Drying characteristics of paddy in an integrated dryer

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Abstract Drying characteristics of paddy (long grain variety PR-118 procured from PAU, Ludhiana) in an integrated dryer using single as well as combined heating source was studied at different air temperatures. The integrated dryer comprises three different air heating sources such as solar, biomass and electrical. Drying of paddy occurred in falling rate period. It was observed that duration of drying of paddy from 22 to 13 % moisture content (w.b.) was 5–9 h depending upon the source of energy used. In order to select a suitable drying curve, six thin layer-drying models (Newton, Page, Modified Page, Henderson and Pabis, Logarithmic and Wang and Singh) were fitted to the experimental moisture ratio data. Among the mathematical models investigated, Wang and Singh model best described the drying behaviour of paddy using solar, biomass and combined heating sources with highest coefficient of determination (r^2) values and least chi-square, χ^2 , mean bias error (MBE) and root mean square error (RMSE) values. However, Page model adequately described the drying behavior of paddy using electrical heating source.

Keywords Paddy · Integrated paddy dryer · Drying models · Moisture ratio

Paddy or rough rice (*Oryza Sativa* L.), the most widely grown food grain crop, is the staple food of over 3 billion people. World and Indian rough rice production in 2010 was 700 million tonnes and 143.9 million tonnes respectively (FAOSTAT 2010). 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. After harvesting, paddy normally goes through two moisture treatments; one is drying that may be required for safe storage, and the other is water absorption in preparation for further processing. 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. Although sun-drying is economical, mechanical drying speeds up the process, prevents losses, ensures use of safer drying temperatures and produces superior product compared to sun drying (Mudahar and Bains 1982). In view of high cost and non-renewable nature of the present conventional electrical energy source, different renewable energy sources such as solar and bio mass may be employed for paddy drying. The combining of conventional and non-conventional energy sources for paddy drying will be helpful for exploiting solar and bio mass sources as much as possible.

The drying characteristics of food is a complex phenomenon and requires simple representations to predict

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the drying behaviour and for optimizing the drying parameters. Thin layer drying equations were used for drying time prediction for generalization of drying curves (Karathanos and Belessiotis 1999). Though research in drying characteristics of paddy was carried out under individual heat source and data was reported on moisture loss and drying rates, systematic studies on the drying characteristics of paddy under integrated paddy drying system are lacking. The objectives of the present study were: i) to study the drying characteristics of paddy in an integrated paddy dryer using single as well as combined heating sources and ii) to evaluate a suitable thin layer drying model.

Materials and methods

A holding bin of one tonne paddy per batch capacity was fabricated and installed at Central Institute of Post Harvest Engineering and Technology, Ludhiana, Punjab, India. The paddy was re-circulated inside the holding bin using bucket elevator (capacity-165 kg/h) till it attained the safe moisture level of 12–14 % w.b. The hot air and the paddy were in cross circulation inside the holding bin. The width of the column where hot air and grain intersect was 20 cm. For heating the air, three heating mechanisms namely biomass fired furnace, solar air heaters and electric air heaters were considered to see the effectiveness of drying under individual as well as combined drying system. The heat energy required for drying the paddy from 22 % w.b. to a safe moisture level of 14 % w.b. was calculated using standard relationship (Chakraverty 1997; Barnwal et al. 2012) and the solar air heaters, bio mass furnace and electrical heating system was developed and integrated based on the calculated heat energy. The solar heater assembly made with 30 solar panels of 1.50×0.92 m size connected in parallel with three blowers of 2 hp each using 50 mm galvanized iron pipe (Goyal et al. 2004b). The bio mass furnace mainly consisted of a cross and counter flow shell, rectangular tube type heat exchanger, grate, hopper, air combustion chamber, main body frame and suction blower. The electrical heating system was made of 15 kW heating capacity coil (Goyal et al. 2004a). The integrated paddy drying system comprising holding bin, air heating system using solar, bio mass and electrical energy is shown in Fig. 1.

Freshly harvested long grain paddy variety PR-118 was procured from experimental farm at Punjab Agricultural University, Ludhiana. Paddy was cleaned and graded using pedal cum power operated cleaner before the drying studies. The initial moisture content

of the samples was determined as per standard hot air oven method (AOAC 1984). The drying experiment was conducted during February 2005 under three individual heating sources and one combined heating source (Solar and electrical system). The temperature of grain as well as air at different points was recorded at regular interval of 60 min.

Moisture ratio of samples during drying was calculated by the following equation:

$$MR = \frac{(M - M_e)}{(M_0 - M_e)} \quad (1)$$

where, MR is the dimensionless moisture ratio, M is the moisture content at time t, and M_0 and M_e are the initial and equilibrium moisture contents, respectively, on dry basis. During thin-layer drying of paddy in integrated paddy dryer, the samples were not exposed to uniform relative humidity and temperature continuously. So the moisture ratio was simplified according to Pala et al. (1996) and Doymaz (2004), to

$$MR = \frac{M}{M_0} \quad (2)$$

To select a suitable model for describing the drying process of paddy, drying curves were fitted with six thin-layer drying equations. The evaluated moisture ratio models are presented in Table 1. Most of the models in Table 1 were derived by simplifying the general solutions of the Fick's second law or the modification of the simplified models. Therefore, most of them were not arbitrarily chosen models; on the contrary, they were based on the physiological bases (Hacıhafızoğlu et al. 2008).

To determine the drying characteristics, paddy was dried in an integrated paddy dryer under individual as well as combined heating sources. About 100 kg cleaned and graded paddy sample was used for the drying experiment. Moisture content of paddy was determined at 60 min interval using standard hot air oven method (AOAC 1984). The drying was continued till the attainment of safe moisture level of 12–14 % w.b. Experiments were conducted in triplicate.

The non-linear regression analysis was done using MATLAB (version 6.5) software package. Coefficient of determination, r^2 was one of the main criteria for selecting the best model. In addition to coefficient of determination, the goodness of fit was determined by various statistical parameters such as reduced chi-square, χ^2 , mean bias error (MBE) and root mean square error (RMSE) values. For quality fit, r^2 value should be higher and χ^2 , MBE and RMSE values should be lower

Fig. 1 A schematic diagram of an integrated paddy dryer **Table 1** Thin layer drying models given by various authors

Model Name	Equation	Reference
Newton	$MR = \exp(-kt)$	Liu and Bakker-Arkema(1997)
Page	$MR = \exp(-kt^n)$	Zhang and Litchfield (1991)
Modified Page	$MR = \exp(-(kt)^n)$	Overhults et al. (1973)
Henderson & Pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a \exp(-kt) + c$	Yaldiz et al. (2001)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978a, b)

MR Moisture ratio; a, b, c, k, k_0, k_1 drying constants; t drying time

(Pangavhane et al. 1999; Sarsavadia et al. 1999; Togrul and Pehlivan 2002; Demir et al. 2004; Erenturk et al. 2004). The parameters were calculated by using the following expressions:

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{\text{exp}} - MR_{\text{pre}})^2}{N - z} \quad (3)$$

$$MBE = \frac{1}{N} \sum_{i=1}^N (MR_{\text{exp}} - MR_{\text{pre}}) \quad (4)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{\text{exp}} - MR_{\text{pre}})^2 \right]^{\frac{1}{2}} \quad (5)$$

N number of observations
z number of drying constants

where,

MR_{exp} experimental moisture ratio
 MR_{pre} predicted moisture ratio

Results and discussion

The time taken for drying of paddy under different sources is given in Table 2. The final moisture content

Table 2 Experimental data, drying rate and moisture ratio of paddy under different heat sources

Source	Time (h)	M.C. (%w.b.)	Grain temperature (°C)	Ambient temperature (°C)	Hot Air inlet temperature (°C)	Hot Air outlet temperature (°C)	M.C. (d.b.)	Drying rate, R (g water/min/kg bone dry material)	Moisture Ratio
Solar and Electrical	0	21.52	37	30	50	35	27.42	-	1
	1	20.28	42	29	51	38	25.44	0.330	0.928
	2	19.01	45	30	52	39	23.47	0.329	0.856
	3	17.96	45	33	52	38	21.89	0.307	0.798
	4	16.63	45	33	52	38	19.95	0.311	0.727
	5	15.17	44	32	52	38	17.88	0.318	0.652
	6	14.29	44	31	52	38	16.67	0.299	0.608
Electrical	7	13.92	42	30	51	38	16.17	0.268	0.589
	0	14.75	19	17	50	17	17.30	-	1
	1	14.25	19	18	50	19	16.62	0.114	0.961
	2	14.09	20	19	50	18	16.40	0.075	0.948
	3	13.33	20	21	51	21	15.38	0.107	0.889
Solar	4	12.78	21	19	50	19	14.65	0.110	0.847
	5	10.54	19	19	50	19	11.78	0.184	0.681
	0	22.24	37	30	50	32	28.60	-	1
	1	21.47	38	31	50	31	27.34	0.210	0.956
	2	19.86	38	30	50	33	24.78	0.318	0.867
	3	18.33	39	31	50	35	22.44	0.342	0.785
	4	17.08	41	31	50	32	20.60	0.333	0.720
	5	16.69	37	31	51	33	20.03	0.286	0.701
	6	15.96	38	31	51	33	18.99	0.267	0.664
Biomass	7	15.32	38	31	51	34	18.09	0.250	0.633
	8	14.67	38	33	50	34	17.19	0.238	0.601
	9	14.15	38	34	50	34	16.48	0.224	0.576
	0	21.22	20	30	50	29	26.94	-	1
	1	20.80	21	28	50	31	26.26	0.112	0.975
	2	19.03	22	28	51	30	23.50	0.286	0.873
	3	18.71	24	27	51	31	23.02	0.218	0.855
	4	17.77	24	25	52	29	21.61	0.222	0.802
	5	17.50	25	24	52	29	21.21	0.191	0.788
	6	16.40	29	23	51	29	19.62	0.203	0.728
	7	14.60	23	22	51	31	17.10	0.234	0.635
	8	14.32	20	21	50	31	16.71	0.213	0.621
	9	13.92	20	21	50	31	16.17	0.199	0.600

Fig. 2 Variation of moisture ratio of paddy with drying time under different energy sources in integrated paddy dryer

of paddy ranged from 10.54 to 14.15 % (w.b.). It was also observed that the drying time for paddy ranged from 5 to 9 h depending on the source of energy used. It is evident that the drying air temperature has an important effect on drying. When the temperature was increased, the drying time reduced. The results are similar with the earlier observations on drying of Thai Hom Mali paddy (Dounporn et al. 2012), parboiled wheat (Mohapata and Srinivasa 2005; Kahyaoglu et al. 2012), garlic slices (Madamba et al. 1996), onion slices (Sarsavadia et al. 1999), egg plants (Akpınar and Bicer 2005), peach slices (Kingsly et al. 2007) and plum slices (Goyal et al. 2007).

The drying rates and moisture ratio were computed and presented in Table 2. The moisture ratio for drying of paddy under different energy sources is given in Fig. 2. From Table 2 and Fig. 2, it is clear that moisture ratio decreased continuously with drying time. It is obvious that the constant rate period was absent, and drying of paddy took place in the falling rate period for the entire duration. Similar observations have been reported for the drying of soybean (Rafiee et al. 2009), mushroom (Arumuganathan et al. 2009), apricots (Doymaz 2004), figs (Piga et al. 2004), peach (Kingsly et al. 2007) and plums (Goyal et al. 2007). The drying in falling rate period shows that, internal mass transfer has occurred by diffusion.

The average moisture ratio of paddy dried under different energy sources was test verified with six different drying

models to find out their suitability to describe the drying process. The drying model constants, coefficient of determination (r^2) and results of statistical analyses such as chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE) values obtained from non linear regression analysis using MATLAB are summarized in Table 3. The best model to describe the drying behaviour of paddy was selected on the basis of high r^2 and low χ^2 , MBE and RMSE values (Togrul and Pehlivan 2002; Demir et al. 2004; Erenturk et al. 2004). It is observed from the Table 3 that the value of r^2 for all six models were greater than 0.90, indicating good fit. From the results, Wang and Singh model gave comparatively higher r^2 value in all the energy sources except for electrical, where as the χ^2 , MBE and RMSE values were also found lowest. Wang and Singh (1978a, b) proposed a new empirical quadratic equation to fit the single-layer drying data for medium-grain rough rice. Thus, Wang and Singh model may be assumed to represent the thin layer drying of paddy under solar, bio-mass and combination of solar and electrical in an integrated dryer. This may be due to the uncontrolled nature of heating source such as solar and biomass which may not fit under the theoretical and semi-theoretical drying models. In the case of paddy drying using electrical energy, page model adequately described the drying characteristics. Das et al. (2004) showed that the Page model describes the experimental data adequately for drying of high moisture rough rice. Basunia and Abe (2005) and Cihan et al. (2007) found that the Page model yields an acceptable fit for the moisture content for their drying data of medium-

Table 3 Results of statistical analyses on the drying of paddy

Drying source	Model	Constants	r^2	$\chi^2 (\times 10^{-4})$	RMSE	$MBE_{(\times 10^{-4})}$
Solar & Electrical	Newton	$k=0.079$	0.944	1.64	0.012	-7.68
	Page	$k=0.078$; $n=1.014$	0.944	1.90	0.012	-4.68
	Modified page	$k=0.079$; $n=0.998$	0.944	1.92	0.012	-9.64
	Henderson and Pabis	$a=1.003$; $k=0.080$	0.994	1.88	0.012	-0.31
	Logarithmic	$a=0.905$; $k=0.093$; $c=0.100$	0.994	2.29	0.011	-0.53
	Wang and Singh	$a=-0.083$; $b=0.003$	0.995	1.63	0.011	-0.15
Electrical	Newton	$k=0.139$	0.969	17.80	0.034	-3.74
	Page	$k=0.120$; $n=1.119$	0.973	17.27	0.032	-0.74
	Modified page	$k=0.118$; $n=1.183$	0.969	19.74	0.034	-33.50
	Henderson and Pabis	$a=1.012$; $k=0.143$	0.971	18.61	0.033	-20.61
	Logarithmic	$a=1.354$; $k=0.097$; $c=-0.349$	0.972	27.25	0.033	-9.15
	Wang and Singh	$a=-0.132$; $b=0.006$	0.973	18.56	0.033	-74.26
Solar	Newton	$k=0.067$	0.975	2.63	0.024	26.86
	Page	$k=0.165$; $c=0.449$; $k=0.087$; $n=0.861$	0.984	4.49	0.019	-20.37
	Modified page	$k=0.073$; $n=0.918$	0.975	7.12	0.024	25.15
	Henderson and Pabis	$a=0.988$; $k=0.065$	0.976	6.47	0.022	10.99
	Logarithmic	$a=0.568$;	0.992	4.33	0.018	-17.32
	Wang and Singh	$a=-0.083$; $b=0.004$	0.992	3.94	0.017	-0.12
Biomass	Newton	$k=0.051$	0.973	5.51	0.022	-3.74
	Page	$k=0.049$; $n=1.0178$	0.973	6.17	0.022	0.27
	Modified page	$k=0.050$; $n=1.008$	0.973	6.19	0.022	-4.06
	Henderson and Pabis	$a=1.002$; $k=0.051$	0.973	6.18	0.022	-0.12
	Logarithmic	$a=0.996$; $k=0.046$; $c=0.001$	0.973	6.91	0.022	2.92
	Wang and Singh	$a=-0.036$; $b=0.335$	0.973	5.30	0.004	-0.05

grain rough rice dried under electrical based convection drying system.

Conclusion

The effect of different energy sources on drying of paddy in an integrated dryer was investigated. From the above study on

drying of paddy under different energy sources in an integrated dryer, the following conclusions were drawn:

1. Increase in drying air temperature decreased the drying time.
2. The drying process occurred in falling rate period.
3. Wang and Singh drying model showed better fit with high coefficient of determination and low χ^2 , MBE and RMSE values during the drying of paddy under

solar, biomass and combination of solar and electrical energy sources.

4. Page model adequately described the drying characteristics of paddy using electrical energy source.
5. The finding of this study will be helpful in drying of paddy under different heating systems.

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