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Development of solar powered air inflated grain dryer

ABHINAV DUBEY[1], P K SHARMA[2] and INDRA MANI[3]

ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

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ABSTRACT

Cereals are generally harvested at 20-23% moisture content in order to avoid shattering losses while harvest. Their milling and long term storage is done at lower moisture content which is achieved by drying immediately after harvest. A solar powered air inflated grain dryer was designed and developed for drying of paddy. The developed dryer performance was evaluated by drying freshly harvested paddy with initial moisture content 22±0.3% (w.b.) in comparison to sun drying. The developed dryer had a significant difference in temperature of the drying air and drying rate compared to sun drying. The time required for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 hr and 11-12.8 hr in sun drying respectively. 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/hr respectively. The developed solar powered air inflated dryers provide a promising alternative for on farm drying of grains because of its low cost of construction, easy operation, green energy utilization and portability.

Key words: Grain drying, Paddy, Solar dryer

India is the second-largest producer and consumer of rice in the world with production 105.48 million tonnes in 2014-15 (Annual Report, Ministry of Agriculture and Farmers' Welfare, Govt. of India, 2016-17). One-third of the food produced (1.3 billion tonnes), is lost globally during post-harvest operations every year (Gustavsson *et al.* 2011). The post-harvest losses in two major food grains, i.e. rice and wheat are about 75% of the total post-harvest losses occurring at the farm level and about 25% at the market level (Nanda *et al.* 2012). Grains are generally harvested at higher moisture content in order to avoid shattering losses during harvesting. High moisture level during storage can lead to grain discolouration, encourage development of moulds, and increase the likelihood of attack from pests. Drying of the grain facilitates the farmers to wait for higher price of commodity and regulate demand supply chain. Thus it becomes crucial to dry the grain as soon as possible after harvesting. Ideally the harvested grain should be dried to safe level of moisture content within 24 hr. In case of cereal crops, field drying and stacking (forms of sun drying) are common methods but lead to large amount of losses and shattering when grains are over dried.In sun drying, the product is susceptible to contamination due to dirt, insects and wastage by birds. In this process grain may be spoiled due to sudden and unpredicted rain. There is no control of temperature over crop drying which may lead to quality deterioration, loss of germination and nutritional quality (Sontakke *et al*. 2015). The commonly used mechanical dryers for drying of paddy are labour intensive, require large amount of fuel, have high initial and maintenance cost and lack of knowledge to operate these dryers, especially with smallholders. Due to these limitations, these dryers are rarely used by smallholders in the developing countries (Alavi *et al*. 2012).

The daily average solar energy incident over India fluctuates from 4 to 7 kWh/m² with around 1500–2000 daylight hours per year (depending upon location) (MNRE 2013). Hence, use of solar dryers in the drying of grains can significantly reduce or eliminate product wastage, improve post-harvest handling at cheaper cost at the same time enhance productivity of the farmers towards better revenue (Sharma *et al*. 2009). Inflatable solar air collectors also find potential application in drying of agricultural commodities. These work on the principle of solar dryers and can provide technical and financially viable solution for drying in energy deficit areas. Solar collectors used in agriculture can be classified as cylindrical or semi cylindrical plastic tunnels inflated by a constant flow of air and ventilated horticultural greenhouses. The inflatable solar collector develops a semi cylindrical format when air is injected in the confined space between the two covers walls (Koury *et al*. 2003). Inflatable solar air heating collectors are compact, lightweight, inexpensive, self-supporting and self-erecting/

[1]PG Scholar (e mail: mystereo.rey14@gmail.com), [2]Principal Scientist (e mail: pksharma40@rediffmail.com), [3]Head (e mail: maniindra99@gmail.com), Division of Agricultural Engineering, ICAR-IARI, New Delhi 110 012.

storing. The performance of these collectors depends mainly on the air flow characteristics and geometry of the structure (Ruskis *et al.* 2011). Thus a need for a low cost, portable dryer for on farm drying of food grains running on green energy prevails and keeping this in view a solar powered air inflated grain dryer was developed for drying of paddy.

MATERIALS AND METHODS

Development of the solar powered air inflated grain dryer required proper selection of material followed by design of the drying chamber. Two different levels of inlet air velocity (1.5 m/s and 3 m/s), upper transparent sheet thickness (200 μm and 300 μm) and grain bed depth (2 cm and 4 cm) were selected. Selected parameters affecting the dryer performance and drying characteristics were studied and the dryer was developed based on the optimum design parameters.

The design of the drying chamber was governed by the physical properties of the grain to be dried. Long Paddy variety Pusa Basmati (PB-1121) was selected for determining design values and evaluation of the dryer. The drying chamber of solar powered air inflated grain dryer was designed based on the amount of grain to be dried in order to study the effect of selected variables. The amount of grain is a function of grain depth and grain bulk density. 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 (IRRI 2013).

Considering maximum bulk density of the selected variety paddy at harvesting moisture content, i.e. at 22 % = 429 kg/m^3 (Nag *et al*. 2018).

$$\text{Volume of drying bed} = \frac{\text{Mass of paddy to be dried}}{\text{Density of the paddy}} = 0.1165 \text{ m}^3$$

Since, the drying chamber was designed sufficient to hold the maximum amount of grain this resulted at the least depth of 2 cm. Considering, mass of paddy to be dried as 50 kg and average depth of grain bed while drying as 2 cm.

$$\text{Area of the drying bed} = \frac{\text{Volume of drying bed}}{\text{Average depth of grain bed while drying}} = 5.82 \text{ m}^2$$

A minimum width of 30 cm on each side of drying bed was provided for inflation of the drying chamber. The length and width of the drying bed were therefore selected as 4.2 m and 1.4 m respectively. Knowledge of volume of drying chamber enables us in selection of air blowing unit and at the same time decide the optimum outlet size for efficient drying.

Volume of drying chamber = cross sectional area × length of the drying chamber

= (Area of the parabola + area of rectangle) × length of the drying chamber = $(\frac{2}{3} \times a \times b + W \times H) \times L = 4.43 \text{ m}^3$

where a, b are base and height of parabola in the cross section respectively and W and H are width and height of the rectangular portion in the cross section. L is the total length of the drying chamber.

Black thick low density polyethylene sheet of 350 micron thickness was used as base of the dryer mainly due to its higher strength, rigidity and moisture impermeability. Black colour of the sheet allowed it to absorb the maximum solar radiations and hence increase the temperature in the dryer.The light weight of the sheet enabled the portability of the dryer. For the top of the drying chamber UV stabilized transparent low density poly ethylene sheets of two variable thicknesses (200 micron and 300 micron) were used. UV stabilized films have excellent capacity to withstand the solar radiations and have a long life. The transparent sheet allowed most of the radiations to pass through it and enter the dryer. Higher flexibility of the top transparent sheet allowed the drying chamber to inflate smoothly and hence form a quonset tunnel while the air is blown through the chamber.

A solar power operated 12V DC axial fan (40 cm) diameter with 3 blades was used for filling the air into the chamber. A solar panel of 12V/100W was used to operate the fan. The frame for the blowing unit was made of angle iron (40×40×6 mm) due to its resistance to vibration, better stability and easy availability.

Paddy (PB 1121) sample at nearly 22-23% moisture content were dried at various treatment combinations of the selected parameters. The drying process was started at 9:30 AM and moisture depletion was recorded for every 30 min interval. All the experiments were replicated three times. The drying process was terminated at 5:00 PM and restarted at 9:30 AM next day. The tempering time provided was of 16 h.

All the experiments were conducted at energy laboratory, 28.63° N latitude and 77.2° E longitude and 228.61 m above mean sea level, located at Division of Agricultural Engineering, Indian Agricultural Research Institute, Pusa, New Delhi. The required amount of Pusa basmati (PB 1121) variety of paddy was procured from Seed Production unit, IARI, New Delhi. The paddy procured was cleaned using air screen cleaner mainly to scalp the larger impurities and stones.The moisture content of the paddy sample was determined by hot air oven method following AOAC standards (Jindal *et al*. 1987).

For testing the performance of Solar PV system the current and voltage were measured for battery and inverter each by the multimeter (FLUKE 73 series multimeter) that provided the power output of Solar PV system. Solar intensity (W/m^2) was measured at 30 min interval with a thermoelectric pyranometer or the solar power meter (KM-SPM-11).The velocity of inlet and outlet air was measured using digital anemometer. The small rotating top in the instrument generates magnetic impulse, which is converted into a precise wind speed by the electronic circuit. Sling psychrometer was used for measuring the dry bulb and wet bulb temperature. A microcontroller based data logging unit was developed for measurement and recording of drying air temperature and relative humidity inside the dryer and in ambient condition. The data logger was developed using

Arduino Uno, DHT11 sensor, SD card module, RTC and LCD display.

Thermal efficiency of the dryer is a measure of amount of energy required in order to evaporate a unit mass of moisture from the grain. Thermal efficiency of the dryer encompasses the attributes of amount of moisture removed and the temperature rise in the air inflated solar powered grain dryer as a result of solar radiations. Thermal efficiency was calculated as:

$$\eta_{thermal} = \frac{Mw \times Hv}{Ms \times Cs \times (Td - Ts)} = 100$$

where Mw, amount of moisture removed from the grain; Hv, latent heat of vaporization of water at drying temperature; Ms, total air flow in the drying chamber; C_s, specific heat of ambient air (1.005 + 1.88 × H) kJ/ kg °C; H is the ambient relative humidity of the air; T_d, average drying air temperature in the dryer and T_s, temperature of ambient air.

Based on the design values obtained solar powered air inflated grain dryer was fabricated in Workshop and Energy Laboratory, Division of Agricultural Engineering, IARI, New Delhi. A heavy duty zipper was used to join the bottom and top halves of the plastic sheets which could also facilitate opening and closing for loading and unloading the grain in the dryer.

Fifty kg of Paddy (PB-1121) with initial moisture content (22±0.3%) was dried in solar powered air inflated grain dryer and sun drying on the concrete floor simultaneously. The grain bed maintained during drying was 4 cm in both solar powered air inflated grain dryer and sun drying. Equal amount of samples were collected at every 30 min time interval from the dryer and sun drying which was used for determination of moisture content and the drying rate.

A sample (150 g) was collected from both sun drying and the developed dryer at the end of drying, i.e. on attainment of 14% moisture content. The collected samples were de-husked in rubber roll Sheller (Model C). The average grain size of the paddy variety PB 1121 is 14.68 mm. The de-husked rice of height greater than or equal to 11.01 mm (75% of original length) was termed as head rice. The head rice and broken were separated manually and weighted to determine the milling recovery yield and head rice yield. Milling recovery yield (MRY) defined as the percentage of finished product (brown rice) obtained from de husking of the paddy is calculated as

$$MRY = \frac{\text{Weight of milled paddy}}{\text{Weight of initial sample}} \times 100$$

Head rice yield (HRY) defined as the mass of head rice expressed as a percentage of the original rough rice mass

$$HRY = \frac{\text{Weight of head rice}}{\text{Weight of initial sample}} \times 100$$

The statistical package SAS was used to analyse the experimental data. This was done to obtain the necessary analysis of variance of the mean and interaction of the selected variables. The experimental data was analysed using Latin square design.

RESULTS AND DISCUSSION

Temperature of ambient air was dependent on the solar intensity. The maximum ambient temperature was recorded between 2 PM and 2:30 PM. Among the temperatures measured at various intervals (1 m, 2.5m and 4 m) of length the temperature measured at 2.5 m length showed the highest value. The relative humidity of ambient air was found maximum at the morning and gradually decreased to lowest value between 3:30 PM to 4:00 PM. After 4 PM an increasing trend was observed in ambient air relative humidity. The relative humidity of drying air at point 1m along the length was lower than the ambient air because of the rise in temperature.

Analysis of variance at 1% level of significance for thermal efficiency of the dryer showed that varying the thickness of top transparent sheet had no significant effect (P=0.0583) on the thermal efficiency. Significant difference was found in the thermal efficiency when inlet air velocity (P<.0001) and grain bed depth (P<.0001) were changed. Least mean square value was calculated for each treatment combination and it was found that treatment combination of top transparent sheet thickness (300 μm), inlet air velocity (3 m/s) and grain bed depth (4cm) showed highest thermal efficiency. The least square mean value of thermal efficiency varied from 18.92-45.75%. Higher thermal efficiency is an indicator of better moisture removal in the dryer (Table 1).

The least square mean for thermal efficiency increased with increase in inlet air velocity and grain bed depth

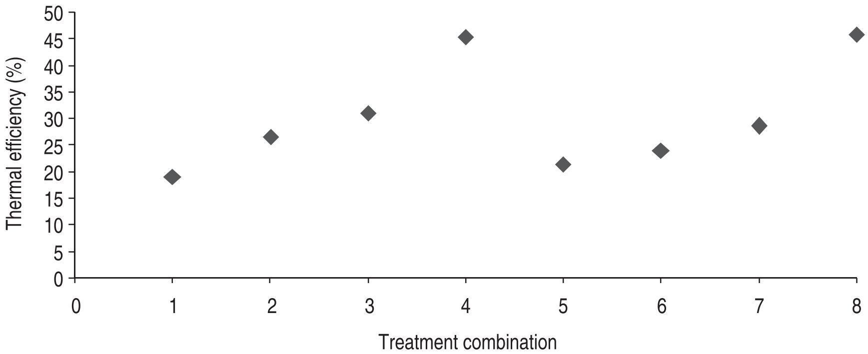

Fig 1 Scatter chart of least square mean for the thermal efficiency in different treatment combinations..

(Fig 1). Temperature rise of the drying air was calculated by difference of average drying temperature and ambient air temperature. Analysis of variances showed that increasing the inlet air velocity (P=0.4166) had no significant effect on the temperature rise in the drying air. Increase in the

Table 1 Least mean square values of thermal efficiency for combination of various levels of top transparent sheet thickness (t), inlet air velocity (V) and grain bed depth (D)

Treatment combination	Thickness of top transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square Mean
1	200	1.5	2	18.92
2	200	1.5	4	26.59
3	200	3	2	30.92
4	200	3	4	45.32
5	300	1.5	2	21.35
6	300	1.5	4	23.93
7	300	3	2	28.56
8	300	3	4	45.75

Table 2 Least mean square values of rise in temperature of the drying air for combination of various levels of top transparent sheet thickness (t), inlet air velocity (V) and grain bed depth (D)

Treatment combination	Thickness of top transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square mean (°C)
1	200	1.5	2	3.35
2	200	1.5	4	4.24
3	200	3	2	3.71
4	200	3	4	4.56
5	300	1.5	2	4.99
6	300	1.5	4	5.42
7	300	3	2	3.82
8	300	3	4	5.81

upper transparent sheet thickness and grain bed depth had significant effect on temperature rise in the drying air.

Top transparent sheet thickness (300 μm), inlet air velocity (3 m/s) and grain bed depth (4 cm) resulted in highest temperature rise. The least square mean value of rise in temperature of drying air varied from 3.35-5.81°C (Table 2).

Scatter chart of rise in temperature of drying air shows the increase in the value of temperature rise with increase in grain bed depth and top transparent sheet thickness (Fig 2). The desired moisture reduction (from 22% to 14% wb) was achieved between 7.5 h to 11 h. Amount of moisture removed was calculated by using the difference in moisture content measured at every 30 min interval (Fig. 3).

Analysis of variances showed that increasing the inlet air velocity (P=0.7240) and the thickness of top transparent sheet (P=0.0139) had no significant effect on amount of moisture removed per unit time interval of paddy in the 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) (Table 3). The moisture removed per unit time varied from 0.36-0.95 kg/h.

Table 3 Least mean square values of amount of moisture removed per unit time interval for combination of various levels of top transparent sheet thickness (t), inlet air velocity (V) and grain bed depth (D)

Thickness of top transparent sheet (microns)	Inlet air velocity (m/s)	Grain bed depth (cm)	Least square Mean
200	1.5	2	0.38
200	1.5	4	0.72
200	3	2	0.38
200	3	4	0.73
300	1.5	2	0.38
300	1.5	4	0.85
300	3	2	0.36
300	3	4	0.95

Scatter chart showed that top transparent sheet thickness (300 μm), inlet air velocity (3 m/s) and grain bed depth (4 cm) yielded highest least mean square values for all the three parameters considered. The moisture removed per unit time was highly scattered showing its variation with grain bed depth and inlet air velocity (Fig 4).

Analysis of variances showed that there was significant difference (P<.0001) in the drying air temperature in the dryer when compared with the sun drying (ambient air temperature). The temperature of drying air in the dryer was found to increase with time reaching its peak value at 1.00 PM. The temperature of drying air ranged between 29.8-38.2 °C compared to ambient air temperature ranging from 25.7-34 °C (Fig 5).

The drying rate for paddy was calculated at each 30 min interval and comparison was made between

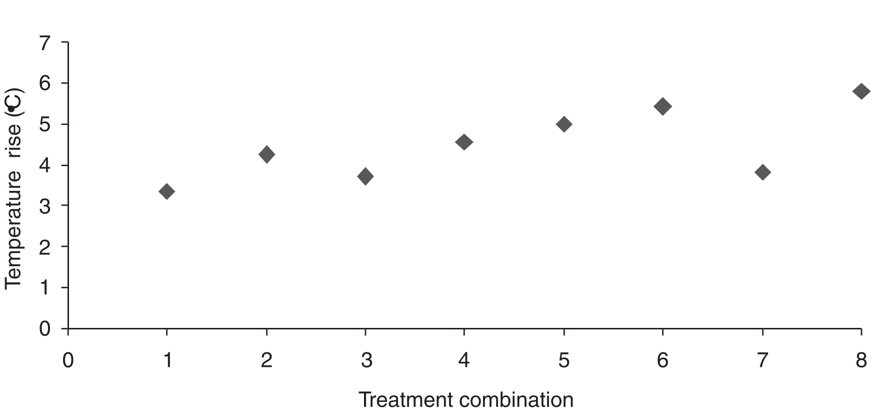

Fig 2 Scatter chart of least square mean for the temperature rise in different treatment combinations.

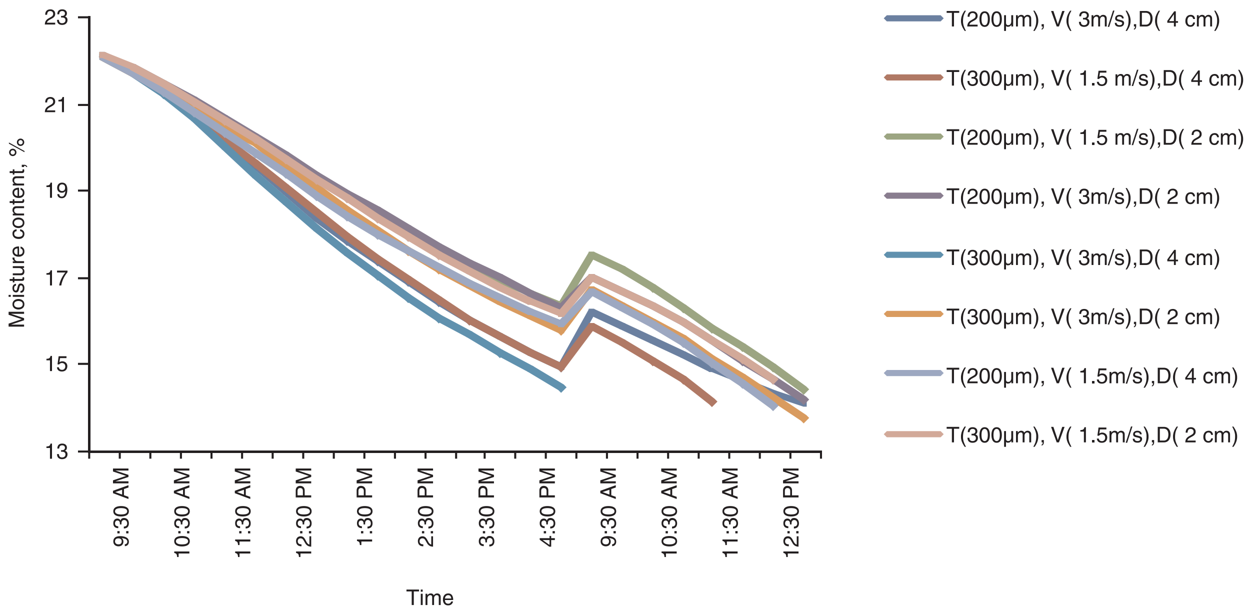

Fig 3 Variation of moisture content with time for different levels of thickness of top transparent sheet, inlet air velocity and grain depth.

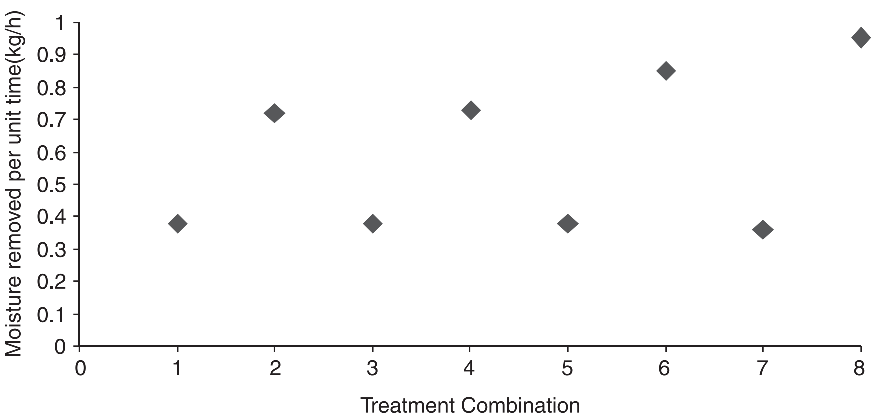

Fig 4 Scatter chart of least square mean for the moisture removed per unit time in different treatment combinations.

the developed dryer and sun drying. It was found that the drying rate produced in the developed dryer was significantly different (P=0.0019) as compared to sun drying.

The dried paddy was dehusked and its quality was evaluated on the milling yield and head rice yield obtained. Analysis of variances at 5% level of significance showed that there was no significant difference (P=0.033) in the milling yield produced in the paddy dried in the developed dryer compared to sun drying but head rice yield of paddy dried in the dried showed significant difference (P=0.002) compared to the sun drying . The rise in temperature was higher when the thickness of top sheet was increased from 200 µm to 300 µm mainly because thicker sheet produced more greenhouse effect. Similar trend was explained by Boldrin (1985) where the greenhouse effect increased from 20 to 30 % on increasing the thickness of polyethylene sheet from 100 to 200 µm.

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. Increasing the grain bed depth had significant effect on the amount of moisture removed per unit time. This was because the amount of moisture removed was higher in case of higher grain bed depth, since larger quantity of grain was dried expelling out larger amount of moisture in unit time. Increasing the top transparent sheet thickness led to increase in the temperature of drying air and hence amount of moisture removal increased significantly.

As the thickness of top transparent sheet increased the temperature rise in the dryer was higher and the amount of moisture removed also increased. The deeper grain bed

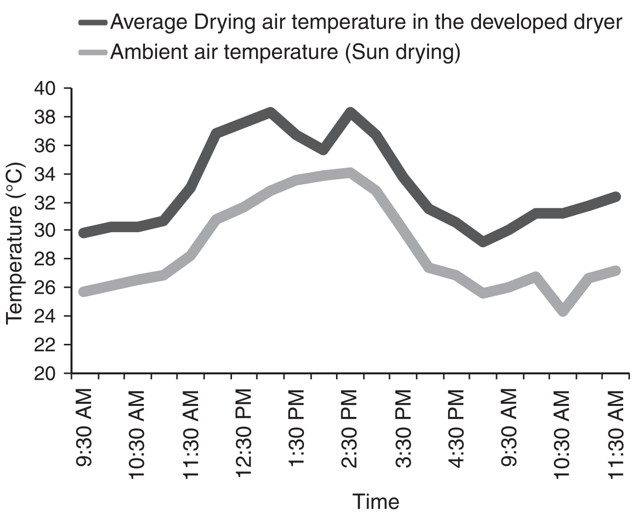

Fig 5 Temperature profile of average drying air temperature in the developed dryer and during sun drying.

depth resulted in more amount of grain in the batch drying process and thus more moisture was removed while drying. This resulted in high thermal efficiency of the dryer in grain bed depth (4 cm). Greater air inlet velocity resulted in carrying the evaporated moisture faster maintaining the gradient between saturation humidity and absolute humidity of the drying air thus resulted in higher values of thermal efficiency.

The drying air temperature in the dryer was higher than the ambient air because of the greenhouse effect (trapping of the solar shortwave radiations by the transparent top sheet). Greenhouse effect produced by the top transparent UV stabilised sheet was the major reason behind the rise in temperature produced in the dryer. Suitable drying temperature for paddy grain is 45-50°C. The major reasons behind increased rate of drying are the rise of temperature of the drying air and forced convection flow which carries away the moisture at a desirable rate. The time saved in the operation is crucial as it allows more quantity of the grain to be dried in short time preventing their spoilage. Higher drying temperature resulted in more moisture removal in paddy in unit time. Similar trends were observed by Putra and Ajiwiguna (2017) that higher air temperature and velocity increased the evaporation rate, Sigge *et al*. (1998) also found that drying rates generally increased with increasing temperatures and decreasing RH.

The higher amount of broken produced in sun drying mainly account for the uncontrolled drying and high temperature of grain due to direct exposure of grains to sun rays. During peak hours of sunshine the grain temperature in sun drying increased to higher values of 60-62°C. Similar trends had been observed by Yamashita (1996) that when drying temperature exceeded 40°C, rice taste quality decreased. Batcher *et al*. (2004) reported that drying at elevated temperatures (71°C) caused neither marked improvement nor deterioration in the cooking quality of milled rice.Total cost of manufacturing the dryer including the cost of labour required was ₹ 10,850. The dryer can be used for 2400 h annually for various grains. The profit obtained can be increased by increasing the batch capacity of the dryer and utilizing it for more number of days in the year.

Conclusions

The power developed by solar PV system was sufficient to run the air blowing unit. The least mean square values of thermal efficiency, temperature rise in the drying air and drying rate of the dryer varied from 18.7-45.7%, 3.35-5.81°C and 0.36-0.98 kg/h respectively. Top transparent sheet thickness (300 micron), inlet air velocity (3 m/s) and grain bed depth (4 cm) had highest least Square mean values in the selected parameters and was selected for optimized operation of the dryer. The dryer had a significant difference in temperature of the drying air ($P<.0001$) and drying rate ($P=0.0019$) compared to sundrying. The time required for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 h and 11-12.8 h in sun drying respectively. Milling yield of the dried paddy in the dryer did not vary significantly ($P=0.033$) but the head rice yield had significancet difference ($P<0.005$) compared to sun drying. The developed dryer costs ₹ 10,850 and can be operated 2400 hours per year for drying of various grain crops. The developed solar powered air inflated dryer provides a promising alternative for on farm drying of grains because of its low cost of construction, easy operation, green energy utilization and portability. This dryer can be used more efficiently in the rural areas where sun drying is still a major practice. Portability of the dryer enables its easy handling and carriage.

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