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Effect of process parameters on in-bin drying characteristics of high moisture paddy

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■ **ABSTRACT :** Appeal of in-bin drying is that the same bin can be used for drying and temporary storage of grains at farm level. Successful adoption of in-bin drying method needs careful research on conditions under which it operates. Effect of process conditions such as inlet air temperature, rate of air flow and bed depth on drying characteristics of high moisture paddy at 25% (wet basis) in cylindrical drying bin was studied. An experimental cylindrical drying bin was fabricated with false floor arrangement. Three factors three levels Box-Behnken experimental design was used for conducting the drying experiments. In total 17 experiments were performed at three levels of temperatures (50, 60 and 70 ^{0}C), air flow rates (0.2, 0.3 and 0.4 $m^3 s^{-1} m^{-2}$) and bed depths (22.5, 33.75 and 45 cm). Five response variables were investigated in this study *viz.*, drying uniformity in terms of moisture differential within drying bin, drying rate (kg $kg^{-1} h^{-1}$), moisture ratio, head rice yield (%) and germination (%) of paddy. It was observed that moisture differential along the height of bed was highly affected by air flow rate and bed depth. Drying of high moisture paddy in bin dryer occurred in falling rate period and no constant rate period was observed. Drying temperature 70 ^{0}C resulted in reduced head rice yield (33.7%) and germination (74%) of paddy.

■ **KEY WORDS :** High moisture paddy, In-bin drying, Process conditions, Drying characteristics

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Paddy production accounts for more than 75 per cent of total food grains produced in Tamil Nadu state. Paddy is cultivated during three seasons namely 'Kuruvai', 'Samba' and 'Navarai' in Tamil Nadu state. In 2012- 2013, Tamil Nadu recorded 4.05 million MT of paddy production which was about 72.25% of total food grains production (Sivagnanam and Murugan, 2015). In most parts of Tamil Nadu state, cloudy and rainy weather conditions during arrival of north east monsoon hinders harvesting activities of paddy crop. Open field sun drying is a commonly used method for on farm drying of freshly harvested high moisture paddy by farmers. Due to prevailing wet and cloudy weather and unavailability of drying facility, farmers have no other option but distress sale of their harvest at lower prices.

High moisture paddy at 22 to 30% (wet basis) soon after harvesting needs to be dried upto 12 to 14% (wet basis) for satisfactory yield of head rice and safe storage. Farmers need mechanical driers on their farms to dry freshly harvested high moisture grains. In-bin drying systems are simple in structure, easy to install, low cost and suitable for drying cum temporary storage of freshly harvested crops (Jia *et al.*, 2016). Performance of in-bin drying system depends on inlet air temperature, air flow rate and depth of grains. Rapid drying is preferable but causes quality deterioration of paddy (Madamba and Yabes, 2005). Attempts were made to investigate in-bin drying of grains by several workers (Naghavi *et al.*, 2010; Ranjbaran *et al.*, 2014 and Srivastava and John, 2002). Drying kinetics of high moisture paddy in laboratory model bin dryer was studied and effect of temperature and bed thickness on milling quality was investigated by Ng *et al.* (2005). Regalado *et al.* (2000) developed experimental dehumidifier assisted radial flow dryer for drying of high moisture paddy to a moisture level of 14% (wet basis). This dryer was found to be suitable alternative for resistance heating systems as it consumed energy more efficiently. Sarker *et al.* (2014) studied and evaluated industrial inclined bed dryer used for drying of freshly harvested paddy. Effect of inlet air temperature and flow rates on energy consumption and rice quality were investigated. Response surface methodology is widely used statistical technique in process optimization studies and to investigate combine effect of multiple parameters on response variables. It involves systematic design of experiments and analysis to give an optimum solution of the problems. Dealing with multivariate problem is a most important feature of this technique (Madamba, 2002). Gupta *et al.* (2013) used response surface analysis to study the drying characteristics of cauliflower in thin layer convective dryer. Process parameters such as drying temperature, air velocity and layer thickness were investigated for vitamin C content, rehydration ratio and browning of the product during drying. Madamba and Yabes (2005) investigated intermittent drying of rough rice in bin dryer. Effect of drying conditions such as inlet air temperature, air velocity and tempering time on the quality of dried product was studied. In-bin drying systems are known for on farm drying and storage of freshly harvested high moisture grain bulks. Major problems with in-bin drying system are non uniformity of moisture distribution along the depth of bed, over drying in bottom layers and spoilage in upper layers. Selection of correct drying conditions is important for proper functioning and performance of in-store drying systems. Effect of drying parameters on moisture differential in bed, drying rate, moisture ratio, head rice yield and germination of paddy needs to be investigated. In order to design and install a large scale an on farm drying bins, drying kinetics and characteristics of material of interest must be known. Therefore present study was aimed to study the drying characteristics of high moisture paddy in experimental drying bin. Effect of parameters such as inlet air temperature, airflow rate and bed depth on in-bin drying characteristics such as uniformity of drying, drying rate, head rice yield and germination of paddy was investigated.

■ METHODOLOGY

This study on in-bin drying characteristics of high moisture paddy (variety CO 50) was carried out in 2015-2016 in the Department of Food and Agricultural Process Engineering, Tamil Nadu Agricultural University, Coimbatore.

Experimental drying bin :

Experimental drying bin as shown in Fig. 1 was fabricated. It consisted of cylindrical bin of 30 cm diameter and 45 cm height to hold a batch of 20 kg paddy grains, plenum chamber of 30 cm diameter and 15 cm height, electric heating coils (N = 4, 0.5 kW each) and centrifugal blower of 0.75 kW capacity. Heating section was insulated by applying coating of plaster of Paris. Centrifugal blower with inlet opening (Ø = 8.5 cm) was equipped with butterfly valve on blower housing to control the air flow rate in the range between 0.2 to 0.4 $m^3\ s^{-1}\ m^{-2}$. Cylindrical bin was made of mild steel. False floor was constructed by placing perforated circular sheet (Ø =30 cm) with round holes of size Ø = 1.5 mm at depth of 45 cm from top. Thermocouple probe was inserted at air inlet and was connected with temperature controller interface between heater and power supply.

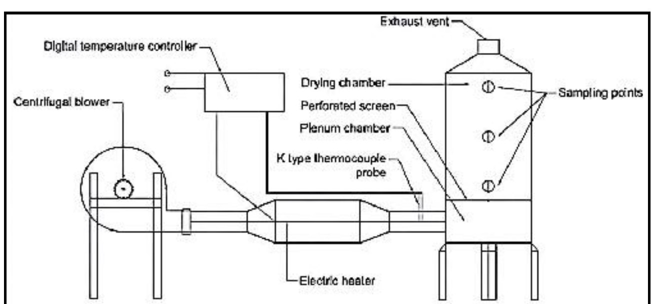

Fig. A : Schematic view of experimental drying bin

Sample preparation :

Raw paddy grains of variety CO 50 were procured from Department of Farm Management of Tamil Nadu Agricultural University, Coimbatore. Initial moisture content of paddy was determined using hot air oven at 130 ^{0}C for 20 h. Paddy material was conditioned for high moisture level upto 25% (wet basis) (Chen, 2003 and Kibar *et al.,* 2010). Conditioned paddy samples were then sealed in plastic bags and stored inside cooling chamber at 5-8 ^{0}C for 24 h in order to equilibrate the moisture. Samples were then taken out and allowed to attain equilibrium temperature with ambient air for about 1 h prior to drying experiments.

Experimental design :

A three factor three level experimental design as reported by Box and Behnken (1960) was used to study the effect of process parameters on drying characteristics of high moisture paddy dried in experimental bin dryer. In total 17 experiments were conducted which were expressed as N = *2k (k-1) + Co* in Box-Behnken three factor three level design, where *k* is number of factors and Co is number of replicated runs. Three factors such as inlet air temperatures, air flow rates and bed depth as shown in Table A were selected as process variables for conducting experiments (Ranjbaran *et al.,* 2014).

Table A : Process variables

Process variables	Levels		
Inlet air temperature ^{0} C	50	60	70
Air flow rate, ($m^3 s^{-1} m^{-2}$)	0.2	0.3	0.4
Depth of paddy, cm	22.5	33.75	45

Drying experimentation :

Experiments were carried out using pilot scale drying bin as shown in Fig. A. Conditioned high moisture paddy samples were fed manually in to the bin upto required depth. Required drying temperature and flow rate were set before conducting the experiments. Inlet air temperature was controlled by using digital temperature controller (Range with K type thermocouple: 0-1300 ^{0}C, Accuracy: ± 0.5%). Air flow rate was controlled by measuring air velocity using anemometer (Model: Equinox EQ 618B, Range: 0 to 45 m s^{-1}) and adjusting butterfly valve mounted on inlet of blower housing. For determination of moisture content, paddy samples were collected hourly from bottom, middle and top sections of drying bin and placed in hot air oven at 130 ^{0}C for 20 h. In order to record temperature and relative humidity at different depths of bin three USB data loggers (Model: Equinox EQ 171, Accuracy: Temperature: ± 2.0 ^{0}C and RH : ± 3.0%) were buried into paddy at bottom, middle and top layers of the bin.

Drying rate :

Drying rate (kg kg^{-1} h^{-1}) was determined by averaging the hourly drying rates of 6 h drying experiments. Hourly drying rate was determined by estimating the average moisture loss from top middle and bottom layer of the drying bin.

Moisture differential within drying bin :

Drying uniformity in terms of moisture differential within bin was determined**.** Paddy samples were collected hourly from top, middle and bottom layers of the drying bin. Moisture content of all collected samples was determined by air oven method. Moisture differential within the drying bin was determined as difference between top layer and bottom layer moisture content at the end of drying experiments (Jia *et al.,* 2016).

Moisture ratio :

Moisture ratio indicates the moisture content of paddy at any given time over total moisture to be removed in drying process (Ondier *et al.,* 2010).

$$MR = \frac{M - Me}{Mo - Me} \quad (1)$$

where, M = Moisture content % (dry basis) at any given time,

Me = Equilibrium moisture content, % (dry basis)

Mo = Initial moisture content, % (dry basis)

Germination test :

After every experimental run, dried paddy was allowed to reach an equilibrium room temperature. After 24 h fifty number of paddy seeds were randomly selected in three replicates for germination test. Paddy seeds were then placed in three Petri dishes containing wet blotting paper. Numbers of germinated paddy seeds were then counted after 8 days. Germination percentage was determined as per Eqn. (2)

$$\text{Germination \%} = \left[\frac{\text{Number of seeds germinated}}{50}\right] \times 100 \quad (2)$$

Head rice yield :

Post drying experiment, dried paddy samples were tempered for 24 h. For milling purpose three 100 g samples were collected randomly. Samples were then milled using laboratory rubber roll dehuller. Again three samples each of 10 g were collected from milled samples and husk was separated manually. Rice grains of size greater than 3/4th of whole grains were separated and weighed. Head rice yield was determined as indicated below:

$$\text{Head rice yield } \% = \left[\frac{\text{Mass of whole rice grains}}{\text{Total mass of milled sample}}\right] \times 100 \quad (3)$$

RESULTS AND DISCUSSION

The results obtained from the present investigation as well as relevant discussion have been summarized under following heads :

Statistical analysis :

Multivariate regression analysis was performed of experimental data shown in Table 1. Third order polynomial models were fitted for the prediction of moisture differential within grain bed, moisture ratio, drying rate, head rice yield and germination. These models were fitted for given experimental data in order to determine the drying behavior of high moisture paddy in bin dryer under the set experimental conditions (process parameters). These equations explained the combine effect of process variables on the performance of bin dryer in terms of aforesaid response variables. Analysis of variance was performed to evaluate the predictability of fitted models and the effect of drying parameters on drying characteristics of high moisture paddy.

Model fitting :

Third order polynomial models were fitted for explaining the effect of drying parameters on the performance of in-bin dryer. Equations were further reduced by eliminating non significant terms to achieve higher predictability. Predictability of these models was acceptable as co-efficient of determination (R^2) was greater than 0.9 and lack of fit was not significant (> 0.05) as shown in Table 2. Reduced cubic models were fitted by backward elimination regression shown in equations 4-8 where T is inlet air temperature, V is air velocity and D is bed depth.

Moisture differential =

$$-354.20+9.38T+83.25V+10.26D-0.06T^2-16.36V^2-.02D^2-1.10TV-0.30TD+2.53T^2D+0.22TV^2 \quad (4)$$

Table 1 : Details of experimental runs and drying characteristics of high moisture paddy

Facto r1 drying temperature ^0C	Factor 2 Air flow rate $m^3 s^{-1} m^{-2}$	Factor 3 Bed depth Cm	Response 1 Moisture differential	Response 2 Moisture ratio	Response 3 Average drying rate kg $kg^{-1} h^{-1}$	Response 4 Head rice yield %	Response 5 Germination %
50	0.4	33.75	4.54	0.767	0.017	65.03	86
60	0.3	33.75	9.21	0.632	0.018	62.86	84
50	0.3	22.50	7.47	0.591	0.014	63.47	90
70	0.2	33.75	7.38	0.763	0.013	30.10	83
70	0.3	22.50	6.83	0.377	0.036	33.49	78
60	0.3	33.75	10.28	0.627	0.021	61.08	85
60	0.4	45.00	3.93	0.654	0.013	68.75	87
70	0.4	33.75	14.74	0.542	0.025	34.08	74
60	0.2	22.50	3.75	0.665	0.011	63.38	86
50	0.2	33.75	8.01	0.782	0.013	61.02	91
60	0.2	45.00	1.33	0.857	0.003	62.42	88
60	0.4	22.50	7.69	0.423	0.055	66.30	85
50	0.3	45.00	9.25	0.725	0.016	60.09	93
60	0.3	33.75	8.05	0.641	0.023	59.76	83
60	0.3	33.75	9.43	0.645	0.020	60.12	85
60	0.3	33.75	11.03	0.613	0.019	57.43	88
70	0.3	45.00	10.29	0.697	0.014	33.70	82

Moisture ratio =

$$-4.03+0.16T+1.67V+0.01D-1.41T^2+0.06V^2-3.86D^2-0.06TV+4.13TD+5.22T^2V \quad (5)$$

Drying rate=

$$0.037-4.71T-0.30V+0.02D+5.10T^2+0.01TV-8.11TD-7.84VD-9.17T^2V+6.33T^2D \quad (6)$$

Head rice yield =

$$-356.16+16.65T-12.33V-1.37D-0.15T^2+2.41V^2+0.02D^2 \quad (7)$$

Germination =

$$395.95-9.66T-102.50V-0.86D+0.07T^2+0.014D^2+3.50TV-0.30T^2V \quad (8)$$

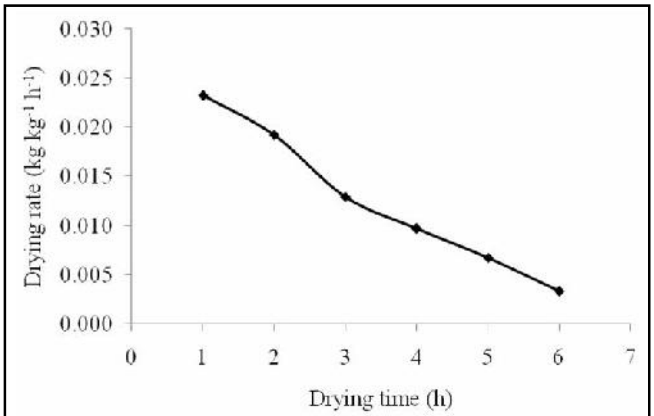

Fig. 1a : Effect of inlet air temperature (50 ^{0}C) on drying rate

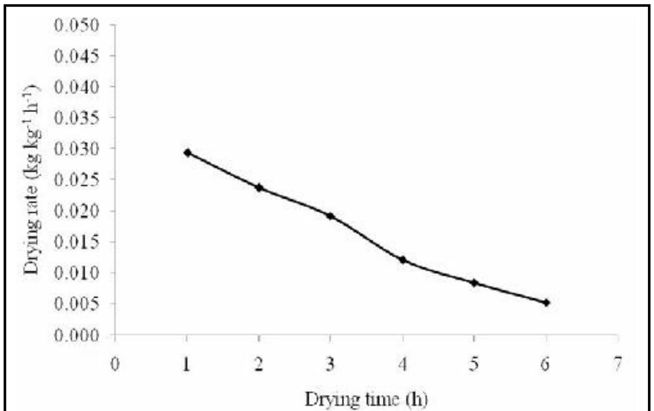

Fig. 1b : Effect of inlet air temperature (60 ^{0}C) on drying rate

Effect of drying parameters on drying of high moisture paddy in bin dryer :

As shown in Table 3 drying parameters such as inlet air temperature, air flow rate and bed depth significantly affected the moisture ratio and drying rates of paddy. It is evident from Fig. 1(a), 1(b) and 1(c) that drying of high moisture paddy in deep bed dryer occurred in falling rate period and no constant rate period were observed. Similar findings regarding drying rates of Malaysian paddy in rapid batch in bin dryer was reported by Ng *et al.* (2005). Higher inlet air temperature (70 ^{0}C) resulted in higher drying rates (0.04 to 0.02 kg kg^{-1} h^{-1}) during first four hours and approached constant value during fifth hour. As depicted in Fig. 2 decrease in drying

Table 2 : Adequacy of multivariate regression models for predicting the drying characteristics

Model		MD	MR	DR	HR	G
Quadratic	P-value	0.075	<0.0001	0.028	<0.0001	0.009
	R^2	0.799	0.9739	0.854	0.992	0.898
	Lack of fit	0.042	0.018	0.014	0.664	0.266
Cubic (Reduced)	P-value	0.001	<0.0001	0.0002	<0.0001	<0.0001
	R^2	0.960	0.995	0.966	0.989	0.949
	Lack of fit	0.629	0.461	0.233	0.758	0.957

($P < 0.05$: Significant, Lack of fit < 0.05: Not significant and $R^2 > 0.9$: Good predictability)
MD-Moisture differential, MR- Moisture ratio, DR –Drying rate, HR-Head rice yield, G – Germination

Table 3 : Effect of drying parameters on drying characteristics of paddy

Drying parameters	Response1 Moisture differential	Response 2 Moisture ratio	Response 3 Drying rate	Response 4 Head rice yield	Response 5 Germination
Inlet air temperature	0.8528^{ns}	0.0001***	0.0375*	0.0001***	0.0001***
Air flow rate	0.0118*	0.0001***	0.0001***	0.0048**	0.4865^{ns}
Bed depth	0.0243*	0.0001***	0.0001***	0.7328^{ns}	0.0200*

*, ** and *** indicate significance of values at $P \le 0.05$, ≤ 0.01 and ≤ 0.001, respectively NS=Non-significant

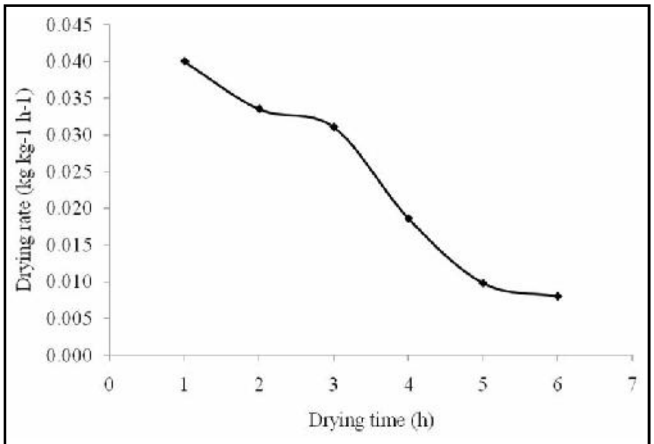

Fig. 1c : Effect of inlet temperature (70 ^{0}C) on drying rate

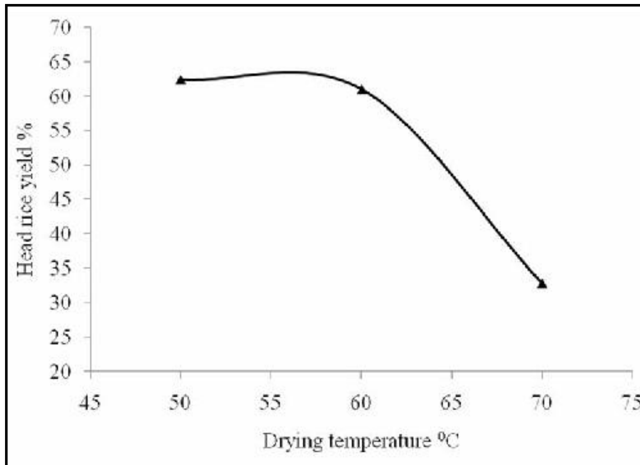

Fig. 3 : Effect of inlet air temperature on head rice yield

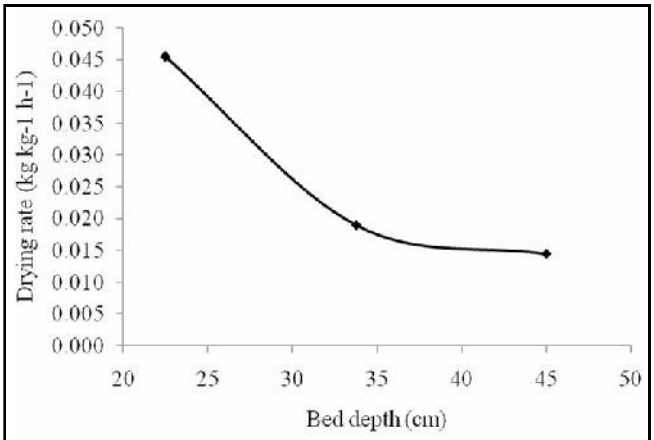

Fig. 2 : Effect of bed depth on drying rates

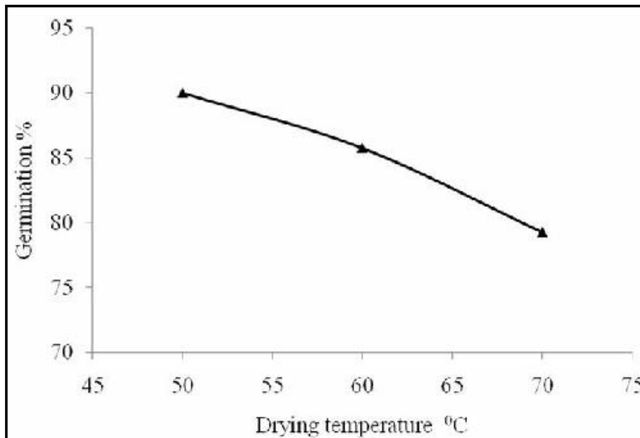

Fig. 4 : Effect of drying temperature on germination

rate was observed at increased bed depth of paddy in drying bin. Drying of high moisture paddy occurred at slower rate (0.014 kg kg^{-1} h^{-1}) at bed depth of 45.0 cm whereas drying rate was faster (0.045 kg kg^{-1} h^{-1}) at bed depth of 22.5 cm. Head rice yield and germination qualities were mainly affected by drying temperature and the same was reported by Sarker *et al.* (2014) and Madamba and Yabes (2005). As depicted in Fig. 3 and 4 qualities deterioration was higher at high (70^{0}C) inlet air temperature. Reduced head rice yield (33.7%) and germination (74%) was observed at temperature 70^{0}C. Similarly, Ng *et al.* (2005) had investigated in bin drying of Malaysian paddy at various temperatures and reported lowest yield of head rice (20%) at temperature above 80^0 C. Also, as per the study conducted by Mabamba and Yabes (2005), the lower drying temperature (45 ^{0}C) resulted in better head rice yield and germination quality of rough rice. Tohidi *et al.* (2017) deduced that rice kernel fissuring was increased with increase in drying rates at temperature 80^{0}C and air velocity 1.1 m s^{-1}. Uniformity of drying *i.e.* moisture differential was significantly affected by air flow rate and depth of paddy in drying bin. Whereas Jia *et al.* (2016) reported that the inlet air temperature 70^{0}C (without tempering) resulted in high moisture differential within bed and drying uniformity of wheat in deep bed was highly affected by tempering time. As depicted in Fig. 5, 6 and 7 higher moisture differential values 14.74 and 10.29 were observed at air flow rates 0.4 and 0.3 m^3 s^{-1} m^{-2}, respectively, which implied that non uniformity of drying and poor moisture distribution were observed at high values of air flow rates.

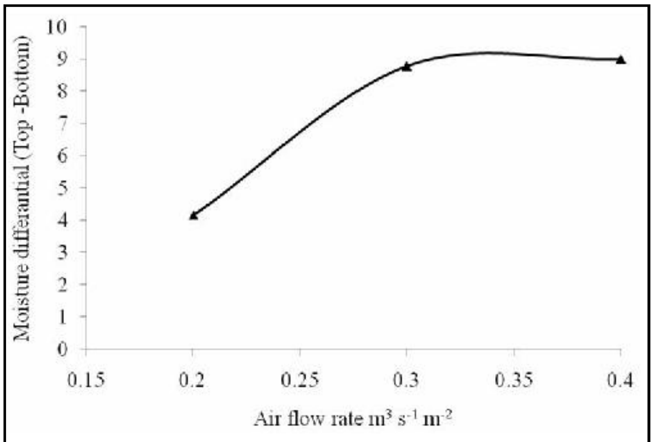

Fig. 5 : **Effect of air flow rate on drying uniformity in bin dryer**

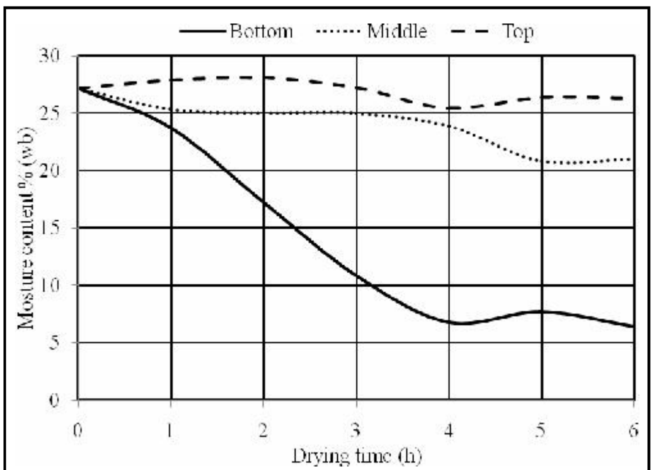

Fig. 6 : **Moisture differential within bed at 70 ^{0}C, 0.4 m^3 s^{-1} m^{-2}**

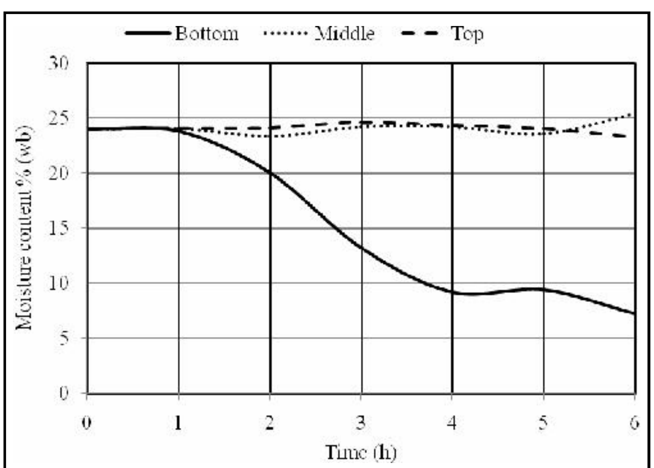

Fig. 7 : **Moisture differential within bed at 70 ^{0}C, 0.3 m^3 s^{-1} m^{-2}**

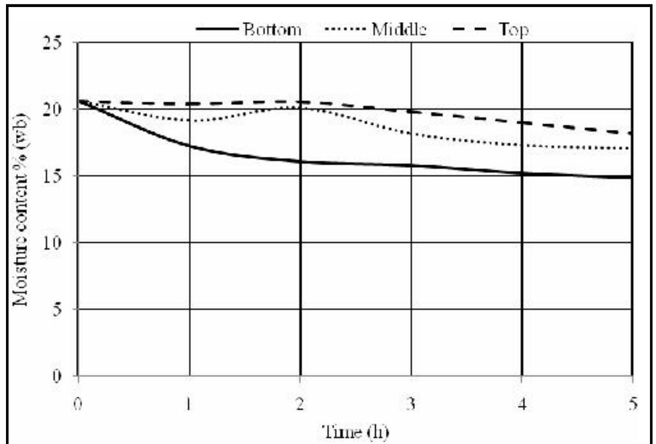

Fig. 8 : **Moisture differential within bed at 60 ^{0}C, 0.2 m^3 s^{-1} m^{-2}**

As shown in Fig. 8 uniform moisture distribution and minimum moisture differential in drying bed was observed at air flow rate: 0.2 m^3 s^{-1} m^{-2}.

Conclusion :

Third order regression models explained all the response variables with predictability of (R^2 > 0.90, P< 0.05 and lack of fit > 0.05). Head rice yield and germination of paddy was highly affected by drying temperature. Higher drying temperature (70^{0}C) resulted in decreased head rice (33.7%) and germination (74%) of paddy. The drying rate and moisture ratio increased with increase in drying temperature and air flow rate. No constant rate period was observed and drying of high moisture paddy in deep bed dryer occurred in falling rate period. Low air flow rate (0.2 m^3 s^{-1} m^{2}) and bed depth (22.5 cm) resulted in uniform drying in terms of minimum moisture differential within the bed.

Future work :

Although the drying high moisture paddy at lower depths in bin dryer results in high drying rates and even distribution of moisture, detrimental effects of faster drying and lower thermal efficiencies are questionable. Therefore, further investigation on drying high moisture grains at near ambient temperatures and lower rates of air flow in deep bin is required.

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