Design, Development and Performance Evaluation of a Small-Scale Solar Assisted Paddy Dryer for on Farm Processing

SIDRAH ASHFAQ*, MANZOOR AHMAD**, AND ANJUM MUNIR**

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ABSTRACT

With the continued escalation in population growth and the expansion of international food trade and demand of high quality product for food security at low cost has created considerable interest in the development of new post-harvest technologies. This is particularly important for developing countries where post-harvest losses of cereals are between 10-20% and of fruits and vegetables as high as 20-100% A new solar assisted paddy dryer with central air distribution model (along the length of drying chamber) has been developed. Due to this distinct feature of the dryer high drying rate was achieved during the drying processes .Other components of the dryer are perforated drying chamber, blower and flat plat solar air collector. Dryer was evaluated using 100kg of freshly harvested paddy at 23.78% moisture content (wb). Performance evaluation results showed that the mean drying rate of the solar assisted paddy dryer was 0.87kg/hr per for every 100kg, whereas 0.46kg/hr was the sun drying rate comparatively. The faster drying rate of the dryer reveals its suability to dry the paddy for its safe storage moisture content rapidly. By using the solar assisted paddy dryer, approximately 50% saving in time was also achieved as compared with the traditional sun drying method. Solar assisted paddy dryer took 10hr for drying the 100kg paddy up to 14%, while sun drying method dried paddy up to 13.89% in 19 hours. Cost analysis also showed that, by using solar assisted paddy dryer we can dry good quality paddy at low cost as compared with the open sun drying method. For development of agriculture in the rural areas, commercial size of the solar assisted paddy dryer can be amplified and produced at community level.

Key Words: **Open Sun Drying, Moisture Content, Drying Rate, Uniform Drying, Central Air Distribution Model.**

1. INTRODUCTION

In the present scenario, Pakistan is facing food security problem and its agriculture sector plays a vital role to overcome the food security issues. Pakistan is the world's largest producer of rice and produces high quality rice for local consumption and to export. According to the International Rice Research Institute, rice is a basic food almost one-half of the world's population and common rice is produced all over the world as a nutritionist food (Maclean, et. al. [1]). In recent years, Pakistan produced about 5.1 million tons but still had to import just 320,000 tons to meet the demand, particularly during the lean months of September to October (Aynanomous, [2]).

*Ph.D. Student, and **Associate Professor,
Department of Farm Machinery & Power, Faculty of Agricultural Engineering, University of Agriculture, Faisalabad.

Paddy is harvested at high moisture content up to 20-24% (wb) when it matures. For preventing the deterioration and to increases the storage life of the paddy, drying is the important post-harvest operation. Drying of paddy is usually done by two ways. One is the open sun drying and other is the mechanical drying by using the different types of dryers. Open sun drying is cheap but now it is absolute because it is labor intensive and degrades product quality. In order to protect freshly harvested paddy from deterioration, and to reduce the wastage through bacterial action, accelerate the time for drying the products, different types of mechanical dryers are designed and used for different types of crops like maize and rice. In these types of dryers air is forced into the drying chamber. When air passes through the grain mass, it formed three zones, dried, drying and un-dried zones within the dryer, which causes the non-uniform drying of grains. All the conventional dryers have this problem and the main causes of this problem are high energy consumption with non-uniform drying. Therefore, it is important to develop such a dryer which deals with the high quality of the product at low energy consumption and uses natural resources.

Bola, et. al. [3] designed the parameters for small scale batch in-bin maize dryer. The author studied the dimensions of the drying chamber 600 mm diameter and 546 mm height, how much amount of water needed to remove from a batch of maize, amount of air required to affect the drying, blower capacity, volume of air required to affect drying, quantity of heat required to affect the drying and actual heat used to effect drying were all designed for. Bola designed and developed a dryer whose capacity was 100 kg. The main components of the dryer are; frame, drying cylinder, agitating shaft, heat exchanger, air blower and electrical control panel. The components were fabricated and assembled according to design. After testing the dryer; the author concluded that this dryer can be used in laboratory for experimental purpose as well as for commercial purpose on the farm.

Olaniyan and Alabi [4] designed, built and tested a column dryer for paddy. The parts of the dryer included, a 0.5 hp centrifugal fan inside a fan casing, thermostatically-controlled electric heaters inside a heating chamber and a drying chamber consisting the plenum chamber surrounded by two perforated grain columns, air vent and locking device. In operation, paddy was fed through the hopper and flow into the vertical grain columns surrounding the plenum unit in the drying chamber. Hence, drying processes took place by heat and mass transfer. A trial test was done on the paddy sample and results showed that this dryer was able to reduce the dryness level of the paddy samples up to 13.37% from 22.36%, this indicated that the performance of the dryer was satisfactory. This dryer powered by a 1.0 hp single phase electric motor. The dryer has a production cost of USD 375 including the cost of electric motor and labor.

Keeping in view, the above problems, the objective of this study to meet the needs of small-scale farmers is to design, develop and evaluated the performance of a solar assisted paddy dryer for on farm processing of small farmers. The purpose of the dryer is to reduce the post-harvest losses faced by the farmers thereby increasing the socio-economic status of the farmers. Kisten and Van [5] stated that the small farmers are one whose scale of operation is too small and they need a simple and low cost technology to increase productivity.

2. MATERIALS AND METHOD

In order to develop a batch type dryer for paddy on farm usage, the following properties and parameters were determined.

2.1 Design Procedure and Calculations

In order to develop an efficient batch type dryer for paddy, the size of the dryer was determined according to the bulk density of the paddy grain. The drying temperature was assumed according to the ambient air temperature and the maximum temperature needed for the good quality drying without developing the stresses within the paddy kernel. Mean average temperature and relative humidity of September and October is 27°C and 70% respectively. The maximum allowable temperature for the drying of paddy was assumed up to 43°C. Initial moisture content was measured at the time of harvest with the help of grain moisture meter that was 24% (wet basis) and the final moisture content for the safe storage of paddy was assumed 14% (wet basis).Others designed values like humidity, enthalpy and air flow rate was measured from the psychometric chart. For the designing purpose, the following properties and parameters were determined.

2.2 Water in the Paddy at the Time of Harvest

The moisture content of the paddy was determined to know how much amount of water need to remove from the freshly harvested paddy. Sample of freshly harvested paddy grains was weighted and dried in a ventilated electric oven set at 130°C for 16 hours. When constant weight was achieved the sample was removed and allowed to air cool (Ratti, [6]). The weight of the dried sample was measured by using the electric balance. The moisture content was measured by using Equation (1).

$$mc = \frac{100\left(W_1 - W_2\right)}{W_1} \tag{1}$$

2.3 Determination of Bulk Density

Bulk density of a material is defined as the mass per total volume of the material. Wratten, et. al., [7] developed an empirical formula which relates the bulk density and moisture content for paddy as stated in Equation (2).

$$Db = 567.2 + 4.13M \tag{2}$$

M is moisture content (%, wet basis). Initial moisture content of the paddy at the time of harvest was 24% (wet basis). Substituting the value of M_{wb} is 24% (wet basis) into Equation (2), the value of Db is calculated as 666.32 kg/m^3.

2.4 Design of Drying Chamber

Bola, et. al. [3] measured the dimensions of the drying chamber with the assumptions that, configuration is cylindrical and mass of paddy is 100kg. The bulk density of the paddy grain was 666.32 kg of freshly harvested paddy occupies 1m^3 by volume. 1 kg of freshly harvested paddy occupies 0.001501m^3 and 100 kg will occupy 0.1501m^3.

$$Volume = Base\ Area * Height \tag{3}$$

Since the dryer was cylindrical and the dimensions of the drying chamber was calculated using Equation (3) and were found to be 500 mm in diameter and 764 mm in height.

2.5 Mass of Moisture to be Removed

How much amount of water needed to remove from the grains is calculated by using the Equation (4). (Henderson and Perry [8]).

$$mw = \frac{W\left(M_o - M_f\right)}{M_o} \tag{4}$$

Where m_w is the mass of moisture to be removed, W is the initial weight of the paddy in kg, M_o is the moisture content at the time of harvest in % (wet basis) and M_f is the required moisture content of the paddy in % (wet basis).W=100 kg, M_o=24%, M_f=14% and M_w is 11.62kg.

2.6 Amount of Air Needed for Drying of Paddy

The quantity of air required for drying the paddy rice was calculated from the basic energy balance equation for drying process (Ichsani and Dyah [9]) is given by the Equation (5).

$$m_a(C_p(T_b-T_c)=m_wL \quad (5)$$

Where m_w is the mass of drying air in kg, L is latent heat of evaporation of free water from the paddy in J/kg, C_p is the specific heat of air at constant pressure in J/kg°C, T_a is the initial temperature in °C and T_b is the final temperature in °C.

The quantity of air was calculated by idealizing the drying processes on the psychometric chart. If ambient air at temperature T_a = 27°C and relative humidity ϕ_A = 70% is heated up to the temperature of T_b = 43°C, safe drying temperature for paddy (Hall, [10]), then ϕ_A will reduce to ϕ_B = 20% .Absolute humidity was measured $W_A = W_B = 0.016$ kg of water/kg of dry air. This heated air is used to remove water, 11.6kg from paddy of 100kg until an equilibrium ϕ_C is reached. The temperature of the drying air was reduced from T_b to T_c and the absolute humidity W, was increased from W_B =0.016 to W_C = 0.022 kg of water/kg of dry air. Change in absolute humidity was measured, that was equal to $\Delta W_{CB} = (W_C - W_B) = 0.006$kg of water/kg of dry air. Mass of air required to remove moisture from the paddy was measured by using Equation (6) (Ichsani and Dyah [9]).

$$M_a = \frac{m_w}{\Delta W_{CB} * n} \quad (6)$$

Where M_a is the mass of air required to remove the moisture from the paddy, mw is the quantity of water to be removed, ΔW_{CB} change in humidity ratio, which is the moisture that can be removed, n is the pickup factor according to (Axtell, [11]), a perfect transfer of moisture is not possible in practical drying of food and biological materials and, therefore, in designing dryers for these products, a pick up factor is introduced. This pick up factor takes into account the nature of the food and biological materials to be dried and the ease with which it releases moisture to the air. Hence, the actual amount of water that would be removed from the products per kg of drying air can easily be determined. Thus from the psychometric chart m_w =11.6kg, $\Delta W_{CB} = (W_C - W_B) = 0.006$ kg of water per kg of dry air, using pick up factor of 0.25 than putting all values in the Equation (5) the m_a is calculated that was found to be 7746.67kg. Drying time was considered as 7h per batch, Hence, m_a = 1106.67 kg/h which is equal to 0.31 kg/s.

2.7 Volumetric Flow Rate

Volumetric flow rate was measured by using Equation (7) (Axtell, [11]).

$$M_v = m_a * v_s \quad (7)$$

Where M_v is the volumetric flow rate of the drying air in m^3/s, vs. is the specific volume of the drying air in m^3/kg. The value of specific volume from the psychometric chart is 0.871m^3/kg and the value of m_a is 0.31kg/s from the Equation (5), hence, Mv=0.26 m^3/s or 0.259m^3/s.

2.8 Fan Selection

The pressure drop for airflow characteristic of the product depends on the depth of the product bed (Brooker, et. al., [12]). From fan chacterestics curve (Flow rate (cfm) vs air flow resistance) value of static pressure measured was 27.7 mm of water. Multiply this pressure drop with a pack factor. Value of 1.3 is commonly used for wheat and 1.5 for other crops. If air is delivered from duct than also add 0.5 to measure the total static pressure. Than the total static pressure was 53.3mm of water (Kenneth, and Hellevang [13]).

$$\text{Fan Horse Power} = \frac{\text{Air Flow Rate} * \text{Static Pressure}}{3814} \quad (8)$$

Thus, the air flow rate is 550.48cfm and static pressure is 2.1, than the required horse power from Equation (7) is 0.5 hp. Therefore, a 0.5 hp centrifugal fan is selected.

2.9 Quantity of Heat for Drying

Quantity of heat energy required for removing the water from the grain mass was calculated with the following Equation (9) (Exell, [14]) as:

$$Q = ML + Mh_{fg} \quad (9)$$

Where Q is the amount of useful heat energy in W, M(11.62kg) is the mass of moisture to be removed, L is the latent heat evaporation from the steam tables as $2.26*10^6$ J/kg, h_{fg} is the heat coefficient and its value is taken from steam tables as 43990 kJ/K mole of water. Than the amount of heat required for drying is 5.5kJ/s.

2.10 Solar Collector Area for Heating the Drying Air

Collector area Ac for the required heat was calculated from the following Equation (8) (Exell, [14]).

$$Q = A_c(I_t\delta_a) - U_L(T_p\text{-}T_a)F_R \quad (10)$$

Where A_c is the area of the collector, I_t is the solar energy received on the upper surface and according to the Faisalabad (Pakistan), it is 850 W/m^2 on average basis , U_L is the heat coefficient and is equal to 7.38W/m^2 ^{o}C, δ_a is the transmissivity and equal to 0.89, F_R is the heat removed factor for collector and equal to 0.9, T_a is the average ambient temperature and is equal to 27^{o}C, T_p is the average required temperature and is equal to is 43^{o}C. Finally, using Equation (10), the area of the collector is calculated as 1.65m^2. The design specifications are shown in **Table 1**.

2.11 Description of the Solar Assisted Paddy Dryer

Dryer design is based on the concept of batch type dryers. Principal of the solar assisted paddy dryer is that it increases the temperature of the ambient air passing through air collector by absorbing the solar energy and then use this heated air to remove the moisture from the moist grains. Solar assisted grain dryer was developed and constructed in the Department of Farm Machinery & Power Workshop, University of Agriculture, Faisalabad, Pakistan. The solar assisted dryer consists of the following components: flat plate solar air collector, drying chamber, air distribution model and a blower. Schematic diagram of the different

TABLE 1. DESIGN SPECIFICATIONS

Items	Conditions and Assumption
Location	Faisalabad, Pakistan
Crop	Paddy
Crop porosity	0.54
Bulk density, Db (kg/m^3)	666.32 kg/m^3
Weight of grains per batch	100kg
Moisture content at the time of harvest, (wb)	24%
Required moisture content for storage, (wb)	14%
Ambient air temperature,	27^{o}C
Ambient relative humidity,	70%
Maximum allowable temperature (^{o}C) (Hall,1980)	43^{o}C
Drying time (sunshine hours)	7h
Incident solar radiation, I_h	850 W/m^2
Collector efficiency, η_c (%)	30-50%
Average thickness of grain, (mm) Gross, 1965	2.5-3
Amount of heat required for drying of 100kg paddy.	5.5kJ
Transmissivity	0.89

components of the dryer are shown in Figs. 1-3. Fig. 4 shows the flow behavior of drying air within the drying chamber. Fig. 5 shows the actual view of the solar assisted paddy dryer.

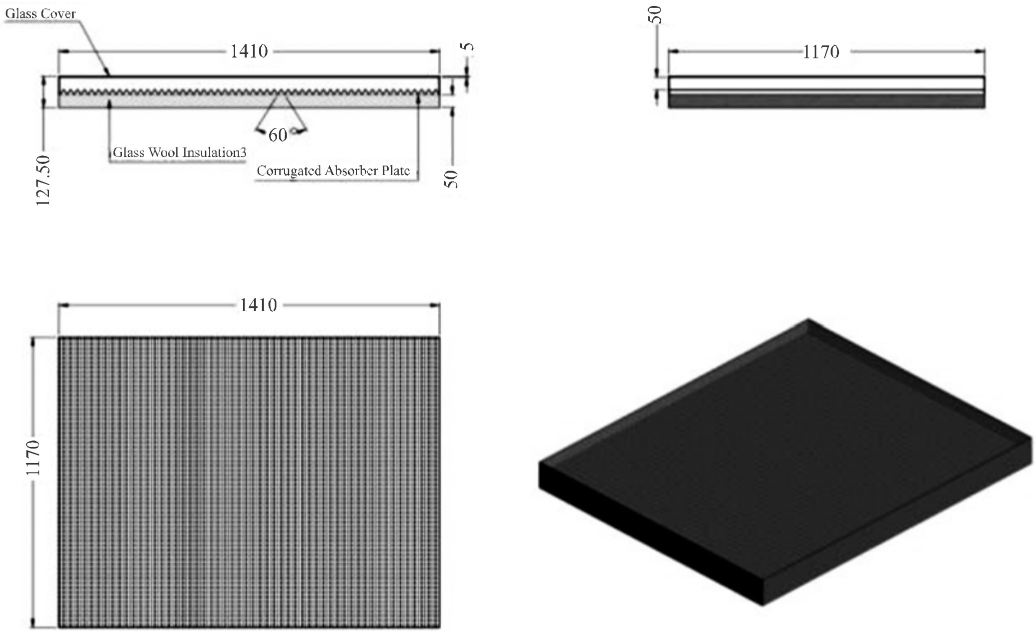

FIG. 1. SECTIONAL VIEW OF THE FLAT PLAT COLLECTOR (ALL DIMENSIONS ARE IN MM)

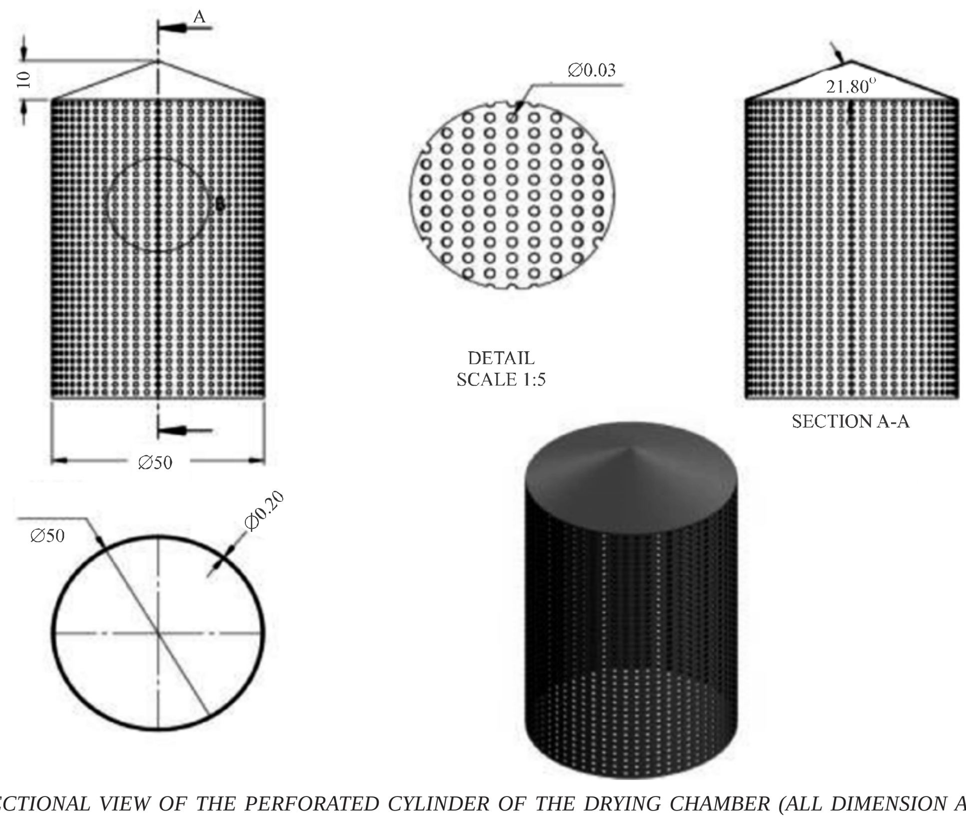

FIG. 2. SECTIONAL VIEW OF THE PERFORATED CYLINDER OF THE DRYING CHAMBER (ALL DIMENSION ARE IN CM)

Fig. 1 shows the cross sectional view of the flat plat solar air collector. The design of the air flat plat collector is simple, with length of 1.410 m and width of 1.170 m, consists of a U-corrugated absorber plat (0.5mm thick, painted black) with triangular fins (10mm wide, 10mm deep) parallel to the direction of the air flow. Collector casing is made of wood to prevent escape of heat. Backside and corner of the collector were insulated with 50mm thick glass wool, having thermal conductivity of 0.032 W/mK A colorless glass sheet (0.5mm) was used as a cover of the flat plat collector because it is more efficient as compared with the other material (Sadiku, et. al. [15]. For the flow of air between the absorber and the insulator, 50mm was the optimum gap provided between the cover and absorber plat according to the (Tabassum, et. al. [16]). Drying chamber is a place where drying processes is take place. The size of the drying chamber was calculated by the method as suggested by the Bola, et. al. [3]. Drying chamber comprises a cylindrical vessel having 600 mm diameter and 750 mm height. Another perforated cylindrical vessel having diameter of 500 mm was fitted inside the large diameter cylinder. The size of the hole on the sieve of drying chamber cylinder is 3mm, which is selected according to the size of the paddy grain (Gross, [16]).Food graded material (Stain less steel) was used for the construction of the drying bin to avoid the health hazards and rusting. For loading and un-loading purpose, a screw conveyor was used at the side of the drying

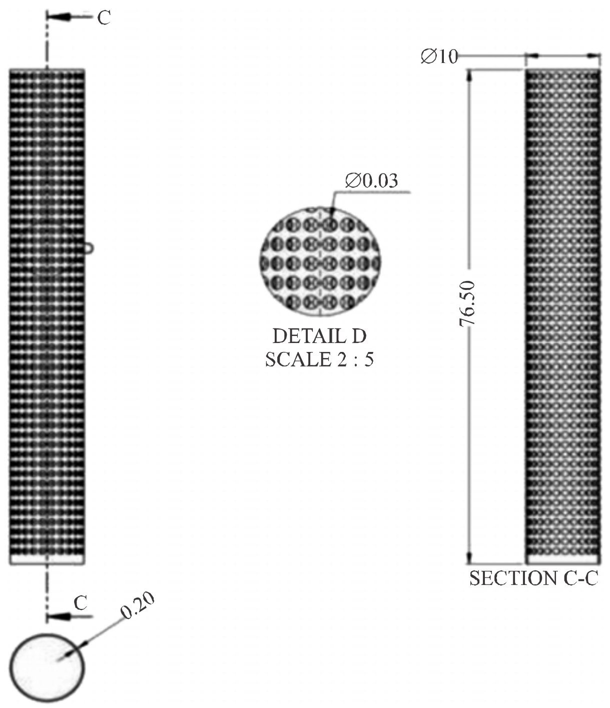

FIG. 3. SECTIONAL VIEW OF THE CENTRAL AIR DISTRIBUTION MODEL OF THE DRYING CHAMBER

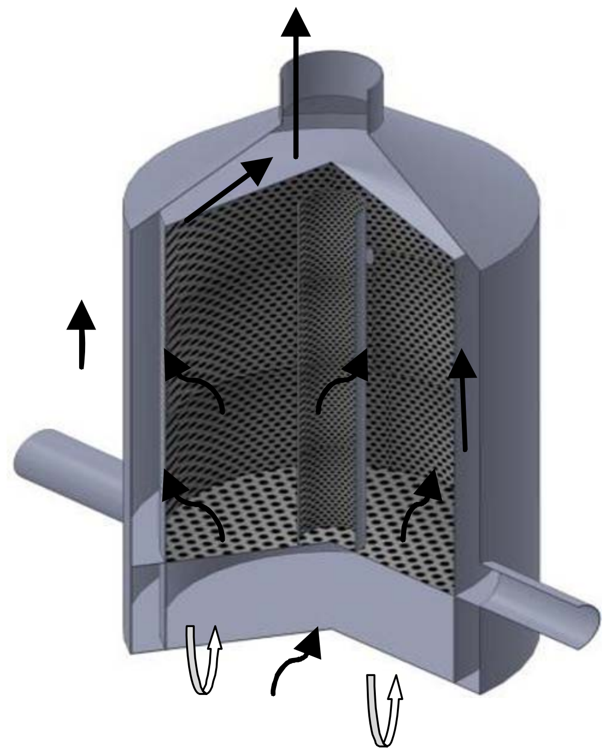

FIG. 4. INTERNAL SECTIONAL VIEW OF THE DRYING CHAMBER

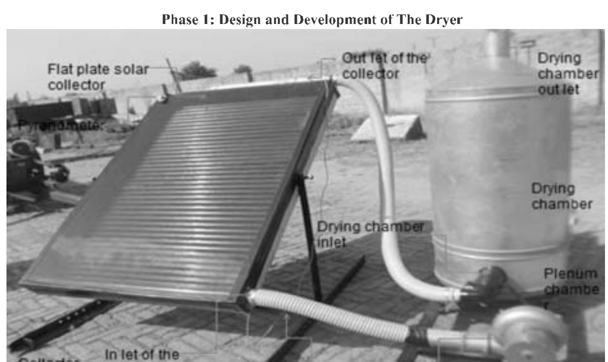

FIG. 5. ACTUAL VIEW OF SOLAR ASSISTED PADDY DRYER

chamber. An air distributor model (100 mm SS duct) was also placed inside 600 mm cylindrical vessel for the proper air distribution within the bulk of paddy mass. A centrifugal blower of 0.5 hp was used to circulate the air through the solar assisted dryer. According to the availability and durability stands of the dryer and the collector was made with the MS (18 gauge) sheet.

3. EXPERIMENTAL PROCEDURE

The dryer was evaluated using 100 kilogram (100 kg) of freshly harvested paddy with initial moisture content varies from 24-17% (Brooker, et. al. [18]). Experiments were performed with heated and ambient air with various combinations of initial moisture content of paddy, temperature, relative humidity of the drying air and air flow rate. Besides the heated air drying, experiment was also performed under the open sun for the comparison of two drying modes. Experiment was replicated three times. For all experiments, loading was carried out at 8:00 am daily and continue till the desired moisture content achieved 14% (Brooker, et. al. [18]) to determine the drying time. Dryer performance was evaluated by using the drying rate and collector efficiency. Drying rate was measured by using the equation (Itodo, et. al. [19]):

$$\frac{dM}{dt} = \left[\frac{M_i - M_f}{t}\right] \times 100\% \quad (11)$$

Collector efficiency was measured by using the Euation (12) (Itodo, et. al. [19]).

$$\eta = \frac{m_a C_P (T_2 - T_1)}{I \times A_C} \quad (12)$$

Temperature at different locations (i) Collector inlet (ii) Collector out let (iii) Drying chamber inlet (iv) Drying chamber out let was measured by using j-type thermocouples connected with data logger (Agilent 34970A). Ambient air temperature was also measured by using k-type thermocouple. Solar irradiance was measured by means of pyranometer which was placed in the plan of the solar air heater and connected with data logger. Air velocity was measured by using hot wire anemometer. All the observations were measured at an interval of 10 second.

4. RESULTS AND DISCUSSION

Fig. 6 shows the typical day results of the diurnal variation of ambient temperature, temperature of the dryer, temperature of the collector, relative humidity and solar radiations intensity. Results shows that the average ambient temperature ranged from 24-32^{0}C, collector outlet temperature ranged from 30-54^{0}C, ambient relative humidity ranged from 70-29% and intensity of the solar radiation ranged from 600-924W/m^2. Fig. 7 shows the collector efficiency of the solar assisted paddy dryer during the test day was varies from 24-31%, which indicating the good performance of the collector. The efficiency values obtained by Ting and Shove [20] for a flat plate collector are similar to those obtained in this work, with a similar influence of the solar radiation and the air mass flow. Fig. 8 shows the variation in moisture content with respect to drying time of paddy for the two drying modes. Results show that for achieving the final desired moisture content up to 14% (according to the run-1 conditions) dryer took 10 hr. and the mean drying rate is 0.87kg/hr per 100kg of paddy. Comparatively, open sun drying method took 19hr for achieving mean moisture content of 13.89% under average ambient air temperature in the range of 21-33.5^{0}C, and giving a mean drying rate of 0.46kg/hr per 100kg of paddy. This can be explained by the fact in the case of dryer, heated air is continuously dried the grains, even though if the grains are not dry in one day it provide provision that we can use a storage unit for heat that can be stored in the storage unit to effect drying in the night time while in case of open sun drying the re-wetting phenomena of the grains occurred during the night time if the drying is not completed in one

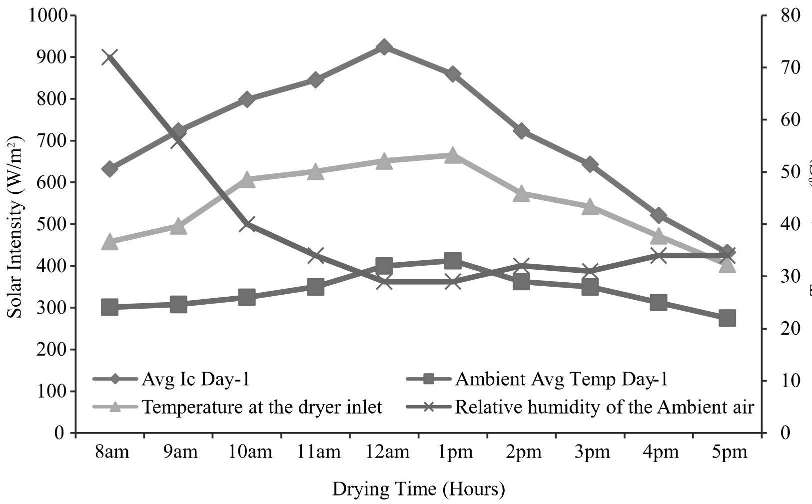

FIG. 6. A TYPICAL DAY RESULTS OF DIURNAL VARIATION OF AMBIENT TEMPERATURE, RELATIVE HUMIDITY, SOLAR RADIATION INTENSITY AND DRYER INLET TEMPERATURE

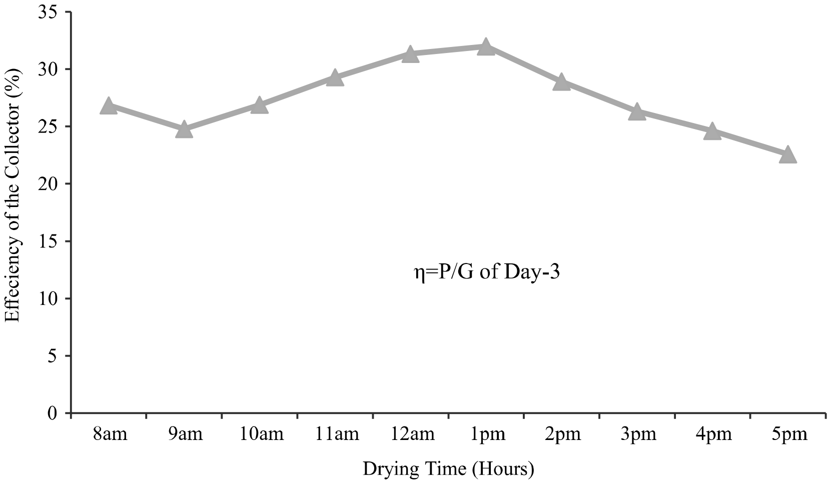

FIG. 7. EFFICIENCY OF THE COLLECTOR FOR THREE TYPICAL DAYS

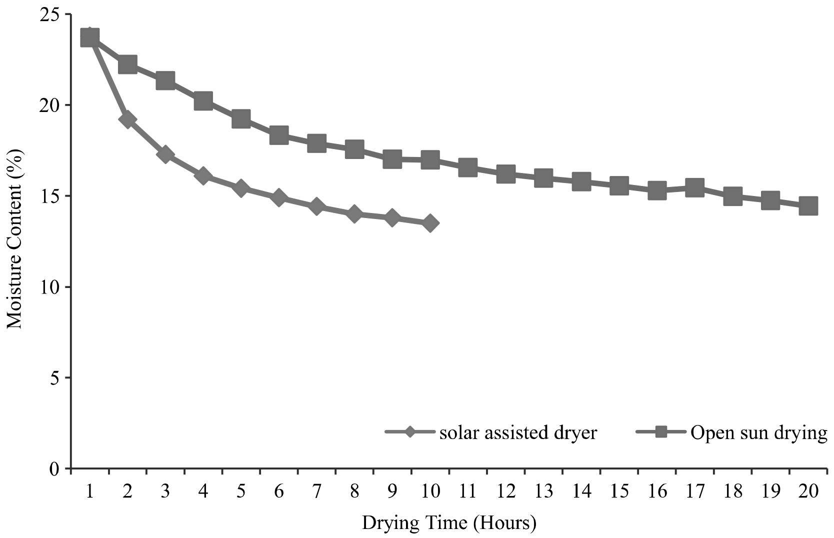

FIG. 8. VARIATION IN MOISTURE CONTENT WITH DRYING TIME

day. Thus, solar assisted dryers approximately 50% cut drying times in comparison to sun drying. Falade, et. al. [21] has been reported the same results with an indirect passive dryer that was used for the deep bed drying of corn. Ezekoye and Enebe [22] indicated that by using the passive grains solar dryers, we can avoid the re-wetting of the grains because in case of dryer there is no need to carrying the crops inside during the night. This drying rate compares favorably to values reported in the literature.

5. ECONOMIC ANALYSIS

The economic analysis is the most important for farmers as well as the end users to find out the cost of drying. The methodology used to anticipate the fixed and variable cost was that presented by Kenneth et. al. [23]. The purchase price of the new solar assisted paddy dryer was estimated to be Rs. 50,000/- and the useful life of solar assisted paddy dryer is assumed to be 10 years. The annual fixed cost of rice paddy dryer was calculated to be Rs. 9575/- Annual drying capacity of paddy dryer is assumed to be 18 tons/year. Therefore, Rs.531.9/ton is the fixed cost the dryer. For paddy drying operation, labor cost is Rs.500/ton of paddy drying. Energy cost for drying of paddy is about Rs.0.2/kg. Hence, the total variable cost is predicted to be Rs.700/ton. This makes the total cost (fixed + variable cost) about Rs. 1112/ton. Therefore, the cost of drying per kilogram of paddy was Rs. 1.2

5.1 Drying Cost Worksheet

5.1.1 Fixed or Capital Cost

Depreciation = Rate x (Purchase Price – Salvage Value) 4500Rs

Interest on investment

$$= (\text{Current Rate} - \text{Infliation Rate}) \times \frac{\text{Purchase Price} + \text{Salvage Value}}{2} \quad 2200\text{Rs}$$

$$\text{Insurance} = 0.5\% \times \frac{(\text{Purchase Price} - \text{Salvage Value})}{2} \quad 1375\text{Rs}$$

Repairs = 3% x Purchase Price 1500Rs

5.1.2 Total Fixed Cost

$$\text{Total Fixed Cost Per Unit} = \frac{\text{Total Fixed Cost}}{\text{Annual Unit Dried}} \quad 0.638\text{Rs/kg}$$

5.1.3 Variable Cost

$$\text{Energy Cost Per Unit Dried} = \frac{\text{Total Energy Cost}}{\text{Units Dried}} \quad 0.2\text{Rs/kg}$$

$$\text{Per Unit Labor Cost} = \frac{\text{Hourly Labor Rate}}{\text{Hourly Drying Rate}} \quad 0.5\text{Rs/kg}$$

5.1.4 Total Drying Cost

=Fixed and Capital Cost+Energy Cost+Labor Cost 1.2Rs/kg = 0.03$/bu

The solar assisted paddy dryer is economical and environment friendly, compared to open sun drying method. Literature and survey report showed that 2-3 Rs./kg (0.5-0.75$/bu) is the cost of drying by using open sun drying method. Thus, by using solar assisted paddy dryer we can dry good quality paddy at low cost as compared with the open sun drying method.

6. CONCLUSIONS

A simple and economic solar assisted paddy dryer was designed and developed by using locally available material. The dryer was able to dry the paddy from initial moisture content 24% to moisture content of 14%. Results showed that the solar assisted paddy dryer has the considerable advantages over the open sun drying method in terms of faster drying rate and handling convince. Mean drying rate for the solar assisted paddy dryer was 0.83kg/hr, comparatively drying rate of the open sun drying rate was 0.324kg/hr respectively. By using solar assisted paddy dryer 50% saving in time was achieved as against the traditional open sun drying method. Furthermore economic analysis was also performed for the developed dryer and it was found by using solar assisted paddy dryer we can dry good quality paddy at low cost because cost of open sun drying in Pakistan varied from 2-3 Rs/kg.

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