Indian Journal of Agricultural Sciences **91** (3): 344–9, March 2021/Article
https://doi.org/10.56093/ijas.v91i3.112442

Validation of thin layer drying models in solar-powered air-inflated grain dryer

ABHINAV DUBEY[1]*, P K SHARMA[2], INDRA MANI[3], ROAF AHMAD PARRAY[4], PRAMOD ARADWAD[5] and ARUN KUMAR T V[6]

ICAR-IARI, New Delhi 110 012, India

Received: 11 May 2019; Accepted: 29 October 2020

ABSTRACT

Cereals are generally harvested at 20-23% moisture content to avoid shattering losses therefore it is necessary to dry the paddy to lower moisture contents (13-14% wb) for safe storage and further processing.A solar-powered air-inflated grain dryer was designed, fabricated and tested for drying of paddy. Different combinations obtained from two different levels of upper transparent polyethylene sheet thickness (200 microns and 300 microns), inlet air velocity (1.5 m/s and 3 m/s) and grain bed depth (2cm and 4cm) were compared based on parameters of thermal efficiency, rise in temperature of drying air and amount of moisture removed per unit time. It was found that least square mean values of thermal efficiency, temperature rise in the drying air and drying rate of the developed dryer varied from 18.7-45.7%, 3.35-5.81°C and 0.36-0.98 kg/hour respectively. Upper transparent sheet thickness (300 micron), inlet air velocity (3 m/s) and grain bed depth (4 cm) have the highest least mean square values in the selected parameters and was selected for optimized operation of the dryer. Eight different thin layer drying models were compared according to their coefficient of determination to estimate drying kinetics as criteria for evaluating the goodness-of-fit. The effects of selected variables on the model constants and coefficients were predicted by the models. The page model fit well with the experimental data and satisfactorily describe the drying kinetics of Pusa Basmati (PB 1121) with a coefficient of determination (R^2) of 0.9995 and RMSE of 0.005464.

Keywords: Paddy, Solar drying, Solar powered air inflated grain dryer.

The post-harvest losses occurring in food grain ranges as high as 10% of the total production. It has potential to feed one-third of India's poor and monetary value is about 500 billion per year. The losses can be minimized significantly with primary processing and drying of agricultural commodities.Paddy grains are generally harvested at higher moisture content to avoid shattering losses, therefore it is necessary to dry the paddy to lower moisture contents (13-14% wb) for safe storage and milling. Generally, the commercially available dryers are designed according to processing industries and their capacity is above the needs of individual or farmers' groups. These dryers are mainly operated by grid power. However, grid power availability in rural areas is not sufficient. Solar energy is an efficient energy source that can substitute non-renewable energy sources with greater reliability. The drying time required in the open sun for these crops is higher in sun drying.In addition to this, sun drying has many disadvantages such as product mixing with dust, sand, insect infestation, high labor costs for transporting, large area requirement, losses due to birds and possibility of microbial cross-contamination (Sontakke and Salve 2015) .

A thin-layer drying is defined as when a layer of material is fully exposed to an airstream. Simulation models are needed in the designs and operations of solar dryers under environmental conditions and to validate it by statistical comparison with experimental data. Hasan *et al*. (2014) conducted drying study in which five thin-layer drying equations were fitted to the experimental data and the Midilli equation was found to be the best followed by the two term exponential equation. Golmohammadi *et al.* (2016) fitted several thin layer drying models to the experimental data of two drying stages. The Midilli and two term model were found most appropriate for the first and second drying stages respectively.The main objective of the study was to determine and test the most appropriate thin layer drying model for drying paddy in the developed solar powered air inflated grain dryer.

[1]Ph D Scholar, abhinaviari001@gmail.com, [2]Principal Scientist, pksharma40@rediffmail.com, [3]Head of Division, maniindra99@gmail.com, [4]Scientist, rouf.engg@gmail.com, [5]Scientist, aradwadpramod4@gmail.com, [6]Scientist, arun.agrilengg@gmail.com. Division of Agricultural Engineering, ICAR-IARI, New Delhi.

Corresponding author: Abhinav Dubey, Ph D Scholar, ICAR-IARI, New Delhi, abhinaviari001@gmail.com.

MATERIALS AND METHODS

Popular variety of Indian paddy Pusa Basmati (PB 1121)) was selected for the study. It was procured from the Seed Production Unit, IARI, New Delhi (2018). Selected physical properties of the grains, i.e. size, volume, bulk density, true density, terminal velocity and moisture content were determined (Jindal *et al*. 1987) .The data was analyzed to arrive at final design values of the dryer. Pre modeling analysis was done using visual basic macro programming in Microsoft Excel software. Part modeling, assembly and drawings were prepared using CAD software solid works SP1. Based on these design values, a solar inflated dryer was designed and fabricated.

Fabrication of the solar-powered air-inflated grain dryer: Based on the optimum operating condition determined and the requirements for proper drying mechanism; a prototype was first designed and dryer components were fabricated and assembled. The dryer consists of a frame, drying chamber, axial fan and a dc motor. The base of the drying chamber was made up of black color low density polyethylene sheet of 350 micron thickness. It has higher strength, rigidity, moisture impermeability and absorbs the solar radiation falling and hence increases the temperature within the dryer.The light weight of the sheet used promoted the portability of the dryer. For the construction of top of the drying chamber UV stabilized transparent low density poly ethylene sheet of two variable thicknesses (200 micron and 300 micron) was used. The frame for the blowing unit was made of angle iron (40 mm × 40 mm × 6 mm) to resist vibration, provide better stability and availability. Solar power operated 12V DC axial fan (40 cm) diameter with 3 blades and high speed copper motor was selected. A DC fan speed regulator was provided to vary inlet air velocity. The dryer was developed for drying 50-100 kg of selected variety of paddy grain in grain bed depths ranging from 2-4 cm which is the recommended depth for paddy drying. A minimum width of 30 cm on each side of drying bed was provided for inflation of the drying chamber (Dubey *et al.* 2019).

Performance Test Procedure: Tests were carried out on the solar powered inflated dryer to determine representative values of the operational parameters and performances under their different levels. Five samples each of 20 g were drawn and the moisture content was found out using hot air oven method. The initial moisture content was found out to be varying from 22–23.8% .50 kg and 100 kg paddy were dried during the experiments when grain depths were 2 cm and 4 cm, respectively. Grain sample each of weight 5 g was collected from each point and stored in properly labeled aluminum container, which was immediately sealed and weighed. Data for the corresponding experiments were recorded. Deductions for the values of the drying time, drying rate of the paddy were made. The experimental design was factorial randomized block design. In the ANOVA, sheet thickess, grain depth and inlet air velocity were the independent parameters and dependent parameters of thermal efficiency, rise in air temperature and drying rate were calculated (Dubey *et al.* 2019). The obtained moisture ratio was plotted against time and its fitting for various thin layer drying models was checked for different treatment combinations. Curve fitting tool of MATLAB (2014 b) was used for checking the fit to various models. Values of various constants were found for 8 different thin layer drying models (Table 1).

Various statistical parameters such as coefficient of correlation (R^2), Error sum of square (SSE), and root mean square of error (RMSE) values were found with the help of same tool to decide the quality of fit.

RESULTS AND DISCUSSION

The amount of moisture removed was calculated by using the difference in moisture content measured at every 30 minutes interval. Analysis of variances showed that increasing the inlet air velocity from 1.5 m/s to 3 m/s (P=0.7240) and the thickness of top transparent sheet from 200 µm to 300 µm (P=0.0139) had no significant effect on amount of moisture removed per unit time interval of paddy in the solar powered air inflated grain dryer. The least mean square values indicate that the amount of moisture removed was highest for top transparent sheet thickness (300 µm), inlet air velocity (3 m/s) and grain bed depth (4 cm). The least mean square values of amount of moisture removed per unit time varied from 0.36–0.95 kg/h.The air inlet velocity of 1.5 m/s was sufficient to carry away the moisture evaporated in the drying chamber thus increasing the inlet air velocity had no significant effect on the drying rate (Dubey *et al.* 2019).

Table 1 Thin layer models evaluated in the study

Model	Equation	References
Newton	$M.R = \exp(-kt)$	Agarwal *et al.* 1977
Henderson and Pabis	$M.R = a \exp(-kt)$	Chinnman 1984
Page	$M.R = \exp(-kt^n)$	Onwude *et al.* 2016
Modified page	$M.R = \exp(-kt)^n$	Wang *et al.* 1978
Wang and Singh	$M.R = M_0 + at + bt^2$	Henderson & Perry 1976
Two terms	$M.R = a \exp(-K_1t) + b \exp(-K_2t)$	Kaseem 1998
Verma *et al.*	$M.R = a \exp(-K_1t) + (1\text{-}a) \exp(-K_2t)$	Verma *et al.* 1985
Approximation of diffusion	$M.R = a \exp(-Kt) + (1\text{-}a) \exp(-Kbt)$	Basunia & Abe 2001

Table 2 Model constants and statistical parameters for various combinations of top transparent sheet thickness, inlet air velocity and grain bed depth for four best fit models

Model name	Conditions	R^2	SSE	RMSE	K (/h)	K_1	K_2	A	B	N
Page	T1	0.998	0.001833	0.01144	0.09331					1.516
	T2	0.997	0.00271	0.0163	0.08942					1.532
	T3	0.9995	0.000401	0.00535	0.07899					1.363
	T4	0.9992	0.000632	0.00671	0.07172					1.407
	T5	0.997	0.003865	0.01661	0.0953					1.579
	T6	0.9984	0.00162	0.01076	0.0789					1.448
	T7	0.999	0.000560	0.00632	0.0967					1.329
	T8	0.9995	0.000418	0.00546	0.0728					1.435
Wang and Singh	T1	0.996	0.004849	0.01861				-0.135	0.0018	
	T2	0.996	0.00374	0.0186				-0.131	0.0013	
	T3	0.998	0.001692	0.01099				-0.100	0.0004	
	T4	0.9982	0.00148	0.01028				-0.094	-0.004	
	T5	0.996	0.005789	0.02033				-0.145	0.0021	
	T6	0.9976	0.002401	0.01309				-0.108	0.0001	
	T7	0.9984	0.001523	0.01043				-0.119	0.0021	
	T8	0.9971	0.002596	0.01362				-0.0989	-0.00032	
Approximation of diffusion	T1	0.995	0.006032	0.02154	0.0275			105.5	0.9599	
	T2	0.990	0.01218	0.0306	0.3886			-240.8	0.996	
	T3	0.9936	0.00536	0.02031	0.03253			57.61	0.9555	
	T4	0.999	0.0008483	0.00807	0.341			-3.601	0.810	
	T5	0.994	0.008349	0.02534	0.5018			-46.81	0.978	
	T6	0.9895	0.01048	0.0284	0.0415			16.69	0.866	
	T7	0.9992	0.000467	0.00599	0.3361			-26.55	0.971	
	T8	0.9992	0.000733	0.007513	0.363			-3.712	0.8102	
Verma *et al.*	T1	0.996	0.003971	0.01748		0.4552	0.4307	-16.85		
	T2	0.993	0.008209	0.0251		0.4018	0.4116	36.48		
	T3	0.9837	0.01363	0.03238		0.225	0.2224	-40.74		
	T4	0.9979	0.00178	0.0117		-0.0111	0.014	-3.314		
	T5	0.991	0.01118	0.02932		0.5197	0.5255	99.54		
	T6	0.9562	0.04379	0.05804		0.1387	0.1574	-0.026		
	T7	0.9994	0.0005724	0.006636		0.3217	0.353	8.999		
	T8	0.9804	0.01779	0.03699		0.05289	0.0566	-18.63		

The values of various model constants obtained and statistical parameters such as coefficient of determination (R^2), Error sum of square (SSE), and root mean square of error (RMSE) values obtained (Table 2,3). The coefficient of determination values was highest and RMSE was lower for Page model for all the treatment combinations of top sheet thickness, inlet air velocity and grain bed depth. The page model was found to have the best fit for the obtained experimental data followed by Wang and Singh model and approximation of diffusion model.

The page model can hence be suitably utilised for prediction of drying behaviour of paddy in solar powered air inflated grain dryer under different operational conditions (Fig 1 a-h). This model is of immense importance for optimization of operating parameters and performance improvements of the drying system.The suitability of page

Table 3 Model constants and statistical parameters for various combinations of top transparent sheet thickness, inlet air velocity and grain bed depth for average fit models

Model name	Conditions	R^2	SSE	RMSE	K (h^{-1})	K_1	K_2	A	N
Modified Page	T1	0.9481	0.06842	0.06991	0.1605				1.245
	T2	0.9455	0.07141	0.07142	0.4676				0.421
	T3	0.968	0.02682	0.04377	1.438				0.09702
	T4	0.9616	0.03217	0.04794	0.3944				-0.3449
	T5	0.9395	0.0893	0.07986	0.2102				1.047
	T6	0.9562	0.04381	0.05594	1.19				0.1327
	T7	0.9728	0.0258	0.04293	0.1494				1.072
	T8	0.9581	0.03803	0.05212	0.2455				0.5853
Two terms	T1	0.997	0.00374	0.0176		0.4255	0.4756	9.454	-8.471
	T2	0.996	0.005241	0.0209		0.4232	0.468	10.44	-9.457
	T3	0.9905	0.007939	0.02572		0.2315	0.2378	18.5	-17.47
	T4	0.9841	0.01333	0.03333		0.2151	0.219	22.6	-21.56
	T5	0.996	0.005046	0.02051		0.0446	0.05618	-10.4	11.5
	T6	0.991	0.008984	0.02736		0.3013	0.2958	-35.0	36.11
	T7	0.99	0.009514	0.02816		0.2523	0.2479	-22.7	23.8
	T8	0.9993	0.000655	0.00738		0.3167	0.3325	18.57	-17.57
Henderson and Pabis	T1	0.9666	0.04397	0.05604	0.224			1.097	
	T2	0.964	0.04717	0.05805	0.2207			1.096	
	T3	0.9812	0.01573	0.03352	0.1536			1.061	
	T4	0.9774	0.01892	0.03676	0.1513			1.067	
	T5	0.9593	0.06012	0.06553	0.2478			1.108	
	T6	0.9693	0.02871	0.04529	0.1751			1.074	
	T7	0.9834	0.01572	0.03351	0.1744			1.06	
	T8	0.9752	0.02254	0.04013	0.1605			1.073	
Newton	T1	0.9481	0.06842	0.06754	0.1998				
	T2	0.9455	0.07141	0.069	0.1969				
	T3	0.968	0.02682	0.04228	0.1395				
	T4	0.9616	0.03217	0.04631	0.136				
	T5	0.9395	0.0893	0.07716	0.2202				
	T6	0.956	0.04412	0.05423	0.1577				
	T7	0.9728	0.0258	0.04148	0.16				
	T8	0.9581	0.03803	0.05035	0.1437				

model for drying of rough rice was also justified by studies conducted by Basunia and Abe (2005) and Das *et al.* (2004).

The drying behavior of paddy dried in the solar powered air inflated grain dryer can hence be suitably predicted using the Page model. The simplicity of the model adds to its utility in describing drying behavior of paddy in the developed solar powered air inflated grain dryer.

In this study, thin layer solar inflated dryer Pusa Basmati (PB 1121) paddy drying was investigated. The solar drying process occurred in the falling rate period, starting from the initial moisture content to the final moisture content of 14% (wb). To explain the drying behavior of Pusa Basmati (PB 1121) paddy eight different thin layer drying models were compared on their coefficient of determination values. According to the results, the Page model could adequately describe the thin layer drying kinetics of solar inflated drying behavior of Pusa Basmati (PB 1121) paddy with 99.9% accuracy. Page model has the least value of root

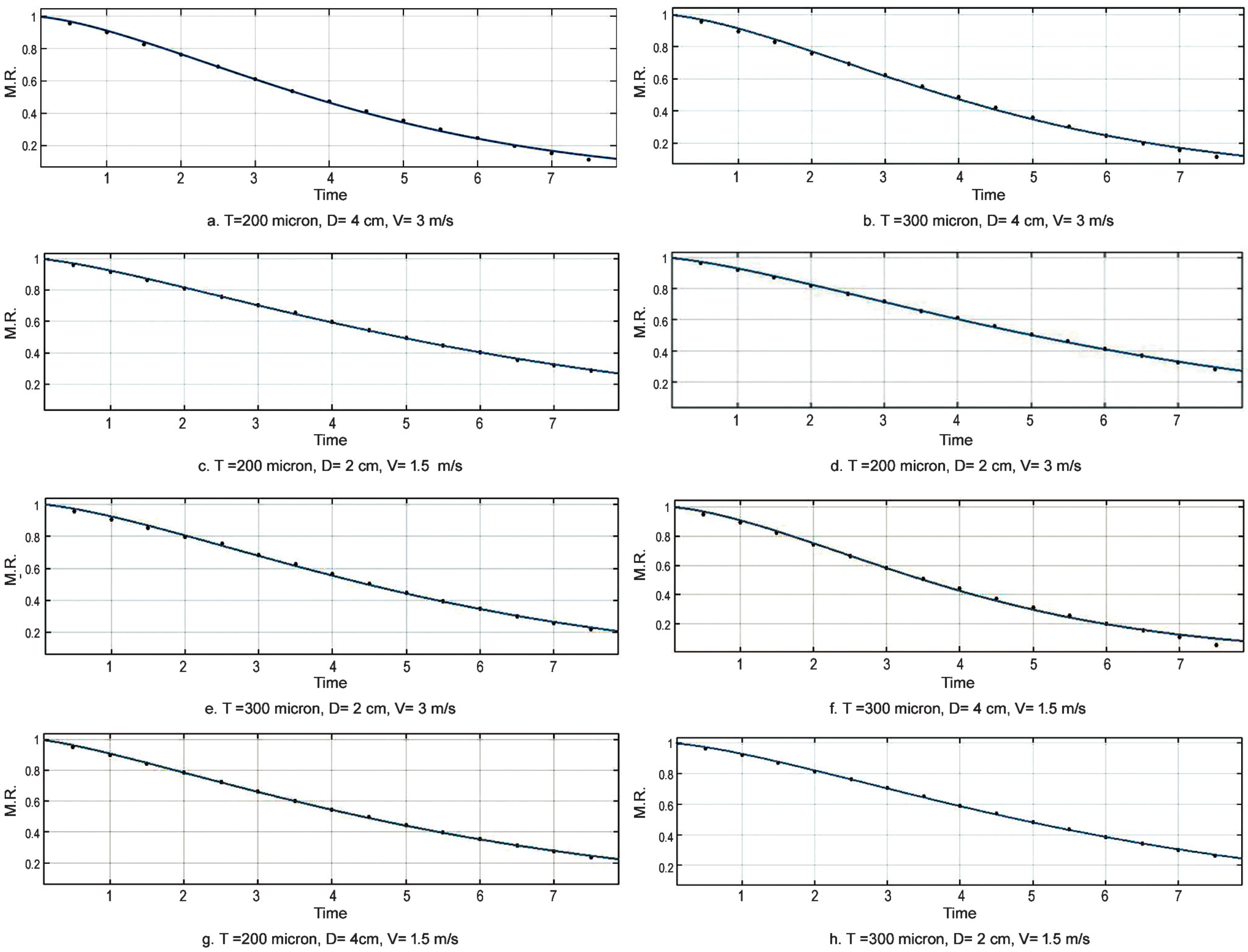

Fig 1 (a-h) : Page model fitting curves of experimental data for different combination of various levels of upper transparent sheet thickness (T), inlet air velocity (V) and grain bed depth (D).

mean square error and the highest value of determination coefficient thus fits the experimental data better compared to other models.When the effect of sheet thickness and velocity on the constants and coefficients of the page model were examined, the resulting model gave an R^2 of 0.0.9995 and RMSE of 0.005464. This final model describes the drying behavior of Pusa Basmati with two different levels of thickness of top transparent sheet (200 and 300 microns), inlet air velocities(1.5 and 3m/s) and grain bed depth (2 and 4 cm).

ACKNOWLEDGEMENTS

The authors acknowledge ICAR-IARI, Division of Agricultural Engineering and staff of Energy Laboratory for support during the experiments.

REFERENCES

Agrawal Y C and Singh R P. 1977. Thin-layer drying studies on shortgrain rice. *American Society of Agricultural Engineers* **77**: (3531)

Basunia M A and Abe T. 2001. Thin layer solar characteristics of rough rice under natural convection. *Journal of Food Engineering*, **47**: 295–301.

Chhinman M S. 1984. Evalution of selected mathematical models for describing thin layer drying of in-shell pecans.*Transactions of the American Society of Agricultural Engineers* **27**: 610–15.

Das I, Das S K and Bal S. 2004. Drying performance of a batch type vibration aided infrared dryer. *Journal of Food Engineering* **64**: 129–133.

Dubey A, Sharma P K and Mani I. 2019. Development of solar powered air inflated grain dryer. *Indian Journal of Agricultural Sciences* **89(**4): 695–700.

Golmohammadi M, Foroughi-dahr M, RajabiHamaneh M, Shojamoradi A R and Hashemi S J. 2016. Study on drying kinetics of paddy rice: Intermittent drying. *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)* **35**(3): 105–17.

Hasan A, Bala B K and Rowshon M K. 2014.Thin layer drying of hybrid rice seed. *Engineering in Agriculture. Environment and Food* **7**(4): 169–75

Henderson S M and Perry R L. 1976. *Agricultural Process Engineering*, 3rd edn. pp. 310–16. Westport CT: AVI Publishing Co. Inc.

Jindal V K and Siebenmorgen T J. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. *Transactions of the American Society of Agricultural Engineers* **30**(4): 1185–92.

Kassem A S. 1998. Comparative studies on thin layer drying models for wheat. *In 13th international congress on agricultural engineering* **6**(2): 6.

Onwude D I, Hashim N, Janius R B, Nawi N M and Abdan K. 2016.Modeling the thin-layer drying of fruits and vegetables: A review. *Comprehensive Reviews in Food science and Food Safety* **15**(3): 599–618.

Sontakke M S and Salve S P. 2015.Solar drying technologies: A review. *International Journal of Engineering Science* **4***:* 29–35.

Verma L R, Bucklin R A, Endan J B and Wratten F T. 1985. Effects of drying air parameters on rice drying models. *Transactions of the American Society of Agricultural Engineers* **28**(1): 296–301.

Wang G Y and Singh R P.1978.Single layer drying equation for rough rice. *American Society of Agricultural Engineers* **7**: 234–38.