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Mathematical modeling of a fixed-bed dryer for paddy-rice and its comparison with a fluidized-bed dryer

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ABSTRACT

The moisture movement and the variation of temperature are simulated for paddy-rice in a fixed-bed dryer and fluidized-bed dryer by taking shrinkage into account. The equations of change were solved with an implicit numerical method. The drying time of Paddy-rice for both a fixed-bed and a fluidized-bed dryer is compared with the respective experimental data. The paddy type was named "Neda" with 25% initial moisture content. The drying process continued until the moisture content of paddy reduced to 12-14%. It was found that drying time in fluidized-bed dryer was 1/3 - 1/2 that of a fixed-bed dryer and this technique could be used instead of fixed-bed dryers.

KEYWORDS

Paddy-rice;
Dryer;
Fixed-bed;
Fluidized-bed;
Mathematical modeling.

INTRODUCTION

Freshly harvested paddy contains about 25% moisture content that should be dried rapidly to prevent its degradation. In order to obtain good quality rice, it is necessary to choose a suitable method for drying of paddy under controlled conditions. Rice quality, head rice yield (HRY) and color depend on the drying conditions.

Using the fixed-bed dryers is a common technique for drying of paddy in the North of Iran. In these dryers, quality of the product is non-uniform, because a lot of material remains in the bed and grains are stale. A better rice quality can be obtained by fluidized-bed dryers, in which the heat and mass transfer coefficients are much higher than those of other types and the drying time is reduced.

Simulation and study of paddy quality for an in-store dryer was done by Can Chun *et al*.[3]. They showed that the drying air temperature between 30-40 °C and relative humidity of 70% were the best conditions for having good quality rice. The simulation of deep-bed grain dryer for paddy was done by Sitompul *et al*.[10]. The model was capable of prediction of the grain moisture content and temperature at any radius of the bed at any time. Simulation of a cross flow continuous fluidized-bed dryer for Paddy-Rice was done by Izadifar and Mowla[4]. The model was based on the differential equations, which were obtained by applying the momentum, mass and energy balances to each element of the dryer and also on the drying properties of paddy. The proposed model was solved by writing a computer program, which took the operating conditions as input and gives the hydrodynamic properties as well as the variation of moisture content of paddy through the dryer as output. Different fluidizing characteristics of paddy, needed in the program, were determined from the drying experiments in the literature.

Tirawanichakul *et al*.[13] used in-store drying technique using ambient air temperature and showed that the head rice yield, stickiness and whiteness of samples dried from initial moisture contents of 18.5–20.6% to 13.3 ±0.6% wet basis at temperature of 30 ± 4 °C and specific airflow rates of 0.65–1.5 m^3/min. m^3 of paddy reduces but hardness increases. As compared with the qualities of control samples which were gently dried by ambient air aeration in thin layer dryer, they were all slightly different. They also proposed a near-equilibrium drying model incorporating the yellowing kinetics of paddy. The model was reasonable to predict the experimental data. The simulation results indicated that the degree of whiteness was dependent on temperature, relative humidity, loading capacity and airflow rate. The relative humidity lower than 70% and specific airflow rate higher than 0.75 m^3/min m^3 of paddy were recommended.

Rafiee and Kashaninejad[9] simulated paddy moisture profile in an in-store dryer. They found that control of drying conditions is vital for quality of rice. They used finite element method for simulating the moisture transport within the paddies. The initial moisture content of their paddy was 32.986%; temperature, relative humidity and velocity of drying air were 40 °C, 32% and 1.5 m/s, respectively. Head rice yield (HRY) and operating time in fluidized-bed dryer was studied by Poomsa-ad *et al.*[7]. They found that moisture content after first-stage drying and tempering have a dominant effect on head-rice yield and operating time in reducing high-moisture contents to a safe level. Based on the simulation results they recommended that the allowable temperature should be not higher than 150 °C for the first stage and the moisture content after first-stage drying should be not lower than 22.5% dry basis, with subsequent tempering for at least 25 min.

A transient heat and mass transfer model was developed for the packed bed drying of paddy rice using the local volume averaging method by Izadifar *et al.*[5]. In their work, the required conditions for the application of the local volume averaging were evaluated including appropriate length, time, and temperature scales and justified for fixed bed paddy rice drying. Taking local thermal equilibrium in each representative elementary volume, transient mass and heat transfer governing equations were derived. The transport mechanisms considered were conduction and diffusion as well as convection heat and mass transfer. In their model, the transport coefficients were functions of moisture content and temperature, and change during drying process. The governing heat and mass transfer equations were simultaneously solved using an implicit numerical method. The simulation results were compared to available experimental data from literatures. Although the physical properties were from different independent research and independent of the experimental data used for model validation, their predicted results showed a reasonable agreement with the measured data.

Simulation and modeling of Paddy-Rice was performed by Bunyawanichakul *et al.*[2] in a simple pneumatic dryer. The effect of specific airflow rate, which depends on dryer diameter, paddy feed rate and inlet-air velocity on the final moisture content, and temperature of paddy grain and air stream was studied. They claimed that this dryer was useful when grain residence time was high and the length of dryer was small.

Aquerreta *et al.*[1] investigated the effect of high temperature intermittent drying and tempering on rough rice quality. In their work the effect of the number of drying cycles associated with different tempering treatments on rough rice kernel fissuring and head rice yield (HRY) has been studied for initial and final moisture contents usually found in the rice processing industry. Results showed that post-drying tempering at high temperature (60 °C) resulted in greater moisture removals and that drying time reductions up to 38% can be achieved. They also claimed that percentage of fissured kernels was drastically reduced when drying was performed in two or three steps compared to drying in one step. Tempering at high temperature reduced the percentage of fissured kernels and enhanced HRY independently of the number of drying steps.

It should be noticed that, in all papers shrinkage effect was neglected and grains were of spherical shape. In this work, in addition to considering the shrinkage effect, the drying time in a fixed-bed dryer is compared with a fluidized-bed dryer. For this purpose both types of dryers are modeled and compared with the respective data. After validation of the models, the comparison is made between two dryers.

MATHEMATICAL MODELING

Mathematical modeling of the fixed-bed dryer

Figure 1 shows the schematic diagram of a bed of paddy grains with a cross sectional area, (A), height, (L). Equations of change are written for a control volume element with the height Δz. Heat transfers from the bottom to the top of the bed in the form of conduction and convection. The following assumptions were made in order to simplify the mathematical modeling of grain drying in a deep bed:

- Grain kernels are uniform in size and internally homogenous /isotropic cylinders.
- Heat and moisture transfer occurs only in z-direction of the bed without any transport in r-direction.
- Dryer walls are well insulated.
- Shrinkage affects the height of the bed.
- Density, diffusivity, heat conduction coefficient, specific heat and porosity are constant.

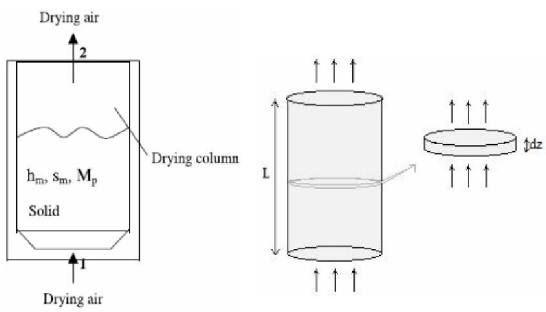

Figure 1 : Schematic diagram of a packed bed as well as a differential element of the bed.

Mass balance equation for drying air

The governing equation for describing absolute humidity of drying air can be written as follows:

$$\frac{\partial(y\rho_a)}{\partial t} = \frac{\partial}{\partial z}\left(D_a \frac{\partial(y\rho_a)}{\partial z}\right) - \frac{\partial}{\partial z}\left(U_z(y\rho_a)\right) + \frac{a}{\varepsilon_b}K_m(y^* - y) \quad (1)$$

The mass transfer coefficient for the fixed-bed dryer was obtained from Strumillo & Kudra[12].

$$J_M = 1.82\,Re^{-0.51} \qquad 40 < Re < 350 \quad (2)$$

$$J_M = \frac{K_m}{\rho_a U_z}\left(\frac{\nu}{D_a}\right) \quad (3)$$

Relative humidity should be evaluated by Henderson´s Equation[11]:

$$1 - RH = \exp[-0.0000078(1.8T_b + 491.7)(100X_e)^{2.088}] \quad (4)$$

and the equilibrium absolute humidity (y^*) by[14]:

$$y^* = \frac{RH.P_w}{P_t - RH.P_w} \quad (5)$$

Energy balance equation for drying air

Energy balance equation for drying air can be written as follows:

$$\frac{\partial}{\partial t}(\rho_a(C_{pa} + yC_{pv})T_b) = \frac{\partial}{\partial z}\left(k_a \frac{\partial T_b}{\partial z}\right) - \frac{\partial}{\partial z}(U_z\rho_a(C_{pa} + yC_{pv})T_b) - \frac{a}{\varepsilon_b}[K_m(y^* - y)\Delta H + h(T_b - T_p)] \quad (6)$$

Heat transfer coefficient for fixed-bed dryer that was reported by Strumillo & Kudra[12] can be obtained as follows:

$$J_H = 1.06\,Re^{-0.41} \qquad 35 < Re < 350 \quad (7)$$

$$J_H = \frac{h}{\rho_a U_z C_{pa}}\left(\frac{\nu}{\alpha}\right)^{2/3} \quad (8)$$

Where, α is thermal diffusivity. The initial and boundary conditions for Eq's 1 and 6 are as follows:

$$t = 0 \qquad 0 \le z \le L \qquad y = y_0 \qquad T_b = T_0 \quad (9)$$

$$t > 0 \qquad z = 0 \qquad y = y_0 \qquad T_b = T_0 \quad (10)$$

$$t > 0 \qquad z = L \qquad \frac{\partial y}{\partial z} = 0 \qquad \frac{\partial T_b}{\partial z} = 0 \quad (11)$$

Mass balance equation for a single rice in the fixed-bed

The vaporized moisture from paddy transfers to the drying air. Mass transfer equation for the bed of paddy grains (see Figure 2) could be written as:

$$\frac{\partial x}{\partial t} = \frac{D_p}{r}\frac{\partial}{\partial r}\left(r\frac{\partial X}{\partial r}\right) \quad (12)$$

The initial and boundary conditions for Eq. 12 are as follows:

$$t = 0 \qquad r = r \qquad X = X_0 \quad (13)$$

$$t > 0 \qquad r = 0 \qquad \frac{\partial X}{\partial r} = 0 \quad (14)$$

$$t > 0 \qquad r = R \qquad -\rho_p D_p \frac{\partial X}{\partial r} = K_m(\bar{y}^* - \bar{y}) \quad (15)$$

Energy balance equation for the fixed-bed

Based on Figure 2, the energy balance equation for the fixed-bed dryer should be written as:

$$\rho_p C_{p_p} \frac{\partial T_p}{\partial t} = \frac{m_s k_p}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_p}{\partial r}\right) \quad (16)$$

The initial and boundary conditions for Eq. 16 are as follows:

$$t = 0 \qquad r = r \qquad T_p = T_{p0} \quad (17)$$

$$t > 0 \qquad r = 0 \qquad \frac{\partial T_p}{\partial r} = 0 \quad (18)$$

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$$t > 0 \qquad r = R \qquad -k_p \frac{\partial T_p}{\partial r} = K_m(\bar{y}^* - \bar{y})\Delta H + h(T_p - \bar{T}_b) \qquad (19)$$

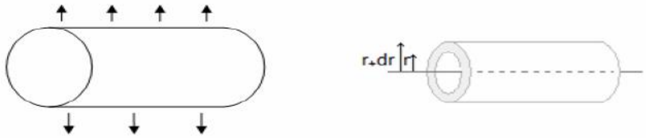

Figure 2 : Schematic diagram of a paddy grain as well as a differential element

Mathematical modeling of the fluidized-bed dryer

Figure 3 shows the schematic diagram of a fluidized-bed with cross sectional area (A), height of fluidization (L) along with a volume element with the height Δz.

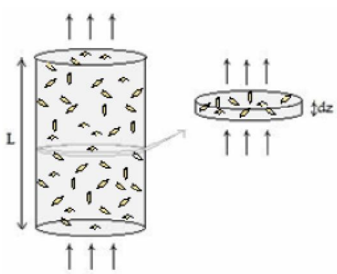

Figure 3 : Schematic diagram of a Fluidized bed as well as a differential element of the bed

Mass balance equation for drying air

The governing equation for describing absolute humidity of drying air can be written as follows:

$$\frac{\partial(y\rho_a)}{\partial t} = -\frac{\partial}{\partial z}(U_z y\rho_a) + \frac{a}{\varepsilon_{mf}} K_m(y^* - y) \qquad (20)$$

The mass transfer coefficient for fluidized-bed dryer (K_m) was obtained from Strumillo and Kudra[12]:

$$Sh = 2.01\ Re^{0.5} \qquad 15 < Re < 500 \qquad (21)$$

$$Sh = \frac{K_m d_p}{\rho_p D_p} \qquad (22)$$

The general correlation for minimum fluidization porosity, ε_{mf} is given by Kunii and Levenspiel[6]:

$$Re_{mf} = \frac{d_p u_{mf} \rho_a}{\mu_a} \qquad (23)$$

$$Ar = \frac{d_p^3(\rho_P - \rho_a)g}{\mu_a^2} \qquad (24)$$

$$\frac{1.75}{\varepsilon_{mf}^3 \varphi_s} Re_{mf}^2 + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 \varphi_s^2} Re_{mf} = Ar \qquad (25)$$

Energy balance equation for drying air

Energy balance equation for drying air can be written as follows:

$$\frac{\partial}{\partial t}\left(\rho_a(C_{pa} + yC_{pv})T_b\right) = -\frac{\partial}{\partial z}\left(U_z\rho_a(C_{pa} + yC_{pv})T_b\right) - \frac{a}{\varepsilon_b}\left[K_m(y^* - y)\Delta H + h(T_b - T_p)\right] \qquad (26)$$

Heat transfer coefficient for fluidized-bed dryer was obtained by Strumillo & Kudra[12]:

$$Nu = 0.316\ Re^{0.8} \qquad 80 < Re < 500 \qquad (27)$$

$$Nu = \frac{hd_p}{k_p} \qquad (28)$$

The initial and boundary conditions for Eq's 20 and 26 are as follows:

$$t = 0 \qquad 0 \le z\ L \quad y = y_0 \qquad T_b = T_0 \qquad (29)$$

$$t > 0 \qquad z = 0 \quad y = y_0 \qquad T_b = T_0 \qquad (30)$$

Mass and energy balance equations for the particles in fluidized-bed are the same as those of the fixed-bed dryer.

Shrinkage effect

The equation for description of shrinkage in the bulk of paddy of long grain rice with variation of moisture content from 39% dry basis to 12% was developed by Preechakul[8] and is given by:

$$V = 0.001997 + 0.0012X \qquad (31)$$

EXPERIMENTAL WORK

The main purpose of this work was the investigation of drying time for paddy-rice whose moisture content had to be decreased from 25% to 14% dry basis in two different types of dryers. Figure 4 illustrates schematic diagram of the dryer. It consists of a cylindrical glass bin with a diameter of 4.7 cm and height of 60 cm. A 2 kW electrical heater was used for heating the inlet drying air. The temperature of the air is controlled by an on-off controller. The same apparatus was used for the experiments of both dryers but with different air velocities (u=0.42 m/s for fixed-bed dryer and u=4.55 m/s for fluidized-bed dryer). A wire screen was installed on top of the dryer for the prevention of particles going out of dryer.

Experiments were performed at four different air temperatures of 34, 44, 54 and 64 °C. For the calculation of moisture content of the bed, paddies were weighted periodically at different time intervals. Paddy samples in

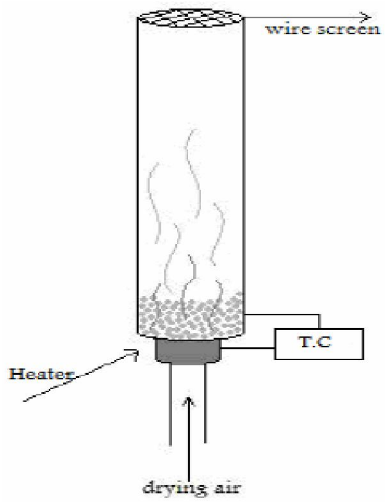

Figure 4 : Schematic diagram of dryer

all tests were Neda species (medium size productive grains that grow in Gorgan, a region in North of Iran) with 25% initial moisture content. Weight of sample in each experiment is 50 g. Grains were of cylindrical shape with ~0.001 m diameter and ~0.005 m height.

RESULT AND DISCUSSION

Equations (1), (6), (13) and (17) for the fixed-bed dryer and Equations (12), (16), (20) and (26) for the fluidized-bed dryer were solved implicitly by numerical methods. The parameters and respected values that were used for simulation are summarized in TABLE 1. Many researchers have studied the accuracy of the implicit method for solving the equations of this type[3,5,9]. They have claimed the good agreement between predicted results by the model with the respective experimental data.

TABLE 1 : Data used for simulation

Parameter	Value	Ref.
C_p	1012	[15]
C_{pv}	2030	[3]
X_0	0.25	Exp.
X_{sat}	0.12	Exp.
ΔH	$2.357*10^6$	[3]
D_p	$7.85*10^{-11}$	[3]
D_a	$2.58*10^{-5}$	[15]
k_a	0.65	[15]
ε_{b0}	0.65	Exp.
ρ_a	1.157	[15]
ρ_b	521	[3]
R	0.5	Exp.

Experimental and calculated drying curves for the fixed-bed dryer are depicted in Figure 5 and for the fluidized-bed dryer in Figure 6 at the drying air temperatures of 34, 44, 54 and 64°C. It could be observed that there exists a good agreement between the predictions of the model with experimental data. The maximum deviation between the predicted and calculated values for the fixed-bed and fluidized-bed dryers was 1.47 and 2.44% respectively. Also the mean absolute deviations were 0.6 and 1.57%. After the validity of the proposed models was checked, the effect of various parameters was predicted by the models.

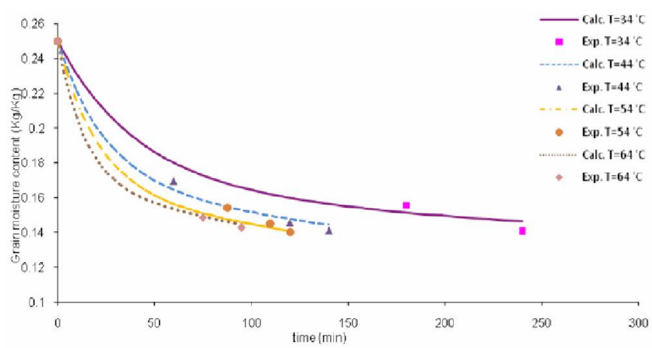

Figure 5 : Predicted and experimental data of paddy rice moisture content in fixed bed dryer

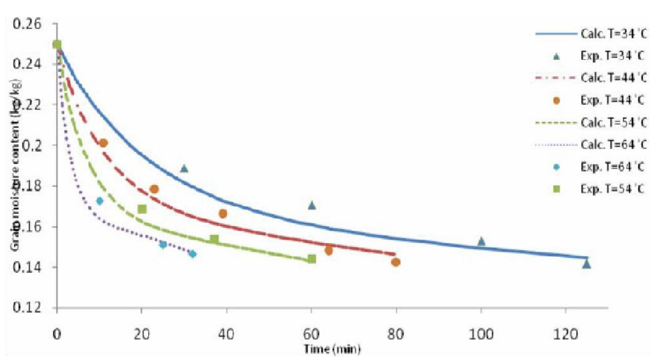

Figure 6 : Predicted and experimental data of paddy rice moisture content in fluidized bed dryer

Investigation of the profiles of absolute humidity of the outlet drying gas across the bed at four different temperatures in two dryers show an increasing trend by increasing the moisture removal from the grains. Figure 7 and 8 illustrates the variation of the drying air temperature with the height of the bed. As it could be seen, reduction of the moisture content of grains due to evaporation causes the decrease of bed temperature from the bottom to top. Temperature decreases from the bottom to the top of the bed.

Figure 9 and 10 present the variation of grain

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temperature with drying time at four different air temperatures. Moisture in the paddy is unbounded, so during the drying process, temperature of the paddy increases. Rate of drying in the fluidized-bed dryer is very high (transfer coefficients are high), so at early stages grain temperature decreases and then increases with elapse of time.

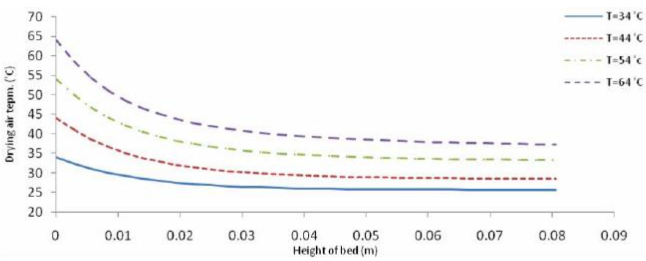

Figure 7 : Variation of drying air temperature with the height of bed in fixed bed dryer

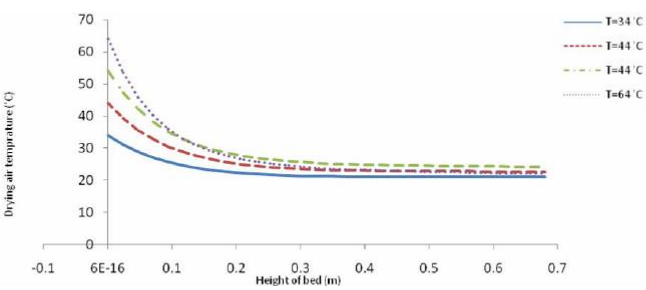

Figure 8 : Variation of drying air temperature with the height of bed in fluidized bed dryer

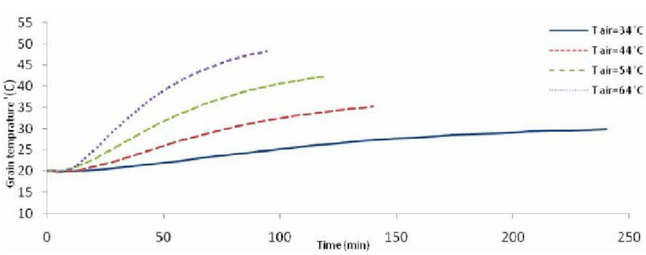

Figure 9 : Variation of grain temperature with the drying time in fixed bed dryer

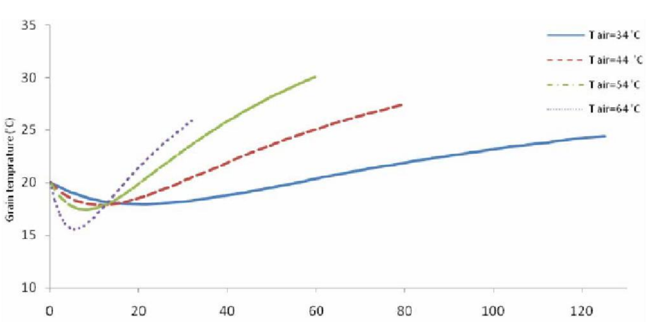

Figure 10 : Variation of grain temperature with the drying time in fluidized bed dryer

Figures 11 and 12 illustrate the variation of moisture content paddy-rice with drying time when shrinkage effect is not ignored in two kinds of dryers. By considering the shrinkage effect into model, the agreement between the predicted results and experimental values increases; although the maximum error due to ignorance of shrinkage is not more than 5.5%.

The comparison of experimental drying time in two types of dryers, (fixed-bed and fluidized-bed dryer) is summarized in TABLE 2. It was found that the drying time in the fluidized-bed dryer was 1/3 – 1/2 of the drying time of the fixed-bed dryer. This should be related to higher transfer rates in fluidized-bed dryers than fixed-bed ones.

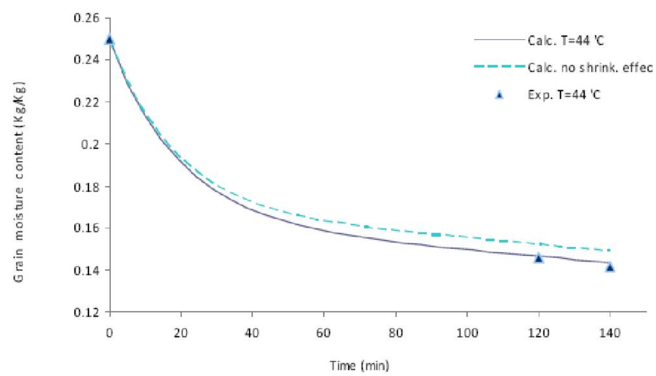

Figure 11 : Predicted and experimental data of paddy rice moisture content with shrinkage effect in fixed bed dryer

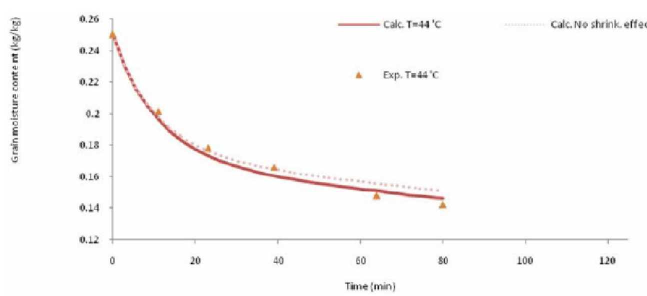

Figure 12 : Predicted and experimental data of paddy rice moisture content with shrinkage effect in fluidized bed dryer

TABLE 2 : Comparison of drying time in fixed and fluidized bed dryers

Temp. (°C)	Drying time (min)	
	Fixed bed dryer	Fluidized bed dryer
34	240	125
44	140	80
54	120	60
64	95	32

The absolute humidity of the drying gas is lower at the bottom of the fixed-bed dryer than other sections.

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The results show that using a fluidized-bed dryer instead of fixed-bed dryer is more feasible, because drying time is much lower in a fluidized-bed dryer and also the quality of the product is better.

NOMENCLATURE

a	Specific area of bed grains, m^2/m^3
$\mathbf{C_{pa}}$	Specific heat of drying gas, J/kg.K
$\mathbf{C_{pv}}$	Specific heat of water vapour, J/kg.K
C_{Pp}	Specific heat of paddy J/kg.K
$\mathbf{D_p}$	Moisture diffusivity (m^2/s)
h	Heat transfer coefficient for fixed-bed, $J/m^2.K.s$
k_G	Thermal conductivity of drying air, (J/m.K.s)
k_p	Thermal conductivity of paddy (J/m.K.s)
$\mathbf{K_m}$	Mass transfer coefficient
$\mathbf{m_s}$	Dry mass of bed grains, kg
P_t	Saturation vapor pressure of moisture on the surface of grains (mm Hg)
R	Radius of particle, mm
Re	Reynolds number
RH	Relative humidity
$\mathbf{T\infty}$	Temperature of ambient air (°C)
T_b	Drying air temperature (°C)
U_a	Inlet air velocity, m/s
U_z	Superficial air velocity, m/s
V	Volume per kilogram of dry matter, m^3/kg
X	Moisture content of bed, kg/kg dry
$\mathbf{X_e}$	Equilibrium moisture content (kg/Kg dry mass)
Y	Absolute humidity of drying air (kg/Kg dry air)
y*	Equilibrium absolute humidity
$\mathbf{y\infty}$	Absolute humidity of ambient air kg/kg dry air
$\Delta\mathbf{H}$	Heat of vaporization of water, J/kg
α	Thermal diffusivity, m^2/s
ε_{mf}	Minimum fluidization porosity
ε_{b0}	Initial bed porosity
ρ_a	Air density, kg/m^3
ρ_b	Initial density of bed, kg/m^3
φ_s	Sphericity of a particle
ν	Kinematic viscosity

CONCLUSION

Mathematical models were developed and presented for the drying of paddy-rice in fixed-bed and fluidized-bed dryers. It was found that the model could predict the average moisture content of the grains as a function of drying time. Air temperature and absolute humidity at different axial levels of the bed as function of time could be predicted by the model and a good agreement was observed.

The comparison of experimental data and simulation results show that, using fluidized-bed dryer for drying of Paddy-Rice was feasible and drying time in a fluidized-bed dryer was 1/3 – 1/2 of the drying time of a fixed-bed dryer.

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