Study on Drying Kinetics of Paddy Rice: Intermittent Drying

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ABSTRACT: *The intermittent drying characteristics of an Iranian popular paddy rice variety were experimentally investigated to determine the drying kinetics and obtain the effective moisture diffusivity. A lab-scale fluidized bed dryer was designed and constructed to enable obtaining the required results while controlling critical drying parameters. The effects of drying temperature and tempering period on drying kinetics and moisture diffusivity were studied. The results showed a significant effect on drying performance and effective moisture diffusivity by adding tempering stage. Drying rate improved sharply by implementing the tempering stage, increase of drying air temperature as well as the tempering duration. Several thin layer drying models were fitted separately to experimental data of each drying stages namely pre-tempering and post-tempering and suitability of these models were examined using the statistical analysis. The Midilli and Tow-Term model were found to be the most appropriate one for the first and second drying stages, respectively.*

KEYWORDS: *Intermittent drying; Drying model; Effective moisture diffusivity; Paddy rice; Tempering; Statistical analysis.*

INTRODUCTION

Paddy rice has been cultivated in many countries all over the world for many years. It is one of the basic food supplies for more than half of the world population. Although harvesting the rice with high moisture usually results in better efficiency and less damaged grains, the moist paddy must be dried as soon as possible in order to avoid the deterioration and preventing germination of the grains. Therefore, one of the most essential post-harvesting operations for paddy is drying. At present, the vast majority of rice mills in Iran use a traditional paddy drying process with low efficiency. In this method, the bulk of grains do not dry uniformly as a result of non-uniform distribution of the hot air. In addition, huge amount of the hot air is exhausted to the ambient which is a total waste [1]. Continuing drying when there is not enough moisture at the surface due to the slowness of moisture diffusion within the grain would also affect product quality because of breakage on the surface crust.

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Moreover, the drying process is controlled manually by switching the heater on and off in accordance to the temperature of the bed surface in undefined time intervals which is based on the skills of the operator. Therefore, the quality of the final product resulting from the arbitrary procedure might not be desirable [2, 3]. Thus, it is essential to improve this inefficient drying process by using an alternative drying technique, which requires the minimal modification to this outdated drying process while avoiding its shortcomings. For this purpose an alternative intermittent drying process is proposed and fully investigated. This process consists of a fluidized bed drying along with tempering stages. Intermittent drying or tempering drying is a non-continuous drying process with intermediate periods [4, 5]. In the other words, during the tempering stage, the hot air is not charged into the dryer chamber and the grain is in the rest stage, while during the drying stage the energy is transferred to the grain and thereby moisture leaves the kernel at mainly near the surface region. Since the diffusion inside the paddy grains is very slow, the evaporated moisture at the surface cannot be replaced by moisture within the kernel and therefore drying should be stopped at specified times in order to facilitate the diffusion of the inner moisture to the grain surface. This would avoid supplying energy while the drying potential is minimal. The drying stage could be followed after the surface moisture content is sufficient enough that the evaporation rate is controlled by heat convection at the surface and not by moisture diffusion within the grain. Therefore, employing the intermittent drying method is completely logical and desirable for grains drying, especially for a heat sensitive grain such as paddy rice.

Several attempts have been made to model and analyze the drying process of paddy rice grain. These studies cover a wide range of topics which include both experimental investigations and mathematical analysis in order to determine the drying kinetics, deriving new empirical correlations for drying rates, and mathematical modeling of tempering or drying stages or both. Investigation of the drying kinetics of paddy grain has a special importance because the drying kinetics express the relationship between the rate of drying, the structure of paddy grain and operating conditions. *Jayas et al.* [6] presented a comprehensive review for thin layer drying. In their work, several thin layer drying and wetting equations were reviewed and discussed. *Agrawal & Singh* [7] used the Logarithmic model [8] to simulate the thin layer drying of short grain rough rice. *Wang & Singh* [9] adopted the quadratic equation for their simulation. *Sharma et al.* [10] presented a two-compartment model for a thin layer of medium grain rough rice. *Noomhorm & Verma* [11] suggested the Two-Term exponential model [12] for drying of rough rice. *Doungporn et al.* [13] conducted the drying of rice under different drying temperature and various gases. According to their result of thin layer drying, the *Midilli* model [14] was suitable for drying under hot air, while the linear type model was selected for drying under CO_2 and N_2 gases. According to this literature review, Table 1, it could be concluded that the best model for every product (species) differs from the others and also depends on drying conditions and techniques used. Overall the multi-parameters models satisfy the fitting of experimental results more properly, however the main criterion for model selection is that the model predicts the results close to experimental data.

Due to the critical role of moisture diffusion coefficient within the grain for developing a drying model, several researchers have tried to determine experimentally the effective moisture diffusivity for variant paddy rice grain. Accordingly, rice grain geometry was represented by sphere, cylinder, spheroid, or ellipsoid shapes in the drying models [19]. Although considering a cylindrical geometry for modeling the rice grain or even modeling the grain as a spindle-shape object is more realistic, using these complex geometries probably adds up different new errors including truncation and round off error inherent to numerical methods and increases computational volume. Hence, it seems that assuming the spherical geometry for modeling the rice grain yield desirable result as well as less calculation. Moreover, Arrhenius equation has been widely employed to relate the effective moisture diffusivity with temperature [20-22].

It should be noted that, Hashemi is one of the most important rice varieties in Iran and there is no reported data for moisture diffusion coefficient and drying kinetic for this variety in the literature. The objective of the present study is: (1) to obtain the best correlation for predicting the drying rate as a function of drying conditions for paddy rice; (2) to investigate the influence

Table 1: Drying models used for grains.

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	[6]
Henderson & Pabis	$MR = a\exp(-kt)$	[15]
Page	$MR = \exp(-kt^n)$	[7]
Geometric	$MR = at^{-n}$	[8]
Logarithmic	$MR = a_0 + a\exp(-kt)$	[8]
Two-Term	$MR = a_1\exp(-k_1t) + a_2\exp(-k_2t)$	[16]
Wang & Singh	$MR = 1 + at + bt^2$	[9]
Two-Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	[12]
Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	[17]
Diffusion Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[18]
Midilli	$MR = a\exp(-kt^n) + bt$	[14]

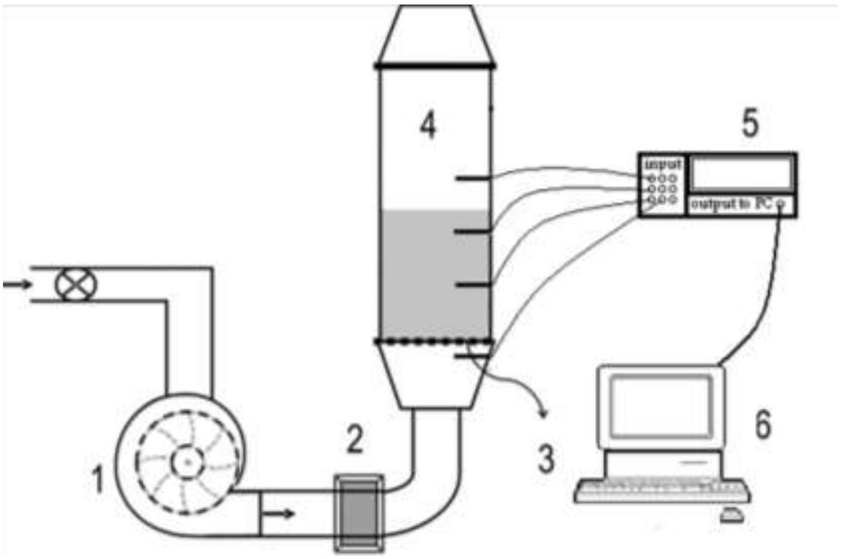

Fig. 1: Overall layout of fluidized bed dryer set up. (1) blower; (2) air heater; (3) distributor; (4) dryer column; (5) data acquisition module; (6) computer.

of tempering time and frequency on drying of paddy and (3) to determine the effective moisture diffusivity for drying with and without tempering at various drying temperature and tempering durations.

EXPERIMENTAL SECTION

The Experimental Setup

A lab-scale fluidized bed dryer was used which was comprised of a fluidization column including a cylindrical and a conical part, both made of plexiglass. Schematic presentation of the experimental set-up is depicted in Fig. 1.

Cylindrical part is 19 cm in diameter and 50 cm long. The conical part diameter is between 10 to 19 cm and its length is 14 cm. For the purpose of obtaining uniform distribution of the drying air a perforated-plate distributor with 9.8% open fraction was used. The drying air was provided by a blower. An electrical heater with eight 0.5-kW fin-striped electric elements covered by a metal cylindrical shell of 25 cm in diameter and 70 cm long was used to heat up the air. The exhaust air temperature was controlled by a PID controller of ±1°C tolerance. The air velocity during the drying stage was measured by a digital anemometer with accuracy of ±2% (Tepkel, AVM712). Four k-type thermocouples with accuracy of ±1°C were utilized to measure the temperature at 4 points, right before column entrance and within the height of 10, 20 and 30 cm along the column. A data acquisition system including signal amplifier, analogue to digital signal converter and Labview software was devised to monitor and record data.

Materials and Drying Procedure

One of the most popular and desirable rice varieties in Iran from Guilan province, Hashemi variety, was used. The sample was cleaned and excess husk and dust were removed. Then, the sample was packed and kept in refrigerator at an approximate temperature of 5°C in order to avoid changes in its moisture. Two hours before experimental run, some paddy was taken out of the refrigerator and was left in the room to reach the ambient temperature. It can be assumed that the grain initial moisture content was similar for all runs. 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 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 samples were 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 [23]. The weight of samples during the drying stages was measured gravimetrically using an electronic balance (OHAUS, Swiss) with the precision of ±0.1g. 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 30 min for the second drying stage, the drying system was switched off, the dryer chamber was discharged, and the weight of samples was recorded. The samples were dried subsequently after each drying interruption. The moisture content of the grains is then calculated using the following equation:

$$\mathrm{M(dry\,basis)} = \frac{(\mathrm{W} - \mathrm{W_{bd}})}{\mathrm{W_{bd}}} \tag{1}$$

Where M is the moisture content of the grain in kg/kg dry, W is the weight of samples at the specified time in kg and W_{bd} is the weight of bone-dry paddy rice in kg.

Mathematical Modeling

In most drying processes, the drying kinetics consists of three drying periods. The initial warm up drying period is usually negligible and is followed by the constant drying rate period in which the drying mechanism is controlled only by heat transfer from the hot air to drying surface with a constant moisture content. The last drying period is falling rate drying period during which the moisture diffusion controls the drying rate. The drying process of paddy rice is mainly controlled by moisture diffusivity within the grain. It is suggested that during the falling rate period in drying of porous materials, the rate of change in material moisture content is proportional to the instantaneous difference between material moisture content and the expected material moisture content when it comes into equilibrium with the drying air at that temperature [24]:

$$-\frac{\mathrm{dM}}{\mathrm{dt}} = \mathrm{K}(\mathrm{M} - \mathrm{M_e}) \tag{2}$$

Where K is drying constant in $\mathrm{min^{-1}}$ and M_e is the equilibrium moisture content in kg/kg dry. This equation is defined for the models of so called thin layer.

In order to apply thin layer drying model, the material layer should be thin enough or the air velocity should be high so that the temperature and humidity of drying air can be assumed to be constant throughout the material layer [24]. Since in this work the drying stages were implemented in a fully mixed fluidized bed, the thin layer model is adequate to predict the moisture changes.

The ten distinctive kinetic models presented in Table 1 have been examined in which the moisture ratio is defined as:

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \tag{3}$$

Where M_0 is the initial moisture content of grain in kg/kg dry and M_e is calculated based on the equation developed by *Chang & Pfost* [25] but using the parameter related to paddy rice:

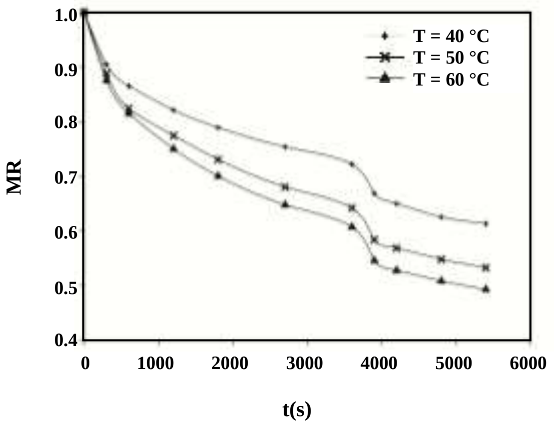

Fig. 2: Effect of drying temperature on the drying curves.

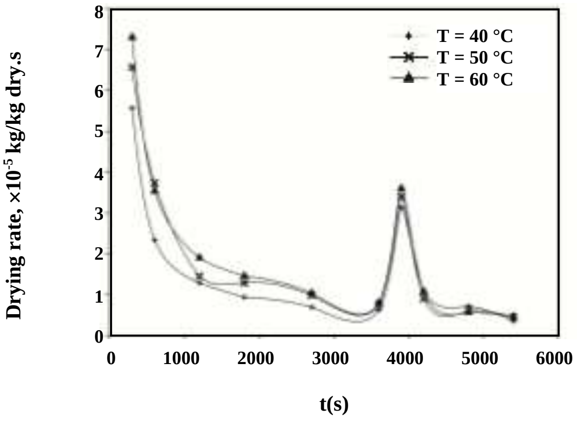

Fig. 3: Effect of drying temperature on drying rates.

$$M_e = \frac{1}{14.93306} \times \left[\ln\left(\frac{4315.76}{8.32 \times \left(T + 191.37513\right)} \right) - \ln\left(-\ln RH\right) \right] \quad (4)$$

Where T is the temperature of drying air in °C and RH is the relative humidity of the air.

Here, the primary criteria used to evaluate the appropriateness of the fit are: a) coefficient of correlation (r); b) the standard deviation (e_s); and c) mean squared deviation (χ^2). These criteria were defined by the following equations [26]:

$$r = \frac{N \sum_{i=1}^{N} (MR_{pre,i} MR_{exp,i}) - \sum_{i=1}^{N} MR_{pre,i} \sum_{i=1}^{N} MR_{exp,i}}{\sqrt{N \sum_{i=1}^{N} (MR_{pre,i})^2 - (\sum_{i=1}^{N} MR_{pre,i})^2} \times \sqrt{N \sum_{i=1}^{N} (MR_{exp,i})^2 - (\sum_{i=1}^{N} MR_{exp,i})^2}} \quad (5)$$

$$e_S = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \quad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{N - n_c} \quad (7)$$

where $MR_{exp,i}$ is the i^{th} experimental moisture ratio and $MR_{pre,i}$ is the i^{th} predicted moisture ratio by model, N is the number of total experiments and n_c is the number of constants in the model. These criteria are explained in detail in the following section.

RESULTS AND DISCUSSION

Effect of Temperature on Drying

In order to evaluate the effect of drying temperature, experiments were carried out at a temperature range of 40, 50 to 60°C with constant air velocity of to 2.2 m/s. The results are plotted in Fig. 2. It is obvious that the higher the temperature of drying air, the lower the moisture ratio. By increasing the air temperature, the moisture diffusion inside the grain is improved therefore the mass transfer from the inner layers to the outer surface is facilitated. In this figure the drying curves have not converged by time due to the fact that the drying has been interrupted intentionally. The drying behaviour can be assessed more clearly in the forms of drying rate, as presented in Fig. 3. According to drying rate, paddy rice has only falling rate period because the paddy rice in this study had low moisture content so the moisture could not cover the surface of the grains. Hence, the thin layer models can be applied to derive the drying kinetics for paddy grain. It is also apparent that the drying rate extremely decreases at the early drying time, so the continuation of drying is not logical and it seems that applying the tempering period between two drying stages is an effective alternative.

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

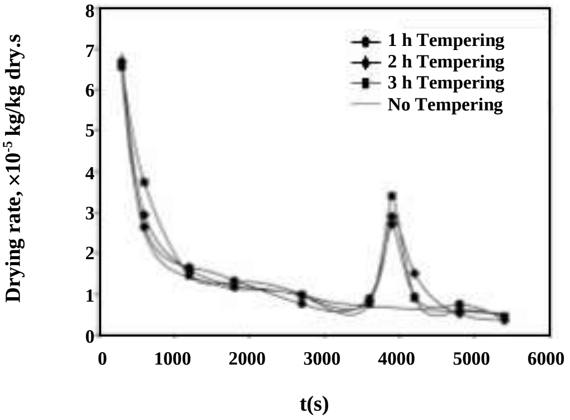

Fig. 4: Effect of tempering time on the drying rates.

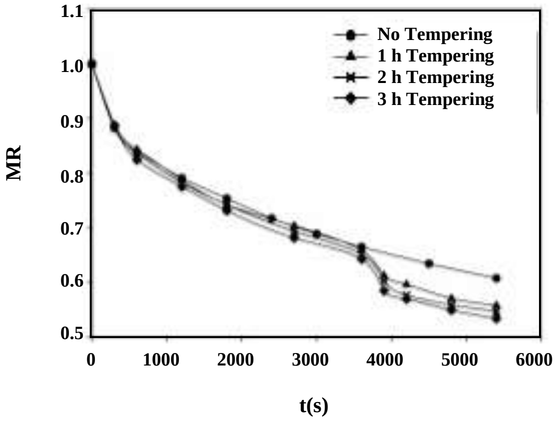

Fig. 5: Effect of tempering time on drying curves.

dried for 90 minutes. All these runs were carried out with 50 °C air with 2.2 m/s velocity. Results are shown in the form of drying rates and drying curves in Figs. 4 and 5, respectively. It should be noted that the significant kink occurred in diagrams is due to applying the tempering periods. The reason for this behaviour is that tempering allows the moisture to transfer from the centre to the surface of the grain, therefore moisture gradients inside the grain, which was imposed during a pervious drying stage, is eliminated. Such elimination causes a uniform moisture profile within the grain, which that results in a higher moisture content at the grain surface and therefore an increase in drying rate in the next drying stage (Fig. 4). Besides, it is observed that by the usage of tempering in the drying process, the lower moisture ratio was achieved and also by increasing the tempering period the moisture ratio were diminished (Fig. 5).

Thin Layer Drying Equations

All of the eleven thin layer drying models given in Table 1 were tried to correlate moisture ratio with drying time. The satisfaction criterion used to select the best model is based on the value of r^2 that has to be close to one. The parameters e_s and χ^2 which indicate the deviation between the experimental and calculated values for the model should also be considered to possess the lowest values. The ideal value for root square errors and mean squared deviation is zero. The results of fitting the thin layer drying models are presented in Tables 2, 3, 4 as well as the constants and coefficients of the correlations. The amounts of these parameters were calculated by Levenberg-Marquardt algorithm [27].

According to the results, the Midilli model exhibited a better agreement with experimental data for the pre-tempering stage and had the highest r^2 values and the lowest χ^2 and e_s values at different conditions. For the post-tempering stage, the best model was Two-Term model. The statistical analysis results also revealed that the most proper model among the two and three parameter models were the Page and the Diffusion Approach model, respectively for both drying stages.

Validation of the Midilli and Two-Term models was also confirmed by comparison of the predicted moisture ratio with the experimental data, (Figs. 6, 7). It is observed that the predicted data from these models are very close to the experimental results which again implies the suitability of these models in describing the drying behaviour of this specific paddy rice, i.e. Hashemi variety.

Determination of Effective Moisture Diffusivities

As mentioned in the previous section, the paddy drying process consists only of the falling rate period; hence, the main resistance for drying is the diffusion of moisture to the grain surface.

Fick's second law of diffusion in spherical coordinate geometry can be used for determining the moisture distribution inside the grain:

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

Where, *D* is moisture diffusion coefficient in m^2/s, *M* is moisture content in kg/kg dry and *r* is the radial coordinate of the grain.

Table 2: Results of statistical analysis for nominated drying models at T=40 ℃, v= 2.2 m/s.

Model	Coefficients		r		e_s		χ^2	
	Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering
Newton	k=0.000112	k=0.00011	0.942303	0.922489	0.047029	0.028291	0.002580	0.001
Henderson & Pabis	a= 0.940724	a= 0.968865	0.938518	0.920279	0.030498	0.020750	0.001302	0.000718
	k=0.000084	k=0.000085						
Page	k=0.007409	k=0.007329	0.999825	0.999340	0.001655	0.001927	0.000004	0.000006
	n=0.461781	n=0.416241						
Geometric	a=1.0056	a=0.997019	0.905224	0.909176	0.038277	0.064951	0.00114	0.007031
	n=0.031099	n=0.018096						
Logarithmic	a_0=0.258792	a_0=0.848042	0.989565	0.996961	0.012723	0.004130	0.000283	0.000042
	a=0.000929	a=0.150063						
	k=0.727142	k=0.001929						
Two-Term	a_1=0.869134	a_1=0.907221	0.999787	0.999356	0.001824	0.001924	0.000008	0.000019
	a_2=0.130447	a_2=0.9256						
	k_1=0.000052	k_1=0.000037						
	k_2=0.003107	k_2=0.003725						
Wang & Singh	a=-0.000183	a=-0.000214	0.926252	0.912558	0.179150	0.119159	0.044932	0.023665
	b=0.000000	b=0.000000						
Two-Term Exponential	a=0.057333	a=0.033556	0.966544	0.954269	0.033966	0.020594	0.001615	0.000707
	k=0.001568	k=0.002609						
Verma et al.	a= 0.095693	a= 0.064274	0.992463	0.988145	0.010823	0.005336	0.000205	0.000071
	k= 0.121303	k= 0.882699						
	g= 0.000067	g= 0.000057						
Diffusion Approach	a=0.130754	a=0.092737	0.999786	0.999357	0.001830	0.001903	0.000006	0.000009
	k=0.003120	k=0.003734						
	b=0.016697	b=0.010008						
Midilli	a= 0.000004	a= 0999965	0.999849	0.999909	0.001557	0.000763	0.000006	0.000003
	k= 1.000143	k= 0.003148						
	n= 0.006583	n= 0.588772						
	b=0.483423	b=0.0000088						

Table 3: Results of statistical analysis for nominated drying models at T=50 ℃, v= 2.2 m/s.

Model	Coefficients		r		e_s		χ^2	
	Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering
Newton	k=0.000154	k=0.000125	0.946693	0.911783	0.075833	0.033735	0.006709	0.001423
Henderson & Pabis	a= 0.930912	a= 0.962285	0.947594	0.909157	0.036796	0.024530	0.001895	0.001003
	k=0.000119	k=0.000095						
Page	k=0.007447	k=0.010715	0.999087	0.999931	0.004919	0.000694	0.000004	0.000001
	n=0.499442	n=0.380753						
Geometric	a=1.006819	a=0.995419	0.889667	0.925714	0.052984	0.073116	0.002183	0.00891
	n=0.041013	n=0.020543						
Logarithmic	a_0=0.339846	a_0=0.833670	0.990750	0.992275	0.015607	0.007307	0.000426	0.000119
	a=0.000883	a=0.163466						
	k=0.643686	k=0.002169						
Two-Term	a_1=0.836191	a_1=0.910241	0.999664	0.999865	0.003048	0.000314	0.000022	0.000005
	a_2=0.164097	a_2=0.089741						
	k_1=0.000075	k_1=0.000052						
	k_2=0.002933	k_2=0.005907						
Wang & Singh	a=-0.000233	a=-0.000235	0.930955	0.900610	0.225247	0.129031	0.071031	0.027748
	b=0.000000	b=0.000000						
Two-Term Exponential	a=0.074148	a=0.036790	0.973595	0.945243	0.038431	0.025200	0.002068	0.001058
	k=0.001659	k=0.002735						
Verma et al.	a= 0.114283	a= 0.089778	0.991589	0.999865	0.014891	0.000970	0.000388	0.000002
	k= 0.130770	k= 0.006280						
	g= 0.000096	g= 0.000049						
Diffusion Approach	a=0.163857	a=0.078051	0.999664	0.998501	0.002984	0.003222	0.000016	0.000026
	k=0.002926	k=0.076230						
	b=0.025466	b=0.000796						
Midilli	a= 0.000008	a= 1.0	0.999152	0.989318	0.004735	0.023962	0.000052	0.002871
	k= 1.000449	k=0.014591						
	n= 0.006181	n=0.321067						
	b=0.533625	b=0.000012						

Table 4: Results of statistical analysis for nominated drying models at T=60 °C, v= 2.2 m/s.

Model	Velocity (m/s)	Coefficients		r		e_s		χ^2	
		Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering	Before tempering	After tempering
Newton	v=2.2	k=0.000172	k=0.000144	0.948498	0.905794	0.095860	0.038630	0.010721	0.001865
Henderson & Pabis	v=2.2	a= 0.927113	a= 0.956999	0.951727	0.902315	0.039089	0.028245	0.002139	0.00133
		k=0.000137	k=0.000106						
Page	v=2.2	k=0.007434	k=0.013154	0.999715	0.999900	0.003043	0.000928	0.000013	0.000001
		n=0.514959	n=0.368863						
Geometric	v=2.2	a=1.006923	a=0.994367	0.891002	0.930614	0.059604	0.082682	0.002763	0.011394
		n=0.045683	n=0.023153						
Logarithmic	v=2.2	a_0=0.377051	a_0=0.81654	0.992912	0.993803	0.0151	0.007282	0.000399	0.000133
		a=0.000871	a=0.180917						
		k=0.605639	k=0.002292						
Two-Term	v=2.2	a_1=0.817038	a_1=0.891744	0.999714	0.999983	0.003047	0.000411	0.000022	0.000000
		a_2=0.182280	a_2=0.108234						
		k_1=0.000084	k_1=0.000053						
		k_2=0.002696	k_2=0.005469						
Wang & Singh	v=2.2	a=-0.000257	a=-0.000259	0.932459	0.892322	0.248545	0.141269	0.086485	0.033262
		b=0.000000	b=0.000000						
Two-Term Exponential	v=2.2	a=0.082799	a=0.041408	0.976941	0.940554	0.039700	0.029059	0.002207	0.001407
		k=0.001683	k=0.002751						
Verma et al.	v=2.2	a= 0.12215	a= 0.108305	0.992246	0.999983	0.015825	0.000424	0.000438	0.000000
		k= 0.126586	k= 0.005463						
		g= 0.000112	g= 0.000112						
Diffusion Approach	v=2.2	a=0.182726	a=0.089713	0.999713	0.997537	0.003049	0.004595	0.000016	0.000053
		k=0.002712	k=0.229444						
		b=0.031083	b=0.000290						
Midilli	v=2.2	a= 0.000014	a= 1.000013	0.999878	0.999901	0.002053	0.000927	0.000010	0.000004
		k= 1.000214	k= 0.012552						
		n= 0.005469	n= 0.377984						
		b=0.570333	b=0.000002						

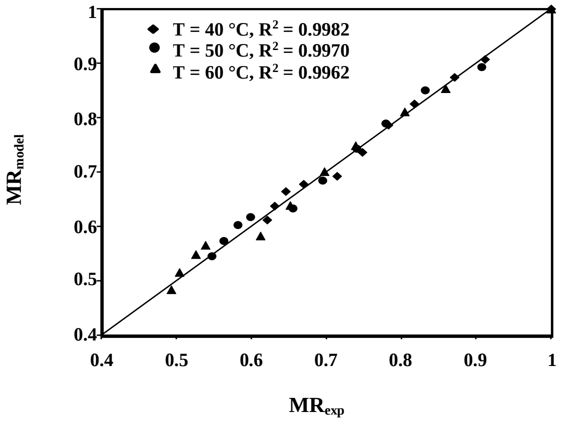

Fig. 6: Comparison of experimental and predicted moisture ratio from the Midilli model (pre-tempering stage, V= 2.2 m/s).

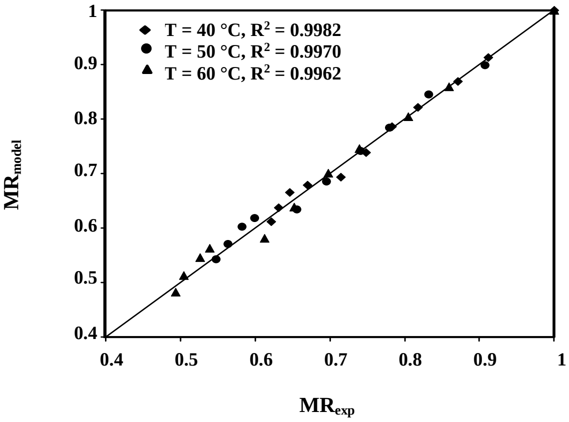

Fig. 7: Comparison of experimental and predicted moisture ratio from the Two-Term model (Post-tempering stage, V=2.2 m/s).

The paddy rice is a heterogeneous material because the rice grain is made of various layers: a) an outer husk layer; b) a bran layer, and c) the endosperm layer in the centre. During drying of the grain, the moisture must transfer through different layers made of non-homogenous materials and with non-uniform properties such as moisture diffusivity. Besides, diffusion in porous media may involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion [24]. All these phenomena can be combined into one parameter in which the paddy grain is considered to be homogenous in order to introduce an effective moisture diffusivity which could be implemented in the Eq. (8), enabling characterization of the drying process.

For the use of the Fick equation, the following assumptions were taken into account: (1) spherical shape for paddy grains; (2) a uniform initial moisture; (3) a uniform, but the transient moisture content on the surface of the grain; (4) effective moisture diffusivity was used; (5) one dimensional moisture transfer in radial direction; (6) no capillarity within the grain; (7) negligible resistance of mass transfer in external gas phase.

With these assumptions, Eq. (8) can be solved analytically:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_{eff}\, t}{R_0^{\,2}}\right) \tag{9}$$

Where, D_{eff} is the effective moisture diffusivity and R_0 is the radius of sphere in m. The Parameter Estimation procedure was carried out to achieve moisture diffusivity using Eq. (9). Although, in the large Fourier numbers ($Fo = D_{eff}\, t/r^2$) the series of the Eq. (9) converges to the first terms, but for the sake of obtaining more accurate and stable results, one thousand terms of the infinite series of Eq. (9) were utilized in the computer programming.

Effects of Temperature on Effective Moisture Diffusivity

In this study the effect of temperature on the effective moisture diffusivity was investigated at 40, 50, and 60 °C using Eq. (9). The results of the computation of effective moisture diffusivity at different temperature are presented in Table 5. It is observed that by increasing the temperature, effective moisture diffusivity increases because of the increment of molecular movement.

Effect of temperature on the effective moisture diffusivity can be characterized by the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \tag{10}$$

Where, D_0 is the diffusivity value for infinite moisture content in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol K, and T is the temperature in ^0C.

By plotting the natural logarithm of D_{eff} vs. 1/T a linear relationship between $\ln(D_{eff})$ and 1/T was developed and used to calculate the activation energy (E_a). Accordingly, the slope of the line is $-(E_a/R)$ and the value

Table 5: Effective moisture diffusivity at different temperature.

Temperature	Effective Moisture Diffusivity
T=40 ^{0}C	3.89×10^{-9}
T=50 ^{0}C	6.08×10^{-9}
T=60 ^{0}C	6.58×10^{-9}

Table 6: Effective moisture diffusivity vs. tempering times periods at T=50 °C.

Tempering Time	D_{eff} First Drying Stage	D_{eff} Second Drying Stage	D_{eff} Overall
No tempering			5.10×10^{-9}
1hr tempering	4.17×10^{-9}	6.03×10^{-9}	5.69×10^{-9}
2hr tempering	4.21×10^{-9}	7.11×10^{-9}	5.96×10^{-9}
3hr tempering	4.29×10^{-9}	7.56×10^{-9}	6.08×10^{-9}

of activation energy would be 22.987 kJ/.mol which shows an acceptable agreement with studies reported by the other investigators [17, 28, 29].

Effects of Tempering on Effective Moisture Diffusivity

Effective moisture diffusivities were calculated using experimental values of moisture ratio and Eq. (9) versus drying time for various tempering time periods, Table 6.

In a paddy drying process, the moisture diffuses from the inner layer toward outer by passing through various layers of different structures, thereby each layer has its own particular resistance to moisture diffusion. This resistance strongly depends inversely on the layer moisture content. During drying process, the moisture content of the surface layers is much less than the moisture content of inner and central layers. This phenomenon develops a high resistance region close to the surface which consequently decreases the effective moisture diffusivity. So, it can be concluded that the surface layers play a key role in the diffusion process. In fact, the extents of layers dryness impose an obstacle against the moisture transfer through the grain. During the tempering stage the moisture distribution throughout the grain becomes uniform and thereby the layers' resistance to moisture diffusion reduces substantially which improves the effective moisture diffusivity. Table 6 reveals that the longer the tempering periods, the more effective moisture diffusivity.

CONCLUSIONS

Intermittent drying process characteristics of Iranian paddy rice (Hashemi variety) were determined by experimental investigation of drying mechanism and drying models. The effects of drying temperature and tempering time period on drying curves and drying rates were evaluated. Various thin layer drying models, proposed in the literature for characterizing the drying process, were fitted to the experimental data obtained from different drying stages, namely pre-tempering and post-tempering to determine the best model. Moreover, the effective moisture diffusivity was estimated based on the analytical solution of Fick’s second law of diffusion in spherical coordinate along with the results of a series of controlled experiments. Then, the effect of tempering time and drying air temperature on the effective moisture diffusivity were evaluated. The experimental results showed a significant enhancement of drying rate by utilizing the tempering stage between two consecutive drying stages as well as by increasing the drying temperature. Fitting results demonstrated that the Midilli model provided the best fit for the first drying stage of each drying process, while the Two-Term model was the most suitable one for describing the drying curves of second stage. Furthermore, the results indicated that both drying air temperature and tempering can improve the drying process by improving the effective moisture diffusivity.

NOTATIONS

a, a_0, a_1	Constants of the model
b	Constant of the model
D	Moisture diffusion coefficient, m^2/s
D_0	Pre-exponential factor of the Arrhenius equation, m^2/s
e_s	Standard error
E_a	Activation energy, kJ/mol
Fo	Fourier number
g	Constant of the model
k	Coefficient of the model
K	Drying constant, s^{-1}
M	Moisture content of the grains, kg/kg dry
MR	Moisture ratio
n_c	Number of constants in model
N	Number of total experiments
r	Radial coordinate for the grain
R	Universal gas constant, kJ/mol K
R_0	Radius of a grain in spherical form, m
R^2	Root square errors
t	Time, s
T	Temperature, °C
W	Weight of sample, kg
χ^2	Mean squared deviation

Subscripts

bd	Bone-dry
e	Equilibrium
eff	Effective
pre	Predict
exp	Experimental

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