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Full Paper

Analysis of a continuous fluidised-bed microwave rice kernel drying system

C. Sangdao [1,*] and M. Krairiksh [2]

[1] Department of Telecommunication Engineering, Mahanakorn University of Technology, 51 Moo 1, Cheum-Sampan Rd., Nong Chok, Bangkok 10530, Thailand

[2] Faculty of Engineering and Research Centre for Communications and Information Technology, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

[*] Corresponding author, e-mail: chokchai@mut.ac.th

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Abstract: This paper presents an analysis of a continuous fluidised-bed microwave rice kernel drying system. Its applicator consists of perpendicular slots on a concentric cylindrical cavity excited by perpendicular waveguides. Bulk rice to be dried is dropped along the vertical direction into the centre of the applicator while ambient air is injected in the opposite direction. Statistical data of electric field and temperature distribution in rice kernels were studied with consideration of the probability of kernel orientation. It was found that a density of kernels at 40 percent of the applicator volume with the air flow rate of 6 metres per second was suitable. With a microwave power of 3,200W, the heating time was 6 minutes. The expected capacity was 3.93 litres/hour. These results were used for implementing a fluidised-bed microwave rice kernel drying system.

Keywords: microwave heating, fluidised-bed, rice drying

Introduction

Fluidisation is the process by which solid particles attain a fluid-like state through suspension in a flowing gas or liquid [1]. This state is achieved when the drag force of the upward-flowing liquid on the particles equals or exceeds the weight of the particles. Fluidised-bed drying offers the advantages of good mixing and high heat and mass transfer coefficients, resulting in an increased drying rate and a shorter drying time [2]. Microwave has been widely applied in food, chemical, and agricultural industries among others [3] due to the feature of volumetric heating. This follows the law of energy conservation which states that the rate of energy incident upon a control surface plus any rate of internal generation must balance the rate at which the energy stored changes within the control volume plus the rate at which energy leaves the control surface. The internal heat generation is a volumetric process and could be due to the flow of an electric current as in ohmic heating or the flow of displacement currents. Therefore, microwave heating does not depend on the transfer of heat through a surface. The existence of a volumetric heat source affords a rapid transfer of energy throughout the body of wet solid and alters the physical characteristics of drying. Many researches were conducted to dry agricultural products [4] and a combination of microwave with hot-air drying resulting in a fluidised-bed microwave heating technique has shown significant improvement in operation cost and quality of products [5]. Varith et al. [6] developed a drying process for peeled longan using combined microwave-hot air. It was shown that the proposed process significantly reduced drying time and specific energy consumption by 64.3% and 48.2% respectively, compared to hot air drying. Feng and Tang [7] applied a microwave spouted-bed in drying diced apples and found a great improvement in temperature uniformity and drying time. The combination of the fluidisation 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 [8-9].

Rice kernel moisture content varies corresponding to water quantity, which exerts an impact on its dielectric property. A multitude of insects are adapted to the relatively dry environment of stored rice. These insects are a considerable threat to maintaining the quality of the rice. Rice kernel infesting insects can develop in kernel moisture as low as 10%, and maximise at 14%. Although some insects can successfully develop in kernel 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% [10]. A previous work proposed an applicator for continuous microwave heating system [11] and showed its performance in rice drying. Since rice occupied the whole volume of the applicator, moisture could not be conveniently removed. In addition, rice must be tempered for 60-90 minutes to reduce moisture content to a desirable level, resulting in a long drying time.

In order to develop a fluidised-bed microwave rice drying system using the above applicator, parameters such as rice density in the applicator and flow rate must be investigated. For the calculation scheme, Chen et al. [12] developed a model to simulate the coupled phenomena of electromagnetic heating and conventional heating by a commercial electromagnetic software based on finite difference time domain (FDTD) with a customer-built heat transfer model. A heat- and mass-transfer model was developed to simulate microwave and spouted bed combined (MWSB) drying of diced apples. A total gas-pressure equation was introduced to take into account internal vapour generation during microwave drying [13]. Vegh and Turner [14] introduced a coupled method for the solution of the governing electromagnetic equations. The free-space component of the solution was computed in the time domain, whilst the power distribution in the load was resolved using a frequency-dependent electric field Helmholtz equation.

The objective of this work is to analyse a continuous fluidised-bed microwave rice drying system which consists of an applicator which is a concentric cylindrical cavity-backed slot array applicator and

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

possesses a simple configuration and design. The cavity was designed to operate in both TM^z and TE^z mode so that horizontal and vertical slot arrays could operate simultaneously. The proposed system was analysed to find an appropriate condition of rice density, temperature, drying rate, microwave energy and ambient air flow rate. Electric field distribution was analysed by using CST microwave studio based on finite integral technique (FIT) while temperature distribution was analysed by finite difference method (FD).

Materials and Methods

A continuous fluidised-bed microwave rice drying system consisted of an array of applicators with perpendicular slots on a concentric cylindrical cavity excited by perpendicular waveguides. Microwave energy from magnetron tubes excited the cavity through perpendicular rectangular waveguides on the outer surface of the applicator. The applicator system was equipped with cylindrical corrugated waveguides at two ends for electromagnetic leakage protection. Kernels to be dried were dropped along the vertical direction into the centre of the applicator while air of ambient temperature from a blower was injected in the opposite direction. The diagram of the proposed system is shown in Figure 1a. The corrugated waveguide and the dimension of the applicator are shown in Figures 1b and 1c respectively.

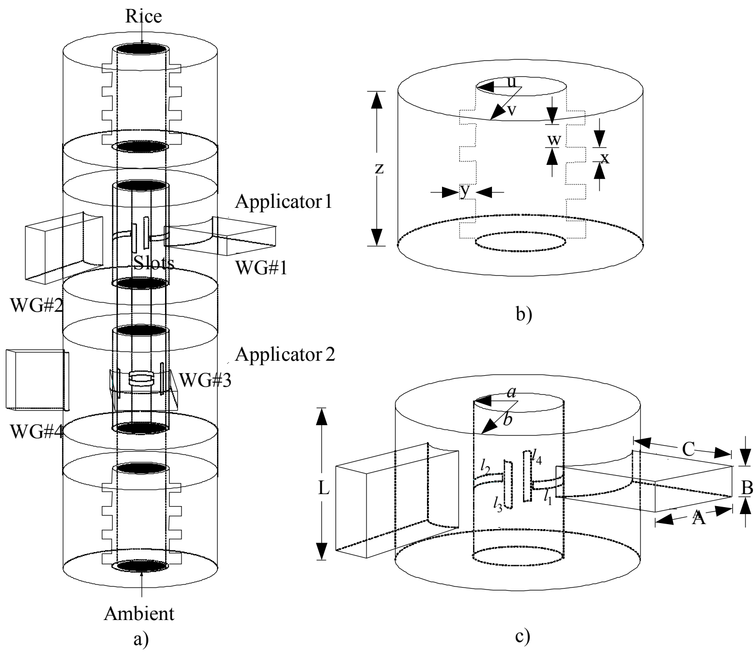


Figure 1. A continuous fluidised-bed microwave rice drying system
a) System ; b) Corrugated waveguide ; c) Applicator
(a=6.1cm, b=7.7cm, L=11.5cm, A=9.0cm, B=4.5cm, C=16.67cm,
$l_1 = l_2 = l_3 = l_4 = 6.1$cm, u=6.0cm, v=8.7cm, w=2.3cm, x=2.0cm, y=2.0cm, z=43.0cm)

The applicator in this work was designed to operate at 2.45 GHz. The cavity that resonated TM^z_{010} and TE^z_{111} modes had an inner radius, outer radius and length of 6.1 cm, 7.7 cm and 11.5 cm respectively. The rectangular waveguides which were employed to excite this cavity were 9 cm wide,

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

4.5 cm high and 16.67 cm long. All perpendicular slots were half-wave long and equal to 6.1 cm. The density of rice in the applicator, temperature, drying rate, microwave energy and ambient air flow rate were calculated to find a suitable working condition that could be obtained from an electric field and temperature distribution.

In this study, the temperature distribution in the rice kernels contained in the applicator was evaluated from the electric field in each input of bulk rice. Each kernel was modelled as having an ellipsoid geometry of 1.056 cm long and 0.247 cm and 0.194 cm thick on the two sides. It has the density, mass and volume of 1.347 $\mathrm{g/cm^3}$, 0.0254 g and 0.00265 $\mathrm{cm^3}$ respectively. The applicator volume was 1,344 $\mathrm{cm^3}$ containing 37,100 kernels or 77 layers of 480 kernels in each layer. The CST microwave studio [15] based on finite integral technique (FIT) [16] was utilised. The space inside the applicator was discretised into a number of hexahedral meshes (there are 12,493 meshes). Kernels were then laid on a plane in the applicator as seen in Figure 2. The rice density was varied with different numbers of layer. The electric field intensity in each kernel was calculated. Once the electric field distribution was obtained, the square of electric field distribution was applied in a heat transfer equation in the last term of (1) while the first (in brackets) and second terms were conduction and convection heat transfer respectively [3]:

$$\frac{\partial T(\rho,\phi,z;t)}{\partial t}=\frac{k_t}{\rho_m c_m}\left\{\frac{1}{\rho}\frac{\partial\left(\rho\frac{\partial T(\rho,\phi,z;t)}{\partial\rho}\right)}{\partial\rho}+\frac{1}{\rho^2}\frac{\partial^2 T(\rho,\phi,z;t)}{\partial\phi^2}+\frac{\partial^2 T(\rho,\phi,z;t)}{\partial z^2}\right\}$$

$$-\frac{v_s}{\rho_m c_m}\left(T(\rho,\phi,z;t)-T_a\right)+\frac{\omega\varepsilon_o\varepsilon_r\left|\vec{E}\right|^2}{2\rho_m c_m} \qquad (1)$$

[where $T(\rho,\phi,z;t)$ = temperature (°C) at arbitrary position and time, T_a = ambient temperature (°C), k_t = heat conductivity of rice (W/m·K), v_s = ambient flow rate ($\mathrm{W/m^3\cdot{}^\circ C}$), c_m = heat capacity of rice (kJ/kg°C), ρ_m = rice density ($\mathrm{kg/m^3}$), ε_0 = permittivity of free space (F/m) and ε_r = the dielectric constant of rice while $\vec{E}$ = the magnitude of total electric field distribution in rice (v/m) and t = time (s).] This equation was discretised into square grids and a uniform electric field in each grid was assumed. It should be noted that constant material properties have been assumed in the simulation. The temperature in the rice can be found from the finite difference method with ambient air temperature of 30°C. The property of rice is shown in Table 1.

An experiment was set up in a fluidised-bed tower to investigate the probability of rice kernel orientation. A rice kernel was placed in a glass tower 100 cm long and 9.3 cm in diameter, into which air of an ambient temperature with a flow rate of 3.8m/s was injected. The kernel was raised to a height of 10 cm and video clips were captured for 90 seconds. They were then sampled for 150 pictures to observe the orientation. It was found that 31%, 26% and 43% were in the radius, circumference and

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

Table 1. Property of rice [17]

Property	Value	Unit
k_t	0.097	$(W/m \cdot K)$
c_m	1,800	(kJ/kg°C)
ρ_m	1.347	(g/cc)
ε_r	4.0	-
σ	10^{-3}	S/m

vertical orientation respectively. These percentages of orientation were weighted to calculate the electric field intensity.

A probability density function (PDF) is a function that represents the probability distribution of a random variable. Here, the electric field intensity and temperature are random variables. In this work, the electric field intensity on each rice kernel was sampled and plotted as histogram which is afterwards smoothed out to present the PDF.

A cumulative distribution function (CDF) for a random variable is defined as the probability that the random variable is less than or equal to a specified value. It is the area under the probability density function up to the specified value.

Simulation Results

The number of kernels was varied for density in the applicator to investigate the probability density function of electric field intensity in rice. A personal computer with Intel Core 2 CPU 4400 at a speed of 2.0 GHz and RAM of 2.00 GB was used in the calculation. The CST microwave studio was utilised in the simulation of electric field intensity with a power of 1W applied to each magnetron. Consequently, a total power of two watts was applied to each applicator. The rice flow rate through the applicator, ambient air (of $30^{\circ}C$ flowing in the opposite direction of the moving rice), flow rate and microwave power were varied.

Electric field distribution

By varying the inner radius (from 5.6 cm to 6.6 cm), outer radius (from 7.2 cm to 8.2 cm), cavity length (from 11.0 cm to 12.0 cm) and slot length (from 5.6 cm to 6.6 cm), a respective value of 6.1, 7.7, 11.5 and 6.1 cm was suitable for providing a maximum electric field intensity in the cavity. It took place near the inner cavity surface at the four positions near the positions of the waveguide and opposite to the waveguides. Hence, slots were cut at these positions.

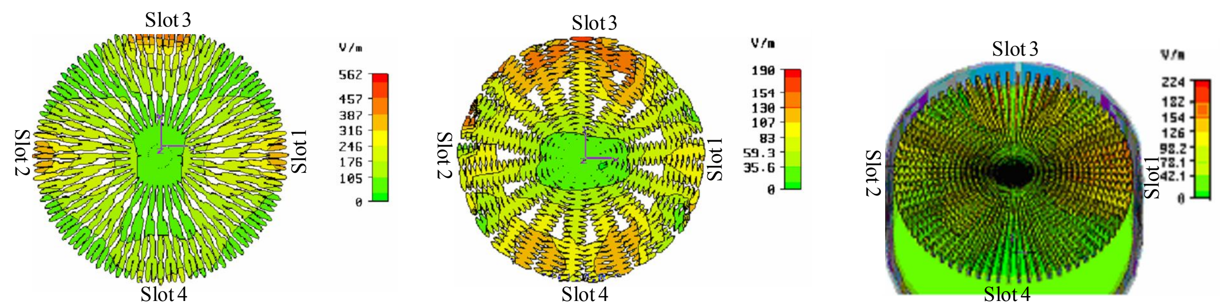
Kernels were oriented in three directions, viz. radius, circumference and vertical, along the applicator geometry (see Figure 2). As rice density was varied from 20% to 80% of the applicator volume, the corresponding bulk density varied as shown in Table 2. It was found that the mean value of electric field intensity varied corresponding to this density in addition to the orientation. The maximum values of 258 v/m, 118 v/m and 82 v/m corresponded to the density of 40% oriented in

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

radius direction, 80% in vertical direction, and 60% in circumference direction respectively.

Table 2. Relationship of grain and bulk density

Grain density (%)	Bulk density (g/cc)
1 Seed	2.6×10^{-5}
10	0.096
20	0.188
30	0.287
40	0.383
50	0.478
60	0.574
70	0.670
80	0.766
90	0.861
100	0.956



a) b) c)

Figure 2. Electric field distribution in rice kernels :

a) Kernels oriented along radius direction

b) Kernels oriented along circumference direction

c) Kernels oriented along vertical direction

(Note: Slots 1 and 2 were horizontal slots, while slots 3 and 4 were vertical slots.)

It is obvious from Figures 2a-c that the electric field distribution has a maximum value at the slot position and decreases to a minimum at the centre of the applicator. A high value of electric field intensity could be obtained when the number of kernels was less. Most kernels were exposed to an electric field at a moderate level at all rice densities and orientations.

Statistical data are illustrated in terms of probability density function (PDF) of the electric field intensity in each kernel (Figure 3). Figures 3a, b and c show the PDF when kernels were oriented along

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

radius, circumference and vertical direction respectively. The highest mean was obtained when rice density was 40%, 60% and 80% along radius, circumference and vertical direction respectively.

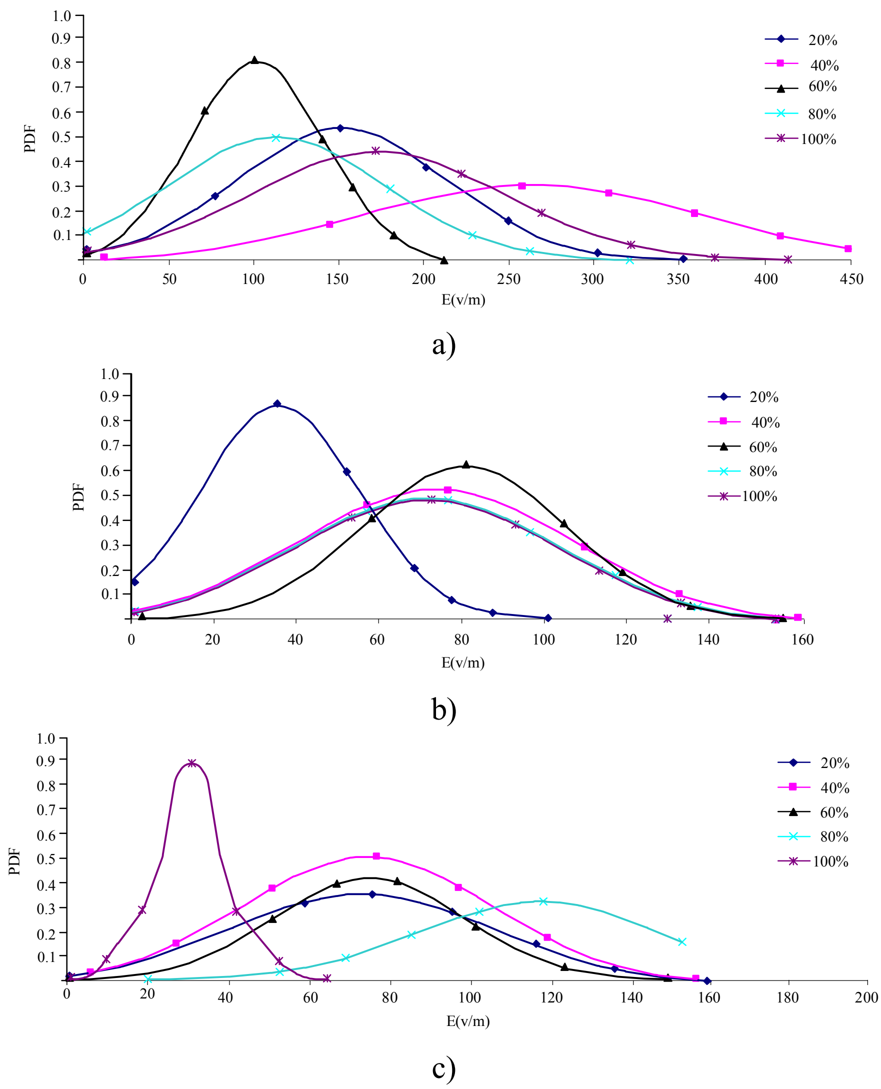


Figure 3. Probability density function of electric field intensity in rice kernels :

a) Kernels oriented along radius direction
b) Kernels oriented along circumference direction
c) Kernels oriented along vertical direction

At 20% density, the mean electric field intensity was 151 v/m, 35 v/m and 75 v/m in the radius, circumference and vertical direction respectively. The measured probability of orientation in the previous section was used to weigh the mean electric field intensity in three orientations at densities of 20%, 40%, 60% and 80%. The weighted means at 20%, 40%, 60% and 80% densities were 88.0 v/m, 133.5 v/m, 88.5 v/m and 105.6 v/m respectively. The PDF of these cases is illustrated in Figure 4. It is clearly shown that densities of 20%, 60% and 80% possessed a low mean electric field intensity ranging

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

from 1 v/m to 200 v/m. The density of 40% had the highest mean value of 135 v/m with scattered data from 1 v/m to 310 v/m. However, it is not clear which density was suitable.

The system was required to provide high electric field intensity, and consequently high temperature, in each kernel. To clarify the reliability of the system on how the probability of the electric field intensity was less than the specified value, the cumulative distribution function (CDF) weighted from the three orientations at densities of 20%, 40%, 60% and 80% was plotted as in Figure 5. It is obvious that the density of 40% has the least probability of the electric field intensity being less than the specified value. For instance, the probability of electric field intensity being less than 150 v/m of the densities of 20%, 60% and 80% was around 75% while those of the 40% counterpart was less than 30%. It could be summarised that a rice density of 40% was suitable in this application.

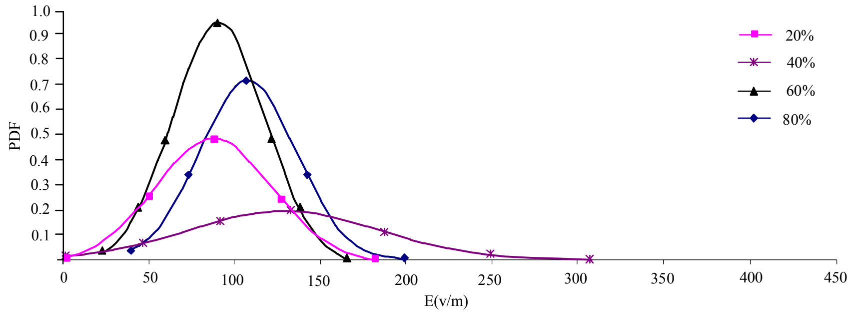


Figure 4. Variation of PDF of electric field intensity in rice kernel weighted by kernel orientation at various kernel densities

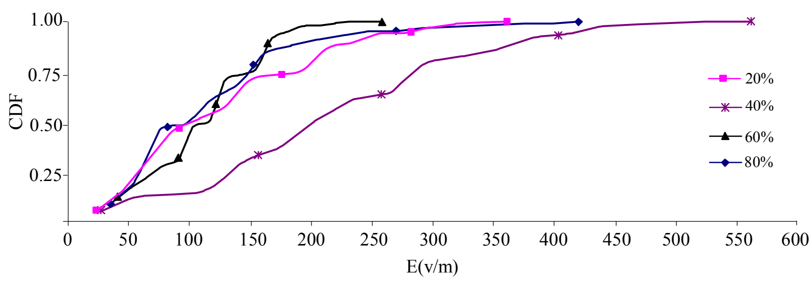


Figure 5. Variation of CDF of electric field intensity in rice kernel at various kernel densities

Temperature distribution

The results in the previous section revealed that rice density should be 40% of the applicator volume. The other parameters included the time the rice was exposed to the electric field and the air flow rate. In this section, temperature distribution was calculated at 40% rice density. The air temperature was set to an ambient temperature of $30^{\circ}C$. The practical air flow rate could be varied from 0.1 m/s to 6 m/s. Hence, calculation was conducted at 3 m/s and 6 m/s. Since a 800W magnetron would be used in future practice, microwave power for the applicator was fixed at the level of 1.6 kW. When two applicators were used, the power was doubled to 3.2 kW. The CDF curves from various cases are shown in Figure 6, depicting the probability of rice temperature being less than the specified value on the horizontal axis. The curves A, B and C are for the cases of 1.6 kW microwave power for 2, 6 and 10 minutes, while solid line and dashed line are for air flow rate of 3 m/s and 6 m/s respectively. It was found that the mean temperatures were $39^{\circ}C$, $58^{\circ}C$ and $77^{\circ}C$ respectively. When two applicators were used, a power of 3.2 kW was excited. Curves D and E show mean temperatures of $47^{\circ}C$ and $75^{\circ}C$ for the time of 2 and 6 minutes respectively.

When the probability of the temperature being less than $50^{\circ}C$ was considered by using one applicator excited by 1.6 kW microwave power as in curve B, it was found that the probability was 5%. The probability that the temperature was less than $60^{\circ}C$ in curve B was 80%, while that in curve C was 5%. The probability of the temperature being less than $70^{\circ}C$ in curve C was 25%, which means that if the temperature was over $70^{\circ}C$, the system shown in curve C would provide the best performance. Consequently, when two 800W microwave magnetrons were used, heating time was in excess of 10 minutes while the air flow rate could either be 3 m/s or 6 m/s. When two applicators that generated 3.2 kW were used, the temperature rose to $47^{\circ}C$ in 2 minutes, as seen in curve D. As time increased to 6 minutes, the temperature rose to $77^{\circ}C$ (see curve E). The system in curve E accomplished the best performance of low probability of temperature less than $60^{\circ}C$ and the least heating time.

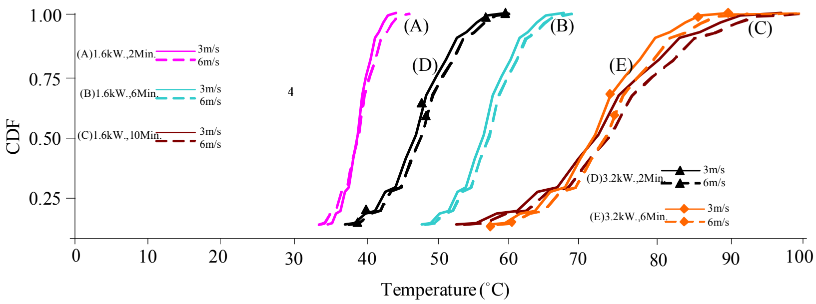


Figure 6. CDF of temperature with microwave power of 1.6 kW and 3.2 kW at different heating time and air flow rates

The results in Figure 6 demonstrated that by increasing heating time in 4-minute steps, the temperature could be elevated by $19^{\circ}C$ to $20^{\circ}C$ from one applicator. The two applicators provided a temperature rise of $30^{\circ}C$. A previous work [11] noted that when the temperature was $80^{\circ}C$, heating time was in excess of 10 minutes in the case of one applicator. Two applicators could reduce heating time to 6 minutes. The expected capacity was 3.93 litres/hour.

Conclusions

This paper reports on the analysis of a continuous fluidised-bed microwave rice kernel drying system. Parametric studies from electric field and temperature distribution revealed that suitable rice density in the applicator should be 40% of the applicator volume. Rice kernels exposed to a 1.6 kW microwave power for 10 minutes with the air flow rate of 6 m/s had a temperature in excess of $77^{\circ}C$ from the initial ambient temperature of $30^{\circ}C$. This condition was sufficient for reducing moisture content in rice. As two applicators were used, microwave power was doubled to 3.2 kW. The temperature in the rice was as high as $75^{\circ}C$ and drying time was reduced to 6 minutes. The expected

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 61-71

capacity was 3.93 litres/hour. The system drastically increased the capacity as compared to that previously reported. The system will be constructed to validate the simulation results in the future.

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