Energy Efficiency in Microwave Drying of Rough and Brown Rice

Dong Tieyou[1], Toshinori Kimura[2], Shigeru Yoshizaki[2], Tomoteru Kawakami[3]
(1. *Department of Machinery Design Engineering, Luoyang Institute of Technology, Luoyang* 471003, *China*;
2. *University of Tsukuba, Tsukuba* 305-8572, *Japan*; 3. *Electrotechnical Laboratory, Tsukuba* 305-8569, *Japan*)

Abstract: According to the experimental data of this study, under well-managed conditions it is possible to utilize microwave energy for drying of rice with relatively high efficiency. Resting time (or tempering time) between every two periods of microwave drying is important for obtaining high energy efficiency, as there are the effects of tempering, or post-radiation, or intermittent radiation. And energy efficiency with resting time between every two periods of drying was much higherthan that without resting time. So, drying methods are important for energy efficiency. Loading methods are also important for energy efficiency. And thin layer drying method is recommended for microwave drying from the viewpoint of energy efficiency.

Key words: energy efficiency; microwave; drying; rough rice; brown rice
CLC number: TQ028.677　　**Document code**: A　　**Article ID**: 1002-6819(2002)05-0043-05

1 Introduction

Energy efficiency has ever been an important subject for cereal grain drying, because the reduction of operation cost of a dryer in large extent depended on it. All possible means have been taken in conventional drying of cereal grain for reducing energy consumption, especially after the oil shock in 1970s. As a result, energy efficiency reached very high level, e.g. for drying rough rice, the energy consumption can be as low as 3.0 to 7.0 MJ kg H_2O[1-3]. Moreover, with the environmental problems being seriously considered nowadays, energy efficiency is becoming a more and more important subject for further development of human civilization. And the judgment of a set of equipment is whether practical or not. As a new technique for the future, microwave drying should be energy saving and efficient. Unfortunately however, little attention has been paid to it until now.

The objectives of this study are to investigate the energy efficiency during deep bed and thin layer microwave drying of rough and brown rice.

2 Energy Efficiency Functions

Energy efficiency N_e (mg kg) in this study is calculated depending on the total energy consumed during microwave drying and the total mass amount of water (moisture) removed from rice.

The total energy consumed during microwave drying N (MJ) is

$$N = N_P + N_V \tag{1}$$

where N_P is the total microwave energy consumed during microwave drying, MJ; N_V is the total electric energy consumed by blower and other equipment of the dryer during microwave drying, MJ.

N_P (MJ) is calculated with the following equation

$$N_P = P_{inc} \tag{2}$$

where P_{inc} is the incident microwave power to drying chamber, MW; is the total drying time (the total microwave heating time), s.

Therefore, the energy efficiency N_e (MJ kg) could be

$$N_e = N \quad W \tag{3}$$

where W is the total mass amount of water removed from rice, kg.

3 Materials and Methods

In this study, Japonica-type Koshihikari rough rice was harvested in August 1997 with an initial moisture content of 26.0% to 27.7% (d.b.), and a loose bulk density of 563.8 kg m^3 and brown rice of the same breed harvested in August 1998 with an initial moisture content of 17.8% to 20.6% (d.b.), and a loose bulk density of 725.6 kg m^3 was used for the tests under loading condition LC1. And rough rice of the same breed harvested in August 1996 with an initial moisture content of 27.7% to 31.9% (d.b.), and a loose bulk density of 620.8 kg m^3 was used for the tests under loading condition LC2. A microwave drying experimental apparatus of Model SUK-12N

Received date: 2002-05-15
Biography: Dong Tieyou, Ph.D., associate professor, Department of Machinery Design Engineering, Luoyang Institute of Technology, Luoyang 471003, China　Email: tydong@hotmail.com

made by Shizuoka Works Co. provided the microwave drying conditions (Fig. 1). And a set of microwave power measuring equipment was used for measuring the total incident microwave power to the microwave-drying chamber and the total reflected microwave power from the microwave-drying chamber in this research, which was mainly composed of a microwave attenuator of Model 4A940, a directional coupler of Model WDC-20H-42SP made by SPC Electronics Corporation (Japan) and a microwattmeter (a kind of microwave power meter) made by Boonton Electronics Corporation (USA) (Fig. 1).

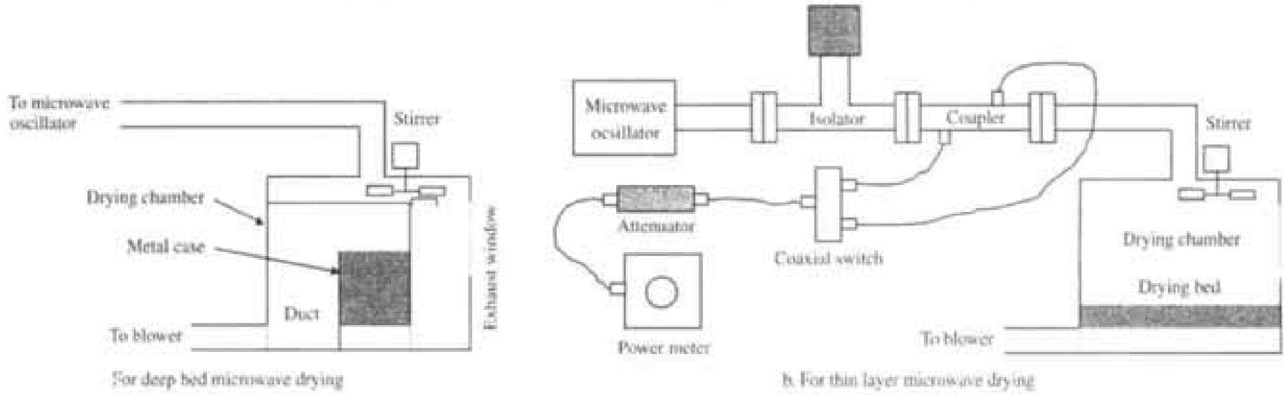

Fig. 1 Schematic diagram of the experimental apparatus

Table 1 Loading conditions for microwave drying experiments

Filling method		Kind of material	Amount of material kg
Symbols	Method and vessel		
LC1	Filled in a metallic case	Rough rice Brown rice	4.51 5.80
LC2	Spread uniformly all over the drying bed	Rough rice	5.42

Reports[4~6] on deep bed microwave drying of rough rice show that energy efficiency of concurrent flow ventilation is relatively high, i.e. the value of N_e is relatively low, compared with counter and cross flow ventilation under the same conditions. Therefore, in this study the experiments of deep bed microwave drying of rough and brown rice (i.e., under the loading condition LC1 shown in Fig. 1a and Table 1) under concurrent flow ventilation conditions were carried out. Concurrent flow ventilation here means the ventilation air flows in the same direction as the microwave propagates (Fig. 1a). A metallic case of cubic shape with a height of 200 mm filled with rice could lead microwaves to propagate only along the depth direction. For this reason, all the side walls of the case are structured by metallic sheets, which serve as microwave shelters and air conduits for ventilation and prevented microwaves from propagating through the side walls. The bottom of the case is made of a piece of metallic net. The top of the case remains open (Fig. 1a). In the case, rice was divided into ten thin layers with a thickness of 2 0 mm each by nine pieces of plastic net, and ten samples were taken from the center part of the thin layers for each test.

Experiments of microwave drying of thin layer rough rice were also carried out under the loading condition LC2 shown in Fig. 1b and Table 1 with the same equipment described above. Under this loading condition, rough rice was spread uniformly with a thickness about 20 mm all over the drying bed (Fig. 1b). The dimensions of the drying bed are 860 mm × 500 mm. Since there is a problem of non-uniform distribution of microwave radiation power density on the drying bed[7], the drying bed was divided into 21 sub-regions evenly, and the temperature and moisture content of rice at every sub-region were measured. Consequently, the drying results could be relative precisely calculated. During thin layer drying, resting time was taken between every two periods of drying.

4 Results and Discussions

The experimental data of thin layer microwave drying of rough rice under loading condition LC2 are shown in Table 2. And the experimental data of deep bed microwave drying of rough and brown rice under loading condition LC1 are listed in Tables 3 and 4. According to these results, it could be known that it is possible to utilize microwave energy for cereal grain drying with relatively high efficiency, or higher efficiency than that in conventional drying (Tests of No. 4 and 6 in Table 2).

Table 2 Energy efficiency during microwave drying of thin layer rough rice

Loading condition: LC2

Test No.	P kW kg^{-1}	M_o %(d.b.)	Drying Methods* Drying time-(resting time) h	N_e MJ kg^{-1}
1	0.04	29.98	5- (10)- 10- (5)- 20- (12)- 20	7.22
2		24.98	5- (7)- 10- (5)- 20- (10)- 20	6.14
3		31.72	5- (10)- 10- (2)- 20- (5)- 20	5.82
4		30.86	5- (10)- 10- (5)- 20- (15)- 20	3.06
5		18.73	20- (5)- 20- (5)- 20	19.52
6	0.09	27.33	5- (7)- 10- (20)- 20- (10)- 10- (10)- 10	3.76
7		27.32	5- (3.5)- 10- (25)- 20- (5)- 10- (5)- 10	4.55
8		22.27	40	8.73
9		21.76		9.83
10		24.09	20	9.49
11		27.54		14.36

Note: * The time unit here is minute, except the subscripted ones.

Drying conditions: Air temperature= 22.3℃; RH = 55%; v_a = 0.02 m s.

Table 3 Energy efficiency, N_e of deep bed microwave drying of rough rice

MJ • kg^{-1}H$_2$O

P kW kg^{-1}	v_a m • s^{-1}					
	0.00	0.05	0.07	0.12	0.20	0.64
0.07	21.06	8.38	7.87	6.30	6.06	8.03
0.10	24.40	10.13	10.05	9.63	11.72	14.32
0.14			13.59			

Note: Drying conditions: Air temperature= 21.0℃; RH = 65%;
Drying time= 90 min.
Loadin condition: LC1

Table 4 Energy efficiency, N_e of deep bed microwave drying of brown rice

MJ • kg^{-1}H$_2$O

P kW kg^{-1}	v_a m • s^{-1}					
	0.04	0.05	0.07	0.12	0.20	0.60
0.06	25.07	19.30	23.49	16.30	17.31	24.23
0.09		16.04	22.47	20.74	25.72	17.96
0.13			23.66	22.83	24.23	20.74

Note: Drying conditions: Air temperature= 22.3℃; RH = 60%;
Drying time= 90 min.
Loading condition: LC1

4.1 Effects of Superficial Air Speed and Absorbed Power on Energy Efficiency

According to the data shown in Table 3 and 4, with the increase of superficial air speed v_a, the energy consumption increased during deep bed drying. If the superficial air speed were too high, the microwave radiation energy dissipated in grain layers would be blown away by it. Therefore, superficial air speed should be as low as possible. There is also a tendency that the energy consumption increased with the increase of absorbed power P, especially for deep bed rough rice drying (Table 3). Thus, microwave power should be as low as possible, unless drying rate is seriously affected.

4.2 Effects of Loading Conditions on Energy Efficiency

According to the microwave transmission theory, microwave-drying device could be treated as transmission lines[8]. Load impedance, which is closely related to reflecting characteristics of the transmission line, depended on the dielectric characteristics, the kinds and the amounts of the materials loaded. Hence, load impedance will change according to the change of loading conditions, e.g. the changes of the kinds and the amounts of loaded materials in a microwave-drying chamber. Consequently, the power reflection coefficient of the transmission line, i.e., the power reflection coefficient of the microwave-drying chamber, will change in turn. As a matter of fact, the total microwave power absorbed by the material (here is rice) in a microwave-drying chamber and the energy efficiency will also change.

In this study, energy efficiency for loading condition LC2 (Table 2) was apparently higher than that for loading condition LC1 (Tables 3 an 4). This is because the power reflection coefficient for loading condition LC2 was generally smaller than that for loading condition LC1[8], with the same amount of rough rice being spread on drying bed and the same microwave power levels. Moreover, the evaporated moisture under loading condition LC2 was much more easily to escape for rice layer than it did under loading condition LC1. As a result, loading methods are important factors for energy efficiency. And thin layer drying method is recommended from the viewpoint of energy efficiency.

4.3 Effects of Drying Methods on Energy Efficiency

If resting time was taken between every two periods of microwave drying, the energy efficiency was obviously high (The tests of No. 3, 4, 6 and 7 in Table 2). The N_e value of the test of No. 6 with resting time between every two periods of microwave drying was about 1 5 that of test No. 11 (in Table 2) which had no resting time during drying process, although the initial moisture contents were almost the same. This might be the effects of tempering or post-radiation[9], or the effects of intermittent radiation[10]. Thus, by this means, microwave energy could be efficiently utilized. The drying results indicate that if the drying method of microwave drying is well managed, energy consumption could be controled at a very low level (Tests of No. 4 and 6 in Table 2). And, it is possible to utilize microwave energy for drying of rice grain with relatively high efficiency. Consequently, drying methods are important for energy efficiency.

4.4 Effects of Initial Moisture Content on Energy Efficiency

According to the experimental data, the lower the initial moisture contents of rice, the higher the energy consumption, since there is a trend that the lower the initial moisture content of rice, the higher the evaporation latent heat of it[11]. Energy efficiency of microwave drying reduced with the decrease of initial moisture content. The higher values of N_e of brown rice drying in Table 4 could be considered as the cause of its low initial moisture content.

5 Conclusions

1) Energy consumption of microwave drying could be at very low level under well managed conditions. And it is possible to utilize microwave energy for drying of rice with relatively high efficiency.

2) Resting time between every two periods of microwave drying is important for obtaining high energy efficiency. And the energy efficiency with resting time between every two periods of drying was much higher than that without resting time. Therefore, drying methods are also important for energy efficiency.

3) Loading methods are important for energy efficiency. And thin layer drying method is recommended for microwave drying for obtaining high energy efficiency.

Acknowledgements

The authors want to express their appreciation to Dr. Chuanping Feng and Dr. Naoto Shimizu (University of Tsukuba, Japan) for their cooperation in this study.

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微波干燥稻谷和糙米的能量效率

董铁有[1]，木村俊范[2]，吉崎繁[2]，川上友晖[3]

(1. 洛阳工学院机械设计工程系, 河南省洛阳市 471003; 2. 日本筑波大学农林工学系, 日本筑波市, 305-8572; 3. 日本通产省工业技术院电子技术综合研究所, 日本筑波市, 305-8569)

摘　要: 对厚层及均匀平铺载荷条件下稻谷和糙米的微波干燥过程中的能量效率问题进行了研究。根据本研究的实验数据, 如果干燥方法和工艺安排合理, 微波干燥稻谷和糙米可达到较高的能量效率, 甚至可达到高于传统干燥方法。在微波干燥过程中安排一定的间歇时间以发挥照射后期作用、间歇照射作用或缓苏作用, 可以有效地提高微波干燥过程中的能量效率。有 2 h 间歇的干燥工艺的能量效率是没有间歇的干燥工艺的能量效率的 5 倍。载荷形式对微波干燥过程中的能量效率影响也较大。微波干燥中建议采用薄层载荷形式。

关键词: 能量效率; 微波; 干燥; 稻谷; 糙米