Experimental and Theoretical Investigation of Moisture Dynamics in Intermittent Drying of Rough Rice

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Abstract

Intermittent drying is a satisfactory technique for drying of heat sensitive grains especially rough rice. This method consists of two separate stages applied intermittently: drying and tempering. In this work, intermittent drying of rough rice is investigated both theoretically and experimentally. In order to characterize this process; a multi-scale model consisting of macroscopic and microscopic submodels has been developed. Macroscopic model calculates the moisture changes of the rough rice bed assuming a lumped model for grains, while the microscopic submodel determines the rate of moisture gradient removal during the resting period. In latter submodel, moisture is assumed to diffuse through the grains governing by Fick's law. Further, a set of experiments were designed and carried out in a lab-scale fluidized bed dryer to estimate the model parameters as well as to evaluate the effects of different parameters such as temperature, air velocity, and tempering time on the drying rate. The model estimates show good agreement with experimental data. Model's results reveal that thermal equilibrium is rapidly obtained within the first two minutes of grain-hot air exposure. Air velocity shows to have no significant effect on drying rate when fluidized condition is prevailed. In addition, a significant kink occurs in drying rate diagrams which implies that drying rate is improved as a result of moisture gradient removal by applying tempering period.

Keywords: Intermittent drying, Mathematical modeling, Parameter estimation Rough rice

Introduction

Rough rice is cultivated on various regions all over the world. This valuable cereal constitutes a major part of meals for the majority of the world's population. Rice is harvested at various moisture contents ranging from 18% to 35% (dry basis) which depend on rice variety as well as climate conditions. Inappropriate drying is the main cause of the cereal losses among the post-harvest processes [1]. However, harvesting the rice with high moisture usually results in better efficiency and less damaged grains. This moist rough rice must be dried as soon as possible; otherwise, it will decay as a result of enzymatic or microbial (mold or bacteria) reactions or even may germinate [2]. Therefore, proper drying of grains is necessary for subsequent long-time storage, milling and whitening processes. Improper drying of rough rice causes fissuring in grains and inclines them to crack. In the case that drying rate is greater than the allowable rate, the grains will be subjected to a thermal shock and it will consequently increase the fissures in the grains.

Since the moisture diffusion inside the grains is very slow, heating should be stopped at specified periods to facilitate the moisture to reach the surface; then, rough rice is ready to receive heat again. This intermediate stage in which drying is stopped is called tempering. This combined method is also called intermittent drying. In other word, surface moisture evaporates during the drying stage. As a result, moisture gradients are generated inside the grains. As a matter of fact, main goal of tempering stage is to degrade these moisture gradients[3,4].

At the present time, most of the rough rice mills in Iran use traditional drying methods [5]. In these methods, the bulk of grains do not dry uniformly as distribution of the hot air is not uniform. In addition, turning on/off the burner is according to the temperature of the bed surface in undefined time intervals which wastes huge amount of the hot air. So, there is a necessity for modification of such out-dated methods. Some alternative drying strate giesareproposed so that to remedy such

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difficulties. Fluidized bed drying along with tempering stages seems to be a reasonable solution for the aforesaid problems.

Several experimental and theoretical works have been conducted to describe the characteristics of an intermittent drying process. Steffe et al. [6] considered the effect of the tempering and drying time on quality of the rice and removal of the moisture. Effects of the tempering temperature on tempering time and head rice yield were also studied by Li et al. [7] and Cnossen et al. [8]. Their efforts showed that the temperature of tempering stage has considerable influence on tempering time. A true description of the drying and tempering stages totally depends on the true description of the moisture profile inside the grains [9]. Dong et al. [10] performed the intermittent drying of two different varieties and predicted the moisture distribution within rice kernel by a simplified spherical model. Intermittent drying of paddy rice was experimentally and theoretically investigated by Cihan et al. [11]. In their study, intermittent drying and behavior of a single rough rice layer was simulated using a liquid diffusion model established on a prolate spheroid geometry. Optimization of intermittent drying of paddy rice was performed by Golmohammadi et al. [3]. In their work the total drying process time including both drying and tempering stages as well as the temperature of each stage was optimized.

Moreover, some researches have been conducted concerning the fluidized bed drying operation. Palancz [12] proposed a mathematical model for continuous fluidized bed drying based on the two-phase model of fluidization [13]. Soponronnarit et al. [14] designed, constructed and tested a commercial scale vibro-fluidized bed paddy dryer with a capacity of 2.5-5 tons/h. In their research, they took the specific energy consumption into account and also established a cost analysis to find the optimal operating conditions. Izadifar et al. [15] developed a mathematical model for a packed bed of paddy rice using local volume averaging (LVA) approach. In their study, the heat and mass transfer governing equations were derived and numerically solved.

In the current study, a lab-scale fluidized bed dryer was designed and constructed in order to consider the effects of different parameters on the process. A parameter estimation problem was initially considered to evaluate the best value for the drying constant according to experimental data. Consequently results of the macroscopic submodel were presented and compared with the experimental data. Effect of tempering time was investigated using microscopic submodel as well as using experimental data. The microscopic submodel was also used to evaluate the effect of tempering temperature. Other parameters such as drying temperature and air velocity were experimentally investigated.

Material and methods

Mathematical modeling

As previously mentioned, the process is performed in two stages: drying and tempering. The drying stage is modeled using a single phase model of fluidized bed drying [13] whereas for the tempering stage, the diffusion equation in a sphere is solved to describe the grains moisture concentration. These two models are explained in detail as follows.

Modelling of drying stage

In a single-phase model, fluidized bed is considered as a continuum [13] so, the whole bed is chosen as a control volume (Fig. 1). Then the heat and mass balances are established to evaluate the dynamics of temperature and moisture of the bulk. The following simplifying assumptions were used:

1. The bed is completely mixed so that there are no temperature and moisture gradients in the bed
2. Conduction heat transfer between grains is negligible
3. The system is assumed to be adiabatic

4. Air mass flow rate is constant along the bed

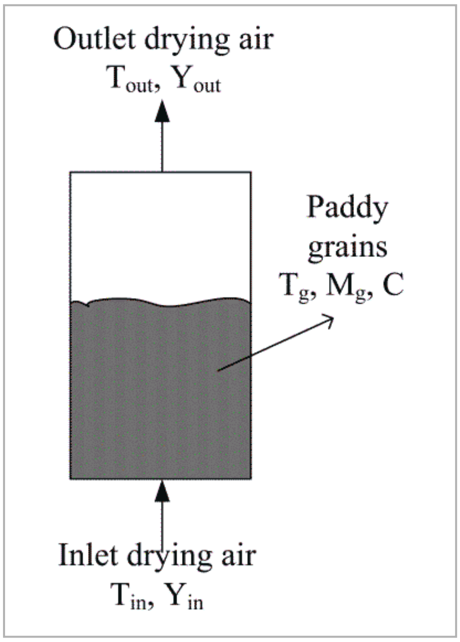

Figure 1: Control volume schematic for single-phase model of fluidized bed dryer

Mass Balance

Mass balance for grains moisture content in the bed can be expressed by the following equation:

$$-R_w \times M_g = \frac{d(M_g W)}{dt} = k(W - W_{eq})M_g \quad (1)$$

Where R_w is the drying rate of rough rice, M_g is the total mass of grains in the control volume, W is the grain moisture content expressed in dry basis (d.b.) and t denotes time. $k$is the drying constant which can be calculated by Eqn. (2) correlated from the experimental work of Iguaz et al. [16] for a large-scale aeration system. $W_{eq}$is the equilibrium moisture of the grains and Eqn. (3) by Chung and Pfost[17] can be exploited to calculate it.

$$k = 0.242261 \exp\left[-\frac{2530.2}{T_a + 273.16}\right] \quad (2)$$

$$W_{eq} = \frac{1}{14.93306} \times \left[\ln\left(\frac{4315.76}{\mathrm{R}(T_a + 191.37513)}\right) - \ln(-\ln(RH))\right] \quad (3)$$

Where T_a, R and RH are the drying air temperature, universal gas constant and relative humidity, respectively. Due to the fact that the bone-dry grains mass does not vary with time, Eqn. (1) can be simplified to take the following form:

$$-R_w = \frac{dW}{dt} = k(W - W_{eq}) \quad (4)$$

Heat balance

Heat balance is expressed as:

$$hA(T_a - T_g) - h_{vap}R_w M_g - R_w M_g c_v (T_a - T_g) = \frac{d(M_g T_g c_g)}{dt} \quad (5)$$

Three terms in the left hand side of Eqn. (5) are the convective heat transfer from air to grains, required heat for evaporation and sensible heat for rising the temperature of moisture in the grains to air temperature, respectively. In this equation, A is the total heat transfer area, c_g is the specific heat capacity of grains, $T_g$is the grains temperature, h is the convective heat transfer coefficient, $h_{vap}$is the water latent heat of vaporization and c_v is the specific heat of vapour. The following equations are implemented for the calculation of grain'sarea and mass, respectively:

$$A = aV \quad (6)$$

$$M_g = \rho_g V \quad (7)$$

Where a is the specific area of the grains, V is the total volume of grains, ρ_g is the grain's density. Correlations and numerical values of thermo-physical properties used in the above equations are presented in Table 1.

Table 1: Thermo-physical properties of the rough rice

Quantity	Ref.
$h = 5.63 c_a \upsilon_a \rho_a Re^{-0.43}$	[16]
$h_{vap} =$ $2260.46 + 20.4167\exp(-21.722W)$	[16]
$c_a = 1 + 1.805Y$	[18]
$\rho_a = \dfrac{1.293}{1 + 0.00367T_a}$	[19]
$c_v = 1.805$	[20]
$\rho_g = 171.02W + 560.16$	[18]
$c_g = 1.2648 + W$	[18]

Modeling of tempering stage

Fick's second law of diffusion is used to predict the moisture content distribution inside the grain. Using this equation for an individual grain yields as below:

$$\frac{\partial C}{\partial t} = D\left[\left(\frac{\partial^2 C}{\partial r^2}\right) + \frac{2}{r}\left(\frac{\partial C}{\partial r}\right)\right] \tag{8}$$

Where D is the water diffusion coefficient in a grain which can be calculated from the following equation [21]:

$$D = 9.33\times10^{-3}\exp(-6420/T_a) \tag{9}$$

Boundary conditions for Eqn. (8) are:

$$\frac{\partial C}{\partial r}(0,t) = 0 \tag{10}$$

$$\frac{\partial C}{\partial r}(R',t) = 0 \tag{11}$$

Where, R' is equivalent radius of the grain. Eqn. (10) denotes that the moisture concentration at the center of the grain is finite and Eqn. (11) shows that during the tempering stage the bed is kept at rest and the surface evaporation can be neglected (impermeable surface). The initial condition is:

$$C(r,0) = f(r) \tag{12}$$

Where, *f(r)*is the moisture distribution which is created during the drying stage and should be diminished using the tempering.

The separation of variables method is exploited to solve Eqn. (8) analytically as:

$$C(r,t) = \frac{3}{R'^3}\int_0^R r^2 f(r)\,dr + \frac{2}{R'}\sum_{n=1}^{\infty} e^{-D\lambda^2 t}\cdot\frac{sin(\lambda_n r)}{r sin^2(\lambda_n R')} \cdot\int_0^R r\left(f(r) - C_{ave}\right) sin(\lambda_n r)\,dr \tag{13}$$

Where, C_{ave} is the final average moisture content of the grain when the time approaches to infinite. In fact C_{ave} is equal to the first term of the right hand side of Eqn. (13). Since the model developed for drying stage is a lumped one, it could not predict the moisture gradient within the grain after drying stage. Therefore, a simple diffusion equation for a single spherical grain was solved to find this distribution (*f(r)*).

Experimental setup

Drying was implemented in a fluidized bed dryer setup (Fig. 2). This experimental setup is comprised of fluidization column including a cylinder and a cone. Cylindrical part is 19 cm in diameter and 50 cm long. Conical part diameter is between 10 to 19 cm and with the length of 14 cm. For the purpose of obtaining a uniform distribution a perforated-plate distributer with 9.8 % open fraction was used. The hot air was provided by a heater with eight 0.5-Kw fin striped elements placed in a metal cylindrical shell before the column. Air was supplied by a 3-Kw blower. Outlet air temperature was controlled with a PID controller within 1°C tolerance. The velocity of the air during the drying stage was measured by a digital anemometer with accuracy of ±2% (Tepkel, AVM712). Four k-type thermocouples with tolerance of 1°C were used to measure the temperature of 4 points along the column. A data monitoring system including signal amplifier, analogue to digital signal converter and Lab view software was devised to monitor and record data.

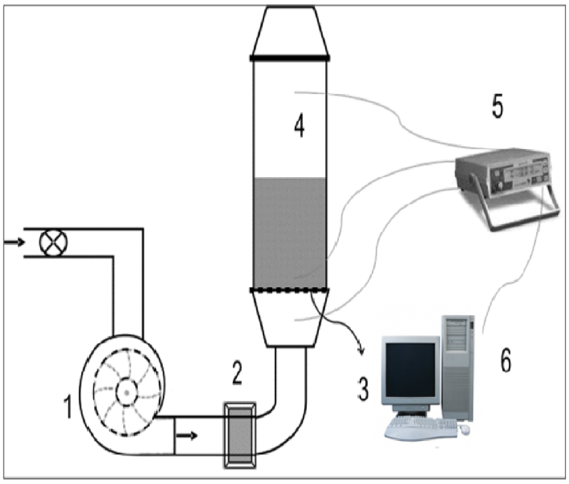

Figure 2: Schematic presentation of experimental set up

(1. blower, 2. air heater, 3. distributor, 4. dryer column, 5. data acquisition module, 6. computer)

Experimental materials

One of the most popular and desirable rice varieties in Iran from Guilan province, Hashemi variety, was used. Initially, 1 kg of sample was dried using hot air with specified temperature and humidity in a one-hour period; then, the fluidized bed content was discharged and packed in a fully sealed pocket and was put in an oven with the same temperature as drying stage (tempering stage). The duration of tempering stages varied from 1 to 3 hours for different runs. After tempering stage, the sample was dried again for 30 minutes. The initial moisture of the sample was measured about 17.65 % (dry basis) by means of hot air oven method [22]. Changes of the moisture content during the drying stages were gravimetrically measured with the precision of ±0.1g after switching off the system at the following drying times: t= 5, 10, 20, 30, 45 and 60 min for the first drying stage and then at t= 5, 10, 20 and 30min for the second drying stage.

Result and discussion

Experimental runs were implemented at temperatures of 40, 50 and 60°C and air velocities of 2.2 and 3.2 m/s. The minimum fluidization velocity was measured 1.6 m/s.

Estimation of drying constant

The correlation used for calculating drying constant, Eqn. (2), was basically proposed for a large-scale industrial fixed bed aeration system. Therefore its value differs from that of the current fluidized bed as a result of different scales of process and rice variety and turbulent mixing in the fluidized bed. Accordingly, a parameter estimation problem was conducted to calculate this value. The fluidized bed drying constant was evaluated by minimizing the average absolute relative deviation (AARD) of all experimental data and is presented below:

$$k = 1.6407 \exp\left[-\frac{2530.2}{T_a + 273.16}\right] \tag{14}$$

Effect of tempering on drying

The effect of tempering period was investigated using four different tempering durations. In the first three runs, tempering periods of 1, 2 and 3 hours were selected between the two drying stages (60 and 30 min drying periods). In the fourth run, the sample was continuously dried for 90 minutes. All these runs were carried out with 50 ^{o}C air with 2.2 m/s velocity. Results are shown in the form of drying rates and drying curves in Figs.3 and 4 respectively.

According to Fig. 3, it is observed that drying rate intensively descends at the earlier time of drying due to the lack of enough moisture at the surface of the grains. Tempering can improve the drying rate because this stage of drying process allows the moisture to migrate from the center toward the surface of the grain, therefore, moisture gradients inside the grain, which was imposed during pervious drying stage, is eliminated. Such elimination causes a uniform moisture profile within the grain which results in a higher moisture content at the grain surface and therefore an increase in drying rate in the next drying stage. The kinks which occurred in this figure can be attributed to applying the tempering stage.

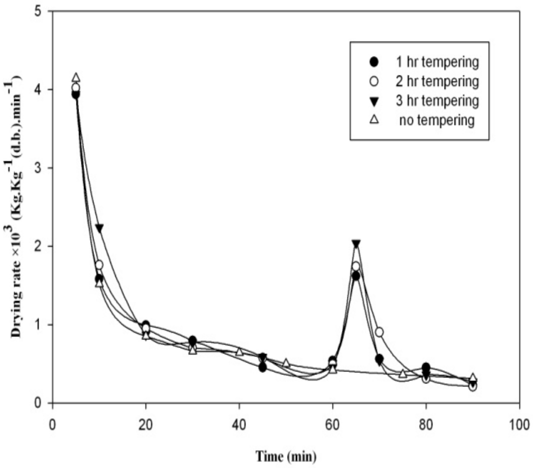

Figure 3: **Effect of tempering stage on drying rate (T_a= 50°C, v_a=2.2m/s)**

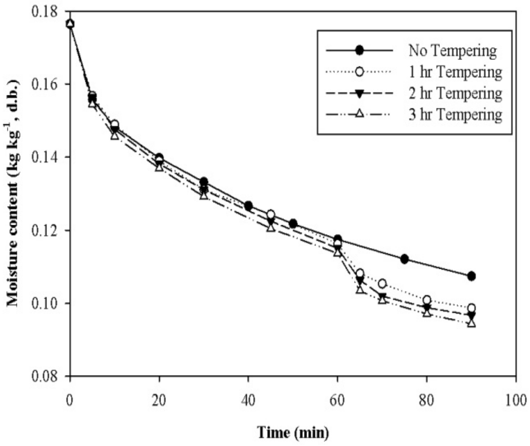

Figure 4: Effect of tempering stage on drying curve (T_a= 50°C, v_a=2.2m/s)

The microscopic submodel can be used to explain what exactly occurs inside the grains, leading to higher drying rates. Fig 5 shows the moisture profiles within a single grain versus radius in different tempering times at the tempering temperature of 50°C.

It is concluded from the figure that the moisture gradient is at its maximum value right after drying stage. As the time passes this profile becomes smoother because of the moisture diffusion from inner layers to the surface. This model also shows that approximately 85% of moisture gradient can be removed in 5 hours of tempering.

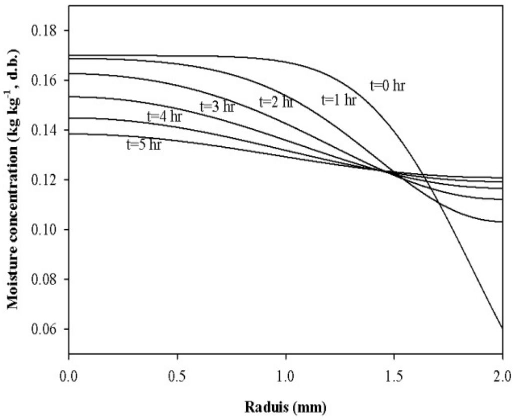

Figure 5: Effect of tempering time on moisture gradient removal

Effect of tempering temperature

Results from the microscopic submodel show that the rate of moisture gradient removing is highly sensitive to the temperature (Eqn. (9)). Moisture profiles in a single grain after 3 hr of tempering at temperatures of 40, 50, 60 and 70°C are depicted in Fig. 6. This figure reveals that the required time to remove 90% of moisture gradient in grains at the temperature of 50 °C is about 7 hr, while tempering stages at 60 and 70°C need approximately 4 and 3 hr of tempering time respectively.

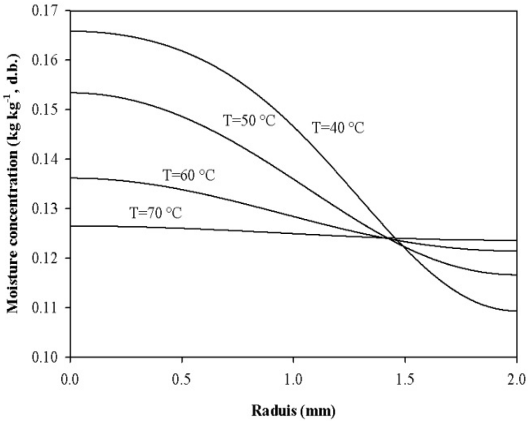

Figure 6: Effect of tempering temperature on moisture gradient removal

Effect of drying temperature

Increasing the air temperature not only improves the drying rate but also increases the diffusion coefficient in the grains and therefore facilitates mass transfer from the inner layers to the outer surface. Three experimental runs were conducted at 40, 50 and 60°C to show the effect of drying temperature on drying curves. In Fig. 7, results of these experiments are presented and compared with modified macroscopic submodel. Similar results were also observed at the velocity of 3.2 m/s.

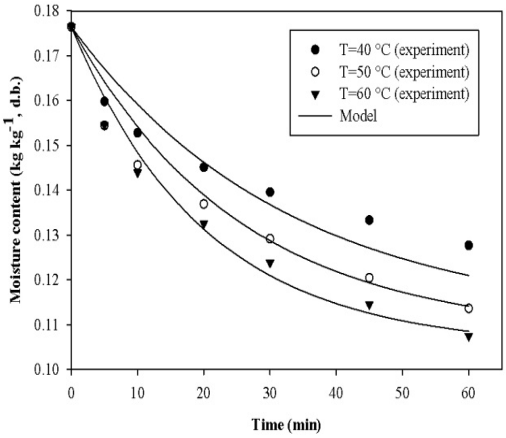

Figure 7: Drying curves at different air temperatures (model and experiment, v_a =2.2 m/s)

Effect of drying air velocity

As it is depicted in Fig. 8, air velocity does not affect much on drying rate. It can be easily justified by assuming that the whole drying process consists of two resistances, the inner and outer resistances. The inner resistance is a diffusion resistance and the outer one is a convection one. Since the moisture diffusion is the determining step and the air velocity only affects the convection resistance, increasing the air velocity has a little effect on the drying rate as also predicted by Hatamipour and Mowla [23].

It should be noted that sensitivity of the macroscopic submodel with respect to air velocity is so little that it is even difficult to recognize the two curves from each other. The experimental data shows the same trend either. Similar behaviors were also observed at other temperatures.

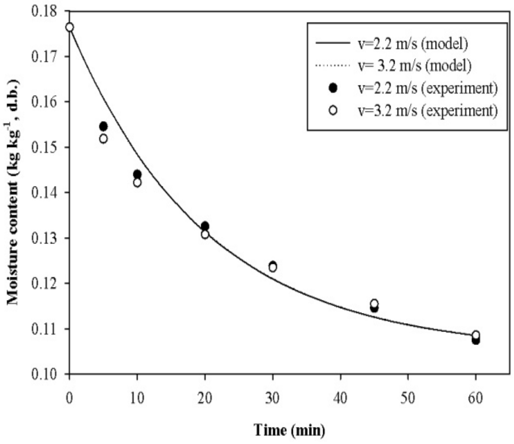

Figure 8: Effect of air velocity on drying curve (model and experiment, T_a= 60°C)

Dynamics of bulk temperature

Temperature changes of grains over time are calculated from the macroscopic submodel and are plotted for different inlet air temperatures (40, 50 and 60°C) in Fig. 9. Immediately after the exposure between the rough rice and the hot air, heat and mass transfer simultaneously begin. Since, fully mixed condition was achieved during the experiments, reaching a rapid thermal equilibrium is predictable. The simulation results confirm this assumption either as the size of grain is small and specific area is large [24].

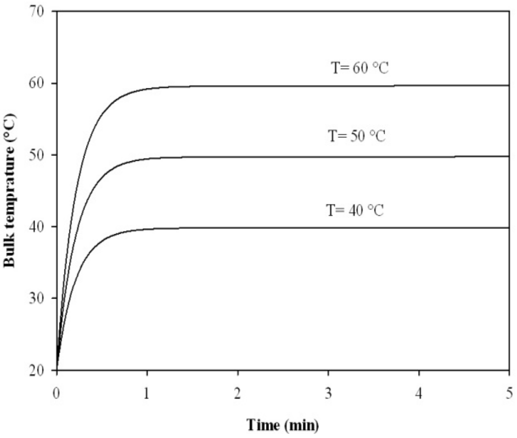

Figure 9: Changes of bulk temperature at different air temperatures (v_a =3.2 m/s)

Conclusion

Intermittent drying technique for an Iranian local rough rice variety in a fluidized bed dryer was mathematically and experimentally investigated. In this technique, quality of the product can be increased by applying a tempering stage. In addition, using a fluidized bed dryer can considerably improve heat and mass transfer rates and consequently reducing the time of the process. In this study, a lab-scale fluidized bed dryer was designed and constructed in order to assess different parameters affecting the drying rate such as air temperature, air velocity and tempering time. The results showed that the air temperature plays a significant role among these parameters. In contrast, air velocity does not seem to be much effective on drying rate. Moreover, the results proved that increasing the temperature of tempering stage can considerably reduce the required time for moisture gradient removal. Accordingly, a 5-hour tempering stage at tempering temperature of 50°C can approximately reduce 85% of moisture gradient formed during drying stage. Furthermore, using the experimental results the best value for drying constant for the constructed fluidized bed was estimated to be about 6.8 times greater than that of fixed bed which proves the higher efficiency of the fluidized bed.

Nomenclature

a	specific surface area, m^2 m^{-3}
A	total area of grain, m^2
C	grain moisture concentration, kg kg^{-1}
c	specific heat capacity, kJ kg^{-1} $°C^{-1}$
D	moisture diffusion coefficient, m^2 s^{-1}
$f(r)$	initial moisture profile
h	convective heat transfer coefficient , kJ m^{-2} $°C^{-1}$
h_{vap}	latent heat of vaporization, kJ kg^{-1}
k	drying constant, s^{-1}
M	mass in the control volume, kg
r	radial coordinate for the grain, m
R	universal gas constant, kJ/kg mol °C
R'	equivalent radius of the grain, m
R_w	drying rate of rough rice, kg kg^{-1} s^{-1}
Re	Reynolds number
RH	relative humidity
t	time, min
T	temperature, °C
V	volume, m^3
W	average moisture of grain, kg kg^{-1}
Y	absolute humidity of the air, kg kg^{-1}

Greek letters

v	velocity, m s^{-1}
ρ	bulk density, kg m^{-3}

Subscripts

a	air
ave	average
bd	bone-dry
eq	equilibrium
g	grain
v	vapor

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