed magnetron) and 1600 W (unsymmetrical double-feed magnetrons) operating at 2450 MHz frequency. Rotation rates of the rotary drum were held constant at 10 rpm. Vacuum Pressure was controlled at the constant pressure of 385 Torr and 535 Torr, respectively. In this study, the system can be operated either in continuous or pulse mode in each experiments.

Figs. 3 and 4 show the drying curves for tea leaves with continuous and pulsed microwave operating modes. It is clearly evident from these curves that the averaged moisture content profiles with respect to elapsed times were depended on microwave operating modes and vacuum pressure levels. Furthermore, the total drying times were reduced substantially with changing the microwave

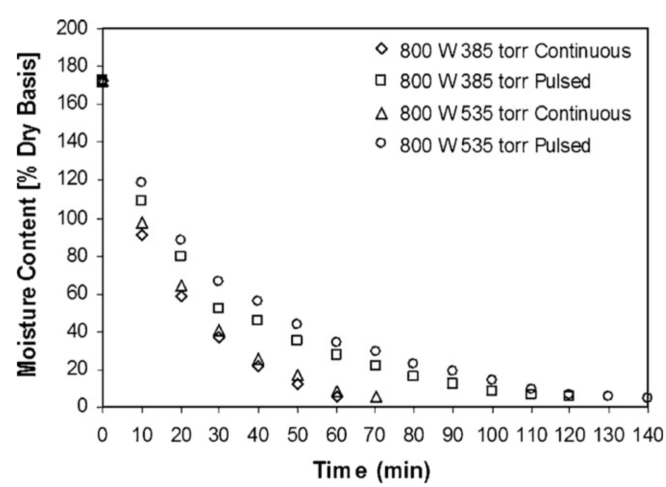

Fig. 4. Variations of moisture content with drying time using continuous microwave operating mode and pulsed microwave operating mode at 800 W magnetron power.

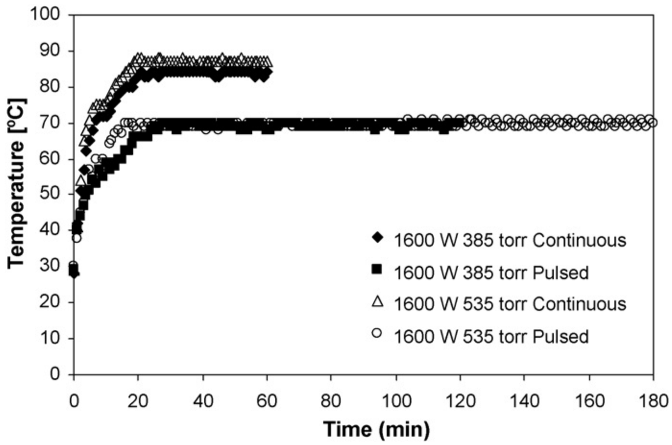

Fig. 5. Variations of cavity temperature with drying time using continuous microwave operating mode and pulsed microwave operating mode at 1600 W magnetron power.

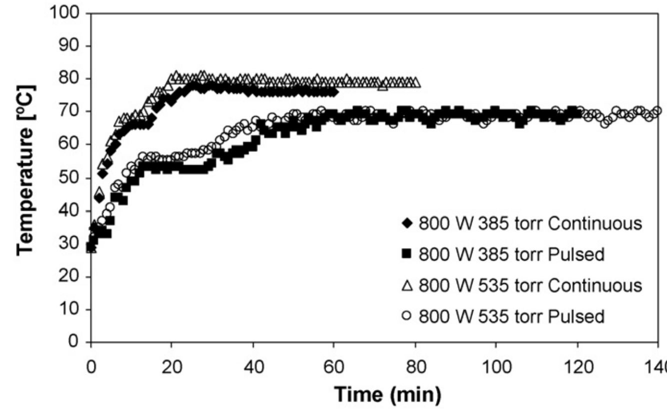

Fig. 6. Variations of cavity temperature with drying time using continuous microwave operating mode and pulsed microwave operating mode at 800 W magnetron power.

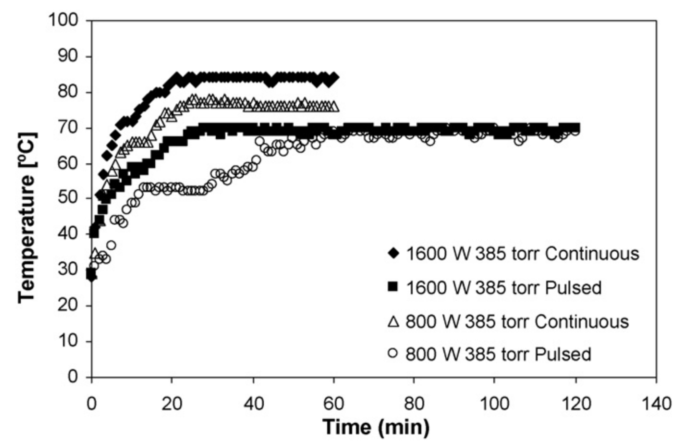

Fig. 7. Variations of cavity temperature with drying time using continuous microwave operating mode and pulsed microwave operating mode at 385 Torr vacuum pressure.

operating modes as compared to the variation of vacuum pressure levels. Particularly, In case of continuous microwave operating mode where the supplying microwave energy continuously gives the more microwave energy absorbed rates which leads to higher temperature and moisture transferred rates within the dried samples. In case of continuous microwave operating mode at 1600 W magnetron power, the drying time of tea leaves was 50 min in relation to the vacuum pressure of 385 Torr, and the drying times was 60 min in relation to the vacuum pressure of 535 Torr. Namely, in case of the continuous microwave operating mode at 800 W magnetron power the drying time was 60 min in relation to the vacuum pressure of 385 Torr and the drying times was 70 min for the vacuum pressure of 535 Torr. In the same figures, in case of pulsed microwave operating mode at 1600 W magnetron power, the drying time of tea leaves was 120 min in relation to the vacuum pressure of 385 Torr and the drying time was 140 min for the vacuum pressure of 535 Torr. Namely, in case of the pulsed operating mode at 800 W magnetron power, the drying time was 120 min in relation to the vacuum pressure of 385 Torr and the drying time was 140 min for the vacuum pressure of 535 Torr.

In analysis the effect of and vacuum pressure levels, the total drying times were reduced slightly with variation of vacuum pressure levels as compared to the case of changing microwave operating modes. The drying process at lower vacuum pressure (stronger vacuum pressure) easily allows water to evaporate at a lower temperature. The drying curves show that the drying time at lower vacuum (385 Torr) is shorter than the drying time at higher vacuum pressure (535 Torr) when microwave power is kept the same. Strong vacuum pressure leads to induce the faster of the drying rate. The continuous microwave operating mode with vacuum pressure of 385 Torr has shorter drying time than continuous microwave operating mode with vacuum pressure of 535 Torr by 16.7% at 1600 W magnetron power and 14.3% at 800 W magnetron power, respectively. At lower vacuum pressure, drying time is shorter due to the reduction of boiling temperature of the dried samples which leads to enhance the moisture transport in the dried samples. The latter arises from the fact that the microwave energy being absorbed as well as the temperature in the dried samples was decreased. It is due to the changing dielectric properties of the tea leaves which are proportionally dependent on moisture content.

Next presentation refers to the discussion on averaged temperatures of bulk load (cavity temperature) with respect to elapsed times with various testing conditions. In Figs. 5–8, the averaged temperature of bulk load (i.e., tea leaves) is influenced by applied vacuum pressure and microwave power level and microwave operating modes. Magnetron power as well as microwave operating mode are strongly effects on the internal heat generation and drying rate of dried samples. Furthermore, the higher microwave power level as well as continuous microwave operating mode can increase the temperature and drying rate by providing more energy for vaporizing water thus accelerating moisture removal at greater

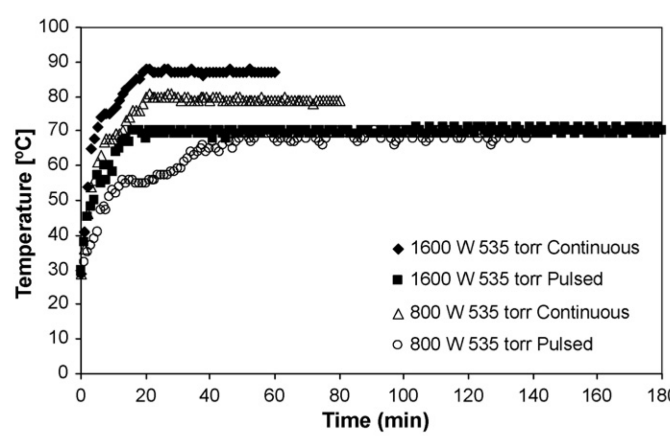

Fig. 8. Variations of cavity temperature with drying time using continuous microwave operating mode and pulsed microwave operating mode at 535 Torr vacuum pressure.

Fig. 9. Tea leaves which were dried with pulsed microwave operating mode at 800 W magnetron power.

Fig. 10. Tea leaves which were dried with continuous microwave operating mode at 800 W magnetron power.

temperature while the stronger vacuum pressure allows water to evaporate at lower temperature.

Figs. 5–8 show the cavity temperatures with respect to elapsed times in case of continuous and pulsed operating modes and variation of vacuum pressure levels. Fig. 5 shows the cavity temperatures with respect to elapsed times at 1600 W magnetron power. It is clearly evident from the figure that the temperature profiles begin to reach a steady state plateau at approximately 20 min after this stage the temperatures remain constantly. For the continuous microwave operating mode, the final average temperatures are reached to 83 °C and 85 °C in the relation to the vacuum pressure of 385 Torr and 535 Torr, respectively. And for the pulsed microwave operating mode the final averaged temperatures are reached to 64 °C and 66 °C in relation to the vacuum pressure of 385 Torr and 535 Torr, respectively. Fig. 6 shows the cavity temperatures with respect to elapsed times at 800 W magnetron power. It is clearly evident from the figure that the temperature profiles begin to reach a steady state plateau at approximately 20 and 60 min in case of continuous and pulsed microwave operating modes, respectively. For the continuous microwave operating mode, the final average temperatures are reached to 77 °C and 80 °C in the relation to vacuum pressure of 385 Torr and 80 °C, respectively. And for the pulsed microwave operating mode, the final averaged temperatures are reached to of 64 °C and 65 °C in relation to the vacuum pressure at 385 Torr and 535 Torr, respectively.

Figs. 7 and 8 show the cavity temperatures with respect to elapsed times are redrawn from Figs. 3–6 in various testing conditions. It can be observed that no clearly difference in temperature profiles for two vacuum pressure levels was shown. However, the clearly difference in temperature profiles for two microwave power levels and microwave operating modes was shown, as previously described. It is observed that in the case of continuous microwave operating mode the averaged final temperature for power of 1600 W gives approximately 10 °C higher than the averaged final temperature for power of 800 W.

Figs. 9 and 10 show the roughly color shades for tea leaves which were dried with pulsed and continuous microwave operating modes, respectively. It can be observed that magnetron control affects of physical appearance of tea leaves. It is clearly evident from these figures that the pulsed microwave operating mode gives better physical appearance.

It should be summarized again that the drying conditions at stronger vacuum pressure are increased the drying rate and decreased averaged temperature of bulk load. Drying at higher magnetron power are increased the drying rate and averaged temperature. Nevertheless, the drying in continuous microwave operating mode with higher microwave power caused higher reflected wave which causes power losses and may damages the microwave components. To avoid this problem it was suggested to use pulse microwave operating mode when drying under higher microwave power. Therefore, it would be recommended to select the higher microwave power in pulsed microwave operating mode for successfully in drying.

As mentioned in the previous work, especially by the authors [5], indicated obviously that the energy consumption by using microwave energy can save potentially more than the purely conventional drying. Nevertheless, in this primary study aimed on drying of biomaterials which has lack of essential factors for assessment the energy consumption and biomaterials, i.e., 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.

5. Conclusion

Generally, in the conventional hot air drying process, the drying rate was fast in the beginning stage, but decreased sharply in the last stage. Rising of the hot air temperature could not enhance the drying rate in the last stage, but caused damages to the food quality. In the microwave–vacuum drying process, the drying rate increased with increase of microwave power and vacuum degree. Furthermore, experiments show that in the case of high power level and continuous microwave operating mode causes greater damage to the structure of tea leaves sample. The drying at 385 Torr ensured the shortest drying time and the best overall quality of dried tea leaves, and thus was chosen as the most appropriate technique for tea leaves drying. Although combined microwave and vacuum drying has found some application in the drying of biomaterials more research and development is needed before the process is used in large commercial scale, especially in continuous process. In particular, the effect of microwave power–vacuum on the drying kinetics should be known quantitatively, so that optimization analysis is needed for this combined drying process to improve the final physical and chemical properties and products quality of the product further.

Acknowledgement

The authors would like to express their appreciation to the Thailand Research Fund (TRF) and Commission on Higher Education (CHE), Thailand for providing financial support for this study.

References

[1] K.G. Ayappa, H.T. Davis, E.A. Davis, J. Gordon, Analysis of microwave heating of materials with temperature dependent properties, AIChE J. 37 (3) (1991) 313–322.
[2] P. Perre, W. Turner, Microwave drying of softwood in an oversized waveguide, AIChE J. 43 (10) (1997) 2579–2595.
[3] P. Ratanadecho, K. Aoki, M. Akahori, Influence of irradiation time, particle sizes and initial moisture content during microwave drying of multi-layered capillary porous materials, Heat Transfer, ASME J. 124 (1) (2002) 151–161.
[4] P. Ratanadecho, K. Aoki, M. Akahori, The characteristics of microwave melting of frozen packed bed using a rectangular wave guide, IEEE Trans. Microwave Theory Tech. 50 (6) (2002) 1487–1494.
[5] P. Rattanadecho, N. Suwannapum, A. Watanasungsuit, A. Duangduen, Drying of dielectric materials using microwave-continuous belt furnace, ASME J. Manuf. Sci. Eng. 129 (1) (2007) 157–163.
[6] P. Rattanadecho, N. Suwannapum, B. Chatveera, D. Atong, N. Makul, Development of compressive strength of cement paste under accelerated curing by using a continuous microwave belt drier, Mater. Sci. Eng. A 472 (2008) 299–307.
[7] S. Curet, O. Rouaud, L. Boillereaux, Microwave tempering and heating in a single-mode cavity: numerical and experimental investigations, Chem. Eng. Process.: Process Intens. 47 (9–10) (2008) 1656–1665.
[8] S. Vongpradubchai, P. Rattanadecho, The microwave processing of wood using a continuous microwave belt drier, Chem. Eng. Process.: Process Intens. 48 (5) (2009) 997–1003.
[9] Z.W. Cui, S.Y. Xu, D.-W. Sun, Dehydration of garlic slices by combined microwave–vacuum and air drying, Drying Technol. 21 (7) (2003) 1173–1185.
[10] Z.W. Cui, S.Y. Xu, D.-W. Sun, Effect of microwave–vacuum drying on the carotenoids retention of carrot slices and chlorophyll retention of Chinese chive leaves, Drying Technol. 22 (3) (2004) 561–574.
[11] A.E. Drouzas, H. Schubert, Microwave application in vacuum drying of fruits, J. Food Eng. 28 (1996) 203–209.
[12] W. Kaensup, S. Chutima, S. Wongwises, Experimental study on drying of chili in a combined microwave–vacuum–rotary drum dryer, Drying Technol. 20 (10) (2002) 2067–2079.
[13] T.M. Lin, T.D. Durance, C.H. Scaman, Physical and sensory properties of vacuum microwave dehydrated shrimp, J. Aquat. Food Product Technol. 8 (4) (1999) 41–53.
[14] J.I. Wadsworth, L. Velupillai, L.R. Verma, Microwave–vacuum drying of parboiled rice, Trans. ASAE 33 (1) (1990) 199–210.
[15] J. Yongsawatdigul, S. Gunasekaran, Pulsed microwave–vacuum drying of cranberries. Part I. Energy use and efficiency, J. Food Process. Preserv. 20 (2) (1996a) 121–143.
[16] J. Yongsawatdigul, S. Gunasekaran, Pulsed microwave–vacuum drying of cranberries. Part II. Quality evaluation, J. Food Process. Preserv. 20 (3) (1996b) 145–156.
[17] A.E. Drouzas, E. Tsami, G.D. Saravacos, Microwave–vacuum drying of model fruit gels, J. Food Eng. 39 (3) (1999) 117–122.
[18] P.S. Sunjka, T.J. Rennie, C. Beaudry, G.S.V. Raghavan, Microwave-convective and microwave–vacuum drying of cranberries: a comparative study, Drying Technol. 22 (5) (2004) 1217–1231.
[19] Robert F. Schiffmann, Microwave and dielectric drying, in: A.S. Mujumdar (Ed.), Handbook of Industrial Drying, 2nd ed., Marcel Dekker, New York, 1995.
[20] A.C. Metaxas, R.J. Meridith, Industrial Microwave Heating, Peter Peregrinus, Ltd., London, 1983.
[21] A.K. Datta, R.C. Anantheswaran, Handbook of Microwave Technology for Food Applications, Marcel Dekker, Inc., New York, 2001.
[22] R.V. Decareau, Microwave in the Food Processing Industry, Academic Press, New York, 1985.
[23] P.O. Risman, T. Ohlsson, B. Wass, Principles and models of power density distribution in microwave oven loads, J. Microwave Power EE (1987) 193–198.
[24] T.V. Chow T. Chan, H.C. Reader, Understanding Microwave Heating Cavities, Artech House, Inc., 2000.
[25] AOAC, Official Methods of Analysis of AOAC International, 16th ed., USA, 1995.