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Development and performance evaluation of mixed-mode solar dryer with forced convection

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Abstract

Based on preliminary investigations under controlled condition of drying experiments, a mixed-mode solar dryer with forced convection using smooth and rough plate solar collector was constructed. This paper describes the development of dryer considerations followed by the results of experiments to compare the performance of the smooth and the roughed plate collector. The thermal performance of solar collector was found to be poorer because of low convective heat transfer from the absorber plate to air. Artificial rib roughness on the underside of the absorber plate has been found to considerably enhance the heat transfer coefficient. The absorber plate of the dryer attained a temperature of 69.2°C when it was studied under no-load conditions. The maximum air temperature in the dryer, under this condition, was 64.1°C. The dryer was loaded with 3 kg of grapes having an initial moisture content of 81.4%, and the final desired moisture content of 18.6% was achieved within 4 days while it was 8 days for open sun drying. This prototype dryer was designed and constructed to have a maximum collector area of 1.03 m^2. This solar dryer been be used in experimental drying tests under various loading conditions.

Keywords: Mixed mode, Forced convection dryer, Solar collector, Grapes

Background

Drying may be required for several reasons. First and most often, water is removed from the fresh crop to extend its useful life. The dried product is later rehydrated prior to use in order to produce a food closely resembling the fresh crops, for example, in the use of dried vegetables. Second a crop may require drying so that it can be further processed. For example, many grains are dried so that they can be ground into flour. Third, fresh crops are sometimes dried so that a new product distinctly different from its original form can be produced.

Fundamentals of the drying process

Drying involves the removal of moisture and in thermal drying this is achieved through the application of heat to the product. The heat increases the vapor pressure of the moisture in the product above that of the surrounding air. Pressure and thermal gradient cause the moisture, both liquid and vapor, to move to the surface of the product. Evaporation takes place and water vapor is transferred to the surrounding air. This air may become saturated, but the process of drying continues if this surrounding moist air is replaced by less-saturated air.

Traditional sun drying

The traditional method of drying known as 'sun drying' involves simply laying the product in the sun. Major disadvantage of this method is contamination of the products by dust, destruction by insects and microorganism, and pecking by birds. Furthermore, some percentage will usually be lost or damaged during handling; it is labor-intensive, nutrients loss occurs, such as vitamin A, and is time-consuming. Lastly, the method totally depends on good weather conditions. The major advantage in the energy requirements for this open sun drying process is that the solar and wind energy is readily available freely in nature; hence, the capital requirement is marginal, making it the viable method of drying agricultural produce even in commercial scale especially in developing country. The safer alternative to open sun drying is drying in a solar dryer. This is a more efficient method of

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drying which produces better quality products; but in this case, initial investments are required.

Solar dryers

A solar dryer is an enclosed unit to keep the food safe from damage from birds, insects, microorganism, pilferage, and unexpected rainfall. The produce is dried using solar thermal energy in a cleaner and healthier fashion. Basically, there are four types of solar dryers:

1. Direct solar dryers. In these dryers, the material to be dried is placed in a transparent enclosure of glass or transparent plastic. The sun heats the material to be dried, and heat also builds up within the enclosure due to the 'greenhouse effect.' The drier chamber is usually painted black to absorb the maximum amount of heat.
2. Indirect solar dryers. In these dryers, the sun does not act directly on the material to be dried thus making them useful in the preparation of those crops whose vitamin content can be destroyed by sunlight. The products are dried by hot air heated elsewhere by the sun.
3. Mixed-mode dryers. In these dryers, the combined action of the solar radiation incident on the material to be dried and the air preheated in solar collector provides the heat required for the drying operation.
4. Hybrid solar dryers. In these dryers, although the sun is used to dry products, other technologies are also used to cause air movement in the dryers. For example, fans powered by solar PV can be used in these types of dryers.

The drying process

The process of dehydration consists of removal of moisture from the produce by heat usually in the presence of a controlled flow of air (Figure 1). Initially, the produce to be dried is washed, peeled and prepared (if necessary), and placed on flat-bottomed trays that are placed into the dryer. The solar rays enter the cabinet through the cover material. Upon reaching the solar collector or the tray surface, they are converted into heat energy, raising the inside temperature. The heat energy is transferred to the produce to be dried. The heated produce gives out water vapor and dries up. Gradually the heated moist air goes up and leaves the drying chamber through the air outlet at the high end of the drier.

The efficiency of drying of the solar dryer is influenced by relative humidity in the air, the moisture content of the materials to be dried and their amount and thickness. The solar radiation intensity on the materials varies with seasons, time of the day, and length of exposure, ambient air temperature, and wind speed, which are important factors.

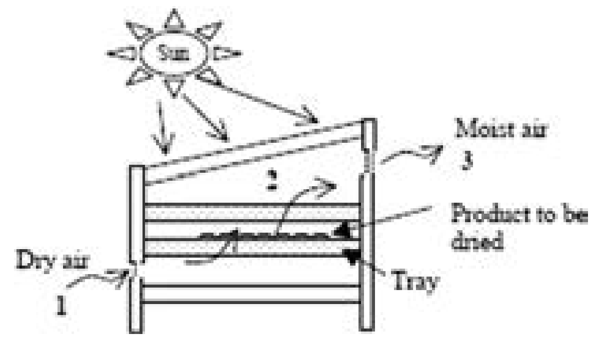

Figure 1 Drying process. (1) Cold dry air enters the drying chamber through the air inlet. (2) The solar rays enter the cabinet through the transparent cover material where they are converted into heat energy, thereby increasing the temperature inside. The heated food gives out water vapor and dries up. (3) Gradually, the heated moist air goes up and leaves the drying chamber through the air outlet at the high end of the dryer.

Literature review

The performance of the solar drying system is highly influenced by the performance of the collector. Therefore, several studies have been conducted in order to improve the performance of the solar dryer Belhamri [1] studied a simple efficient and inexpensive solar batch dryer for agriculture products. During periods of low sunshine a heater is used. Onion was chosen as the dried product because of its swift deterioration characteristic. The results showed that drying is affected by the surface of the collector, the air temperature, and the product characteristics. Muller et al. [2] designed and constructed a dryer with a collector area of 16.8 m^2 which is expected to dry 195.2 kg of fresh mango(100 kg of sliced mango) from 81.4% to 10% wet basis in 2 days under ambient conditions during harvesting period from April to June. Ismail et al. [3] designed and constructed a solar dryer based on preliminary investigations for mango slices drying under controlled conditions. The designed dryer with a collector area of 16.8 m^2 was expected to dry 195.2 kg of fresh mango (100 kg of sliced mango) from 81.4% moisture level to 10% on wet basis in 2 days under ambient conditions during harvesting period from April to June. Mujumdar et al. [4] studied briefly the emerging drying methods and selected recent developments applicable to postharvest processing. In their study, they included the heat pump-assisted drying with multimode and time-varying heat inputs, low and atmospheric pressure superheated steam drying, modified atmosphere drying, intermittent batch drying, osmotic pretreatments, microwave-vacuum drying etc. Bolaji et al. [5] developed a simple and inexpensive mixed-mode dryer from locally sourced materials. Bukola et al. [6] experimentally found out the performance evaluation of a mixed-mode solar dryer for food preservation. The temperature increase inside the drying cabinet was up to 74% for about 3 h immediately after 12noon. The drying rate and system efficiency were 0.62 kg/h and 57.5%, respectively. Sarsavadia [7] developed a solar-assisted forced convection dryer to study the effect of airflow rate (2.43, 5.25, 8.09 kg/min), air temperature (55°C, 65°C, 75°C), and fraction of air recycled (up to 90%) on the total energy requirement in drying of onion slices. Kumar et al. [8] used a natural convection mixed-mode solar dryer in performing the experiments on potato cylinders and slices of the same thickness of 0.01 m with respective length and diameter of 0.05 m to investigate the convective heat transfer coefficient. Sreekumar et al. [9] developed a new type of efficient solar dryer with an arrangement to absorb maximum solar radiation by the absorber plate. Abene et al. [10] studied experimentally to improve the efficiency-temperature rise couple of the flat plate solar collector by considering several types of obstacles disposed in rows in the dynamic air vein of the flat collector. Ramana Murthy [11] studied various aspects of solar driers applied to drying of food products at a small scale. Karim et al. [12] studied experimentally the effect of different operating variables on drying potential and drying time. Smitabhindu et al. [13] used a simulation and optimization model to minimize the drying cost per unit of dried banana.

Methods

Solar dryer design considerations

The following points were considered in the design of the natural convection solar dryer system:

1. The amount of moisture to be removed from the given quantity of grapes
2. Harvesting period during which drying is needed
3. The daily sunshine hours for the selection of the total drying time
4. The quantity of air needed for drying
5. Daily solar radiation to determine energy received by the dryer per day and
6. Wind speed for the calculation of air vent dimensions.

Construction of mixed-mode solar dryer

The materials used for the construction of mixed-mode solar dryer were inexpensive and easily obtainable in the local market. Figure 2 shows the essential features of the dryer consisting of the solar collector (air heater), drying cabinets, and drying trays.

Solar collector setup

The experimental setup is an open-flow loop that consists of a test duct with entrance and exit sections, a blower unit, control valve, orifice plate, various devices for measurement of temperature, and fluid head. The flow system consists of an entry section, a test section, exit section, a flow meter, and a centrifugal blower. The setup consists of two identical wooden ducts: one is rough absorber duct and other one is smooth absorber duct. Each duct size is 2,030 mm × 200 mm × 25 mm (dimensions of inner cross section) and is constructed from wooden panels with 32 mm thickness. The test section length is 1,500 mm (33.75 D). The entry and exit lengths were 177 mm (2.3√WH) and 353 mm (5√WH), respectively, as shown in Figure 2.

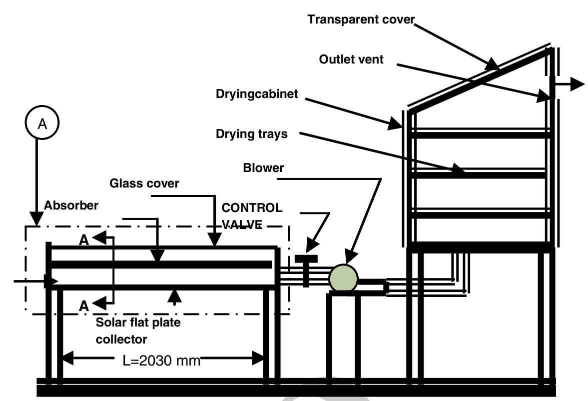

Figure 2 Schematic diagram of experimental setup.

The absorber plate material which is an aluminum sheet with 1,500 mm × 200 mm in size has a thickness of 3 mm which is painted black to increase the absorbing capacity of the plate. Another absorber plate is roughed with strips to provide obstacle to the path of air to obtain the maximum temperature. The solar collector assembly consisted of airflow channels enclosed by transparent cover (glazing).

The glazing is a single layer of 4-mm thick transparent glass sheet. It has a surface area of 200 mm by 1,500 mm. The outlet of duct is connected to the orifice meter with an inclined manometer to measure the mass flow rate of air. The outlet of the orifice meter is connected to the inlet of the blower. The outlet of blower is connected to the inlet of the cabinet dryer.

The drying cabinet

The drying cabinet, together with the structural frame of the dryer, was built from well-seasoned wood which could withstand termite and atmospheric attacks. An outlet vent was provided toward the upper end at the back of the cabinet to facilitate and control the convective flow of air through the dryer. The roof and the two opposite side walls of the cabinet are covered with transparent glass sheets of 4-mm thick, which provided

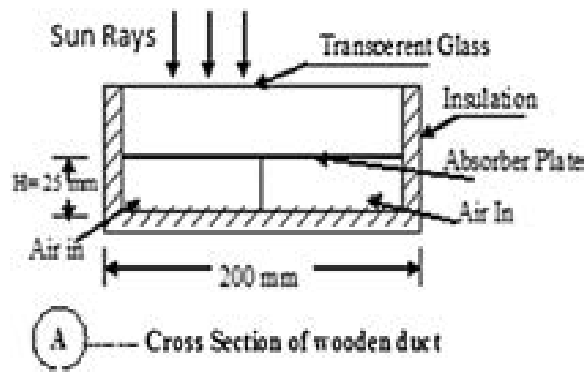

Figure 3 The drying cabinet.

additional heating due to greenhouse effect as shown in Figure 3.

Construction details

In the constructed solar drying cabinet, the materials used in the construction include 3/4 plywood, perspex glass, wooden bars, (for construction of the body) nails, wire mess, black paint, and hardwood (Figure 4). Perspex glass was used as glazing surface to cover the top and the sides. The top glazing measures 550 mm × 500 mm, and the each two side measures 640 × 520 mm. The plywood with 550 mm × 600 mm size was used in covering the base. The door of the dryer was made of the wood 520 mm × 500 mm, while the opposite side of the door was covered by 540 × 500 mm of the Perspex glass. The dryer skeleton was formed with wood raised 200 mm from the ground.

Drying trays

The drying trays are contained inside the drying chamber and are constructed from a double layer of fine chicken wire mesh with a fairly open structure to allow drying air to pass through the food items. The three trays were separated with a gap of 100 mm. The trays are arranged in a zigzag manner. The trays were made of wire mess and hardwood measuring 30 mm in depth and with dimension of 300 mm × 540 mm, as shown in Figure 5.

The orientation of solar collector

The flat plate solar collector is kept horizontally and oriented in such a way that it receives maximum solar radiation during the desired season of use. The best stationary orientation is south in the northern hemisphere and north in the southern hemisphere. Therefore, solar collector in this work is orientation facing south.

Experimental condition and assumption

We summarize the conditions during our experiment and our assumptions in Table 1.

Operation of the dryer

The dryer was a passive system in the sense that it had no moving parts. The sun rays entering through the collector glazing energizes it. The absorption of the rays is enhance by the inside surface of the collector that were painted black and the absorbed energy heats the air

Figure 4 Photograph of the experimental set.

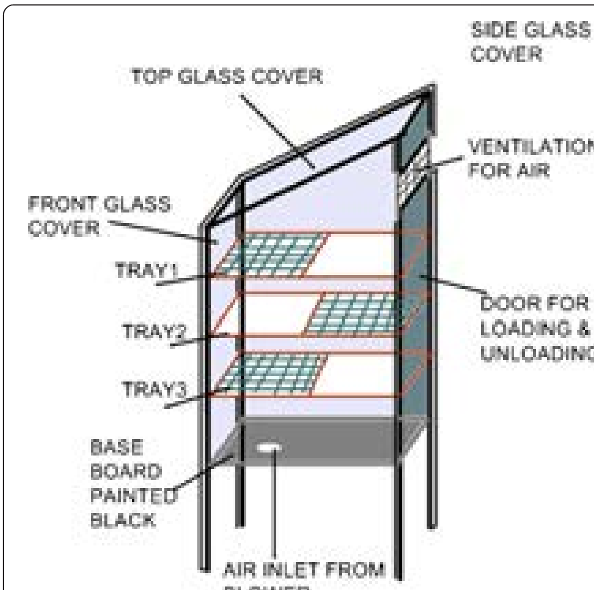

Figure 5 Three-dimensional view of the drying cabinet.

Table 1 Experimental condition and assumption

Item	Condition or assumption
Location	Bhopal
Crop	Grapes
Drying period	March to April 2009
Drying material quantity	3 kg
Loading rate (mp)	1 kg/tray
Initial moisture content, Mi	81.4% wb
Final moisture content, Mf	18.2% wb
Ambient air temperature, Tam	30°C (average for April)
Ambient relative humidity, RH_{am}	15% (average for April)
Max allowable temperature, T_{max}	65°C
Drying time (sunshine hours)	7 h (average for April)
Reynolds number, *Re*	3,000 to 12,000
Flat plate type	Smooth and rough
Test size	1500 mm length and 200 mm wide
Hydraulic diameter (D_x)	44.44 mm
Insulation, *I* (W/m^2)	700 to 900 W/m^2
Plate material	GI sheet

inside the collector. The greenhouse effect achieved within the collector drives the air current through the drying chamber. If the vents are open, the hot air rises and escapes through the upper vent in the drying chamber while cooler air at ambient temperature enters through the lower vent in the collector.

Therefore, an air current is maintained as cool air at a temperature T_a enters through the lower vents and hot air at a temperature Te leaves through the upper vent. When the dryer contained no items to be dried, the incoming air at a temperature T_a has a relative humidity H_a and the outgoing air at a temperature Te has a relative humidity H_e. Because $Te > T_a$ and the dryer contains no item, $H_a > H_e$. Thus, there is a tendency for the outgoing hot air to pick more moisture within the dryer as a result of the difference between $H_a > H_e$.

Dryer performance evaluation

The mixed-mode solar dryer shown in Figure 2 was tested during the months of March and April 2009 to evaluate its performance. During the testing period, the air temperatures at collector inlet, collector outlet, drying chamber, and ambient were measured by laboratory-type digital thermometer (accuracy ± 0.01°C) at regular interval of 1 h between the hours of 0900 and 1600 local time. The solar intensity was measured by means of a portable pyranometer placed horizontally and facing south. The dryer was loaded with grapes (1 kg in each tray) and the weight was measured at the start and at one-hour intervals thereafter. The initial weight and the final weight of grapes up to the stage when no further weight loss occurred were known. The dryer performance was evaluated and comparison was made with the result obtained with natural drying process and by forced convection with smooth and rough absorber plate.

Data reduction

Pressure drop calculation

Pressure drop was across the orifice plate measured by using the following relationship

$$\Delta P\text{o} = \Delta h \times 9.81 \times \rho\text{m} \times 1/5,$$

where ΔPo is the pressure difference, Δh is the difference of liquid head in manometer, and ρm is the density of mercury, i.e., 13.6×10^3

Mass flow measurement

Mass flow rate of air has been determined from the pressure drop measurement across the orifice plate by using the relation

$$m = \text{Cd} \times \text{Ao} \times \left[2\rho \;\; \Delta\text{Po}/\left(1{-}\beta^4\right)\right]^{0.5},$$

where m is the mass flow rate of air (kg/s), Cd is the coefficient of discharge of orifice 0.62, Ao is the area of orifice plate (m^2), ρ is the density of air 1.157 kg/m^3, and β is the ratio of diameter (Do/Dp) = 26.5/53 = 0.5.

Velocity measurement

The velocity of the air flow V was measured by using the relation

$$V = m/\rho\text{wh},$$

where m is the mass flow rate in kilograms per second, ρ is the density of air 1.157 kg/m^3, h is the height of duct in meters, and w is the width of duct in meters.

Reynolds number

Reynolds number is calculated as the ratio of viscous force to inertia force

$$Re = VD/\nu,$$

where V is the velocity of air (m/s), D is the hydraulic diameter (m), and ν is the kinematic viscosity, 16.70×10^{-6} m^2/s.

Heat gained by air

The heat transfer rate Q_a is given by

$$Q_a = m \;\; \text{Cp}(\text{To}{-}\text{Ti}),$$

where m is the mass flow rate of air (kg/s), Cp is the specific heat of air (kJ/kg), To is the outlet temperature (°C), and Ti is the inlet temperature (°C).

The heat transfer coefficient for the heated test section has been calculated from

$$h = \mathrm{Qa}/A_{\mathrm{p}}\left(t_{\mathrm{pav}} - T_{\mathrm{fav}}\right).$$

where Tpav is the avearge temperature of plate and Tfav is the average temperature of fluid.

Thermal efficiency

The thermal efficiency is calculated by using the relation

$$\eta = \mathrm{Qa}/I\mathrm{Ap},$$

where Qa is heat gain by air (W); Ap is the area of plate of collector (m^2); and I is the solar insolation (W/m^2).

Removal of moisture

The amount of moisture in kilogram to be removed from the product was calculated using the following equation:

$$\mathrm{Mw} \;=\; \mathrm{Mp(Mi–Mf)/(100–Mf)},$$

where Mp is the initial mass of product to be dried (kg), Mi is the mass of sample before drying, and Mf is the mass of sample after drying.

Moisture content

The moisture content (MC) is given as

$$\mathrm{(MC)\%} = \mathrm{(Mi–Mf)/td} \;\times\; 100\%,$$

where Mi is the mass of sample before drying, Mf is the mass of sample after drying, and td is the drying time.

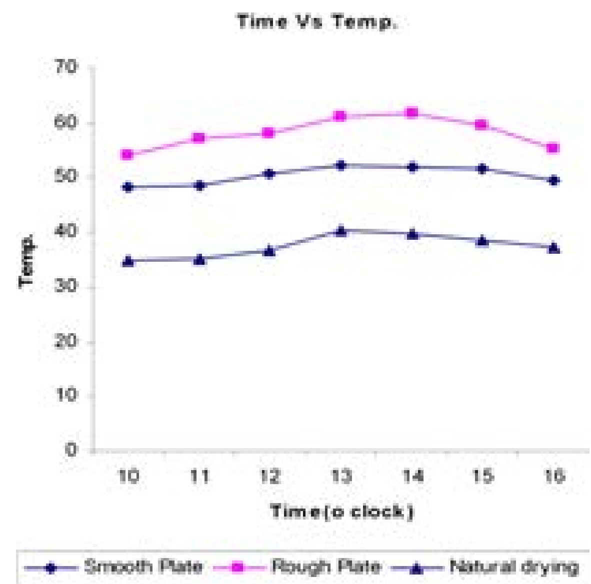

Figure 7 Variation of temperature with respect to time.

Results and discussion

The test is carried out without load to collect the data at various Reynolds number ranges from 3,000 to 15,000. The various parameters such as Nusselt number, Heat transfer coefficient, friction factor, and thermal efficiency are calculated at each set of Reynolds number.

Figure 6 shows the variation in thermal efficiency with Reynolds numbers of different values. As Reynolds number increases, the thermal efficiency also increases. The maximum efficiency is obtained at Reynolds number 12,000. Beyond Reynolds number 12,000, it is found that

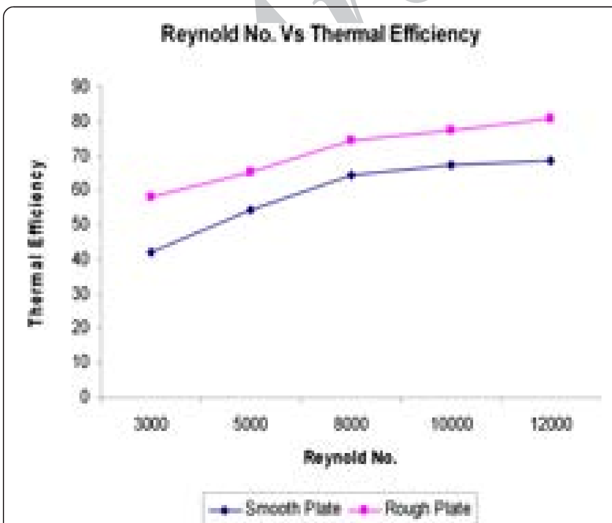

Figure 6 Variation of thermal efficiency versus Reynolds number.

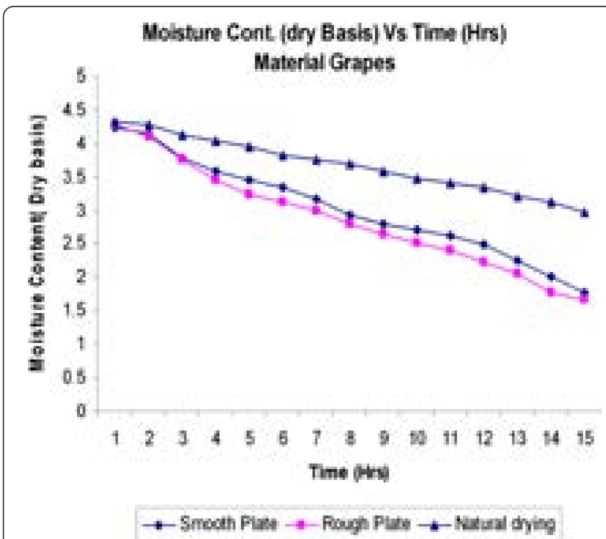

Figure 8 Variation of moisture content (dry basis) versus time.

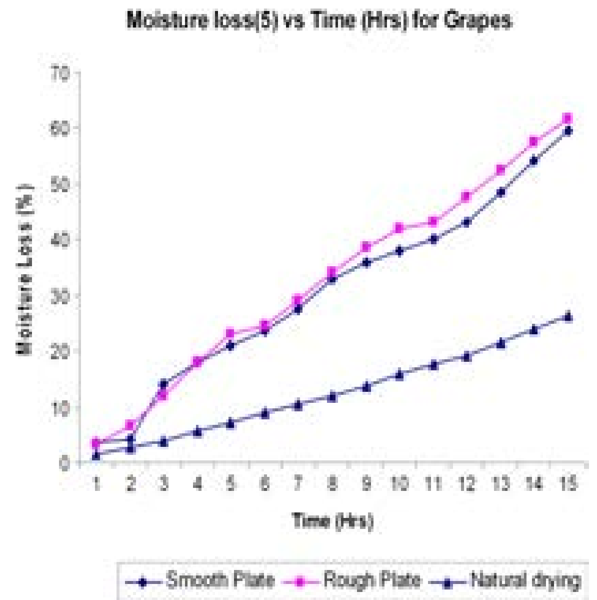

Figure 9 Variation of moisture loss (% basis) versus time (h).

the thermal efficiency decreases. Hence, the entire tests are carried out at fixed Reynolds number of 12,000.

Figure 7 shows a typical day results of the hourly variation of the temperatures in the solar collector and in the drying cabinet compared to the ambient temperature. The dryer is hottest about mid-day when the sun is usually overhead.

The plot shows temperatures versus the local time in hours for performance evaluation of grapes drying. The ambient temperature is quite low, varying from a minimum of 32°C to a maximum of 40°C. This is followed by the temperature of smooth plate which ranges from a minimum of 48°C to a maximum of 53°C. The temperature in the roughed plate is the highest, ranging from 54°C to 62°C. Thus, the hourly variation of the temperatures inside the cabinet and air heater is much higher than the ambient temperature during most hours of the daylight. The temperature increase inside the drying cabinet was up by 22°C for 72.0% of the time of exposure. This indicates a prospect for better performance than open-air sun drying.

Figure 8 shows the drying curve for grapes in the mixed-mode solar dryer. It was observed that the drying rate increased due to the increase in temperature. It was observed that the moisture removal rate is increased by using the roughed plate collector as compared to smooth plate and open sun drying. Moisture content (dry basis) of grapes reduces with time and is more in the roughed plate. Thus, it shows that the time period required for drying is greatly reduce by using roughed absorber plate.

Figure 9 shows the moisture loss percentage basis versus time period. The moisture loss for smooth plate and rough plate collectors is nearly almost the same with some small differences as compared to the natural (open sun) drying process. The moisture loss (% basis) is more in the roughed plate compared to the smooth plate. To remove the moisture (81.0%) from grapes by open sun drying, it takes around 7 to 8 days. By using mixed-mode solar dryer, this time is reduced to 3 to 4 days.

Conclusions

Based on the above results, the following conclusions can be drawn:

1. A simple and inexpensive mixed-mode solar dryer was designed and constructed using locally sourced materials.
2. The hourly variation of the temperatures inside the cabinet and air heater is much higher than the ambient temperature during the most hours of the day.
3. The temperature increase inside the drying cabinet was up to 22°C (64.5%) for most the hours in the noon time. The drying rate, collector efficiency, and percentage of moisture removed (dry basis) for drying grapes were 0.38 kg/h, 67.5%, and 85.4%, respectively.
4. The dryer exhibited sufficient ability to dry food items at a reasonable rapid time to a safe moisture level and simultaneously ensured a superior quality of the dried product
5. The drying of grapes in the open sun takes 7 to 8 days during clear sunny weather conditions. However, it only takes 4 to 5 days in the solar cabinet dryer under similar weather conditions. Also, the quality of dried grapes is remarkably better in cabinet dryer compared to open sun drying as the product is protected from dust and insects.
6. The drying rate of the dryer for grapes is 0.24 kg/day while that of open air is 0.1 g/day. This shows that the dryer performance is much better than open sun drying. The moisture to be removed from the grapes is 0.7 kg. The dryer efficiency is 31.0% per day.
7. The dryer is easy to build and required only semi-skilled laborer and limited facilities to fabricate. Thus, the dryer is suitable for use in urban as well as rural areas of the country.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Both authors, CBP and JLB, contributed equally and significantly in writing the paper. Both authors read and approved the final manuscript.

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CBP is an assistant professor in the Department of Mechanical Engineering in SISTec-R, Bhopal. JLB is an associate professor in the Department of Mechanical Engineering in MANIT, Bhopal.

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