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Design and performance evaluation of a multi functional passive solar dryer for paddy

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ABSTRACT

A multi functional passive solar dryer was designed and constructed by adding the solar water heater and the solar air heater. The dryer consists of solar collector, reflector, riser tube cum heat storage unit and drying chamber. The storage tank of the conventional solar water collector is modified as riser tubes and header, which is fitted in the bottom of the solar air heater as an absorber in the normal air heater. The drying chamber was located under the collector. The system is worked as a solar dryer only, by preventing the flow of water, during the sun-shine (without water heating) in a sunny day, the drying system efficiency was found 21.44% whereas, it found 35.83% when adding heat energy from the water heater with a low intensity of solar radiation during the sun-shine and the drying process by the multi functional solar dryer only. The solar dryer was tested for drying of paddy. The capacity of the dryer was to dry about 5-10 kg of paddy in 8 h in sunny day from an initial moisture content of 76.4% to the final moisture content of 9.4% (wb). For a drying time about 8 h, the moisture content of the paddy using the solar dryer was 0.16 kg/kg (db) and for the dried paddies by the sun drying was 0.44 kg/kg (db). Thermal efficiency of the solar drier was estimated to be about 35.83% with drying rate of about 6.12 kg/kg of dry matter h. In all cases the use of this drier led to better results in colour, aroma, texture and drying time of the solar dried products in comparison to traditional open-sun drying.

Key words : *Solar dryer, Heat storage material, Paddy drying, Storage energy, Drying efficiency, Drying rate*

Introduction

Drying is an essential process in the preservation of agricultural products. Food products, especially fruits and vegetables require hot air in the temperature range of 45–60°C for safe drying. Sun drying is the most commonly used method in India. In sun drying, the agricultural products are spread in a thin layer on the ground then exposed directly to the sun and other ambient conditions. Sun drying even though cheap method of drying but often results to inferior quality of products due to its weather conditions with the attack of dust, dirt's, rains, insects, pests, and microorganisms (Esper and Muhlbauer 1998). Solar dryer has been developed for drying various agricultural products in tropical and subtropical countries to minimize the disadvantages of sun drying (Müller *et al.*, 1991; Ekechukwu and Norton 1999).

Drying under controlled conditions of temperature and humidity helps the agricultural food products to dry reasonably rapidly to safe moisture content and to ensure a superior quality of the product (Sharma *et al.*, 1994). Basically, there are four types

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2. Principal

of solar dryers; (Ong 1999) direct solar dryers, indirect solar dryers, mixed-mode dryers, and hybrid solar dryers.

Based on the heating modes the solar drying systems are further classified into two major groups, namely active solar energy drying systems (most of which are often termed hybrid or forced circulation solar dryers) and passive solar energy drying systems (conventionally termed natural circulation solar drying systems). (Fudholi *et al.*, 2010).

Several studies have been reported on natural convection system for solar drying of agricultural products. (Gbaha *et al.*, 2007) designed and tested experimentally a direct type natural convection solar dryer for drying agricultural products. They found that the thermal performance is higher compared to open sun drying for the selected food materials. However, there exist some problems associated with solar drying i.e. reliability of solar radiation during bad weather condition. In a multi functional passive solar dryer, drying is continued during low intensity of solar radiation by additional heat energy or storage heat energy. Therefore, drying is continued and the product is saved from possible deterioration by microbial infestation (Arinze *et al.*, 1999; Bala and Woods 1994).

The main disadvantages of the direct solar dryers are (i) small capacity of the crop, hence cannot be used for commercial purpose, (ii) required drying time is large, (iii) due to evaporation of moisture and its condensation on the glass cover, the transmittivity of the glass cover is reduced, (iv) overheating of the crop may take place due to direct exposure to sunlight, and hence, the quality of the product may deteriorate, and (v) the efficiency is low because part of the solar energy input is used to induce airflow, and the product itself acts as an absorber(Tiwari *et al.*, 1997; Tiwari *et al.*, 1994).

In order to solve the above problems, various design of indirect solar dryer has been developed and tested. Exell has been developed a low-cost mixed-mode natural convection solar dryer (chimney-type solar dryer) for drying paddy. This dryer is discontinuous-type solar dryer, based on natural convection. Paddy could be dried safely in 2–3 days. Igbeka(1986) have presented a method of evaluation and comparing three different solar dryers, solar concentrator/dryer (Dryer 1), flat-plate collector solar dryer with in-bin storage (Dryer 2) and drying chamber with chimney (Dryer 3). Paddy was used as reference product. He found that the drying efficiency were about 18%, 30% and 58% for Dryer 1, Dryer 3 and Dryer 3, respectively. The air temperature difference recorded from Dryer 1 was the highest, but Dryers 2 and 3 were found to be more effective than Dryer 1.

Some hybrid dryers were developed to control the drying air conditions throughout the drying time independent of sun-shine especially at night when it is not possible to use the solar energy using alternative sawdust burner (Bassey 1985) or by using a biomass stove (Prasad and Vijay 2005). It is reported that significant improvement was registered after the heater is added to the solar dryer during periods of low sun-shine (Bennamoun and Belhamri 2003; Janjai and Praditwong 1992).

Rice is rich in genetic diversity, with thousands of varieties grown throughout the world. Rice cultivation is the principal activity and source of income for about 100 million households in Asia and Africa. Rice has potential in a wide range of food categories. Besides having nutritional and medicinal benefits, the by-products of rice are equally important and beneficial. By-products from growing rice create many valuable and worthwhile products. The unedible parts that are discarded through the milling process and the edible part could be transformed into some of the following suggested products. Rice can be used to treat skin conditions. The rice is boiled, drained and allowed to cool and mashed. The rice is made into a paste or moulded into balls and these can be applied to boils, sores, swellings and skin blemishes. Other herbs are sometimes added to the rice balls to increase their medicinal effects. Sticky glutinous rice is often taken to treat stomach upsets, heart-burn and indigestion. Extracts from brown rice have been used to treat breast and stomach cancer and warts. They have also been used to treat indigestion, nausea and diarrhea. Therefore, there is a scope of drying of paddy in the tropical and subtropical countries (Bala and Woods 1994).

Several studies have been reported on simulation of forced convection solar drying of agricultural products for different configurations of forced convection solar dryers (Ivanova and Andonov 1994; Hodali and Bougard 2001). A forced convection solar drier was constructed and tested to dry paddy at a farmer's house in Thailand as reported by Soponronnarit (1995). Drying tests indicated that one tonne of paddy could be dried from a moisture content about 17% to 14% in 1–4 days depending on weather conditions. As well, Soponronnarit (1995) reported a forced convection hybrid solar dryer to dry paddy in Thailand.

In all above modified designs main aim was to increase efficiency by the various design of solar air heaters in drying of products. Since the solar air heater is the most important component of the indirect solar drying system, improvement of the solar air heater would led to better performance of the drying system. Therefore; more studies to investigate and improve the thermal performance of double pass flat, v-corrugated and finned plate solar air heaters is still of considerable interest. Choosing the right drying system is thus important in the process of drying agricultural products. Therefore, an improved and simplified model should be developed in this part of work.

The objective of the this study was to design and test the multi functional, underflow solar air heater with a tray type dryer for producing efficient, uniform, and hygienic drying of grains resulting in products of superior quality. According to the heat requirement multi functional dryer can be performed by two modes. In the first mode it can be act as a conventional dryer by prevent the flow of water for less heat requirement. Through the second mode high heat energy can be achieved by obtaining the heat from the riser tubes which is fitted in the bottom of air heater. During the bad weather condition the stored solar energy in riser tubes is used to reduced the drying cost, improved the quality of dried products, and to prevent the microbial growth during the drying.

Materials and Methods

Description of the solar dryer

A multi functional passive solar dryer was designed, constructed and tested in the month of may 2013. The solar dryer consisted with several parts: solar water collector, solar air collector, storage tank with riser tubes and drying chamber. A schematic view of the solar dryer is shown in Fig. 1. The components and specifications of the multi functional passive solar dryer are given in Table 1

Solar water heater

Solar water heaters are characterized by its thermal performance and it largely depends on the transmission, absorption and conduction of solar energy and thermal conductivity of the working fluid. The details of the natural circulation solar water heater and the cross sectional view, having overall dimensions of 2035×1035×100 mm as shown in Fig. 2 and 3 respectively. The photographic view of a solar water heater is shown in Fig. 4.

The experimental set-up was designed and constructed in order to obtain data for the investigation. This flat plate collector consists of one cover glass with an absorber plate area of 2m^2. The connecting pipes connect water heater and air heater. The ab-

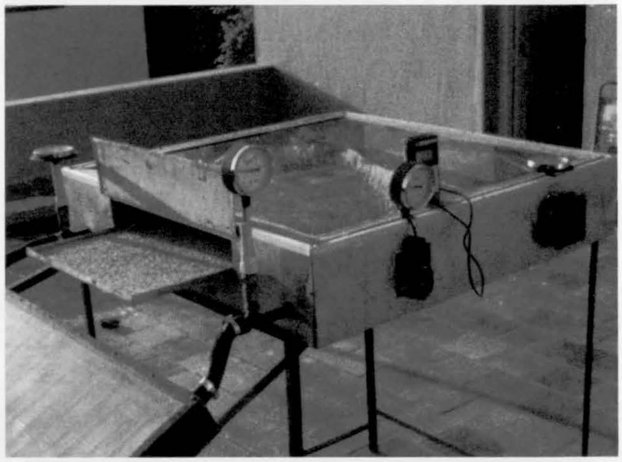

Fig. 1. Photographic view of solar dryer.

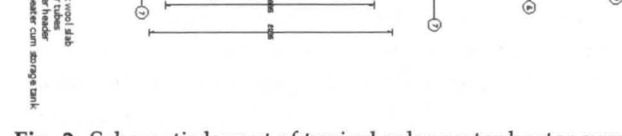

Fig. 2. Schematic layout of typical solar water heater cum air heater with storage tank

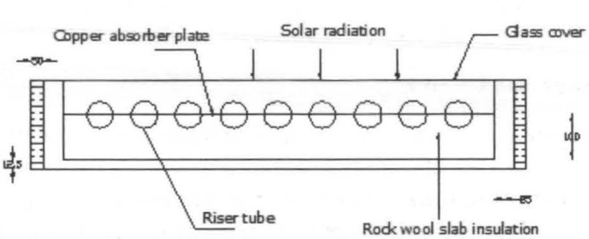

Fig. 3. Cross sectional view of the solar water heater

Fig. 4. Photographic view of a multifunctional solar drying system.

sorber plate is formed, from a corrugated sheet to accommodate the water pipes and headers in the grooves to maintain good heat transfer with the pipes. The effect of annular space between the riser tube and absorber plate of solar collector has been analyzed experimentally and theoretically by many researchers (Ghamari and Worth1992).

A good contact between the riser tube and absorber plate is found to increase the thermal performance and has been analyzed experimentally by Whiller and Saluja (1965). In this set-up, copper riser tubes are used with a length of 1980 mm and a diameter of 12.5 mm. The pipes are placed close together and parallel to each other with a space of 100 mm in between and welded at both ends to the header.

The top cover glass of 4 mm thick was mounted on the solar water heater with the effective glazing area of 2.08 sq.m. The absorbing plate and the absorbing surface of the pipes are absorbed by the solar radiation and then it is transmitted to the water in the pipes. Under the mode of natural convection, the water rises through the pipes by the thermodynamic force and enters the storage tank (riser tubes) in the air heater. The design details of solar water heating system are illustrated in Table 1.

Table 1. Component and specifications of the multi functional passive solar dryer

Component	Specifications
1. Solar water heater	
Gross collector area	2035 mm × 1035 mm
Aperture area	2 m × 2m
Working fluid	Water
Absorbing material	Copper
Rear plate	Aluminium
Collector tilt angle	30°
Number of glass cover	One
Cover plate material	Toughened glass
Plate thickness	4 cm
Insulation material	Rock wool
Insulation thickness	50 mm
Outer diameter of the tube	12.5 mm
Inner diameter of the tube	12 mm
Tube center to center distance	100 mm
Plate to cover spacing	10 mm
2. Solar air heater	
Gross collector area	1.07 m × 1.07m
Aperture area	1 m × 1m
Working fluid	Air
Absorbing material	Aluminum
Number of absorber plates	Two
Rear plate	Galvanized Iron
Collector tilt angle	0
Number of glass cover	One
Cover plate material	Toughened glass
Plate thickness	5 mm
Number of riser tubes	17
Outer diameter of the tube	25 mm
Inner diameter of the tube	24.5 mm
Tube center to center distance	41mm
Insulation material	Rock wool
Insulation thickness	50 mm
Mode of air flow	Under flow
Air inlet area	10 cm ×10 cm
Air outlet area	10 cm ×10 cm
3. Drying Chamber	
Gross dimensions	1 m × 1m
No. of trays	1
Size of tray	0.5 m x 0.5 m
Material for tray	Aluminium
Insulation material	Rock wool
No. of axial fans	1

Solar Air Heater

The solar air heater consists of absorber plate, transparent cover, insulation material, frame, air passage and storage tank with headers and risers. A schematic diagram with different measuring points and design details of solar air heater are shown in fig 5 and table 1 respectively. The outer dimension of the collector is 1070 × 1070 mm. The air heater was mounted horizontally above the level of water heater . The latitude and longitude of the locations are 10.81°(N) & 78.69°(E). The underflow type solar air heater is 1m long and 1m wide, giving a gross collector area of $1m^2$ with a single glass cover. The absorber plate of 1 m wide was fitted in the frame using rivets. The absorber plate and isolation materials are made up of aluminium with the thickness of 2 mm and rock wool slab respectively. The riser tube was fitted below the absorber plate of the air heater. The dimensions of riser tubes are 700 mm in length 25mm in diameter and the distance between the riser tube is 41 mm. The total number of riser tubes are 17 which is shown in Fig. 5. Air is driven through the empty place between the absorber plate and riser tubes. Two square openings of 100 mm side are used as an inlet and outlet air passage. A centrifugal fan is used to make the air flow through the collector. The solar water heater and air heater are connected with flexible hose tube of 14 mm diameter. The heaters are placed at the direction of north and south without any shadow and 7.5 cm above the ground level. The radiations are measured by solarimeter and it is placed parallel to the collector surface.

The drying chamber

The length and width of the solar dryer were same as the collector 1070 × 1070 mm. It was located directly under the solar collector and 200 mm under the absorber plate. There was single tray for drying. The drying air is passed across the crops spread in thin layers on a single horizontally stacked tray. The tray was made of Aluminium frame and with dimensions of 500 x 500 mm. The drying air was heated up in the multi functional solar collector and passed to the drying chamber through a sectioned metal part at the end of the solar drying unit. Through this sectional part, the direction of the air could be changed inside the solar drying unit. The drying air came from the solar collector through sectioned part and turning towards the drying unit and flew over the drying tray before exhausting from the outlet. The air passage of the solar air heater to increase the air fill factor. In addition to that, a fan was used to suck the atmospheric air to the solar air heater then the hot air from the air heater was provided in the dryer for uniform circulation through the dryer.

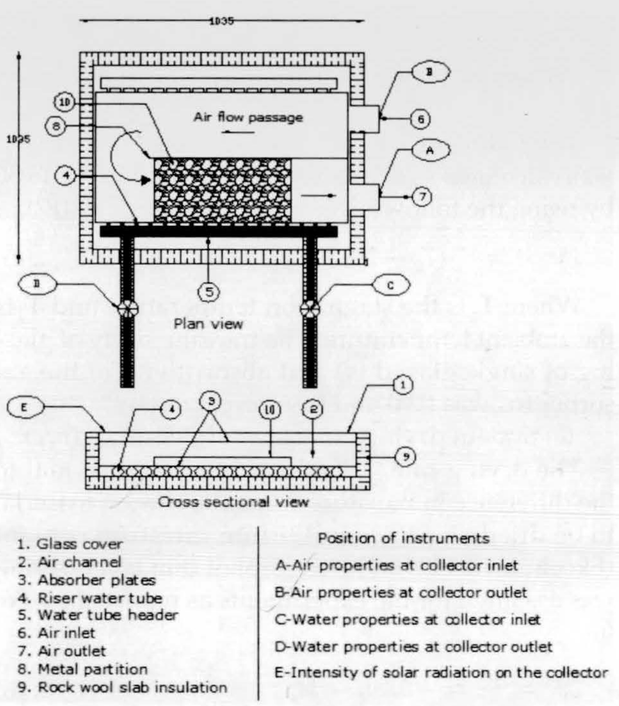

Fig. 5. Schematic layout with different measuring point of typical solar air heater

To increase the efficiency of the solar drying unit, multi functional solar dryer is designed by adding the solar water heater and the solar air heater. The storage tank of the conventional solar water collector is modified as riser tubes and header. It is fitted in the bottom of the solar air heater as an absorber in the normal air heater. Heat energy absorbed by the air in the air heater is circulated over and transferred to the drying product through the convection mode of heat transfer. The heat energy available in the hot water is being transferred to the bottom the tray through the conduction mode of heat transfer.

Experimental procedure

Several experimental runs for different drying conditions for solar and sun drying of paddy were carried out during the summer conditions period. Fresh and uniform size of paddy was purchased from supermarket. Before starting an experimental run, the whole apparatus was operated for at least 1 h to stabilize the air temperature and air velocity in the dryer. Paddy was placed them in single layer on the drying trays in the dryer with a weight of 1 kg. To compare the performance of the dryer with that of sun drying, control samples paddies were placed on trays in a single layer beside the dryer in the open sun. Drying was started after completion of the loading, usually at 08:30 h and discontinued up to reach the final moisture content of paddies.

The drying process can be performed according to the heat requirement by adding water heater with the conventional solar air dryer. In the convection mode of heat transfer weight loss of paddies were measured by the conventional solar air dryer for preventing the flow of water from the solar water heater. Through the conduction and convection mode of heat transfers the performance of the dryer were calculated by achieving the heat from the both solar water heater and from the conventional solar air dryer.

Weight loss of both the samples in the multi functional solar dryer and the control samples in the open sun were measured during the drying period in day time (08:30–16:30 h) at 5 min interval with an electronic balance. During the day time, the positions of the collector was oriented facing south and tilted to an angle of 45° with respect to the horizontal to maximize the solar radiation incident on the glass covers. A digital thermo Anemo meter of model Lutron AM-4201 (make air flow) with a range of 0.1-20 m/s was used to record the air velocity with the accuracy of 3%. Pre- calibrated thermocouples were used to record collector air, drying air temperatures, then inlet air and outlet air temperature and relative humidities at 10 min interval. Solar radiation intensity was measured with a calibrated Solarimeter, locally named Suryamapi (Make-Central Electronics Limited, SM 201 series), having a least count of $2mW/cm^2$ with an accuracy of 2.5%. The Solarimeter was fixed parallel to the collector surface. The moisture content of the Paddies were measured by drying the samples in a vacuum oven at 70°C until the weight of the dried sample became stable, according to AOAC (1984). After completion of drying, the dried paddy samples were collected, cooled in a shade to the ambient temperature and then sealed it in the plastic bags.

Performance and data analyses

The thermal efficiency of the solar water collector, solar air collector and system drying efficiency of the multi functional passive solar dryer were calculated using following formula:

(a) Solar water Collector efficiency:

In water heating system, the thermal energy is gained through the heat stored by the water in the tank.

$$Q_w = m_w \times C_{p,w} \times (T_{f,t} - T_{i,t}) \quad ..(1)$$

Where m_w is Water flow rate per unit collector area ($kg.m^{-1}m^{-2}$), c_{pw} is specific heat capacity of water (J/kg°k), $T_{i,t}$ is temperature of water at the inlet of solar water heater (°C) and $T_{f,t}$ is temperature of water at the outlet of solar water heater (°C) (Bo-Ren *et al.*, 2009).

The solar water heating system efficiency, ς_{ts}, is the ratio of stored energy in the storage tank (Q_w) to the total solar radiation (I_t) on the collector, which can be expressed as (Hussain 2006; Natthaphon *et al.* 2008).

$$\eta_{ts} = \frac{Q_w}{A_t \times I_t} \quad ..(2)$$

(b) Solar air Collector efficiency

In air heating system, the thermal energy is gained through the enthalpy increase of flow air between the outlet and inlet, expressed as (Jinwei *et al.*, 2011).

$$Q_U = m_a \times C_{pa} \times (T_{f,o} - T_{f,i}) \quad ..(3)$$

Where m_a is mass flow rate of air (kg/s), c_{pa} is specific heat of air (J/kg°k) , $T_{f,o}$ is temperature of air at the outlet of solar air heater (°C) and $T_{f,i}$ is temperature of air at the inlet of solar air heater(°C).

The instantaneous efficiency of the collector is the heat gained due to the air (Q_U) divided by incident solar radiation (I_t) as

$$\eta_{th} = \frac{Q_U}{A_t \times I_t} \quad ..(4)$$

Where 'A_t' is the total aperture area of the collector.

The values of overall heat loss coefficient (U_L) was calculated every half an hour from 8:30 to 16:30 by using the following equation (Gill *et al.*, 2012).

$$I(\tau\alpha) = U_L(T_S - T_a) \quad ..(5)$$

Where T_S is the stagnation temperature and T_a is the ambient temperature. The transmissivity of glazing of single glazed (τ) and absorptivity of the absorber (α) was 0.90 and 0.85 respectively.

(c) System drying efficiency of the solar dryer:

The drying rate, *DR*, should be proportional to the difference in moisture content between material to be dried and the equilibrium moisture content (Ekechukwu 1999). The concept of thin layer drying was assumed for the experiments as reported by Eq. (6).

$$DR = \frac{dM}{dt} = -k(M_t - M_e) \quad ..(6)$$

Where DR is the drying rate (kg of water / kg of dry matter.h), k is the drying constant, M_t intial mass of the sample at any time (g) and M_e equilibrium moisture content (%)

The effective total area surface of the dryer for collecting incident radiation is related to the overall system drying efficiency ($ç_d$), which is given by

$$\eta_d = \frac{M_W L_t}{I_t A_T t} \quad .. (7)$$

Where M_W is mass of evaporated water from the product (kg) in time t, L_t is latent heat of evaporation of water (kJ kg^{-1}), I_t is solar radiation on the aperture surface (Wm^{-2}), A_t is aperture area of the drier (m^2) and t is time of drying (s).

The quantity of moisture present in a material can be represented on wet basis and expressed as percentage. The moisture content, M_{wb}, which is given by

$$M_C = \frac{\lfloor M_i - M_f \rfloor}{(M_i)} \quad .. (8)$$

Where M_i is the initial moisture fraction on wet basis; M_f, is the final moisture fraction on wet basis.

(d) Rate of heat flow into the dryer

Heat flow rate into the dryer is the sum of the convective heat q_c, conductive heat q_k, and radiative heat transfers q_r and is expresses (Butter and Goodrum 1998; R.E.A 1999) as

$$q = q_c + q_k + q_r \quad .. (9)$$

$$\frac{q}{A} = \frac{T_a - T_d}{1/h_a + \Delta x/k + 1/h_d} + \varepsilon\sigma(T_a^{\ 4} - T_d^{\ 4}) \quad .. (10)$$

where q/A is the heat transfer per unit area, h_a is the heat transfer coefficient for the ambient, h_d is the heat transfer coefficient for the dryer chamber, T_a is the ambient temperature, T_d is the drying chamber temperature, ó is the Stefan-Boltzman constant, $Ä_{5e}$ is the thickness of the glass cover, and å is the emissivity and k is the thermal conductivity.

Uncertainty analysis

Detailed uncertainty analysis of the various calculated parameters are estimated according to Holman (2007). In the present study, temperatures, relative humidity,solar radiation, energy consumption and velocity were measured with instruments as mentioned in the previous section. The uncertainties arising in calculating a result due to several independent variables is given by the following equation.

$$w_r = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots\cdots\cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad .. (11)$$

The total uncertainties for the calculated parameters such as moisture content, drying rate and drier thermal efficiency are about 3.3, 3.1 and 4.5% respectively.

Results and Discussion

Collector Performance

Heat Collection Only With Water Flow

The inlet and outlet passage of solar air collector is closed to determine the stagnation temperature of the solar air heaters with zero useful heat gain. Stagnation temperature of solar air heater and ambient temperature were recorded. The solarimeter was placed adjacent to the glazing cover of solar water heater, in the same plane i.e. inclined at 45°, facing due south. Solar irradiation on the aperture of the solar air heaters, ambient temperature and stagnation temperature in the solar air heaters were recorded every half an hour.

Fig.6. Shows the variation in ambient temperature, solar radiation intensity and stagnation temperature in the multipurpose solar air heaters for the entire period of the day. The maximum stagnation temperature is recorded for solar air heaters as 88°C. The corresponding solar radiation and ambient temperature for solar air heater are 768 W/m^2 and 37°C respectively. The overall heat loss coefficients of solar air heater based on aperture area has been calcu-

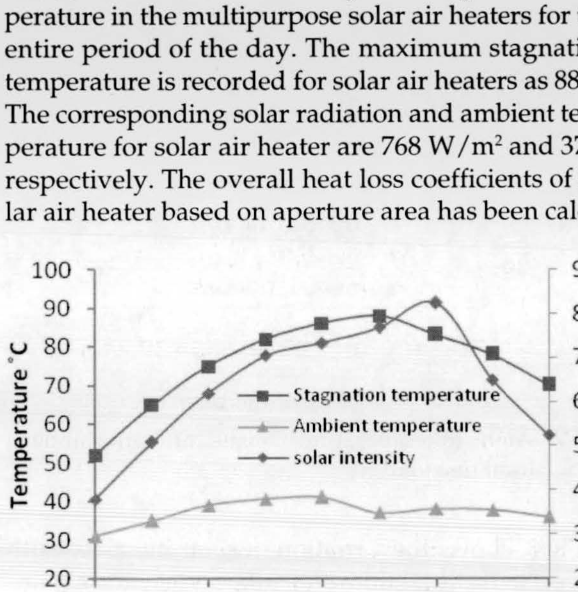

Fig. 6. Variation of ambient temperature, solar radiation intensity on aperture and Stagnation temperature during the day with only water heating.

lated from the experimental data depicted in Fig.6. using Eq. (5). It is observed that the value of overall heat loss coefficient for solar air heater is varied from 11.79 to 13.84 W/m^2-K during the day. The average overall heat loss coefficient of solar air heater is calculated as 12.83 W/m^2-K for the entire day.

Heat Collection without water Flow

The experimental set-up for the schematic is shown in fig.4. Initially, the test passage of SWH was closed and the air passage is opened for free air circulation for half an hour before the commencement of experiments. Air velocity from the outlet of SAH is measured with a digital thermo Anemo meter. Air temperature for the inlet and outlet of solar air heater, air flow rate, ambient temperature, humidity and solar radiation are measured at regular intervals. Inlet air temperature is measured from the ambient air. All parameters are recorded for the different mass flow rate of air from morning 08:30 am to 04:30 pm.

Fig. 7. shows the variation of the inlet temperature for the period of experimentation.(i.e., ambient temperature). It is observed that the ambient temperature variation during the period of experimentation was only 6°C.

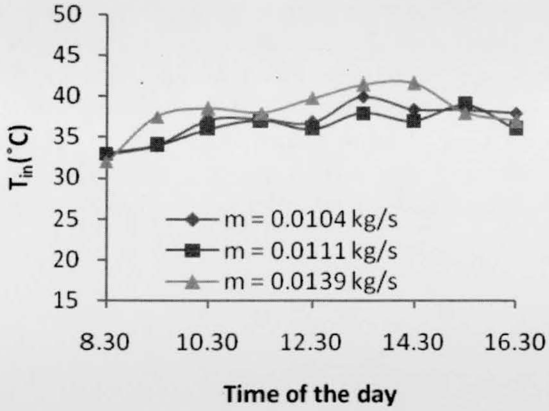

Fig. 7. Ambient temperatures versus different standard local time of days

Fig.8. shows the variation of solar intensity with respect to the local time of the days when the experiments have been done. The solar radiations are 380 W/m^2 at the morning and 876 W/m^2 at noon and then decreased until sun sets.

Fig. 9. shows the temperature difference "T = (T_{out} – T_{in}) for different mass flow rates of air in the SAH.

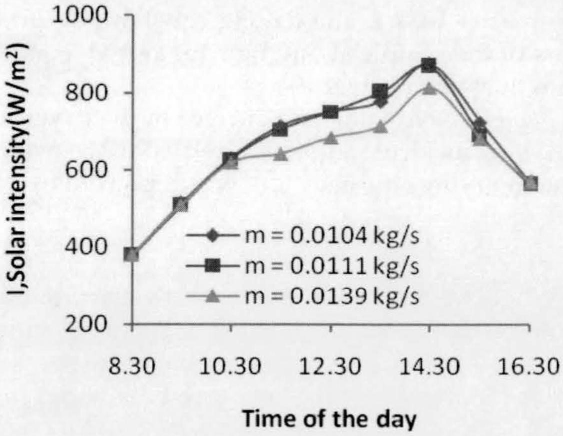

Fig. 8. Hourly variation of solar intensity versus different standard local time.

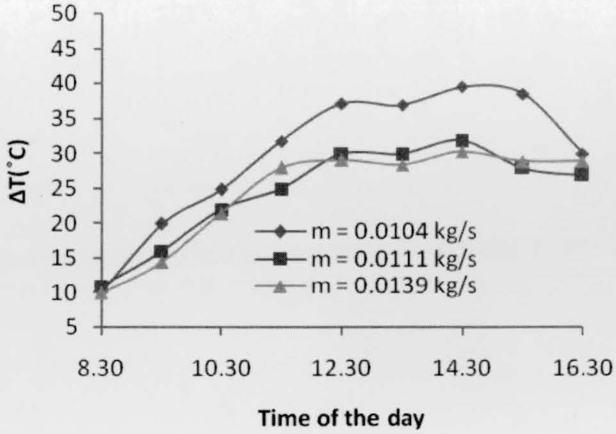

Fig. 9. Temperature difference versus standard local time of the day at different mass flow rates

The "T increases from the morning up to the noon and then decreased until the end of the experiment. It is observed that the "T increases due to increasing convective heat transfer coefficient with the mass flow rate thereby increasing the heat gain of the air. The solar energy available in the water at raiser tube of solar water heater also contributed for increasing the "T. The peak "T is obtained between 12:00 h and 12:30 h of the local time. The highest average and instantaneous peak "T are 29.92° C and 39.6 °C respectively for the SAH with mass flow rate of 0.0139 kg/s of air.

From the literature review, the maximum temperature difference recorded by Esen (2008) was about 23°C at solar radiation of 880 W/m^2 and mass flow rate of 0.02 kg/s. Sopian *et al* (2009) reported that the maximum temperature difference was 40°C for the solar intensity of 950 W/m^2 with air mass flow rate of 0.0995 kg/s by using double pass SAH. Ramadan *et al* (2007) investigated experimentally and theoretically a double-glass double pass solar air heater with a packed bed above the heater absorber plate. They reported that the maximum "T was 35°C at solar intensity 850 W/m^2 and mass flow rate of air was 0.0105 kg/s. El-Sebaii *et al* (2007) reported that the maximum value of "T was 48°C when iron scraps were used as packed bed above the absorber plate and 39°C for gravel used as a packed bed where the air mass flow rate was 0.0105 kg/s and solar intensity was 850 W/m^2.The highest average and instantaneous peak "T in the present work are comparatively high due to the high transfer rate with the above literature.

The instantaneous thermal efficiency at noon as a function of temperature parameter $(T_o-T_a)/I$ for the multifunctional solar collecting system at different flow rates are shown in Fig.10. It is absorbed from

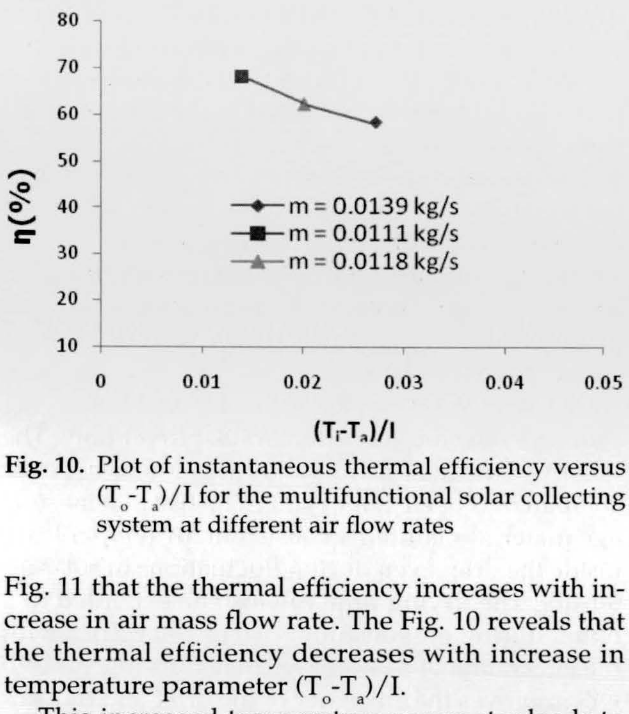

Fig. 10. Plot of instantaneous thermal efficiency versus $(T_o-T_a)/I$ for the multifunctional solar collecting system at different air flow rates

Fig. 11 that the thermal efficiency increases with increase in air mass flow rate. The Fig. 10 reveals that the thermal efficiency decreases with increase in temperature parameter $(T_o-T_a)/I$.

This increased temperature parameter leads to increase in absorber temperature and also increase the heat losses as a whole efficiency is decreased.

The thermal efficiency of the SAH is shown in Fig. 11. for different days and mass flow rate. It is observed that the thermal efficiency is increasing with the mass flow rate of air is increased. The maximum efficiency is obtained from the SAH is 85.09% for the mass flow rate of 0.0139 kg/s at noon time. This efficiency is increasing from the morning till

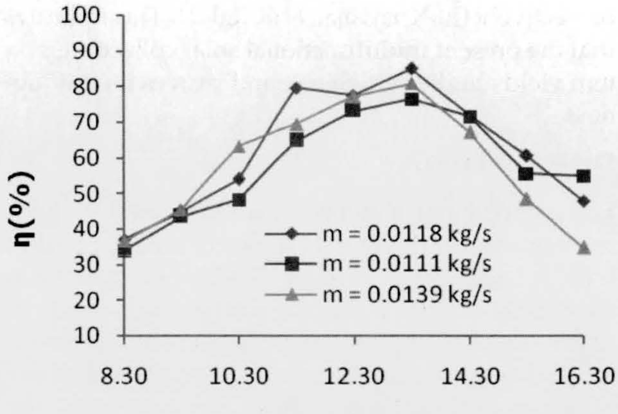

Fig. 11. Thermal Efficiency for solar air heater during the day for summer season at different air flow rates.

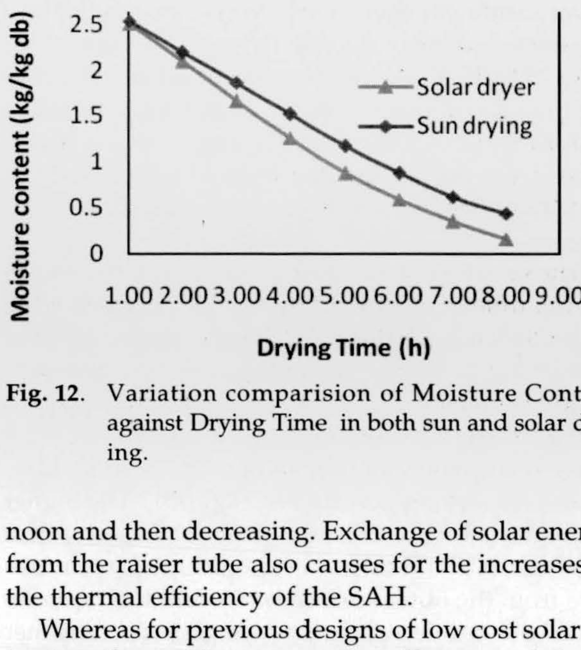

Fig. 12. Variation comparision of Moisture Content against Drying Time in both sun and solar drying.

noon and then decreasing. Exchange of solar energy from the raiser tube also causes for the increases in the thermal efficiency of the SAH.

Whereas for previous designs of low cost solar air heaters the maximum average efficiency of single glazed, double glazed and packed bed solar air heater was 30.29, 45.05 and 71.68%, respectively, for the flow rate of 0.020 m^3/s per m^2 aperture Area (Gill *et al.*, 2012). In dual function solar collector the efficiencies varied from 40.8% to 55.0% under the flow rate from 0.007 kg/sm^2 to 0.016 kg/s m^2 (Jinwei *et al.*, 2011). The maximum average daily efficiency for the 6, 4, and 2 fins SAH where 79.5%, 75.3% and 68.9% respectively with mass flow rate of 0.042 kg/s. Depending on the air mass flow rate, the average efficiency of the 6 fins collector was 5.6–10.5% and 15.4–19.1% higher compared to 4 and 2 fins SAHs respectively (El-Khawajah *et al.*, 2011). This indicates that the present multifunctional solar collectong system yields higher efficiency and proves its uniqueness.

Dryer performance

Fully loaded experiments were performed to check the capacity of the dryer. A single layer of paddy with initial moisture content 75–85% (wet basis) was used in this study. It was found that the capacity of dryer was 5–10 kg of this product. The system is worked as a solar dryer only, by preventing the flow of water, during the sun-shine, but with using the water as a additional heating media for the multi functional solar dryer during the time of low intensity of solar radiation.

The system was worked as a multi functional solar dryer with additional heating unit to heat up the water inside the riser tubes, during the time of low sunshine and it can rise the drying air temperature from 25 to 35 °C above the ambient air and the drying time was about 8 h. When heat energy stored in water from the solar water heater were used in a solar dryer during the day with a low intensity of solar radiation, the drying time was extended to 10 h.

The variation of moisture content (wet basis) with drying time is illustrated in Fig. 12. To achieve the high efficiency for this solar dryer comparing to the sun drying, a comparison of solar and sun drying of paddy is given in Fig. 12. For a drying time about 8 h, the moisture content of the paddy using the solar dryer was 0.16 kg/kg (db) and for the dried paddies by the sun drying was 0.44 kg/kg (db). The higher moisture reduction during the initial stages of drying was observed due to evaporation of free moisture from the outer surface layers and then gets reduced due to internal moisture migration from inner layers to the surface, which results in a process of uniform dehydration.

Temperature inside drier was higher than ambient temperature and corresponding relative humidity in the drier was lower than ambient relative humidity. As a result, drying rate of paddy in a multi functional passive solar drier was found to be higher than that of conventional solar dryer. Fig. 13 shows the variation of drying rate against drying time between CSD and MFSD. High drying rate of about (6.12 kg/kg of dry matter h) was observed during the initial stages of drying in MFSD and (5.61 kg/kg of dry matter h) in CSD. Drying rate gets decreased

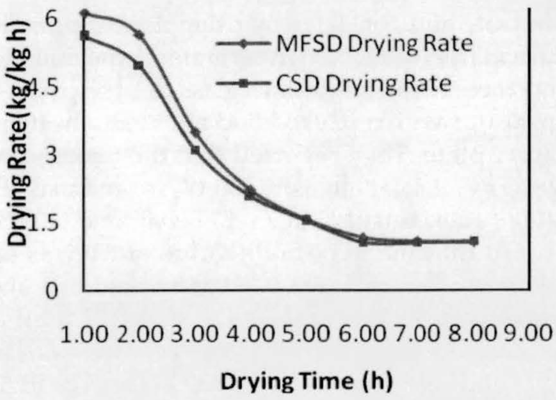

Fig. 13. Variation comparision of Drying Rate against Drying Time Between CSD and MFSD.

with increase in drying time. Drying occurs in the falling rate period with steep fall in moisture content in initial stages of drying and becomes very low in the later stages. The reason for sudden increase in drying rate in a multifunctional solar dryer is due to increase in collector out let temperature. During low sunshine hours, drier utilizes the heat energy stored in the riser tubes which is fitted in the bottom of absorber plate.

The drying system efficiency using different drying methods were calculated. The system is worked as a solar dryer only, by preventing the flow of water, during the sun-shine (without water heating) in a sunny day, the drying system efficiency was found 21.44% whereas, it found 35.83% when adding heat energy from the water heater with a low intensity of solar radiation during the sun-shine and the drying process by the multi functional solar dryer only. The quality of the final dried paddy was found to better compared to open sun drying. The use of heat storage material maintains consistent air temperature inside the drier even during fluctuations in solar intensity. The drying time can also be extended to 2 hours during off sunshine. Use of solar drier with the integration of heat storage materials (riser tubes) will improves the efficiency of the drier and reduces the dependency of conventional energy sources, which reduces indirect global warming.

Conclusion

The performance of an multi functional passive solar drier integrated with heat storage material was designed, fabricated and investigated for paddy drying. The drier with heat storage material enables to maintain consistent air temperature inside the drier. The inclusion of heat storage material also increases the drying time by about 4 h per day. The paddy was dried from initial moisture content 76.4% to the final moisture content about 9.4% (wet basis) in the drying tray. It could be concluded that, multi functional passive solar drier is more suitable for producing high quality dried paddy for small holders. Thermal efficiency of the solar drier was estimated to be about 35.83% with drying rate of about 6.12 kg/kg of dry matter h.

Abbreviations

MFSD - Multi Functional Solar Dryer
CSD - Conventional Solar Dryer
SAH - Solar Air Heater
SWH - Solar Water Heater
wb - wet basis
db - dry basis

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