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Drying paddy by microwave vibro-fluidized bed drying using single mode applicator

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Abstract

This study aimed to develop the system of microwave-assisted vibro-fluidized bed (MVFB) drying for particulate agricultural products by applying the single mode applicator (SMA), where the microwave field can be focused. SMA- and multi-mode applicator (MMA)-MVFB dryers were set up and their microwave efficiency at different levels of microwave power density (0.82, 1.04 and 1.70 kW/kg) was investigated in water system. Types of applicator did not affect microwave generation efficiency but significantly affected microwave absorbance efficiency. Almost 100% efficiency of microwave absorbance was achieved when heating water in SMA. Therefore, SMA-MVFB drying was selected to perform drying characteristics of paddy, the representative of particulate agricultural products. Four drying techniques including MVFB drying at 850 W, low temperature (LT)-MVFB drying at 850 W and 60ºC, LT-vibro-fluidized bed (VFB) drying at 60ºC and high temperature (HT)-VFB drying at 150ºC were used to dry paddy from 27 to 17% w.b. under constant air velocity of 5 m/s and vibration of 1200 rpm. In addition, it consumed the lowest energy and removed the highest amount of water from paddy. The hybrid system of LT-MVFB drying was proven to be superior to the other drying techniques. This study confirmed successfully application of SMA-MVFB drying for paddy.

Key words: Microwave drying, vibro-fluidized bed drying, single mode applicator, paddy drying.

Introduction

Particulate agricultural products as cereal grains mostly have too high moisture content to safe from microorganisms. Drying of particulate agricultural products is considered the most important process of post-harvest operations. It extremely affects the product quality. Such a kind of solid particles, fluidized bed (FB) drying is recognized the most suitable water removal process among other drying techniques [7]. In this drying system, solid particles are in intimate contact with the drying medium. The drying temperature is also rather uniform throughout the bed of particles. There is also the suggestion to improve particle fluidization by mechanical vibration [6, 10]. Air velocities applied in the vibro-fluidized bed (VFB) dryer for minimum and complete fluidization are relatively lower than the air velocities required by the conventional FB dryer. The lower air velocities also contribute to the minimization of attrition due to vigorous particle-particle and particle-wall interactions. More importantly, both FB drying and vibration systems are recommended to be used for improving the heat and mass transfer.

On the other hand, microwave radiation drying has recently been considered as an alternative drying technique. Heating by microwave energy has the distinct advantages over conventional thermal processing. The microwave energy can directly penetrate into materials and hence induce volumetric heating inside the materials. Due to the volumetric heating characteristic of microwave, drying time and energy consumption are lowered, and overall product quality is improved.

A hybrid system of microwave-assisted FB drying was first introduced by Smith [11] to dry granular products. In addition to dry material due to thermal gradients, FB acts as a wave guide for microwave radiation. Fluidization provides the pneumatic agitation, which helps individual particle receive microwave energy effectively. Up to present, there are a number of studies on combined microwave-fluidized bed (MFB) drying. Various materials such as macaroni beads [2], potato slices [8], garlic [12] and carrot [13] have been dried by this technique.

Regarding to microwave heating, the design of applicator, including wave-guide, travelling wave applicator and single mode or multi-mode cavities, is critical. Multi-mode cavity is the type of applicator used in kitchen microwave oven. It is recommended to use multi-mode applicator (MMA) for processing of large, complicated shaped objects because this type of applicator can provide multiple hot spots within the microwave cavity and its dimension can be adjusted to achieve uniform heating. However, it is very difficult to achieve even and optimized heating in MMA. Electromagnetic field distribution is very much predictable in single mode applicator (SMA) because of the size of SMA in the order of one wavelength. The applicator in SMA has only one hot spot where the microwave field strength is high. These offer some distinct advantages, especially for small-shaped or low lossy materials.

Although there are a number of microwave applications for food drying, none of them was conducted in SMA. VFB of specific cylindrical cavity which represents SMA for microwave radiation could ensure effective distribution of microwave field. Therefore, the present study was concentrated on the investigation of the effects of different microwave applicators, i.e. SMA and MMA, on microwave generation and absorbance efficiency. Microwave vibro-fluidized bed (MVFB) drying characteristics of a selected particulate agricultural product in SMA and the product quality were also determined. Energy consumption of the developed dryer was evaluated.

The particulate agricultural product selected in this study was paddy as it has uniform shape and contains high moisture. After harvesting, paddy must be dried as soon as possible for safe storage. Moreover, FB drying of paddy has recently been conducted by many researchers and suggested to be superior to conventional hot air drying [3, 9, 14]. There was also a report on successful using mechanical vibration for infrared drying of paddy for faster and uniform drying [1]. Notably, MVFB drying in SMA of paddy has not been studied till. This is the novel report describing the use of this drying technique for paddy.

Experimental Set-Up

The laboratory-scale MVFB drying system was designed and fabricated at the Food Engineering Workshop, Asian Institute of Technology, Thailand. The schematic diagram of the MVFB dryer is illustrated in Fig. 1. The dryer consisted of three main components including microwave heating, VFB drying and control systems.

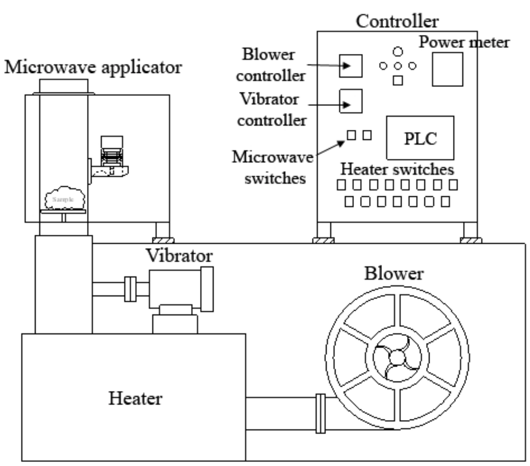

Figure 1. Schematic view of MVFB-SMA dryer.

Microwave heating system: The high frequency microwave generator of an 850 W magnetron (T-185, Panasonic Industrial Co., Ltd., China) was fitted with a rectangular waveguide (12.8×6.4cm^2 cross-sectional area). A circulator and matching tuner were equipped at the outlet of the waveguide as the protective devices to prevent magnetron damage due to microwave reflection. Two types of microwave cavity or applicator (SMA and MMA) which promote different patterns of microwave radiation were used to evaluate and compare their efficacy. The characteristics of the two applicators (Fig. 2) were described as follows.

SMA: The applicator was cylindrical with a diameter of 15 cm and a height of 38 cm. It was made of stainless steel No. 316 with a thickness of 3 mm. One side of the applicator was adjusted to be plain to fit well with the rectangular waveguide. Microwave magnetron was placed in the position of one wavelength generation. The upper and lower sides of the applicator were equipped with a microwave filter to prevent microwave leakage. The microwave filter was made by aluminium having a mesh size of 4 mm, and the total area of the mesh was equal to 30% of the total area of the filter in order to prevent microwave leakage.

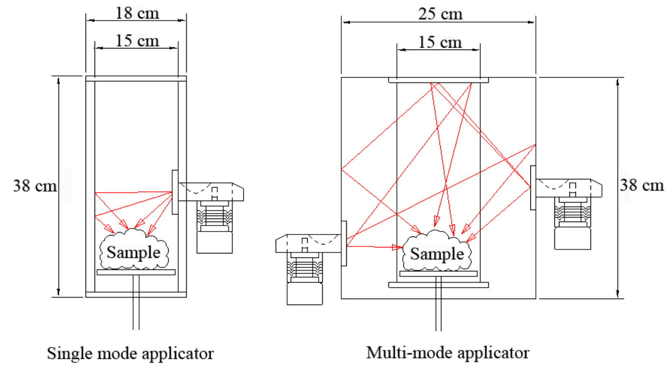

Figure 2. Schematic views of SMA and MMA of the MVFB dryer.

MMA: The applicator was rectangular with a volume of 25×25×38 cm^3. It was made of stainless steel No. 316 with a thickness of 3 mm. A glass tube having a diameter of 15 cm and a height of 38 cm was installed inside the applicator as a drying chamber. Two magnetrons were fitted with rectangular waveguides and installed at the upper left side and lower right side of the applicator. In this system, microwave moved in the applicator randomly. The random movement of microwave caused microwave to radiate and reflect in various directions.

VFB drying system: The drying system was designed to be conducted both in static and dynamic systems. It consisted of a high pressure blower and fifteen 1.5-kW fin heaters which were capable of generating heat up to 200ºC. The drying system was fitted with an electromechanical vibration unit to enhance the heat distribution to the materials within the drying chamber.

Control system: The Programmable Logic Controller (PLC) (V280, Unitronics, USA), which is accepted as the most accurate and stable control system available, was used as the main controller. PLC was managed through the Visilogic program version 8.0 to control the equipment attached such as solid state relay to control the electricity supplied to electrical heaters, blower and vibrator etc.

Materials and Methods

Material: Long grain paddy (Khao Daok Mali 105) was collected from the Pathumthani Rice Research Center, Thailand and stored in a refrigerator at 4±1ºC. Before use, the paddy was remoistened to the desired moisture content of 27% (wet basis, w.b.) and then kept in the refrigerator for 5-7 days to ensure uniform moisture throughout the kernels.

Methods:

Generation and absorbance efficiency of microwave in water system: Distilled water (500 g) was used as a standard material to test the efficiency of microwave generation and absorbance (Equations 1 and 2) in SMA and MMA [5]. The microwave output power was calculated from the changes in water temperature while heating for 5 min at different microwave power density (0.82, 1.04 and 1.70 kW/kg).

$$\text{Generation efficiency} = 100 \times \frac{\text{microwave output power}}{\text{input electrical power}} \quad (1)$$

$$\text{Absorbance efficiency} = 100 \times \frac{\text{thermal energy absorbed}}{\text{microwave output} \times \text{heating duration}} \quad (2)$$

Drying procedure: Drying of paddy (500 g) was carried out in SMA using VFB and MVFB drying systems. There were four drying treatments as described in Table 1. In the VFB dryer, paddy was dried at the low temperature of 60ºC (LT-VFB drying) and high temperature of 150ºC (HT-VFB drying). For MVFB drying, the microwave output power was set at 100% power level of 850 W. The low temperature of 60ºC was also used in combination with microwave heating for the LT-MVFB drying treatment. The velocity of air passing through the system was 5 m/s. The vibrator was conducted at 1200 rpm. Drying was continued until the final moisture content of the paddy was approximately 17% (w.b.). Each of the drying treatments was done in triplicate.

Table 1. Drying experiments of this study.

Drying treatment	Microwave energy (W)	VFB drying conditions: Temperature (°C)	Air velocity (m/s)	Vibration (rpm)
MVFB	850	Ambient	5	1200
LT-MVFB	850	60	5	1200
LT-VFB	-	60	5	1200
HT-VFB	-	150	5	1200

Moisture content determination: The moisture content of dried paddy at each drying time increment was determined by drying in a hot air oven at 130ºC for 24 h [4]. Drying intervals of 30 s was used for initial 5 min followed by 1 min up to 10 min and 5 min for the rest of the drying period. The amount of water loss while drying was also quantified from the difference in the gross weight of the sample before and after drying.

Moisture content data obtained from the drying experiments were converted into the dimensionless moisture ratio (MR). MR and drying rate (DR) were calculated using the following equations:

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (3)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

where M_i, M_t, M_e and M_{t+dt} are moisture content (g water/g dry matter) at initial, specific time, equilibrium and t+dt, respectively; t is drying time (min). Prolonged drying yields burnt paddy, of which the moisture content closes to zero. Hence, it was reasonable to omit M_e.

Energy consumption: Energy consumption of the dryer was analyzed by the Visilogic program, version 8.0, which was installed in PLC. During the process of drying paddy from 27 to 17% (w.b.), energy required by the dryer was determined. It was divided into three parts: energy for blower and control system, for heaters and for microwave. The total energy consumption was the sum of the energy from these three parts. The energy used during heating up was excluded. The measurements were repeated three times.

Statistical analysis: The experimental data were analyzed using the analysis of variance (ANOVA) technique in a completely randomized design. Duncan's multiple range test ($p \leq 0.05$) was used to determine the significance of differences between treatments. All the analyses were performed using the SPSS (version 16.0) computer program.

Results and Discussion

Comparison of microwave generation and absorbance efficiency between SMA and MMA: The efficiency of microwave generation in SMA and MMA is presented in Fig. 3. The similar results of about 60% generation efficiency were obtained either from SMA or MMA and either at microwave power density of 0.82, 1.04 or 1.70 kW/kg. These showed that microwave generation was applicator type- and microwave power density-independent.

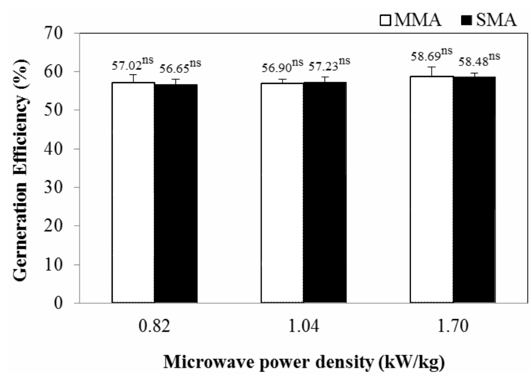

Figure 3. Efficiency of microwave generation in MMA and SMA at various microwave power density.

Although the amounts of microwave generated in SMA and MMA were similar, the amounts of microwave absorbed by water in the two applicators were significantly different (Fig. 4). The efficiency of microwave absorbance in SMA was almost 100% while that in MMA was about 80% at every microwave power density. It was obvious that water could absorb the greater amount of microwave when heating in SMA. This confirmed that the strength of microwave field in SMA was much higher than that in

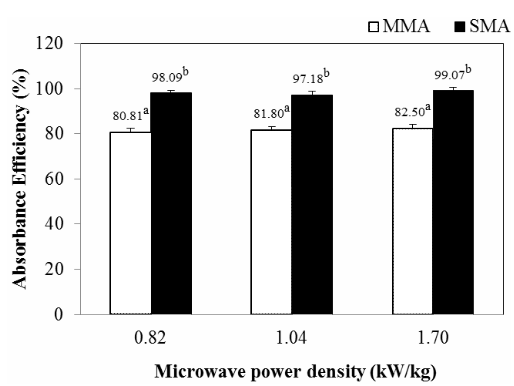

Figure 4. Efficiency of microwave absorbance by water in MMA and SMA at various microwave power density.

MMA. However, both of the generation and absorbance of microwave energy remained unaffected by varied microwave power density. These results are in agreement with the observation of Lakshmi *et al.* [5]. They revealed that the generation and absorbance of microwave by water did not vary much with power level ranging from 60 to 100% at a power of 800 W.

Drying characteristics of paddy in SMA: Drying curves of paddy dried in SMA by four drying methods are presented in Fig. 5. To reduce moisture content of paddy from 27 to 17% (w.b.), drying time for MVFB, LT-MVFB, LT-VFB and HT-VFB drying was 6, 3, 40 and 3 min, respectively. It was evident that at the same drying temperature of 60ºC (comparing between LT-MVFB and LT-VFB drying), microwave assisted drying could reduce drying time by 92.5% when combined microwave to VFB drying. This finding was superior to previous studies on microwave-assisted fluidized bed drying. A 50% reduction in drying time was found when added microwave to FB drying of macaroni beads [2] and potato slices [8]. These studies applied microwave combination drying in MMA. The outstanding time reduction obtained in this study could contribute to the best microwave field strength generated in SMA. In addition, the drying time required for HT-VFB and LT-MVFB drying was similar. This meant that short time drying as normally achieved by drying at high temperature of 150ºC could be reached at lower temperature (60ºC) with the assistance of microwave.

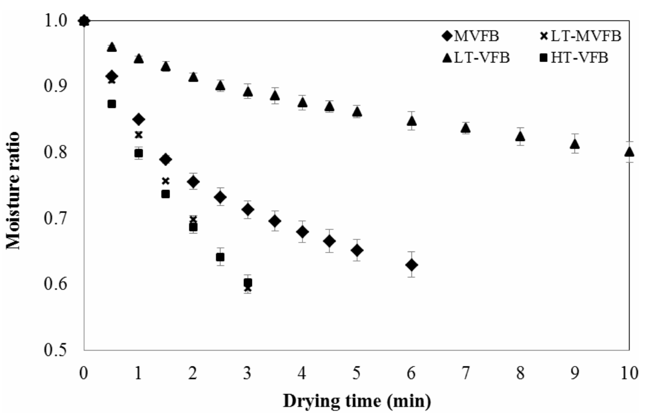

Figure 5. Drying curves for paddy dried by four drying methods.

As shown in Fig. 6, the peak drying rate was the greatest for HT-VFB drying, followed by LT-MVFB, MVFB and LT-VFB drying, respectively. However, it was observed that LT-MVFB drying could sustain high rate of water removal from paddy than HT-VFB drying. Therefore, LT-MVFB drying offered the highest average drying rate of 0.1159 g water/g dry matter.min. The average drying rate obtained by HT-VFB, MVFB and LT-VFB was 0.1134, 0.0598 and 0.0170 g water/g drying matter.min, respectively. It should be noted that the coupling effect of hot air and microwave drying considerably fasten the drying rate. Drying rate of LT-MVFB drying (hot air and microwave combination effect) was almost double and nine times as fast as that of MVFB drying (microwave single effect) and LT-VFB drying (hot air single effect), respectively.

Energy consumption and water loss during MVFB drying: The energy consumption and water loss during drying of paddy by four drying methods are presented in Table 2. The highest energy was required by LT-VFB drying, followed by HT-VFB, MVFB and

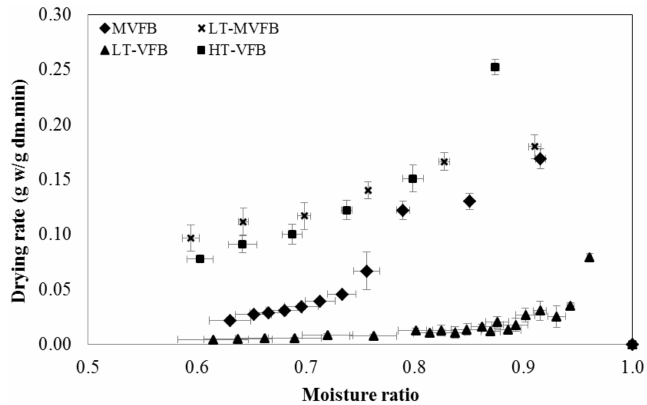

Figure 6. Drying rate curves for paddy dried by four drying methods.

Table 2. Energy consumption and water loss during drying of paddy by four drying methods.

Analysis	Microwave drying	MVFB drying	LT-VFB drying	HT-VFB drying
Total energy consumed (kW)	862.46	474.73	3,352.98	1108.23
- Operating energy	117.64	120.43	119.70	122.1
- Heating energy	376.54	216.71	3,233.28	986.13
- Microwave energy	368.28	137.59	-	-
Water loss (kg/h)	25.29	26.44	25.83	24.78

LT-MVFB drying, respectively. The longest drying time of LT-VFB drying (40 min) led to the highest energy requirements for drying, which was about 10 times higher than the energy required by LT-MVFB drying. Although the same drying time of 3 min was obtained from HT-VFB and LT-MVFB drying, HT-VFB drying required about 3 times higher energy than MVFB drying. In addition, it was clear that microwave magnetron consumed lower energy than heater required. Although MVFB drying needed longer time to dry, it still required lower energy.

Water loss of sample after drying can be used as an indirect measure for assessing the efficiency of heat utilization [5]. The greatest water loss was found from LT-MVFB drying, followed by LT-VFB, MVFB and HT-VFB drying, respectively. It was observed in this study that LT-MVFB drying, which required the lowest energy, could provide the highest efficiency of heat utilization. Therefore, LT-MVFB drying is the best method for the least energy consumption and highest water loss.

Conclusions

Microwave power density had no effect on generation and absorbance efficiency of SMA and MMA in water system. Comparing between SMA and MMA, generation efficiency of microwave was similar while absorbance efficiency of water was significantly different. Water in SMA could absorb greater microwave energy than that in MMA. Therefore, SMA-type drying chamber was selected to perform drying characteristics of paddy. In comparison with MVFB drying and LT- and HT-VFB drying, LT-MVFB drying required shorter drying time and offered higher drying rate at lower drying temperature. Furthermore, LT-MVFB drying consumed the lowest energy while reduced the greatest amount of water from paddy. This study presented the successful development of SMA-MVFB dryer for paddy drying.

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