Performance of a Continuous Fluidized Bed Microwave Paddy Drying System using Applicators with Perpendicular Slots on a Concentric Cylindrical Cavity

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Abstract— **This paper presents a continuous fluidized bed microwave drying system which can enhance the capacity of a system without a microwave fluidized bed. The applicator consists of perpendicular slots on a concentric cylindrical cavity excited by perpendicular waveguides. Paddies to be dried are dropped along a vertical direction into the center of the applicator while air of $60^{\circ}C$ from magnetron ventilation is injected in the opposite direction. The proposed system was constructed and tested. It provides paddies with the same quality as the ones from the fluidized bed drying system. The leakage power was within the safety standard. With 5.2kW power consumption, the system reduces moisture content from 24% to 14% with a capacity of 3.1kg/hour.**

Index Terms—**Microwave heating, Fluidized bed, Fluidized bed microwave heating, Paddy drying.**

I. Introduction

Rice grain infesting insects can develop in grain moisture as low as 10%, and maximizes at 14%. Although some insects can successfully develop in a grain moisture content of 18% or greater, fungal growth becomes a more critical concern at this point. Rice is typically stored at a moisture content of around 14% [1]. Fluidization is the process by which solid particles attain a fluid-like state through suspension in a flowing gas or liquid [2]. This state is achieved when the drag force on the particles of the upward-flowing liquid equals or exceeds the weight of the particles. Fluidized bed drying offers the advantages of good mixing, high heat and mass transfer coefficients and hence increased drying rates resulting in a shorter drying time [3]. Microwaves have been widely applied in food, chemical, agricultural industries and so on [4] due to the feature of volumetric heating. Many researches were conducted to dry agricultural products [5] and a combination of microwave with hot air drying resulting in a fluidized bed microwave heating technique has shown significant improvement in operation cost and quality of products [6]. The excellent mixing which can be obtained between the solid and the gas, and the high homogeneous temperature, make the fluidized bed well suited to several applications. The combination of the fluidization technique with microwave heating has provided significant benefits. Improvements such as lower energy cost, appreciable reduction in processing time, and enhanced product quality have been accomplished [7]-[8].

A number of microwave applicators have been developed to fulfill the requirements of uniform heat distribution in the material to be heated [9]-[11]. The previous work proposed an applicator for a continuous microwave heating system [12] and showed its performance in rice drying. Since rice was contained in the whole volume of the applicator, moisture cannot be conveniently removed. In addition, rice must be tempered for 60-90 minutes to reduce moisture content to the desirable level resulting in a long drying time. This paper illustrates the design of a fluidized bed microwave drying system and its performance in paddy drying. Comparison of paddy quality with conventional fluidized bed heating is demonstrated.

II. System Principle

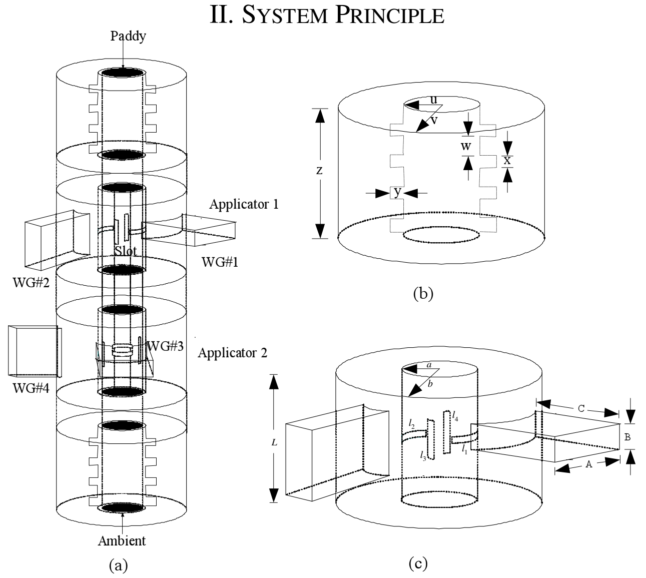

Fig.1. A continuous fluidized bed microwave paddy drying system.
(a) System. (b) Corrugated waveguide. (c) Applicator.

A continuous fluidized bed microwave paddy drying system consists of an array of applicators with perpendicular slots on a concentric cylindrical cavity excited by perpendicular waveguides [12]. Microwave energy from magnetron tubes excites the cavity through perpendicular rectangular waveguides on the outer surface of the applicator. The applicator system is equipped with cylindrical corrugated waveguides at two ends for electromagnetic leakage protection. Paddies to be dried are dropped along the vertical direction into the center of the applicator while air is injected in the opposite direction. The diagram of the proposed system is shown in Fig.1(a). Corrugated choke and dimensions of the applicator are depicted in Fig.1 (b) and (c), respectively.

The cavity that resonates TM^{z}_{010} and TE^{z}_{111} modes has inner radius *a*, outer radius *b* and length *L*, respectively. The rectangular waveguides which are employed to excite this cavity has width *A*, height *B* and length *C*. All perpendicular slots have lengths equal *l*.

III. System Performance

A. Design

The system was designed and constructed to comply with the safety standard based on the ASAE S248.3 standard [13]. The dimensions are listed in Table I and the photograph of the system is shown in Fig.2 where paddies are fed to the system through a hopper on the top and taken away from the bottom. Note that the number of corrugations in the corrugated waveguide is four. By utilizing the calorimeter technique, power generated from each magnetron supplied to each waveguide is measured and tabulated in Table II with the power consumption of each magnetron. Power consumption of the motor for air injection is 363 W. Hence, the system efficiency is 61.5%.

Fig.2. Photograph of the system.

TABLE I
Dimensions

Dimension	*a*	*b*	*L*	*A*	*B*	*C*	*l*	*w*	*x*	*y*	*z*
(cm)	6.1	7.7	11.5	9.0	4.5	16.7	6.1	2.3	2.0	2.0	4.3

TABLE II
Power Generated from Each Magnetron

	WG # 1 (W)	**WG # 2** (W)	**WG # 3** (W)	**WG # 4** (W)
Power generated	750	795	837	774
Power consumption	1200	1210	1219	1205

B. Power Generated and Leakage Power Density

Since exposure to sufficiently high levels of microwave will cause heating, in the case of human tissue, excessive heating could have serious health effects such as deep tissue burns and hyperthermia. Therefore, it is necessary to avoid all known adverse health effects by limiting exposure to levels below those at which heating occurs. The standard value of Maximum Permissible Exposure (MPE) for controlled environments at the frequency of 3kHz to 300GHz is about $8mW/cm^2$ at 2.45GHz [13].

It was found from experiments that leakage power density from all six sides of the system are less than $8mW/cm^2$. Fig.3 shows leakage power density at various distances from each side of the system. It is clearly seen that leakage power density is less than the standard level.

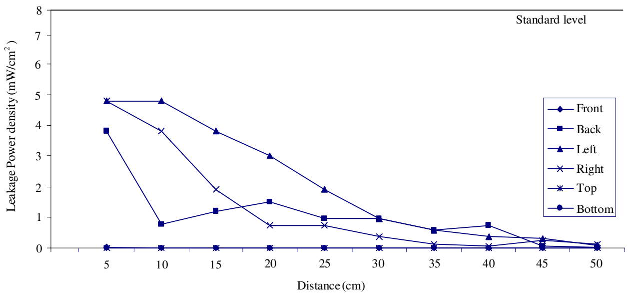

Fig.3. Leakage power density at various distances from the system.

C. Capacity of the System

In order to compare capacities of the proposed system with the conventional drying systems, experiments were set up to reduce moisture content from 24% to 14% in the constructed system. For fluidized bed drying with ambient air of $30^{\circ}C$, paddies (density of 40% of applicator volume) were dried in the system when microwave power was turned off. An ambient air temperature of $30^{\circ}C$ was injected into the system with a flow rate of 6m/s. Power consumption, capacity and energy cost were 0.36kW, 0.38kg/hr and 445US$/ton, respectively. When hot air of $60^{\circ}C$ was injected into the system, power consumption was increased to 1.32kw with an increased capacity to 1.30 kg/hr. It should be noted that energy cost was less than the previous case due to drying time being reduced from five hours to one hour. For microwave drying, a bulk of paddy was continuously fed to the system. It was heated for 30 minutes, tempered for 60 minutes and heated for another 30 minutes. Although power consumption was markedly increased to 4.80kW, capacity was increased to 2.15kg/hr. However, energy cost was increased to 210US$/ton. The capacity was further increased to 2.63kg/hr with slightly higher power consumption when a fluidized bed microwave with ambient temperature air was injected. Energy cost was reduced to 188US$/ton. The last case was the fluidized bed microwave drying when hot air from magnetron ventilation of $60^{\circ}C$ was injected into the system. It was obvious that power consumption of 5.2kW and energy cost of 157US$/ton provides the highest capacity of 3.1kg/hr. It can be pointed out that the constructed fluidized bed microwave drying system with hot air from magnetron ventilation outperforms the other drying schemes.

D. Quality of Paddy

The term food quality includes three principal areas: nutritional value, acceptability and safety. Acceptability includes a large array of attributes, among them visual appeal, aroma, flavor, texture, mouth feel, convenience, and cultural appropriateness [14]. Sticky rice paddy was dried using a fluidized bed microwave drying system and a normal ambient air drier which was used as a control. After drying the paddy to 14% moisture content, the paddy was sent to the Department of Food Science and Technology, Kasetsart University for quality evaluation. The paddy was milled using the laboratory rice milling machine. The head rice yield and the quality of milled rice were determined. The color of milled rice was measured by the CIELAB colorimeter [15]. Water absorption ratio and volume expansion ratio were determined. Four replications were done and T-test statistical analysis was conducted to determine the difference between the two samples. Head rice yield is increased around 7% while the color of white rice, water absorption ratio and volume expansion ratio are almost identical to the reference rice. Sensory evaluation of cooked rice including color, odor and taste are in the same level while texture is markedly improved. Overall acceptability of rice from fluidized bed microwave heating is better than the reference rice.

There is no significant difference at the 95% level between the two treatments in the head rice yield, color of milled rice, the water absorption ratio and the expansion ratio and the sensory preference. The test results are summarized in Table III.

TABLE III
Paddy Quality

Quality	Fluidized bed Microwave (FBM)	Reference Rice (RR)
Head rice yield (%)	36.97	32.61
Color of white rice		
L*	81.496	81.356
a*	-1.858	-1.736
b*	10.754	10.662
Water absorption ratio	2.5	2.44
Volume expansion ratio	2.33	2.31
Sensory evaluation of cooked rice		
Color	6.60	6.65
Odor	6.15	6.05
Taste	6.55	6.35
Texture	6.30	5.65
Overall acceptability	6.30	6.20

Rice cracking was tested by using a scanning electron microscope. The appearance of the reference rice is rougher than the one from the fluidized bed microwave drying one. The cross section views exhibit similar cracks in both samples. The enlarged views show a similar size of cracks in both samples. Therefore it can be concluded that the fluidized bed microwave drying system has a good performance and produces good quality sticky rice.

IV. CONCLUSION

A fluidized bed microwave drying system was proposed for paddy drying. It consisted of two applicators which each had four perpendicular slots. Each applicator was excited by two magnetrons. The system was designed and constructed. Four 2M226 magnetrons each of 900W were used to apply microwave power and 363W was used for blowing hot air from magnetrons to the bed. The system efficiency was 61.5%. Leakage power density was markedly lower than the safety standard which ensured a safe operation. The system outperforms the other drying schemes and possesses a capacity of 3.1kg/hour with power consumption of 5.2kW. It is a promising system for paddy drying.

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