Experimental study of deep-bed drying kinetics of rough rice

M. Torki Harchegani[1], A. Moheb[2], M. Sadeghi[1*], M. Tohidi[1], Z. Naghavi[2]

(1. *Department of Farm Machinery*, *College of Agriculture*, *Isfahan University of Technology*, *Isfahan 84156-83111*, *Iran*;
2. *Department of Chemical Engineering*, *Isfahan University of Technology*, *Isfahan 84156-83111*, *Iran*)

Abstract: A non-equilibrium model for the numerical simulation of rough rice drying in a deep-bed dryer was evaluated for predicting the variation of average grain moisture content with time. For this purpose, a laboratory scale deep-bed dryer was designed and built, and the average moisture content of the bed was experimentally determined during the drying process. The effects of temperature, velocity, and relative humidity of the drying air on the average grain moisture content were similarly investigated. Relative error and mean relative error were calculated for the simulation results, and found to be in acceptable range (10%-15%, and <10%, respectively). Results revealed that the temperature of drying air was the most influential parameter on the drying time. Finally, the model proved to be able to predict the variation of the average moisture content with respect to the time with a good accuracy.

Keywords: rough rice, deep-bed dryer, drying kinetics, mathematical modeling, non-equilibrium

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1 Introduction

Grains are often harvested at moisture content levels that are too high for safe storage. In fact, high moisture content is one of the most important factors affecting products physical, chemical, and nutrient quality during the storage period. Therefore, implementing a proper post harvest process is an essential step to have grains with a high quality. The moisture removal from a moist material using a heating media for evaporating water is known as drying. The drying process not only needs a great amount of energy, but also can cause different changes in physical, mechanical, and chemical properties of the final product. Hence, it is very important to properly carry out this process to prevent undesirable changes in the product and reduce energy consumption. Drying behavior of grains can be significantly affected by drying conditions such as temperature, velocity, and relative humidity of the air as well as the grain properties including grain density, permeability, and porosity. Therefore, drying of moist porous materials is a complicated process involving simultaneous phenomena of heat and mass transfer in two phases (Zare and Chen, 2009).

Computerized modeling of the drying process is a powerful, cheap, and fast tool to predict the variation of important operational parameters including air temperature and humidity, grain temperature, and especially grain moisture content, during the drying process. Having enough reliable information about these parameters can be useful to design more efficient dryers and improve the quality of the final products (Babalis et al., 2006).

Thin layer model is widely used by the researchers for investigating the drying process of grains, and is based on which various mathematical models have been developed to simulate the dynamic behavior of these type of dryers (Cihan,Kahveci and Hacıhafızoğlu, 2007; Basunia and Abe, 2001; Das, Das and Bal, 2004; Iguaz et al., 2003). In mathematical modeling of a thin layer of grains, temperature and moisture content gradients are not

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* **Corresponding author: Morteza Sadeghi,** Email: sadeghimor @cc.iut.ac.ir.

usually considered. Therefore, the thin layer models cannot properly describe the transfer phenomena in a convective deep-bed dryer. Moreover, in commercial dryers deep-bed mode is used. Hence, the information obtained from the studies on the thin layer dryers cannot accurately predict the behavior of the deep-bed dryers due to the difference in behavior of an individual cereal kernel and a bulk or batch of grain (Brooker, Bakker-Arkema and Hall, 1992). In deep-bed dryers, convective heat transfer is the major heat source for the drying in which as hot air moves through the bed it absorbs the moisture from the grains. During this process, the level of the air temperature, the grain temperature, the air humidity, and the grain moisture content all depend on the local position in the bed and the drying time. After an infinitely long period of drying, the grain bed reaches equilibrium. However, for the lower part of the bed the temperature and moisture content gradient are eliminated earlier compared to that for the higher regions in the drying bed.

The mathematical models proposed to simulate deep-bed grain drying can be divided into three categories: non-equilibrium, equilibrium, and logarithmic models. Equilibrium models in a stationary bed can be classified into high temperature and low temperature drying models. The non-equilibrium and the logarithmic models are applied in all grain drying systems. In the equilibrium and logarithmic models, restrictive assumptions are introduced to simplify the set of partial differential equations (PDEs). The non-equilibrium models are more detailed, accurate, and valid for cereal drying, while the others are less accurate owing to more assumptions being made during model development (Tang, Cenkowski and Muir, 2004). The non-equilibrium grain drying model is a theoretical model for grain drying systems. In this model, by assuming that in a deep-bed, there is no equilibrium between the drying air and grain, a set of PDEs are derived by implementing the heat and mass transfer conservation laws, and the mathematical theory of drying for individual kernels (Srivastava and John, 2002). In general, non-equilibrium models are based on either mass and energy balance inside of a control volume isolated from the bed and the appropriate thin layer drying rate equation. The system of equations of the non-equilibrium models cannot be solved by analytical methods. Therefore, they are simplified in order to reduce the complexity or the required computational time (Aregba and Nadeau, 2007).

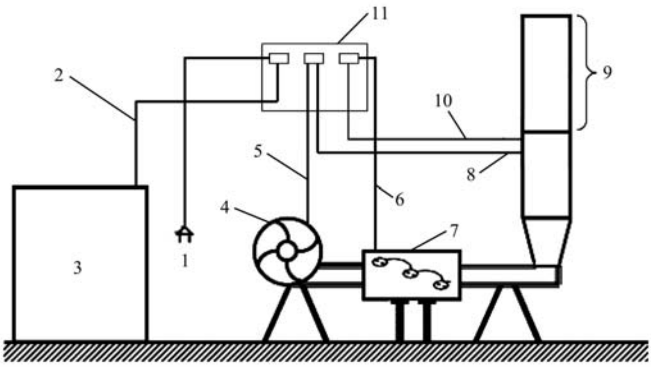
Many researchers have conducted studies on deep-bed dryers. However, in the most proposed non-equilibrium models for grain stationary deep-bed drying, the accumulation terms were neglected or simplified. Giner, Mascheron and Nellist (1996) developed a stationary deep-bed drying model for cross-flow drying of wheat. In their model, they simplified the accumulation terms and the drying time was chosen as the criteria to evaluate the model. However, they did not investigate the grain moisture content, the drying air temperature, and the grain temperature. Their results showed an average error of 6% when comparing drying time predictions with experimental values. Srivastava and John (2002) proposed a grain drying model by keeping the accumulation terms in the mass and energy balance equations. They used an implicit numerical scheme and Runge-Kutta method to solve the resulting equations, but they did not compare the results with any experimental data. Aregba and Nadeau (2007) used two non-equilibrium models to design two grain deep-bed drying computer codes. In the first model the accumulation terms were kept, while in the second model these terms were neglected. Both models were discretized by second order semi-implicit schemes. They used the computer codes to simulate wheat static bed drying and compared their predictions. They investigated the conditions allowing one to neglect the accumulation terms as in the first model. Zare et al. (2006) simulated a transient deep-bed batch dryer for drying of rough rice using heat and mass balance together with an appropriate empirical thin layer equation. They solved the set of PDEs using finite difference method and validated the results of computer simulation experimentally. Their results showed a good agreement between the predicted and experimental moisture content values. Also, they concluded that more mass transfer occurred as the height of bed increased. The bed porosity had little effect as air temperature drops by a few degrees; however, the grain temperature was not much affected.

This study is aimed at evaluating the accuracy of a non-equilibrium model developed by Naghavi, Moheb and Ziaei-rad (2010) for the numerical simulation of rough rice drying in a deep-bed dryer by comparing the simulation results and the experimental data, based on temperature, velocity and relative humidity of the drying air.

2 Materials and methods

2.1 Experimental set-up

In order to carry out the experiments, a laboratory-scale dryer was designed and fabricated in Farm Machinery Department, College of Agriculture, Isfahan University of Technology. A schematic diagram of the set-up is shown in Figure 1. The drying chamber was made of a plexiglas cylinder which was connected to the air channels by flexible PVC tube. This part was located on a digital laboratory balance (Sartorius 18100P with accuracy of 0.01 g) for online weighing of the bed. Air was blown by a centrifugal fan into an electrical heater. A 1 to 3 phase frequency inverter was used to adjust and control the airflow in the range of 0-0.4 m^3 s^{-1}. This airflow range ensures having the bed particles at a wide range of conditions, i.e., from fixed bed state to fluidized bed state. Ten 0.7 kW electrical coils were used in the heating chamber to supply enough thermal energy to heat up the drying air to the desired temperature. The coils were connected to the electric mains through a temperature controller. An ultrasonic humidifier equipped with microcontroller was used to adjust and control the relative humidity of the isolated drying room, in which the experiments were conducted.



1. Relative humidity sensor 2. Ultrasonic humidifier power supply 3. Ultrasonic humidifier 4. Fan 5. Fan speed controller 6. Heater power supply 7. Heater 8. Hot wire 9. Drying column 10. Thermocouple 11. Controller set

Figure 1 Schematic view of the experimental set-up and instrumentations

2.2 Physical properties of materials

In order to simulate the drying of rice in a batch dryer, it is necessary to determine rice physical properties. The common rough rice variety in Isfahan province (Iran) called Sazandegi which is a Japonica, medium-grain, and aromatic type variety was selected for this study. The samples were taken from Agricultural and Natural Resources Research Center of Isfahan, and were stored at 4-8℃ in a cold storage (Basunia and Abe, 2001). The measured dimensions and densities of this variety of rice at different moistures contents are presented in Table 1 (Sadeghi et al., 2010).

Table 1 Dimensions and densities of the Sazandegi rough rice cultivar

Moisture content/%, w.b.	Length/mm	Width/mm	Thickness/mm	Bulk density/kg m^{-3}	Particle density/kg m^{-3}
11-13	8.65	2.80	1.84	578.9	1116.6
13-15	8.74	2.44	1.86	573.3	1135.9
15-17	8.65	2.48	1.92	578.3	1141.2

Equivalent diameter (d_e), sphericity (ψ), and static porosity (ε_{st}) of Sazandegi rough rice were calculated by using Equations (1) to (3), respectively (Sadeghi et al., 2010). In these equations, a, b, and c are the length, width, and thickness of the grain (m), respectively, while ρ_p and ρ_b are the particle and bulk density of the grain (kg m^{-3}), respectively. Table 2 shows the values of these properties at different moistures contents.

$$d_e = (abc)^{\frac{1}{3}} \tag{1}$$

$$\psi = \frac{(abc)^{\frac{1}{3}}}{a} \tag{2}$$

$$\varepsilon_{st} = \frac{\rho_p - \rho_b}{\rho_p} \tag{3}$$

Table 2 Equivalent diameter, sphericity and porosity of Sazandegi rough rice cultivar

Moisture content /%, w.b.	Equivalent diameter /mm	Sphericity	Porosity
11-13	3.41	0.39	0.48
13-15	3.41	0.39	0.49
15-17	3.46	0.40	0.48

2.3 Modeling

In the previous study (Naghavi, Moheb and Ziaei-rad, 2010), the detailed description of a non-equilibrium model development for drying of rough rice in a fixed deep-bed was presented. The model was developed by using mass and energy balance inside of a differential control volume of the bed as well as implementing a rate equation for the thin layer drying. The control volume was composed of two thermo-dynamical systems: intergranular air and grains. In the proposed model, the accumulation terms were kept in both energy and mass balance equations. The set of partial differential equations derived from the model was simultaneously solved by using the backward implicit method. Based on the discrete set of equations, a computer program was developed and implemented in MATLAB environment to simulate the grain drying process. The technique was capable of predicting the temperatures of the air and grains, the air humidity and moisture content of the grain at different locations (one dimensional, height of material bed column) of the dryer at any time.

In the development of the model, the volume shrinkage, temperature gradients within the individual particles, as well as the particle-to-particle heat conduction were assumed to be negligible during the drying process. The air flow was considered to be plug-type and the bin walls were assumed to be adiabatic, with negligible heat capacity. Also, the heat capacities of moist air and grains were considered to be constant during short time periods, and heat and mass transfer to be one-dimensional.

Non-equilibrium model of grain stationary deep-bed drying, upon simplification, included Equations (4) to (7) that explain the mass balance of air humidity, enthalpy balance of intergranular air over the control volume, grain enthalpy balance over the control volume, and grain moisture change with time, respectively (Naghavi, Moheb and Ziaei-rad, 2010).

$$\frac{\partial y'}{\partial x} = -\frac{\varepsilon}{v_a}\frac{\partial y'}{\partial t} - \frac{\rho_p}{\rho_a v_a}\frac{\partial M}{\partial t} \tag{4}$$

$$\frac{\partial T_a}{\partial x} = \frac{1}{\rho_a v_a (C_a + C_v y')}\{-\rho_p \frac{\partial M}{\partial t}[C_w(\theta - T_0) + h_v] + \rho_p \frac{\partial M}{\partial t}[C_v(T_a - T_0) + \lambda_0] - h_a(T_a - \theta)\} - \frac{\varepsilon}{v_a}\frac{\partial T_a}{\partial t} \tag{5}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\rho_p (C_p + C_w M)}[h_a(T_a - \theta) + h_v \rho_p \frac{\partial M}{\partial t}] \tag{6}$$

$$\frac{\partial M}{\partial t} = (M - M_e)(-XYt^{Y-1}) \tag{7}$$

In Equations (4) to (7), T_0, T_a, and θ are the reference, air, and grain temperatures (°K), respectively, while specific heat capacities (J kg^{-1} °K^{-1}) of dry air, dry grain, water vapor, and liquid water are represented by C_a, C_p, C_v, and C_w, respectively. Also, λ_0 and h_v are used to present latent heat of vaporization (J kg^{-1}) at reference and operating temperatures, respectively. M is the dry basis moisture content of grain (kg kg^{-1}) whereas M_e is the equilibrium moisture content. The other parameters used in Equations (4)-(7) are: $\acute{y}$ (absolute humidity of air, kg kg^{-1}), h_a (grain bed volumetric heat transfer coefficient, J m^{-3} °K^{-1} s^{-1}), x (vertical coordinate in the bed, m), t (time, s), ρ_a (air density, kg m^{-3}), v_a (air velocity, m s^{-1}), and ε (bed porosity).

After solving the model according to the numerical method, the desired parameters including the air humidity, the air temperature, the grain moisture content, and the grain temperature were calculated for each thin layer of the deep-bed. Having moisture content of the thin layers at any time, the average moisture content of the whole bed was obtained by arithmetic averaging over the layers.

For each test, the accuracy of the model was evaluated by calculating the percent relative error (*RE*, %) and the percent mean relative error (MRE, %) by using Equations (8) and (9) respectively.

$$RE = \frac{|M_{exp} - M_{pre}|}{M_{exp}} \times 100\% \tag{8}$$

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|M_{exp,i} - M_{pre,i}\right|}{M_{exp,i}} \times 100\% \qquad (9)$$

In these equations, M_{exp} and M_{pre} represent the experimental and predicted moisture content of grain, respectively.

2.4 Data acquisition

Fresh rough rice samples were obtained from the Isfahan Centre for Research of Agricultural Science and Natural Resources. The samples were put in sealed bags to avoid moisture variation due to evaporation, and were stored at 4-8℃. Prior to each drying experiment, the samples were placed in the laboratory for 4 h to reach thermal equilibrium with the environment. The initial moisture content was determined by carrying out the standard procedure, at the temperature of 130℃ for 24 h (ASAE Standards, 2000). Then, a uniform height (20 cm) of the grains was placed in the drying chamber. The experiments were started after adjusting such operating parameters as the temperature, velocity and relative humidity of the drying air to the predetermined values given in Table 3. The velocity of the drying air was measured by using a hot wire anemometer (Lutron, AM-4204 model, Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan) with ±0.1 m s^{-1} accuracy. The experiments were conducted to reduce the grain moisture content from its initial content of 25.63 (%, d.b.) to the average final value of 14.41 (%, d.b.).

Table 3 Operational conditions of the experiments together with mean relative error (*MRE*) and maximum relative error (*RE*$_{\max}$) values

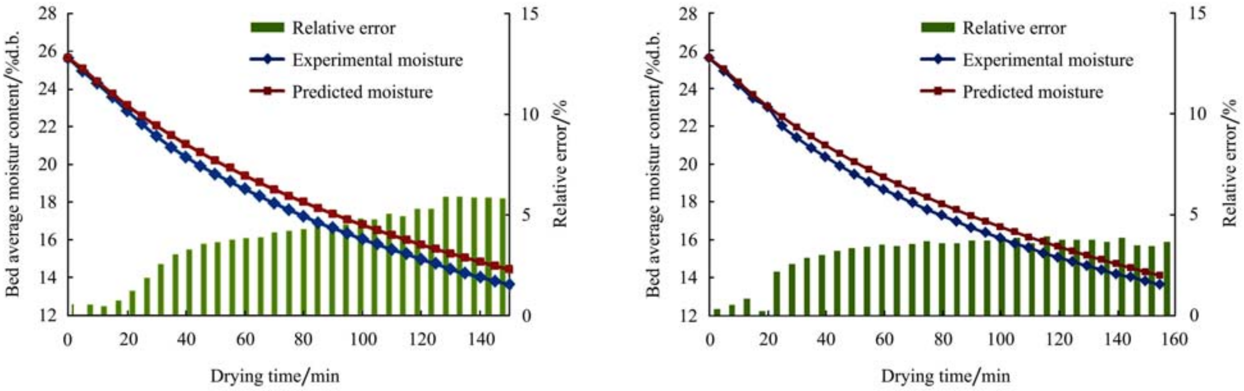
Drying air temperature/℃	Drying air velocity/m s^{-1}	Drying air relative humidity/%	*MRE* /%	$RE_{\max}$ /%
50	0.5	40	3.77	5.85
50	0.5	50	2.96	3.85
50	0.5	60	2.04	3.09
50	0.5	70	0.73	1.78
50	0.8	70	2.50	3.83
50	1.1	70	3.20	4.95
60	0.5	70	5.06	9.28
70	0.5	70	7.39	15.88

3 Results and discussion

3.1 Effect of operating parameters on the drying time

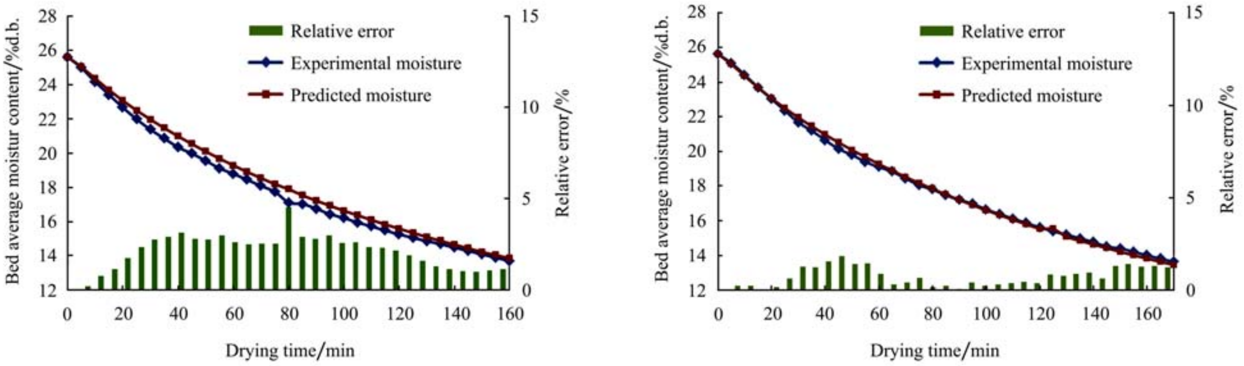
The experimental and calculated results obtained for the variation of average moisture content of the grains with time for eight different drying conditions are shown in Figures 2 to 4. The effect of the initial relative humidity of the drying air on drying time can be discussed by using Figure 2a to Figure 2d. The drying curves are for the experiments conducted with the constant air velocity and temperature of 0.5 m s^{-1} and 50℃, respectively, whereas the relative humidity of the air varied between 40%-70%. From the curves, the increase in the air relative humidity led to a slight increase in the drying time. It is evident that increase in drying air relative humidity or the equilibrium relative humidity causes an increase in equilibrium moisture content and consequently, a delay in losing moisture content. It is clear that, as the relative humidity increased from 40% to 50%, 50% to 60%, and 60% to 70%, the drying time increased about 5, 5 and 10 min, respectively. Thus, the slight reduction in the drying time for lower air humidity is due to the fact that the experiments were conducted at relatively high relative humidity of air, and therefore, changing in the air humidity had no significant effect on the mass transfer driving force. In addition, the initial moisture content of the grains was high enough to cause a high mass transfer driving force, and hence, it was the main influential parameter on the mass transfer rate.

The effect of air velocity on the drying time can be discussed by comparing Figures 2d, 3a, and 3b. In these set of experiments the air temperature and relative humidity were constant values of 50℃ and 70%, respectively, while the air velocity ranged from 0.5 to 1.1 m s^{-1}. The results show that changing the air velocity from 0.5 to 0.8 m s^{-1} and from 0.8 to 1.1 m s^{-1} caused about 20 and 10 min reduction in the drying time, respectively. This is due to increase in mass and heat transfer coefficients with increasing the air velocity. It is worth noting that the relative effect of the air velocity on the drying time was more than that of the air humidity. One reason could be the range of the air velocity used in the experiments. As mentioned before, the initial humidity of the drying air was relatively high, and a moderate variation in this parameter had no significant effect on the drying time. But the air velocity was in the moderate range. Consequently, even a modest variation in this parameter can cause considerable effect on the mass and heat transfer coefficients, and subsequently on the drying time.



a. 40%

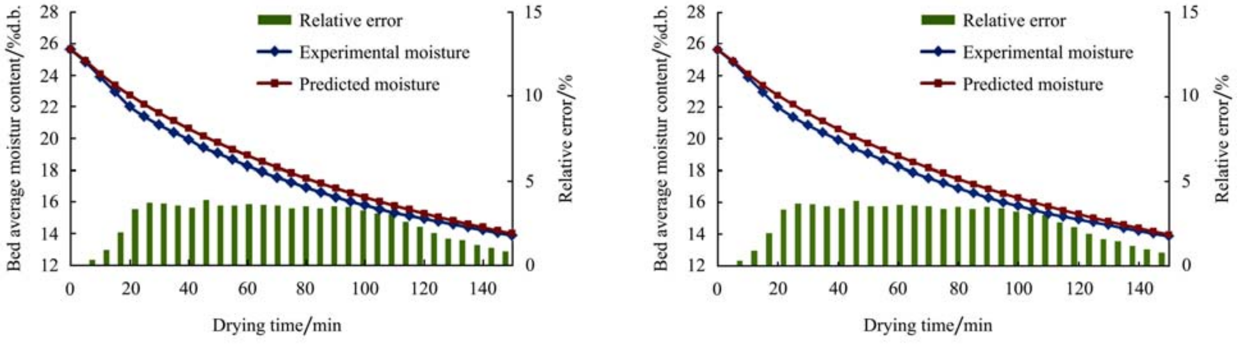
b. 50%



c. 60%

d. 70%

Figure 2 Variation in average moisture content of bed with drying time at air temperature of 50℃, air velocity of 0.5 m s^{-1}, and relative humidity of

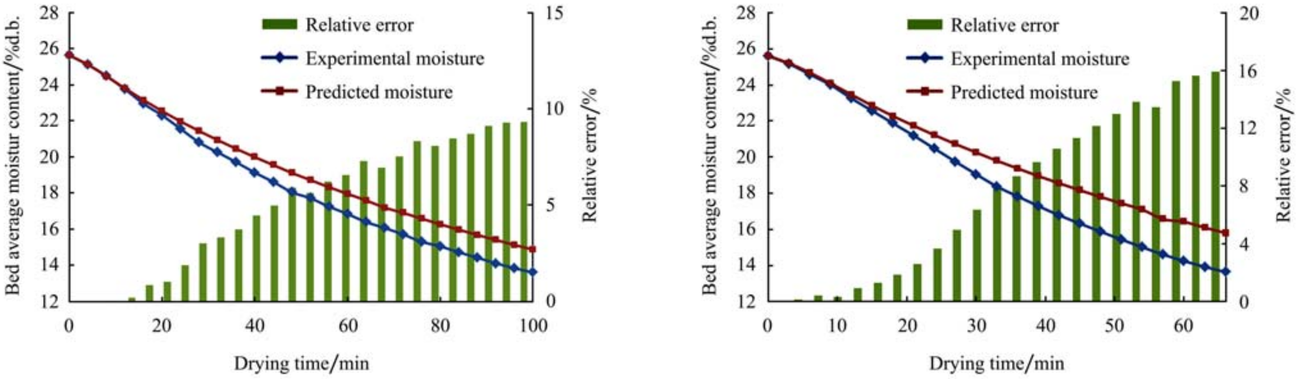


a. 0.8 m s^{-1}

b. 1.1 m s^{-1}

Figure 3 Variation in average moisture content of bed with drying time at air temperature of 50℃, relative humidity of 70%, and air velocity of

Figures 2d, 4a, and 4b demonstrate the effect of air temperature on the drying time, in which air velocity and relative humidity were constant values of 0.5 m s^{-1} and 70%, respectively, and air temperature was adjusted at 50, 60, and 70℃ for three experiments. As is shown, the air temperature had the most effect on the drying time among the operational parameters. Increasing air temperature led to decrease in the drying time, with reduction of 41% and 34% for changing the air temperature from 50 to 60℃, and 60 to 70℃, respectively. When the air temperature increases, the heat transfer rate between air and grains is higher. This leads to faster moisture evaporation, and hence, lowers the drying time. In addition, at a constant relative humidity the interfacial moisture concentration for grains is higher as temperature increases. The reason is that the interfacial concentration is a function of wet bulb temperature of the air and, at higher temperatures this concentration and resulting driving force for mass transfer increases. In turn, this effect causes faster mass transfer between the grains and drying air and hence, less the drying time.



a. 60℃ b. 70℃

Figure 4 Variation in average moisture content of bed with drying time at air velocity of 0.5 m s^{-1}, relative humidity of 70%, and air temperature of

3.2 Model validation

Table 3 shows the values of mean and maximum relative error for the eight drying conditions. Relative error of 10%-15% is usually reported to be satisfactory for drying simulation (Sitompul et al., 2001; Tang et al., 2004; Kalbasi, 2003; Madhiyanon et al., 2001; Dimitriadis and Akritidis, 2004). Also, a mean relative error of less than 10% is generally considered as a good degree of agreement between simulation and experimental data in the case of dryer simulation (Park, Vohnikova and Brod, 2002). As the validation results show, the implemented model could describe drying process with a high accuracy. The lowest and the highest values for MRE are 0.73% and 7.39%, respectively, whereas the minimum and maximum obtained values for $RE_{\max}$ are 1.78% and 15.88%, respectively. In addition, all MRE values are in the acceptable range (Park, Vohnikova and Brod, 2002). Only in one case (T=70℃, RH=70%, and V=0.5 m s^{-1}) $RE_{\max}$ is more than the acceptable value (>15%). However, for other experiments the value of this parameter is less than the lowest limit of the acceptable range (<10%).

The experimental data along with the modeling results (variation of average moisture content with respect to the drying time) are presented in Figures 2 to 4. The relative error bars are also given in the figures. Comparing the calculated and experimental data presented in Figures 2 and 3 shows that they are close to each other. The MRE for these conditions varies only from 0.73% to 3.77% (Table 3). This can be explained by the fact that no specific simplifying assumptions were made on air humidity and velocity for model development. On the other hand, it can be predicted that the relative error increases if the experiments are conducted at higher air temperature.

Figures 2a and 4 reveal that the relative error increases with increase in the drying air temperature. This is explained by noting the contribution of the air temperature on heat and mass transfer driving forces, which was discussed previously. The higher predictive values for the average moisture content compared with the experimental measured values could be due to simplifying assumptions made on the thermal parameters during model development. In other word, the model predicts longer necessary time for a specific reduction in the average moisture content.

4 Conclusion

A deep-bed dryer was designed and constructed for rough rice drying, and experiments were conducted at different operational conditions to evaluate the effect of influential parameters of air temperature, velocity, and relative humidity. Experimental results revealed that the air temperature had the highest contribution to the drying time for a specific reduction in the moisture content of the grains.

Analysis of the relative errors showed that the results of modeling, based on a developed non-equilibrium model, were in good agreement with the experimental results. The highest calculated mean relative error obtained 7.39%, which is in an acceptable range. Therefore, the model proved to be capable of simulating the unsteady state deep-bed dryer for rough rice drying with a good degree of accuracy for predicting the average moisture contents over the drying time under different drying conditions.

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