Dimensionless variable groups for the free-fall grain dryer

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Abstract: Dimensionless variable groups (DGs) of free-fall grain dryer were developed by using the characteristic scaling method and engineering intuition. These DGs were intended for the analyses of drying characteristics and sizes of this dryer. Experiments of the free-fall rough rice dryer were carried out using different drying chambers (small and medium scales), drying air temperatures (100°C-150°C), and drying air speeds (1-3 m/s). Experimental data were used to study relationships and to validate similarities among these DGs. The results of the study showed the five appropriate dimensionless variables representing and describing the drying mechanism of the free-fall dryer. These DGs could be applied to design and analyze scaling up the dryer. In addition, the dimensionless correlation was established to predict the moisture contents of rough rice while being dried by the free-fall dryer. The predicted values from this correlation were in relatively good agreement with the experimental data under the proposed drying conditions (R^2=0.989, MRD=1.82% and RMSE=0.0168).

Keywords: dimensionless variable, similarity, free-fall dryer, rough rice

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1 Introduction

Drying process is one of the most complicated procedures because it concerns a simultaneous combination of mass, momentum, and heat transfer. The changes of moisture phases and grain compositions are also involved. Furthermore, the process depends on drying medium, drying techniques and the scales of the dryers[1]. To achieve a preferable grain dryer, many interacting design variables of drying process must be well understood and analyzed. Usually, dryers are developed in a small scale first and later upscale into an industrial scale. Due to scale effects, this upgrading scale causing problems is the concentration of this study.

The dimensional analysis method (DMA) focuses on mixing the effects of various primitive variables to form fewer dimensionless variables (DVs). In this manner, the primitive variables are scaled to exhibit similar effects on physical models of different sizes and others[2]. Additional benefit of DMA is the reduction in number of independent variables, resulting in fewer experimental trials required to scale up the operation and analyze the performance of the equipment[3].

The studies on DMA for ‘drying’ characteristics of grain dryer have been scantly conducted. Commonly, they often rely on drying conditions, grain types and drying media but do not account for the dryers’ sizes and geometries. Thus, the common DVs in drying field existing in engineering and applied mathematics literature are usually involved in one or more sub-phenomena in conventional drying process such as heat and mass transfer, fluid flow, evaporation, sublimation, moisture flow in materials, and equilibrium relationships. Two or more common DVs can be used to model a dimensionless correlation for describing a specific drying process[3]. In addition, the simultaneous heat and mass transfer equations in non-steady state for food and grain drying can be rewritten in terms of the common DVs. The magnitude orders of these DVs define the controlled mechanism both in heat and mass transfer which can be used to predict food and grain drying behavior[4]. However, they cannot be statically used to describe the effect of dryer scaling on drying behavior.

For a fluidized bed dryer, it is necessary to analyze the effect of dryers’ sizes and geometries on drying characteristic and scaling up. However, the proper type of fluidization regimes has to be specifically applied. For the case of dry particles (or partially dry, no surface moisture), according to Geldart classification of powder, if the fluidizing gas increases, the bed of particles goes through different types of fluidization regimes depending on the types of particles. For drying propose, grains, which are usually categorized in group D, fluidized bed dryers are normally operated in the regimes of large bubbling fluidization and/or turbulence. Then, the particle bed in a fluidized bed dryer is rather consistently mixed with the drying air. This condition yields insignificant difference of heat and mass transfer among the particles inside the bed along the drying intervals. Also, the DMA research for ‘drying’ characteristics does not often focus on the dimensions of the drying chambers (the thickness and the width of the bed) which are generally specified as constant values for sustained and desired fluidization regimes[5,6]. To investigate the ‘drying’ characteristics of a dryer, DMA is usually used to find the influenced DVs and create functional relationship between dependent DVs and other independent DVs. The Rayleigh dimensional analysis method is used to obtain the general non-dimensional correlation model for drying agricultural products in a fluidized bed dryer. This model is a function of independent DVs consisting of Lewis number, velocity ratio and temperature ratio, and moisture ratio as a dependent DV[5]. Moreover, DMA is applied for analyzing the energy and exergy efficiency of fluidized bed drying. DVs influencing the efficiency including Fourier

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number, Reynolds number, moisture ratio and temperature ratio are investigated in the form of a non-dimensional correlation equation to predict the energy and exergy efficiency of wheat and corn drying[6].

Although there have been some studies on the dryers' sizes and the geometries, researchers have found only the application for deep bed (batch) dryers and rotary dryers. For a batch dryer, grain bed thickness is the geometric parameter more influencing on drying characteristics and scaling up of the dryer. Kachru and Matthes[7] have presented a prediction equation for drying time and instantaneous moisture content of rough rice within a deep-bed dryer using similitude and dimensional analysis. This equation was created from five DVs including drying ratio (moisture ratio), depth ratio, relative humidity, velocity ratio and temperature ratio. The validation results showed its relatively good agreement between the experimental data and the prediction results[7]. In the case of animal feed drying within batch dryers, DVs were obtained from the analysis of mass, momentum and energy transfers. The drying chamber size effect and the animal feed were taken into account in the dimensional analysis steps. The experiment of the animal feed drying in the batch dryer was conducted to obtain the results to ascertain the similarity of the proposed DVs. The results indicated that the proposed DVs were moderately appropriate for obtaining similarities between different drying conditions and sizes of the batch dryer[1]. Zare et al.[8], for deep bed drying of rough rice, have presented eight DVs from which General dimensionless model of rough rice drying was created by the partial differential equations (PDEs) analyzed by the dimensional analysis of Buckingham theorem. The simulation results of validated PDE model were used to acquire coefficients of the general dimensionless model and evaluate the accuracy of its predicted values (R^2=0.866, MRD=6.85% and RMSE=0.01468). For a rotary dryer, drying chamber dimensions (rotary cylinder length and diameter) and flight number influencing scaling parameters of the dryer, Zheng et al.[9] have studied alfalfa drying by a rotary dryer using improved DMA to develop a non-dimensional equation to predict drying capacity. This equation consisted of four DVs i.e. capacity number, temperature number, velocity number and flight number.

The free-fall grain dryer has been invented and experimentally proven by rough rice drying application. The experimental results revealed that this dryer was fast and energy efficient. It also produced high product qualities (such as head rice yields and whiteness when compared to other types of dryers[10].

The purpose of this study was to use dimensional analysis methodology to establish DG, representing drying characteristics of a rough rice dryer based on counter -flow free-fall drying techniques. The similarities between the small-scale dryer (called the model) and the medium-scale dryer (called the prototype) were verified by the experimental results of the free-fall dryer obtained from our previous studies[11,12]. The dimensionless correlation equation was also developed to predict the moisture content of rough rice during drying process.

2 Free-fall grain dryer

From the schematic as depicted in Figure 1, the heated drying air flows through the vertical drying column in the upward direction opposite to the downward free fall direction of the grain being dried. Grains are fallen down by gravity force from the top hopper into the drying tube without any obstruction from the frontal grain layer (unlike the stack flow pattern). This is the unique design which is different from conventional counter-flow grain dryer. As a result, grain velocity and grain bulk porosity inside free-fall grain dryer are higher than those of conventional grain dryer. The high porosity of the column of the free falling grain (about 0.96-0.98), together with the highly relative velocity between the air and the grain (about 4-6 m/s), helps enhance heat and moisture transfer processes[11]. Furthermore, churning and turbulence additionally boost transfer enhancement. Therefore, the moisture content uniformity of the grain bulk at the end of drying process can be expected while it is not found in fixed deep bed drying[13]. The contacting time between the grain and the air is typically very short. In case of rough rice drying, the contacting time is only about 0.5 s for the 1.15 m long drying column[11]. Despite the short contacting time, it is expected that in an industrial scale dryer, where the drying column length is typically 5 m, the exhausted air would be fully utilized in terms of its drying potentiality which is essential to be further studied because partial recycling of exhausted air is necessary for an economical operation in case of industrial fluidized bed paddy dryer[14,15].

This free-fall dryer has a built-in rest period; much like the spouted bed dryer, as the grains leaving the drying column has to wait in the storage bin for the conveyor to carry them into the next round of drying in the drying column. The duration of this rest period depends on the size of storage bins and the feed/conveying rates. It should be noted that this bin rest is not exactly the same as the tempering rest since the environment is not controlled to be airtight and adiabatic.

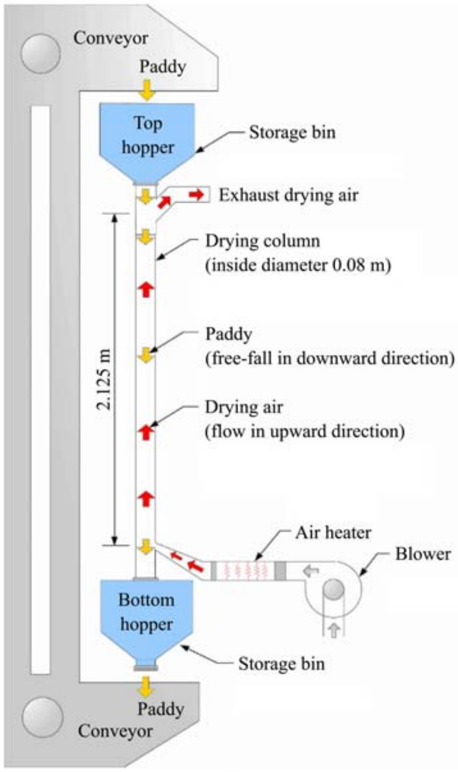

Figure 1 Schematic of the medium scale free-fall dryer

3 Materials and methods

3.1 Dimensionless analysis

Governing equations of the counter-flow model for a drying process were derived from heat and mass balances between grains and the drying air. The single-kernel drying equation[16] was applied for the dimensionless analysis of the free-fall grain dryer in this study.

Mass (moisture) balance of a grain and the drying air:

$$G_p \frac{dM}{dy} = G_a \frac{dH}{dy} \tag{1}$$

Heat (energy) balance of the drying air:

$$\frac{dT_a}{dy} = \frac{h_a a_p (T_a - T_p)}{G_a C_a + G_a C_v H} \tag{2}$$

Heat transfer equation (energy balance of the grain):

$$\frac{dT_p}{dy} = \frac{h_a a_p (T_a - T_p)}{G_p C_p + G_p C_w M} + \frac{\lambda + C_v (T_a - T_p)}{G_p C_p + G_p C_w M} G_a \frac{dH}{dy} \tag{3}$$

Diffusion equation for a sphere (drying rate of the grain):

$$\frac{\partial M}{\partial t} = D_{eff} \left[\frac{\partial^2 M}{\partial r^2} + \left(\frac{2}{r} \right) \frac{\partial M}{\partial r} \right] \tag{4}$$

where, the indispensable variables, which were used to solve this system of equations, included initial and boundary conditions namely the initial moisture content (M_i), the initial grain temperature (T_{pi}), the initial drying air temperature (T_{ai}), the initial absolute humidity (H_i) and the initial grain mass (m). In addition, geometric variables of the free-fall dryer, including the length (L) and the diameter (D) of the drying tube, should be incorporated to obtain DVs.

By observing the above governing equations and boundary conditions, with the assumption that thermal properties of grain and drying air were quite constant in the range of the desired air-grain flow regime, the primitive variables involved in this study were proposed to be: M, M_i, m, H, H_i, T_a, T_{ai}, T_p, T_{pi}, G_p, G_a, r, L, D, t and y. Perhaps the simplest and the most important DV to be proposed was the moisture ratio (MR) since it has been widely used in the literature, therefore,

$$\Pi_1 = MR = \frac{M - M_{eq}}{M_i - M_{eq}} \tag{5}$$

where, equilibrium moisture content (M_{eq}) is the minimum moisture content limited at which a grain can be dried under a given set of drying conditions. M_{eq} depends on grain species, grain variety, the temperature and the humidity of the drying air. Henderson's model [16] was implemented to predict M_{eq}

$$M_{eq} = \frac{1}{100} \left(\frac{\log(1 - RH)}{C_1 T_{a,abs}} \right)^{\frac{1}{C_2}} \tag{6}$$

where, the values of product constants, C_1 and C_2, for rough rice moisture desorption (RD23 varieties) were -3.146×10^{-6} and 2.464, respectively[17]. RH was calcula $t^* = \frac{r^2}{D_{eff}}$ ted from T_a, and H. Since M_{eq} incorporated the effects of drying air temperature and humidity together, therefore, T_a, T_{ai}, H and H_i can be removed out of the list of primitive independent variables.

Grain moisture content (M) in free-fall dryer varies depending on the bed coordinate (y) in drying tube/resting bin and the drying time (t), $M(y,t)$. To simplify the number of variables, grain moisture content was considered at the outlet of the bottom hopper where the grains were more convenient to collect and their properties were easier to measure during the drying process and at its end. Therefore, the distance or bed coordinate (y) was ignored; it was also discarded from the group in this study.

In most cases of rough rice drying, the rate of moisture content reduction mostly reduces in the 'falling rate' drying period, when the internal diffusion resistance is the main controlling mechanism of drying[18]. Therefore, diffusivity is an important parameter representing internal moisture diffusion ability. The grain moisture diffusivity (D_{eff}) is usually presented in the Arrhenius-type equation as a function of grain temperatures[16].

$$D_{eff} = \frac{C_1 \exp\left(\frac{C_2}{T_p} \right)}{3600} \tag{7}$$

For rough rice drying temperature, it was in the range of 20°C-100°C, the constant coefficients, C_1 and C_2, were 33.6 and –6420, respectively[19].

Seven steps in DMA in this study were listed as follows:

Step 1: Propose the variables affecting the moisture ratio as:

$$MR = f'(m, G_a, G_p, r, L, D, t, D_{eff})$$

Step 2: Use mass (α), length (β) and time (γ) as the fundamental dimensions (FD).

Step 3: The dimensions of the listed variables were expressed in multiple powers of α, β, γ as shown in Table 1.

Table 1 Powers of primitive variables in terms of fundamental dimensions

	MR	m	G_a	G_p	r	L	D	t	D_{eff}
Mass (α)	0	1	1	1	0	0	0	0	0
Length (β)	0	0	–2	–2	1	1	1	0	2
Time (γ)	0	0	–1	–1	0	0	0	1	–1

Step 4: Choose m, L, r and D_{eff} as the scaling (repeating) variables. The choice of scaling variables is quite arbitrary if they form a complete independent basis. However, engineering interpretation can help a judicious selection.

Step 5: The scaling method was used to form dimensionless groups. In this method, 'pure' dimensions were extracted from 'compound' dimensions embedded in the fundamental variables by combining them together. This method could be analogous to chemical reaction process in extracting pure substances[20]. (Note: This method which has been applied for DG investigation of solar chimney power plant[2] and animal feed drying[1]. It yielded the same result as Buckingham's pi theorem.

$$\alpha = m \tag{8}$$

$$\beta = L \tag{9}$$

$$\gamma = \frac{r^2}{D_{eff}} \tag{10}$$

Generally, the pure dimensions can be simply extracted by observation, without the solutions of algebraic equations. In rare cases, solving all relevant algebraic equations might be necessary, but the equations need to be solved only once and for all.

Step 6: The DG of G_a is $\alpha^1\gamma^{-1}\beta^{-2}$ and it can be easily determined.

The scaling variable obtained was mD_{eff}/r^2L^2. Therefore the DG for this is:

$$\Pi_2 = \frac{G_a\, r^2 L^2}{m\, D_{eff}} \tag{11}$$

The same procedure was repeated for G_p, t and D, hence, additional DGs are obtained as follows:

$$\Pi_3 = \frac{G_p\, r^2 L^2}{m\, D_{eff}} \tag{12}$$

$$\Pi_4 = \frac{t\, D_{eff}}{r^2} \tag{13}$$

$$\Pi_5 = \frac{D}{L} \tag{14}$$

The DG2 (Π_2) and the DG3 (Π_3) was combined into one by taking ratio of the two, therefore,

$$\Pi_6 = \frac{G_a}{G_p} \tag{15}$$

This ratio implies the magnitude of (1) the velocity ratio between the grain velocity and the drying air speed in drying tube and/or (2) the bulk porosity of the moving bed in the drying tube. As the velocity ratio indicated the intensity of drying air flow through the moving bed and the porosity represented the grain surface area that contacts with the surrounding air, this directly affected the heat and mass transfer rate between the grain and the air in the drying tube.

The fourth DG (Π_4) was interpreted as the time ratio of the drying time to the time for moisture diffusion from inside to the grain surface. This time ratio had the same value as the Fourier number for mass transfer[3]. The fifth DG (Π_5) was the geometric ratio indicating the slenderness of the drying tube. The size of the width was linked to the capability of the grain flow, which was related to the porosity in the moving bed.

Step 7: Finally, the functional relationship of all DGs is

$\Pi_1 = f^n(\Pi_6, \Pi_4, \Pi_5)$ or:

$$\frac{M - M_{eq}}{M_i - M_{eq}} = f^n\left(\frac{G_a}{G_p}, \frac{t D_{eff}}{r^2}, \frac{D}{L}\right) \tag{16}$$

3.2 Experimental drying kinetics

To study the relation between the moisture ratios (Π_1) with dependent DGs of the free-fall dryer, it is necessary to conduct a rough rice drying experiment on the free-fall dryer. The experimental data were collected from previous studies in a small scale dryer, called the model[11], and a medium scale dryer, called the prototype[12]. The dimensions of the dryers and the selected drying conditions were shown in Table 2.

Table 2 Dimensions and drying conditions of small and medium free-fall dryers

Dimension and drying conditions	Small dryer[11] (Model)	Medium dryer[12] (Prototype)
Drying tube length (L)/m	1.15	2.125
Drying tube diameter (D)/m	0.0449	0.0800
Drying air temperature (T_a)/°C	100, 130, 150	100, 130, 150
Drying air velocity (V_a)/m·s^{-1}	1, 2, 3	2
Rough rice flow rate (G_p)/kg·s^{-1}·m^{-2}	133.35	173.74
Resting period (t_{rest})/s	60	60
Initial rough rice mass (m)/kg	3	52.4
Equivalent rough rice radius (r)/m	0.0018	0.0018

The fresh rough rice with moisture content of 27% d.b. was poured into the hopper mounted on top of the drying column. The shutter at the top of column was then opened to let the rough rice free-falling down. The drying air stream was blown in opposite direction of the falling rough rice and a timer was started. The rough rice was emptied from the hopper and enriced in the bucket at the bottom of the drying column. The bulk temperature of the rough rice pile was then measured, a sample of rough rice was collected (for moisture measurement), and the rough rice was rested in the hopper for 60 s resting period. The drying was repeated until the moisture level of the paddy reached 16% d.b. [11]

4 Results and discussion

4.1 Characteristics and similarities of the dimensionless variable groups (DG)

Figures 2-4 represent the drying behavior of the model obtained by plotting the normalized moisture content of rough rice (moisture content in dry basis scale divided by initial moisture content) against drying duration, at the drying air velocity of 1 m/s, 2 m/s and 3 m/s, respectively. It was observed that all the distributions were quite linear with different slopes. The moisture content reduction curves were close to linear fashion because the same rest period resulted in approximately the same amount of rough rice moisture evaporation in all drying rounds. In this free-fall dryer, most moisture evaporated from rough rice in the drying column in which rough rice lost only moisture around its surface due to the short contact time between rough rice and hot air. Then, in the resting hopper (rest period), moisture diffused from inside to the surface of rough rice leading to more moisture level at a rough rice surface. Then the rough rice's surface moisture was ready to evaporate in the drying column in the next drying round. It was also observed that the higher air temperatures and the higher air speeds tended to produce progressively faster drying while still maintaining the linear characteristics of drying curves. The drying characteristics of free-fall dryer were very different from the fluidized bed technique in which the drying curve showed the exponential decay fashion[21].

Moreover, Figures 2-4 showed the effect of the glass transition temperature to the drying rate of rough rice. It was observed that the increasing of drying air temperature from 100°C to 130°C increased drying rate substantially when compared with the increasing of drying air temperature from 130°C to 150°C. Because the rice grain has higher grain temperature than its glass transition temperature (Tg) when using the drying air at 130°C, the starch structure within the grain transforms from the glassy state to the rubbery state. At this state, moisture can diffuse much faster from the grain core to the grain surface than in case of glassy state region. As a result, moisture content of rough rice would be reduced in a drying tube faster. However, a rice grain was in the rubbery state during drying at 130°C and 150°C drying air temperature. Therefore, the raising of drying air temperature from 130°C to 150°C can be increased drying rate moderately due to the reduction of heat and mass transfer resistance at the grain surface. Moreover, the faster drying air speed can be increased more moisture reduction clearly. For more discussions were presented in Meesukchaosumran and Chitsomboon[11].

Figure 5 shows the drying curves of the prototype at 2 m/s of the drying air velocity. The drying curve of the prototype in Figure 5 has quite similar linear characteristics to that of the model in Figure 3. The moisture content reduction of the prototype should be faster than that of the model at the same drying air conditions. This was because the longer drying tube length of the prototype originated longer contacting time between rough rice and drying air in drying tube of each drying round. This longer contacting time promoted more heat absorption and moisture evaporation while grains were passing through the drying tube. However, from Figures 3 and 5, the average drying rate of the prototype was slightly slower than that of the model, especially at drying air temperature 130°C and 150°C. This was because the paddy mass flow rate flux (G_p) was raised by 30% when drying tube diameter (D) increased from 0.0449 m of the model to 0.08 m of the prototype, the bulk porosity of grain bed in drying tube of the prototype was much lower. Therefore, in this case, the longer drying time was required. These results indicated that the effect of the geometric scaling up on the average drying rate of the free-fall dryer was quite complicated. The free-fall dryer analysis could be easier and clearer when applying the dimensionless variables as shown in the next paragraph.

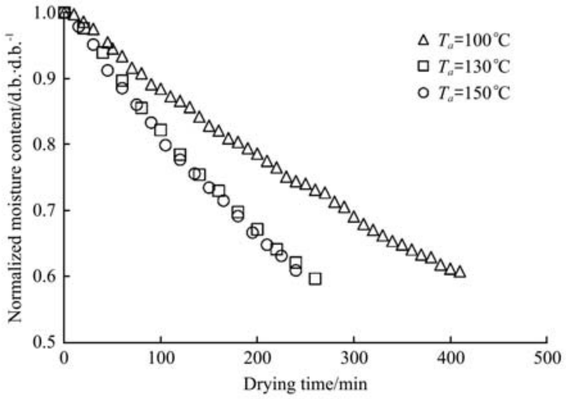

Figure 2 Drying curve for the model dryer at 1 m/s of drying air velocity[11]

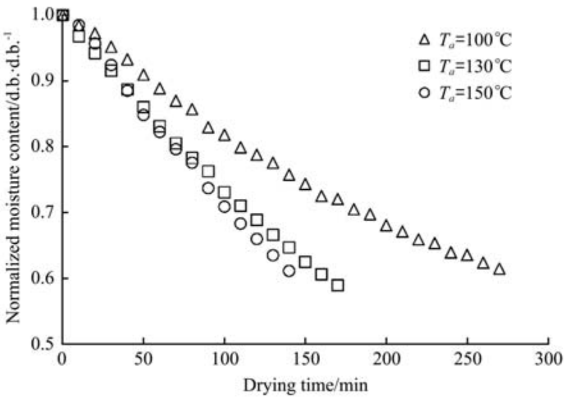

Figure 3 Drying curve for the model dryer at 2 m/s of drying air velocity[11]

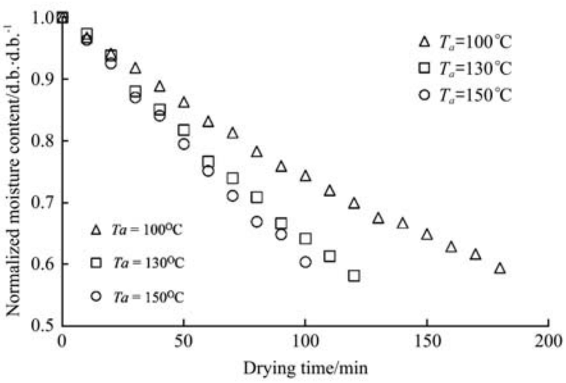

Figure 4 Drying curve for the model dryer at 3 m/s of drying air velocity[11]

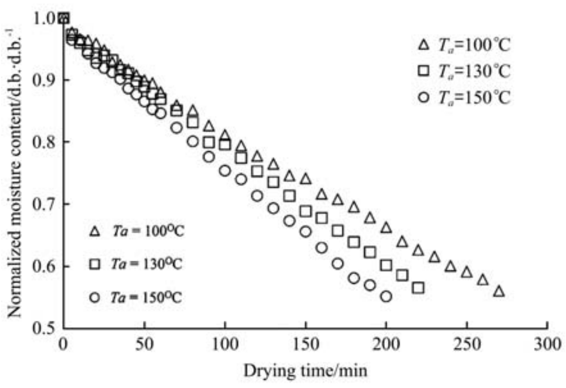

Figure 5 Drying curve for the prototype dryer at 2 m/s of drying air velocity[12]

Figure 6 shows the distributions of the moisture ratio (Π_1), computed from the experimental data, as related to the mass flow rate ratio (Π_6) at the corresponding time ratios (Π_4 = 0.01, 0.04) and the geometry ratios (Π_5 = 0.37, 0.38) of both the model and the prototype drying experiments. The relationship of Π_1 and Π_6 was a non-linear function. The moisture ratio (Π_1) decreased as the mass flow rate ratio (Π_6) increased. This inverse correlation was based on heat and mass transfer principles. Mass flow rate ratio (Π_6) could be increased with increasing in the drying air mass flow rate flux (G_a) and/or decreasing in rough rice mass flow rate flux (G_p). The increasing of G_a results in reduction of the boundary layer resistance which induces grain moisture evaporated faster. In addition, the residence time of the rice grain in drying tube would be longer because using higher drying air speed cause increasing in the counter flow direction between grain and drying air which induce higher aerodynamic drag. The decreasing of G_p leads to increase porosity in the drying-moving bed that increases the contact surface area between rice grain and drying air in drying tube which allows better heat and mass transfer.

In addition, the relation of the moisture ratio (Π_1) and the mass flow rate ratio (Π_6) from the prototype data showed comparable values with the relation from experimental data of the model which exhibited the similarity of these DVs (Π_1 and Π_6).

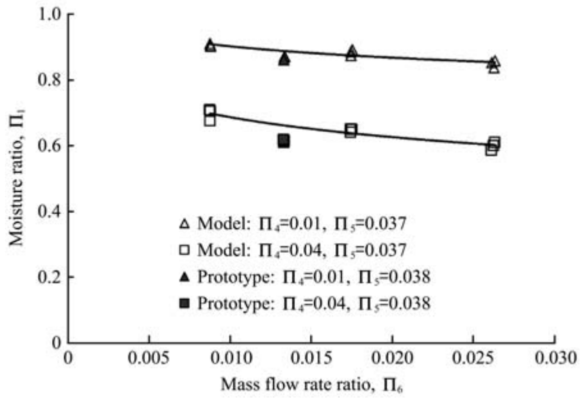

Figure 6 Effect of the mass flow rate ratios (Π_6) on the moisture ratios (Π_1)

Figure 7 shows the relation of the moisture ratio with the time ratio from the model and the prototype at different drying air temperatures. Clearly, the moisture ratio data from different drying air temperature conditions collapsed onto straight lines, and suggested a similarity. In addition, the moisture ratio (Π_1) reduced as the time ratio (Π_4) increased. The increase in drying air temperature induced high grain temperature that changed the grain internal pore structure and increased the grain internal vapor pressure, resulting in greater internal moisture diffusion[21]. Since the ability of the moisture to diffuse is greater, the diffusion coefficient becomes larger, and the time scale value (r^2/D_{eff}) is smaller. Meanwhile, the high vapor pressure difference between the grain interior side and the environment was generated, and thus the grain moisture was rapidly evaporated. This reduced the drying time. Accordingly, the increase in the drying air temperature reduced both the drying time and the time scale at the same proportion, and thus the time ratios of different drying air temperatures were equal (Figure 7).

Moreover, a close similarity of the moisture ratio reduction between the model and the prototype clearly existed in Figure 7. However, some deviations occurred due to a slight difference of the mass flow rate ratio and the geometry ratio between the model and the prototype. In this case, the mass flow rate ratio of the prototype was lower than that of the model, and the geometric ratios of the prototype and the model were considerably close. According to engineering intuition, the moisture ratio reduction of the model should be faster than that of the prototype; nonetheless, this concept was not consistent with the experimental result. For this reason, other DVs should be established.

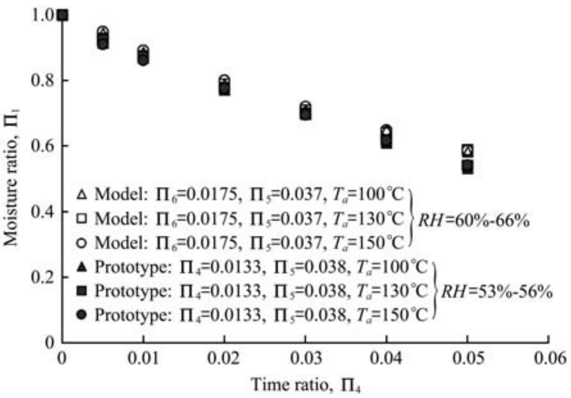

Figure 7 Effect of the time ratios (Π_4) on the moisture ratios (Π_1) at various drying air temperatures

After a grain left the drying column, it had to sit in the storage bin, which was not controlled to be airtight and adiabatic, for the conveyor to carry the grain to the next round of drying in the drying column. In the storage bin, the moisture within the grain equalized due to diffusion, and some moisture was evaporated from the grain surface to the environment. The mechanism controlling the evaporation rate was the vapor pressure difference between the grain surface and the environment, which was inversely related to the relative humidity of the environment. Although this mechanism had slower evaporation rate in the storage bin than in the drying chamber, it still affected the overall drying rate because the ratio of the resting time in the storage bin to the drying time in the drying tube was large, about one minute in the storage bin against one second in the drying tube. For this reason, the relative humidity of the environment was added to the DG.

$$\Pi_7=RH_{amb} \tag{17}$$

Then, the final functional relationship is $\Pi_1=f^n(\Pi_6, \Pi_4, \Pi_5, \Pi_7)$.

$$\frac{M-M_{eq}}{M_i-M_{eq}}=f^n\left(\frac{G_a}{G_p},\frac{t\,D_{eff}}{r^2},\frac{D}{L},RH_{amb}\right) \tag{18}$$

Because of the limitation of laboratory and the lack of controller equipment, ambient relative humidity around the dryer could not be controlled to be constant value throughout the drying process. The relative humidity of the environment was in the ranges of 60%-66% and 53%-56% for the model and the prototype, respectively. The data indicated that the moisture ratio reduction of the prototype would be slightly faster than that of the model because the lower relative humidity of the environment helped increase the rate of moisture evaporation in the storage bin.

4.2 Development of the dimensionless correlation equation

To obtain the dimensionless correlation for rough rice drying in the free-fall dryer by using the DG presented above and the experimental data from literature [11], the geometry ratio (Π_5) and the ambient relative humidity (Π_7) were discarded from the dimensionless correlation development due to the lack of sufficient data of these two DVs from the literature. Thus, the final functional relationship was reduced to $\Pi_1=f^n(\Pi_6, \Pi_4)$.

In Figure 8, the relationship of the three DVs was considered, and the relationship between the moisture ratio (Π_1) and the time ratio (Π_4), when the mass flow rate ratio (Π_6) was constant, was found to be as an exponential decay function:

$$\Pi_1=e^{(Coefficient\ of\ \Pi_4)\Pi_4} \tag{19}$$

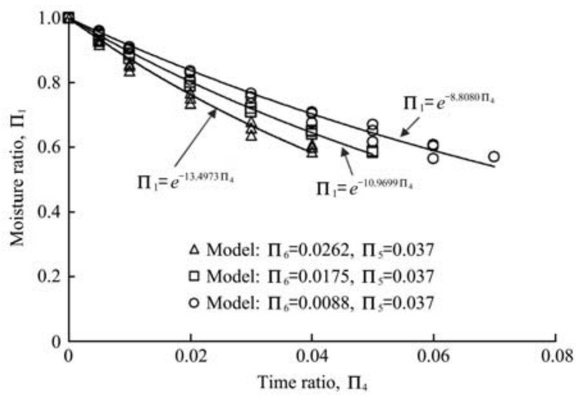

Figure 8 Effect of the time ratios (Π_4) on the moisture ratios (Π_1) at various mass flow rate ratios (Π_6)

The coefficients of Π_4, as shown in Figure 9, were –13.4973, –10.9699 and –8.8080, when the mass flow rate ratios were 0.0262, 0.0175 and 0.0088, respectively. The relationship between the coefficients of Π_4 and the mass flow rate ratios from Figure 8 were presented in Figure 9. The coefficient of Π_4 was less negative or increased when the mass flow rate ratio (Π_6) were decreased, this imply that lower drying rate could be achieved when using lower air speed and/or higher feed rate. The equation of a coefficient of Π_4 was obtained as:

$$Coefficient\ of\ \Pi_4=-4.1749\log(\Pi_6)-28.3764 \tag{20}$$

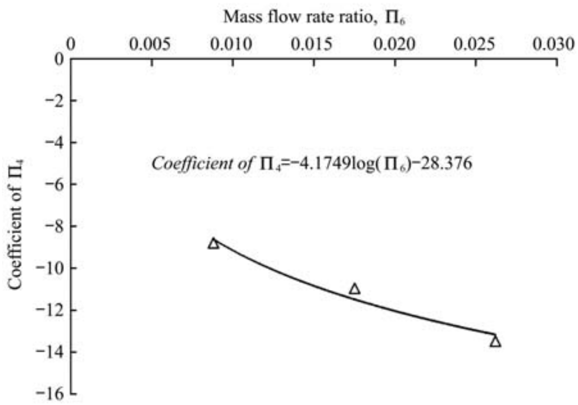

Figure 9 Relationship between the coefficients of Π_4 and the mass flow rate ratios (Π_6)

Substituting Equation (20) into Equation (19) gives:

$$\Pi_1=e^{(-4.1749\log(\Pi_6)-28.3764)\Pi_4} \tag{21}$$

Then, the dimensionless correlation for rough rice drying in the free-fall dryer was:

$$\frac{M-M_{eq}}{M_i-M_{eq}}=\exp\left(\left(-4.1749\log\left(\frac{G_a}{G_p}\right)-28.3764\right)\left(\frac{t\,D_{eff}}{r^2}\right)\right) \tag{22}$$

As shown in Figure 10, the predicted moisture ratios from the dimensionless correlation (Equation (22)) were plotted against the computed moisture ratios (Π_1) from the experimental data. The points scattered narrowly around the line, $X=Y$, demonstrated the suitability of the dimensionless correlation to describe the drying behavior of rough rice in the free-fall dryer. Likewise, the values of coefficient of determination (R^2), mean relative deviation (MRD) and root mean square error (RMSE) were 0.989, 1.82, and 0.0168, respectively. It could be concluded as a satisfactory correlation.

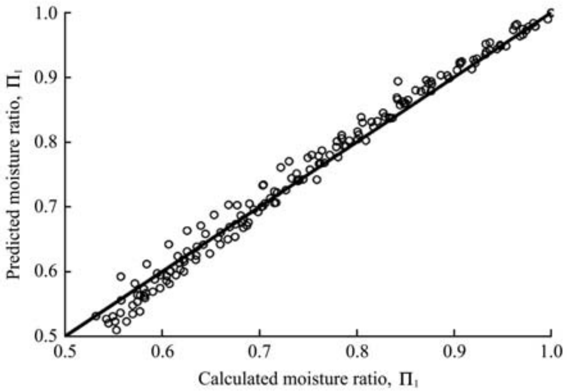

Figure 10 Predicted moisture ratios (Π_1) from the dimensionless correlation vs. calculated moisture ratios (Π_1) from the experimental data.

Further studies with various geometric ratios may be necessary to reveal the complete correlation for scaling up the design of the free-fall dryer. While the ambient relative humidity was considered in this study, this variable could be discarded from the DG because the ambient relative humidity had a small effect on the moisture ratio and was hard to be controlled in a practical drying setting due to the fluctuation of the environment.

5 Conclusions

This study was proposed, for the free-fall grain dryer, to obtain five dimensionless variables (DVs) with similarities, which have been proved to be valid both in the model and the prototype dryers by using experimental data from different drying chamber (small and medium scale), drying air speed (1-3 m/s) and temperatures (100°C-150°C). The DVs included the moisture ratio, the mass flow rate ratio, the time ratio, the geometric ratio and the ambient relative humidity. The time ratio incorporated the effect of different drying air temperatures in the moisture ratio. The moisture ratio decreased as the mass flow rate ratio increased due to the higher air flow and/or the higher bulk porosity. The geometric ratio revealed the similarity of the data between the model and the prototype of other DVs. Due to the long resting period in the storage bin, the ambient relative humidity could have an effect on the moisture ratio reduction. This effect, however, may not be crucial when compared to the effect of other DVs. The dimensionless correlation equation of rough rice drying by the free-fall dryer was developed from the drying experimental data. The results showed that this correlation could significantly predict the rough rice moisture contents.

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Nomencalture

Symbols

a_p	particle surface area, m^2/m^3
c_a	specific heat of dry air, J/(kg·K)
c_p	specific heat of particle, J/(kg·K)
c_v	specific heat of vapor, J/(kg·K)
c_w	specific heat of water, J/(kg·K)
D	diameter of drying tube, m
D_{eff}	effective diffusion coefficient, m^2/s
G_a	mass flow rate flux of drying air, kg/(s·m^2)
G_p	mass flow rate flux of particle, kg/(s·m^2)
h_a	heat transfer coefficient, J/(m^2·K·s)
H	absolute humidity of air, kg/kg
L	length of drying tube, m
m	initial mass of particle, kg
M	moisture content (dry basis, decimal)
M_{eq}	equilibrium moisture content (dry basis, decimal)
MR	moisture ratio content (decimal)
r	equivalent radius of particle, m
RH	relative humidity of air (decimal)
t	drying time, s
t_{rest}	resting time per drying interval, s
T_a	drying air temperature, K
T_p	particle temperature, K
y	depth in bed from particle inlet, m

Greek Letters

α	fundamental dimension of mass, kg
β	fundamental dimension of length, m
γ	fundamental dimension of time, s
λ	latent heat of vaporization, J/kg
Π	dimensionless variable

Subscripts

i	initial
amb	ambient

Abbreviations

CFD	computational fluid dynamic
DEM	discrete element method
DG	dimensional variable group
DMA	dimensional analysis method
DV	dimensionless variable
PDE	partial differential equation

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