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Impact of hot air velocity on paddy drying through STR dryer

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Abstract

Drying characteristics of paddy in STR dryer was studied at three air velocities 1.0, 1.5, 2.0 and 3.0 ms^{-1} respectively. Drying of paddy occurred in falling rate period. It was observed that duration of drying of paddy from 14.5 to 8 % moisture content (w.b) was 4–6 h depending upon the source of energy used. In order to select a suitable drying curve five drying models (Exponential, Henderson and Pabis, Page, Logarithmic and Power law) were fitted to the experimental moisture ratio data. Among the mathematical models investigated, Page model best described the drying behaviour of paddy with highest coefficient of determination (r^2) values and least chi-square, x^2, mean bias error (MBE) and root mean square error (RMSE) values. Among all the drying models, Page model adequately described the drying behaviour of paddy using electrical heating source.

Keywords: Drying, moisture content, falling rate, models

Introduction

India is the second largest rice producer in the world. Rice provides more calories per hectare than any other cereal crops. Its nutritional value is high among cereals and grains. Though the protein content of rice is less than that of wheat, the protein digestibility and biological value of rice protein are the highest among wheat and other cereals. Paddy is harvested in moisture range between 16 to 28% (w.b.) dependent on harvest method, variety and location. In general situation, higher moisture content increases efficiency of paddy milling to rice. Whereas lower moisture content reduces drying required energy. In view point of researchers, paddy moisture content for storage should be about 13% (w.b.) and for milling operations is better to be in range of 10 to 13% (w.b.) dependent on variety of paddy. Quality deterioration takes place if fresh paddy is not immediately dried to safe moisture level. Drying reduces bulk quantity, thus, facilitates in transportation, handling and storage. If the moisture content of paddy is inappropriate for storage, it will be exposed to fungal diseases and chemical reactions and damaged after paddy husking [1]. In this context, it is important to understand the temperature and moisture distributions inside the grain bulk during drying.

Drying is the process of removing water from a porous media by evaporation, in which drying air is passed through a thin layer of the material until equilibrium moisture content (EMC). Moisture removal from an agricultural product depends on drying air temperature, velocity, relative humidity,

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variety, and maturity. Hence, various isolated and combined methods are involved in moisture removal from a grain [2]. Several researchers have developed simulation models for natural and forced convection drying systems and there is no information available on vertical drying and development of predictive model for drying of raw paddy [3]. In this study, the vertical drying behaviour of paddy in a STR dryer has been investigated and various drying models have been validated.

Materials and methods

Sample preparation

Rajendra sweta variety of paddy was procured from directorate of seed and farm, BAU, Sabour, Bhagalpur in the state of Bihar (India) for this study. A sample was, then cleaned to remove any impurities followed by mechanical grading to achieve quality paddy.

Measurement of Moisture Content

Hot air oven method was used to determine the initial moisture content of the selected paddy. A pre weighed paddy sample of 15 g was kept in a pre-dried and weighed moisture box in oven at 80ºC for 24 hours [4]. The dried samples were cooled in desiccators to room temperature and then weighed using electronic balance and moisture content (d.b.) of sample which was expressed as g water/g dry matter was used for calculations.

Short Time Residual (STR) dryer

A STR dryer has been developed at Bihar Agricultural University, Sabour after modification of existing one. The drying setup mainly consists of a fan (dia-200 mm, 1600 rpm), 1hp motor, heating stove, metal perforated (0.4 mm) net, inner hollow pipe (dia-300 mm), outer hollow pipe(1100 mm) and pressure gauge. Drying air temperature was measured using K-type thermocouples (±0.1°C accuracy) and air velocity was measured using a digital hot wire anemometer (Lutron, Taiwan, Model: 4204, range 0-20 $m.s^{-1}$, accuracy ±0.1 $m.s^{-1}$).

Drying Procedure

Once the dryer reached equilibrium condition, about 400 kg of paddy was filled in the drying chamber. The experimental runs of vertical drying were conducted at initial moisture content of 14.5 % (w.b.) and three air velocities (1.0, 1.5, 2.0 and 3.0 $m.s^{-1}$). The moisture content was measured using probe sensor digital moisture meter at a time interval of 15 min during first hour of drying, 30 min for second hour, 45 min for third hour and 60 min from fourth hour till the end of drying. Drying was terminated when the grains reached less than 8% moisture content (w.b.).

Mathematical Modelling of Drying Curves and Formulation

The moisture ratio of paddy during STR drying experiments was calculated using the following equation

$$MR = \frac{M - M_e}{M_0 - M_e}$$

Where; MR is moisture ratio (dimensionless); M is moisture content (g water per g dry matter) at specified time; M_0 is initial moisture content (g H_2O/ g dry matter) and M_e is equilibrium moisture content (g H_2O/g dry matter). Five thin layer drying equations listed in Table 1 were tested to select the best model to describe STR drying of paddy.

The effects of some parameters related to the product or drying conditions such as drying air velocity, air temperature, relative humidity, *etc.* were investigated [5]. Modelling of drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationships between different variables, especially, those for which no established empirical relationship exists. In this study, the relationships of the constants of the best suitable model with the drying air velocity were also determined.

The regression analysis was performed using SYSTAT-8.0 software. The coefficient of determination (R^2) was primary criterion for selecting the best equation to describe the drying model. In addition to this, the goodness of fit was determined by reduced mean square of the deviation (x^2), mean bias error (E_{MB}) and root mean square error (E_{RMS}). For quality fit, R^2 value should be higher and close to one and x^2, E_{MB} *and* E_{RMS} values should be low [6]. The above parameters were calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{R,\exp,i} - M_{R,pre,i}\right)^2}{N - z}$$

$$E_{MB} = \frac{1}{N}\sum_{i=1}^{N}\left(M_{R,pre,i} - M_{R,\exp,i}\right)$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R,pre,i} - M_{R,\exp,i}\right)^2\right]^{1/2}$$

Where; $M_{R,exp,i}$ and $M_{R,pre,i}$ are the experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations and z is the number of drying constants

Table 1: Mathematical models widely used to describe the drying kinetics

Modelequation	Name	Reference
$MR = \exp(-kt)$	Exponential	[15]
$MR = a\exp(-kt)$	Henderson and Pabis	[16]
$MR = \exp(-kt^n)$	Page	[17]
$MR = a + b\ln(t)$	Logarithmic	[18]
$MR = At^B$	Power law	[18]

Moisture Diffusivity

In drying, diffusivity is used to indicate the rapidness of flow of moisture or moisture out of material. In falling rate period of drying, moisture is transferred mainly by molecular diffusion. The diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material [7].

The falling rate period in drying of biological materials is best described by simplified mathematical Fick's second law diffusion as given below:

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta X^2}$$

Where; D = Diffusion coefficient, M = Moisture content, g water per g dry matter, X= Characteristic dimension i.e. distance of surface from the centre line of product and t = Time elapsed during the drying.

Certain assumptions were considered in estimation of moisture diffusivity during drying process, which are given herewith as follows:

1. Moisture is initially uniformly distributed throughout the mass of sample.
2. Mass transfer is symmetric with respect to the centre.
3. Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.
4. Resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample.
5. Moisture transfer is by diffusion only.
6. The length of the material L was assumed constant throughout the drying process.

The solution of Fick's model for infinite slab [9] as

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 D_{eff}t}{L^2}\right]$$

Where;

$D_{-eff=}$ Effective diffusivity in m^2/s

L = Characteristic dimension i.e. length of paddy

t = Time elapsed during the drying (s)

An experimental value of the effective diffusivity is calculated by plotting experimental drying data in terms of ln (*MR*) versus drying time *t*. It gives a straight line and the slope of the line would be used to measure the moisture diffusivity.

Results and Discussion

Drying Curve

The initial moisture content of paddy was 14.5 % (wb) and the equilibrium moisture content was 8 % (wb) when no more change in moisture content during drying was observed. The moisture content versus drying time for paddy at selected air velocity is shown in fig 1. It is apparent that moisture content decreases continuously with drying time. The moisture content after 50 min of drying at air velocity of 1.0, 1.5, 2.0 and 3.0 m/s was 11.67, 10.79, 9.76 and 8.31 % (wb) and after 107 min it was found to be 10.09, 9.37, 8.55 and 7.89 % (wb) respectively. The drying times to reach the equilibrium moisture content for paddy were 390, 300, 227 and 150 min

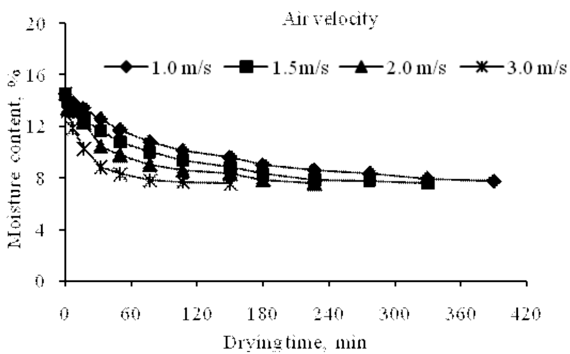

Fig. 1: Effect of air velocity on drying curve

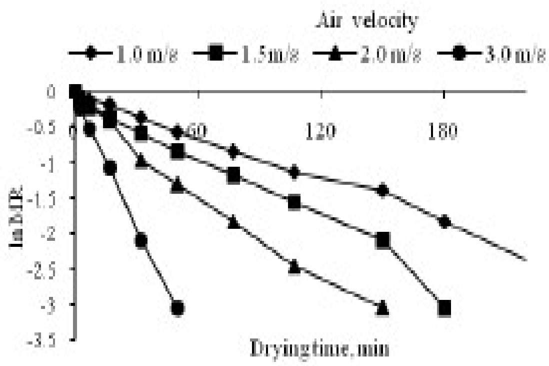

Fig. 2: Variation in ln (MR) with drying time at different air velocity for paddy

at 1.0, 1.5, 2.0 and 3.0 m/s respectively. As indicated in the curves (fig1), there was no constant rate period in drying of paddy. All the drying process occurred in the falling rate period, starting from the initial moisture content of paddy (14.5 % wb) to final moisture content (8 % wb). It was studied that in the falling rate period the material surface is no longer saturated with water and drying rate is controlled by diffusion of moisture from the interior of solid to the surface [9].

Mathematical Modelling of STR Drying Curves

The moisture content data at the different drying air velocity were converted to the more useful moisture ratio and coefficients of Exponential, Henderson and Pabis, Page, Logarithmic and Power law models were calculated and are presented in Table 2. It was observed that in all models the values of R^2 were greater than 0.90, indicating a good fit except for power law and logarithmic model. The values of coefficient of determination (R^2) of paddy for page model at all velocities were in the range of 0.994 to 0.998 and the values of root mean square error (E_{RMS}), reduced mean square of the deviation (x^2) and mean bias error (E_{MB}) for page model were

Table 2: Values of coefficients of model and statistical parameters used in STR drying of paddy

Name of models	Air Velocity	Drying constant				Statistical parameters			
	(m/s^2)	k	N	A	b	R^2	x^2	E_{MB}	E_{RMS}
Exponential	1.0	0.007	-	-	-	0.972	0.013	0.010	0.057
1.5	0.011	-	-	-	0.948	0.004	0.013	0.069	
2.0	0.013	-	-	-	0.942	0.006	0.007	0.072	
3.0	0.024	-	-	-	0.970	0.008	0.016	0.080	
Henderson and Pebis	1.0	0.007	-	1.067	-	0.984	0.002	0.016	0.041
1.5	0.012	-	1.143	-	0.978	0.003	0.009	0.064	
2.0	0.018	-	1.168	-	0.982	0.004	0.013	0.069	
3.0	0.028	-	1.224	-	0.981	0.007	0.023	0.084	
Page	1.0	0.001	1.321	-	-	0.994	0.004	0.006	0.040
1.5	0.001	1.475	-	-	0.998	0.003	0.004	0.032	
2.0	0.003	1.491	-	-	0.996	0.0007	0.008	0.024	
3.0	0.004	1.584	-	-	0.997	0.001	0.005	0.029	
Logarithmic	1.0	-	-	1.658	-0.256	0.885	0.033	0.032	0.173
1.5	-	-	1.694	-0.291	0.887	0.044	0.040	0.198	
2.0	-	-	1.708	-0.321	0.889	0.051	0.051	0.209	
3.0	-	-	1.730	-0.363	0.891	0.060	0.061	0.224	
Power law	1.0	-	-	2.132	-0.323	0.738	0.085	0.038	0.264
1.5	-	-	2.227	-0.364	0.741	0.105	0.051	0.288	
2.0	-	-	2.347	-0.419	0.757	0.119	0.065	0.303	
3.0	-	-	2.641	-0.513	0.787	0.134	0.074	0.322	

Table 3: Effective moisture diffusivity of paddy during STR drying

S. No.	Air velocity (m/s)	Diffusivity (m^2/s)	R^2
1	1.0	3.7356×10^{-11}	0.962
2	1.5	6.0812×10^{-10}	0.970
3	2.0	2.0242×10^{-9}	0.981
4.	3.0	2.2478×10^{-9}	0.989

in the range of 0.024 to 0.040, 0.0007 to 0.004 and 0.004 to 0.008 respectively which were lower than the rest of other four models (Exponential, Henderson and Pabis, logarithmic and power law) used in this study. The moisture ratio of the samples decreased continually with drying time. As expected, increase in air velocity of drying reduces the time required to reach given level of moisture ratio since the heat transfer Increases. In other words, at high air velocity the transfer of heat and mass is high and water loss is excessive. These results are in agreement with drying of paddy [10][11].

Moisture Diffusivity of Samples

The natural logarithms of moisture ratio (ln MR) were plotted against average drying time (t) for different air velocity, and are shown in Fig 2. It was observed from the figure that the relationship was non-linear in nature for all drying conditions. This non-linearity in the relationship might be due to reasons like shrinkage in the product, variation in moisture diffusivity with moisture content and change in product temperature during drying [12]. The non-linearity of the curves, an indicative of the variation in moisture diffusivity with moisture content, was used to estimate effective moisture diffusivity of STR dried paddy samples at corresponding moisture content, under different drying conditions. The moisture diffusivity value of food material was affected by moisture content as well as air velocity level. At lower level of moisture content, the diffusivity was less than that at high moisture content.

Also, it was observed that moisture diffusivity increased with increase in velocity in STR drying process shown in Table 3. The average effective moisture diffusivity $(D_{eff})_{avg.}$ values of STR dried paddy varied considerably with moisture content and air velocity were 3.7356×10^{-11}, 6.0812×10^{-10}, 2.0242×10^{-9} and 2.2478×10^{-9} m²/s. These values are within the general range of 10^{-08} to 10^{-12} m²/s for drying of food materials [13]. These values are in fact consistent with those existing in literature for hot air drying of rice [14].

Conclusion

In this technique, quality of the product can be increased by applying a different air velocities range. A model to simulate the drying of paddy was developed and solved with SYSTAT software. It was observed that STR drying of paddy occurred in the falling rate period and no constant rate period of drying was observed. The results showed that the air velocity plays a significant role for complete drying of paddy. A good agreement between model predictions and experiments at different velocities was obtained. Page model was found to be the most suitable for describing drying of paddy with R^2 of 0.998, x^2 of 0.0007, E_{MB} of 0.004 and E_{RMS} of 0.024. The effective moisture diffusivities increased from 3.7356×10^{-11} to $2.2478 \times 10^{-9} m^2 s^{-1}$ with the increase in air velocity. The results show that the proposed model can be used to optimize the drying process in order to obtain higher quality dried paddy from a quality standpoint.

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