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Research Article

Experimental studies on drying characteristics of green chilies in a solar dryer

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ABSTRACT

Green and clean technology is the demand of today's world. Solar dryer, for drying agriculture produce is one of the major applications of the solar energy. The flat plate air collector plays crucial role for drying the agricultural produce in solar dryer application. This research work, focuses on the design and development a solar collector for drying agriculture produces using waste aluminum cans of beverages. A solar air collector is designed and developed in the laboratory as per IS 1933, 2003 standard. A solar collector developed has been tested and an overall performance of the system is evaluated for three different mass flow rates (0.01 kg/s, 0.008 kg/s and 0.006 kg/s) for drying 15 kg of green chilies. The selective coating material made by mixing activated charcoal and black board paint is applied on the cylindrical curved surface of the tubes considering the critical radius of insulation. The inlet and outlet temperature of air has been recorded for different mass flow rate and the overall collector efficiency is calculated. Further, the moisture removal rate from green chilies is evaluated for every 30 minutes of time interval in a day. It is found that the efficiency is decrease with increase in mass flow rate. A maximum moisture removal rate of 88% is observed for a mass flow rate of 0.01 kg/s and the maximum efficiency of solar collector of 50.27%. is attained for a mass flow rate of 0.006 kg/s.

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INTRODUCTION

Solar energy is free and clean energy of source, and hence it is acknowledged as a most promising alternative energy source. Solar drying for agriculture products is an essential process in long time food preservation. Food drying is a process of removing moisture using a heat and mass transfer technique. It is a classical method for preservations of food products like fruits and vegetables. Generally, a traditional and oldest open sun drying method

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is used to preserve the agriculture foodstuffs like grains and vegetables in many developing countries. But such conditions can severe losses in quantity (extra weight) and quality of the dried products [1]. Some regularly used food products, especially foods and vegetables require a 45-60 °C temperature range for safe drying. For storing and preserving the perishable agricultural produce for prolonged period, it must be dried effectively up to 5 % to 8 % moisture content [2]. A controlled condition of humidity and temperature for drying agriculture products always helps to maintain superior quality of the products [3]. In other way, there are chances of food contamination by surrounding dust, dirt, insects, birds, and animals in an open sun drying method. Hence, there is a need of solar dryers in many developing countries to reduce the chances of crop degradation and improving the quality of dried products. There are four methods used for solar drying to remove the moisture; 1) Sun drying: the material is directly placed under solar radiations in ambient conditions, 2) Direct solar dryers: Products can be placed inside a transparent enclosure or cover, 3) Indirect solar dryers: an external pre-heated air from solar dryer can be used for drying products, and 4) mixed-type solar dryer: a combined method of direct and indirect solar dryer.

Several solar drying techniques have been designed and developed as a substitute option for open sun drying method. Several studies have been reported on the direct and indirect type solar drying system [4, 5]. The simple wooden hot box solar cabinet type direct solar dryer has been studied by Fudholi et al. [6]. A transparent polyethylene cover has been used at the upper side of the dryer while a wood and metal sheet were placed at the bottom. Sharma et al. [7] has achieved the highest plate temperature of 80-85° for no load conditions, while it is 45-50° for 20 kg of wheat food. The main drawbacks of such open type direct solar dryers are: 1) small in size, hence cannot be used on large scale crops, 2) high drying time, 3) overheating of the crop may take place [4]. Hence, the researchers have been attracted towards the design and development of indirect solar drying system. Three main indirect type dryers *viz.* chamber type dryers, wind ventilated dryers and chimney type dryers are used for drying food crop.

A solar collector plays key role in indirect type dryer for enhancing the air temperature for a required level. Hence, the development in the solar collector with respect to higher efficiency is a key attraction of the today's researchers. There are two types of solar collectors *viz.* 1) concentrated type, 2) flat plate has been used for drying system. The concentric collectors are very costly, difficult in manufacturing and high maintenance cost. In conventional type FPC, the absorbing plate is generally made up of high thermal conductivity metal. The selective coating materials (like black paint) of lower thermal conductivity are coated on the top surface of the absorbing plate, which has high absorptivity and less emissivity. The low thermal conductivity coating materials create the thermal resistance for decreasing the heat transfer rate between coating material to the air. Many studies are reported on the indirect type solar drying system. In the year of 1986, Maroulis and Saravacos [8] did an experimental study for drying agriculture products. They developed a thermal storage bed for agriculture product heating using a heated air from flat plate collector. Bolaji [9] did a study on indirect type solar dryer using a box type solar collector. A black absorber plate has been employed at the collector for maximum absorption of heat. He found a maximum of 60.5 % efficiency of box type absorber system. He reported 64° C of average temperature inside the collector while he reached up to 57° C maximum average temperature inside the drying chamber. Pangavhane et al. [10] developed multipurpose natural convection based solar air heater with finned absorber (painted with matte black) for drying products. An aluminum matrix foil type fins are attached with a U-shaped aluminum duct through which air was passed. Fudholi et al. [11] did an experimental study of a double pass solar air dryer to investigate the performance of air dryer for palm oil fronds. They did a study for 22 h of solar drying study for 100 kg of palm oil fronds from 60% moisture content to 10 % moisture content. They observed a minimum and maximum collector efficiency of about 9-48% with 0.29 kg/kWh moisture extraction rate.

One of the reasons of increasing surface area and thermal conductivity of the absorbing plate is it helps to improve the efficiency of the dryer. Different types of extended surfaces like corrugated structure [12], V-groove type [13], truncated cone [14] and plate finned [15] was employed as an absorbing plate FPC by the various researchers. A review-based study on a different solar air flat plate collector was presented by Fudholi and Sopian [16]. They majorly focused on various analysis methods used for assessment of solar collector overall performance. They mentioned a range of 28-62% energy efficiency and 30-57% exergy efficiency of solar flat plate collector. Yahya [17] designed and developed solar dryer with fluidized bed and finned solar collector. A total 12 kg of Paddy product has been dried to the moisture content from 20% to 14% in 0.66 h. He found a maximum of 60% collector efficiency for 900 W/m^2 solar radiation. Karsli [18] presented a performance analysis of finned collector with varying angle. The first and second law efficiency for four different types of collector were calculated. He found better performance for the finned collector than the base collector with a maximum air temperature of 75° C. Karim and Hawlader [19] presented a comparative performance analysis for flat plate, finned and v-corrugated type solar collector. They found a v-corrugated fin type collector was most efficient collector than finned and plate collector. Karwa and Chitoshiya [20] performed an experimental study for v-down discrete ribs type solar collector. The enhancement in the thermal efficiency due to roughness of the rib was studied and found 12.5 to 20 % higher for different air flow rate. They also developed a mathematical model for evaluation of performance analysis. Pakdaman et al. [21] investigated a performance analysis of rectangular finned collector for natural convection heat transfer. A longitudinal rectangular fin array was used for heat transfer enhancement in solar collector. An empirical model was developed and studied for various dimensionless variables, efficiency, and air temperatures.

From the above discussion of the studies on solar dryers and type of solar collector for enhancing the heat transfer, it is inferred that, the development on the solar collector can help to enhance the overall performance of the solar dryer system. The main objective of this study is to investigate the performance of a newly developed flat plate solar collector from a waste aluminum can of beverages. A solar air flat plate collector is designed and developed in the laboratory as per IS 1933, 2003 standard. The performance of the system is evaluated on the basis of three different mass flow rates for drying green chilies. Green chili is selected for the experimentation because India is the second largest producer of green chili in the world and it has shelf life of only 3 to 4 days. But in practice other agriculture produce such as onion, slices of potato, beetroot can also be dried. The characteristic of the dried chilies is observed by evaluating a moisture content removed in a day. Outlet air temperature is measured, and collector efficiency is also calculated.

MATERIAL AND EXPERIMENTAL SETUP

Flat Plate Collector

A solar air collector is the main part in the solar drying system. A flat plate solar collector has been developed using a waste aluminum can of soft drinks. The top surface of the empty can is removed while the bottom surface is cut in the shape of a star and twisted in inward direction to create turbulence. All the cans are connected in series using silicon material to make it as a straight through pipe. The can has an outer diameter of 60 mm, and thickness of 0.3 mm, and has a lower thermal resistance. All collected cans were connected to each other to make a pipe through which air passes as shown in figure 2 (a). The surface area of the FPC must be increased by adopting circular surface area like hollow pipe. Higher the surface area, more is the absorption of solar radiation. The selective coating material has high absorptivity, very less emissivity and less thermal conductivity. It offers a thermal resistance to transfer the heat from selective coating surface to the air flowing through the pipe. Hence, the critical radius of insulation principle is used for deposition of selective coating on cylindrical curve surface. The paste formed by mixing selective coating (SC) Activated charcoal with black board paint is deposited over the surface of the absorbing pipe that has absorptivity of 78.9 % and emissivity of 21.1 %. A thermal conductivity of the selective coating and absorbing plate are the important parameters for transferring heat from the selective coating to the air which is further used for drying agriculture produce. Hence concept of Critical Radius of Insulation (CRI) is used for effectively transferring more heat from selective coating to the air. A photograph of the assembly of solar collector is shown in figure 2 (b).

Experimental Setup

Figure 3 shows the schematic of the lab scale experimental setup developed in Pune, India (altitude 1840 ft above sea level, latitude 18.32° N and Longitude 73.85 ° E). It consists of flat plate collector made from a waste aluminum cans, wooden cabin with insulation for drying agriculture products, air blower, pyrometer, and measuring equipment's. A flat plate collector is kept facing south with an inclination angle of 33.54°. A pyrometer made by Tempsens Instruments Ltd. with an accuracy of ± 1 W/m^2 is used for measuring the solar radiation data with time interval of 30 mins. Six copper-Constantine (K-type) type thermocouples with an accuracy of ±0.1 °C are used for temperature recording. An air blower is connected at the bottom of collector to

Figure 1. Process of making solar collector from waste cans.

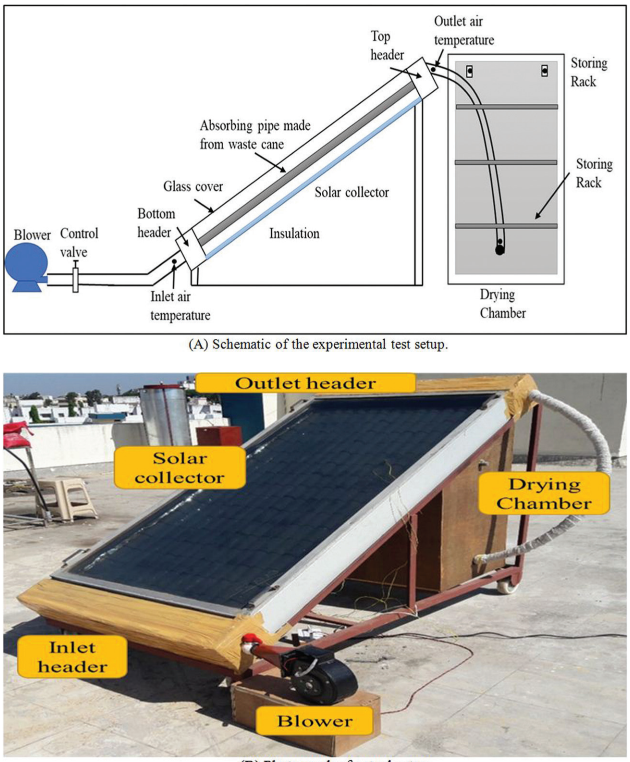
(B) Solar air collector made up of waste aluminum can.

Figure 2. (a) Manufacturing process of solar collector (b) Photograph of solar collector from waste can with coating.

circulate the air inside thye cabinet. An anemometer with accuracy of ±0.01 m/s is used for measuring the air velocity. The variable mass flow rate blower is kept at the inlet of the FPC to measure the mass flow rate of the air. Rock wool insulation is provided at bottom and both sides of the FPC.

Experimental Procedure

Before starting the experiments, initial readings of the ambient conditions are taken and a mass flow rate for a particular case is set. The solar radiation is recorded by pyrometer at an equal interval of 30 mins. The radiation at the start of experiment at 08:00 A.M. was 343 W/m^2 and it reached a maximum level of 891 W/m^2 at 12:00 P.M. While an average radiation was found to be 577.72 W/m^2 for a total time of 10.5 hours from 8 A.M. to 6.30 P.M. for a mass flow rate 0.01 kg/s. Similarly, for the next two days the aver-age solar radiation data recorded were 567.77 W/m^2 and 571.5 W/m^2 for the mass flow rate of 0.008 and 0.006 kg/s respectively. The ambient air temperature for all the cases is found to be in the range of 30 °C to 33 °C. All the experi-ments were performed in the month of March 2019 at Pune, India. The experimental tests were done to investigate the thermal performance of the solar collector. The air inlet and outlet temperature of the solar collector is recorded with respect to time. The setup is placed in such a way that, the



(A) Schematic of the experimental test setup.

(B) Photograph of actual setup.

Figure 3. (a) Schematic of the experimental test setup, (b) photograph of actual test setup.

maximum surface area of the tubes is exposed to the solar radiations. The relative humidity inside the dryer chamber is recorded. For, three different mass flow rates the testing procedure were repeated for three consecutive days, so that the deviation between the solar radiations will be minimum. A time dependent radiation plot for three consecutive days is shown in figure 4. This setup is used for the application of drying the agriculture products.

ANALYSIS OF THE SYSTEM

Critical Radius of Insulation

From the Fourier's law and thermal electrical analogy,

$$Q = \frac{\Delta T}{\Sigma R} \tag{1}$$

The equation (1) shows that rate of heat transfer is inversely proportional to equivalent resistance of the system. Obviously, the amount of change in value of ΣR will decide whether the heat flow will increase, decrease or remains unchanged [17]

Consider a pipeline coated with selective coating (Mixture of Activated charcoal and Black board paint). If r_1 is inner radius of pipe, r_2 is the outer radius of the pipes and r_3 is the radius of selective coating deposited on the pipe then as per electrical analogy the equivalent thermal resistances is given by,

$$\sum R = \frac{1}{Q.2\pi r_1 l.h_1} + \frac{ln\left(\frac{r_2}{r_1}\right)}{Q.2\pi lk_1} + \frac{ln\left(\frac{r_3}{r_2}\right)}{Q.2\pi lk_2} + \frac{1}{Q.2\pi r_3 l.h_2} \tag{2}$$

To find Maximum thermal resistance equation 2 is differentiated with respect to r_3 and equated to 0.,

$$\frac{d\Sigma R}{dr_3} = 0 \tag{3}$$

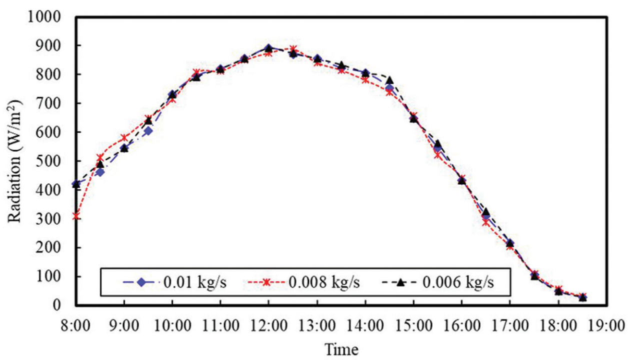


Figure 4. Solar radiation falling on the surface in W/m2.

$$\left(\frac{1}{Q.2\pi l.k_2}.\frac{1}{r_3}\right)+\left(\frac{1}{Q.2\pi lh_2}.\frac{-1}{r_3^2}\right)=0 \tag{4}$$

$$\frac{1}{k_2}=\frac{1}{h_2 r_3} \tag{5}$$

$$r_3=\frac{k_2}{h_3} \tag{6}$$

This equation indicates that, at $r_3=\frac{k_2}{h_3}$, the function ΣR has maximum or minimum value. To determine whether ΣR is maximum or minimum, the second derivative is evaluated hence,

$$\frac{d^2\,\Sigma R}{dr_3}=\frac{d}{dr_3}\left(\frac{1}{2\pi lk_2r_3}-\frac{1}{2\pi\, lh_2r_3^2}\right) \tag{7}$$

$$\frac{d^2\,\Sigma R}{dr_3}=\left(-\frac{1}{2\pi lk_2r_3^2}-\frac{1}{2\pi\, lh_2r_3^3}\right) \tag{8}$$

$$At,\, r_3=\frac{k_2}{h_2} \tag{9}$$

$$\frac{d^2\,\Sigma R}{dr_3}=\frac{1}{\pi\left(\frac{k_2}{h_2}\right)}\left(\frac{1}{k_2}-\frac{1}{2k_2}\right) \tag{10}$$

$$\frac{d^2\,\Sigma R}{dr_3}=\frac{h_2^2}{2\pi k_2^2}>0 \tag{11}$$

Since, $\frac{h_2^2}{2\pi k_2^2}$ is always positive, it indicates that, at $r_3=\frac{k_2}{h_2}$, ΣR is minimum.

Hence, at this value of outer radius of selective coating, ΣR is minimum and the rate of heat flow is maximum. This value of r_3 of selective coating of critical radius of insulation calculated is used to manufacturing the pipe of flat plate collector.

Thermal Performance Evaluation

Total heat received by solar collector due to solar radiation is calculated using the following equation,

$$E_t=I_t.A=Q_u+Q_l \tag{12}$$

Where, I_t is the incident solar radiation, A is the surface area exposed to the radiation, Q_u is the useful heat gain and Q_l is heat loss.

Useful heat gain (Q_u) is the heat gained due to an increase in temperature of air in a flat plate collector because of solar radiation and is calculated as,

$$Q_u=A_p.I-q_l=m.cp.(T_{out}-T_{in}) \tag{13}$$

Where, I is total incident radiation.

Hence, the thermal efficiency of the collector can be calculated using equation,

$$\eta=\frac{Usefull\,heat\,gain(Q_u)}{Incident\,radiation\,on\,collector\,surface} \tag{14}$$

Determination of Moisture Content

Moisture content of chilies can be assessed either on wet basis or dry basis. The percentage of moisture content removed from the green chilies can be evaluated using following equation,

$$M_{removed}=\left(\frac{M_w-M_d}{M_w}\right)\times 100 \tag{15}$$

RESULTS AND DISCUSSION

Performance of Solar Collector

A novel design of solar collector from the waste aluminum beverage cans has been manufactured and tested. A thermal performance of solar collector has been investigated for different mass flow rates of 0.006, 0.008 and 0.01 kg/s air. Figure 5 shows the air outlet temperature of the flat plate collector for a day for different mass flow rates.

The maximum temperature attained by FPC with mass flow rate of 0.01 kg/s is 72.3 °C and the average temperature with black board paint selective coating 54.44 °C. It

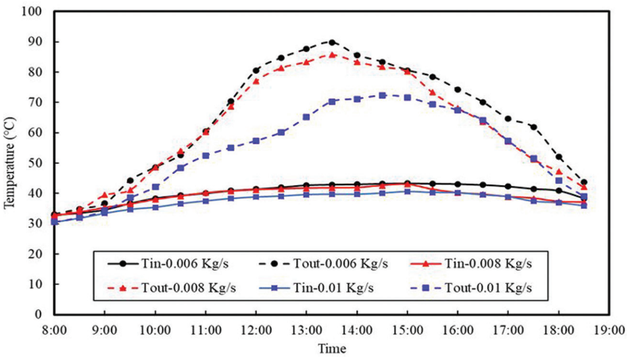


Figure 5. Graph of inlet and outlet temperature versus time for different mass flow rate.

is noted that, the outlet temperature of the air from solar collector increases with decrease in the mass flow rate. As the resident time of the air particles is higher with lower mass flow rate, the temperature of outlet air is found to be maximum. The star shape in base of each can helps to increase the turbulence in it. The maximum outlet air temperature is 64.9 °C for the mass flow rate of 0.006 kg/s and the average temperature is 64.35 °C. The temperature difference between the inlet and outlet of the solar collector is the driving force to enhance the efficiency of the collector. Figure 6 shows the difference between the inlet and outlet air temperature for three different consecutive days. The maximum temperature difference of 46.9 °C is observed for mass flow rate of 0.006 kg/s, while the minimum temperature difference (32.2 °C) was found for 0.01 kg/s mass flow rate.

The useful heat gain in solar collector by solar radiation is calculated using equation 13. The potential difference between the inlet and outlet temperature of the air enhances the useful heat gain. The figure 7 indicates the useful heat gain from the FPC which can be used for drying applications. The maximum useful heat gain is obtained as 508.55 kJ at 01:30 PM and average value is 262.109 kJ for a day for a mass flow rate of 0.006 kg/s. Similarly, the average heat gain for the mass flow rates 0.008 kg/s and 0.01 kg/s were found to be 243.03 kJ and 182.51 kJ, respectively.

Figure 8 shows the thermal efficiency performance of the solar collector made of aluminum waste cans (evaluated using equation 14). The collector efficiency is calculated for every time interval. The efficiency of the collector is found to increase for lower mass flow rate, as the useful heat gain is maximum for the mass flow rate of 0.006 kg/s. At the end of the day the maximum thermal efficiency obtained is 50.62% for the mass flow rate of 0.006 kg/s. A temperature difference between inlet and outlet of the solar collector is observed to be 4 ° C to 5 ° C at the end of the day, when the solar radiations are almost negligible. The average thermal efficiency for full day is 14.27% for mass flow rate of 0.006 kg/s, and 10.03% for mass flow rate of the 0.01 kg/s.

Characterization of Dried Chilies

The weight of green chilies reduces with the reduction of moisture content. Figure 9 shows, the graph of reduced weight of the green chilies with respect to time. The

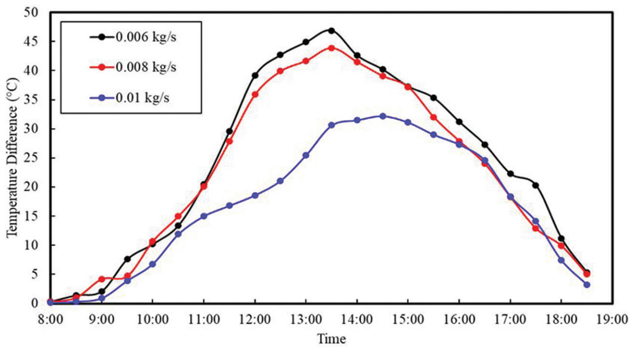


Figure 6. Temperature difference between inlet and outlet of the solar collector.

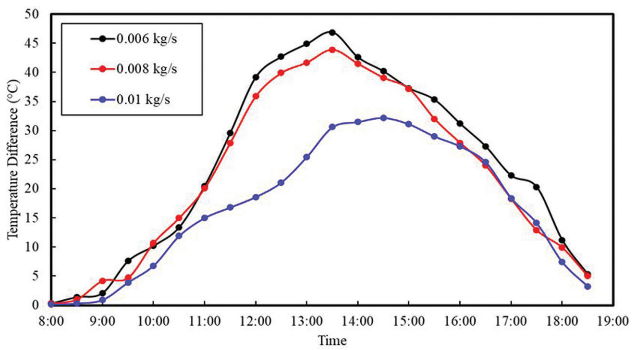


Figure 8. Thermal efficiency of the solar collector for different mass flow rate.

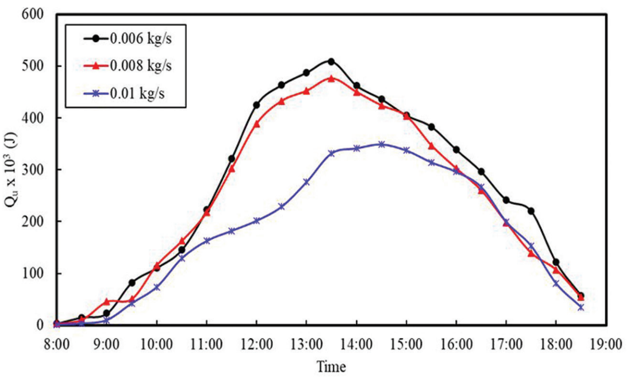


Figure 7. Plot of total useful heat gain from the solar collector to the air for different mass flow rate.

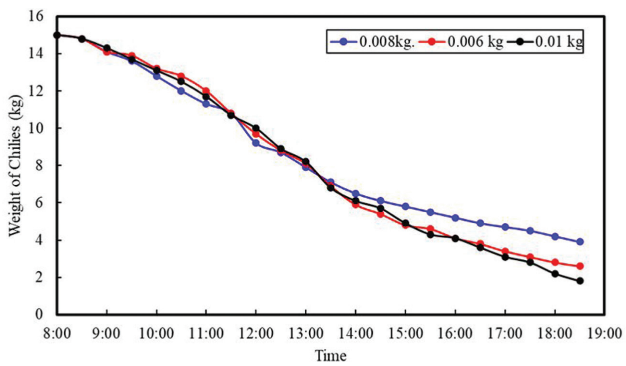


Figure 9. Weight reduction of green chilies with respect to time for three different mass flow rate.

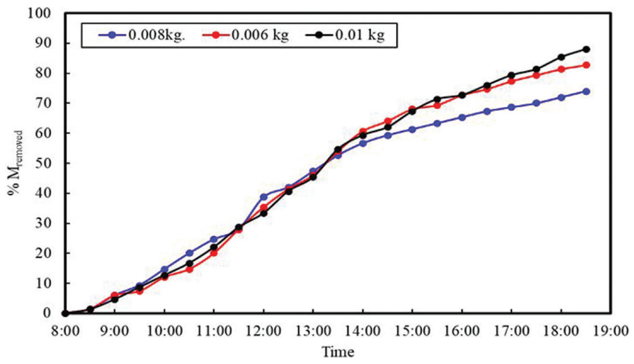


Figure 10. Percentage moisture content removed for chilies for three different mass flow rates of air.

temperature of the outlet air is 89.8 °C for the mass flow rate of 0.008 kg/s, that helps to reduce the moisture content in the green chilies. The weight of the green chilies reduced to 1.8 kg from the initial weight of 15 kg. for the mass flow rate of 0.01 kg/s in approximately 18-19 hours. The maximum temperature reached for mass the flow rate of 0.01kg/s is 72.3 °C. The moisture removal rate is higher at the start of the day compared to the moisture removal rate after 2 P.M. The moisture removal is faster in the start of the day due to higher evaporation capacity till 2 P.M.

The percentage of moisture removed with respect to time is shown in the figure 10. The maximum moisture content removed is 88 % for the mas flow rate of 0.01 kg/s. While, for the mass flow rate of 0.008 and 0.006 kg/s the maximum moisture content removed is 74% and 82.66 % respectively. Hence it is observed that, the increase in mass flow rate increases the moisture removal rate.

CONCLUSION

A solar dryer with a solar collector made of waste aluminum cans of beverage is designed and developed. of. A lab scale setup is manufacture with IS 1933, 2003 standard. Experiments are performed for three different mass flow rates namely 0.006 kg/s, 0.008 kg/s and 0.01 kg/s. The inlet and outlet temperature of the air is recorded and the overall performance is evaluated on the basis of moisture removal rate and dryer efficiency. The experimental investigation concludes the following,

1. The tube made from waste aluminum cans of beverage has the potential to increase the outlet air temperature of the solar collector. The star shape of each cans bottom helps to enhance the heat transfer due to turbulence in the air flow.
2. The outlet temperature of solar collector increases with decrease in the mass flow rate of air. The maximum difference between the inlet and outlet temperature of air is observed to be 60 °C for a mass flow rate of 0.006 kg/s.
3. The difference in air outlet temperature of flat plate collector for different mass flow rate is range of 4-7%
4. Maximum thermal efficiency of the solar collector is 50.62% at the end of the day. The average efficiency of the collector is 14.27% for the mass flow rate of 0.006 kg/s. The thermal efficiency of the collector reduces with increase in the mass flow rate.
5. There is a significant impact of the mass flow rate on the moisture removal rate. The moisture removal rate can be increased with increase in mass flow rate of outlet air.
6. The total cost incurred to manufacture the experimental setup including all the accessories is 61000 Indian Rupees. The commercially available vacuum tube collector in the market for same capacity costs196000 Indian Rupees Hence for the same capacity there is an overall saving of almost 135000 Indian Rupees that is almost twice the cost of experimental setup developed.

CONFLICT OF INTEREST

There is no conflict of interest from authors sides.

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NOMENCLATURE

Q	Heat gain (w/m^2)
T	Temperature (°c)
R	Total resistance (°c/w)
r	Local resistance (°c/w)
l	Length (m)
h	Heat transfer coefficient (w/m^2.°c)
k	Thermal conductivity (w/m °c)
M	Moisture content (%)
C_p	Specific heat of an air (kj/kg. °c)
I	Incident solar radiation ((w/m^2)
A_p	Area (m^2)
Greekwords	
η	Efficiency
	Subscript
t	Time
w	Wet basis
d	Dry basis

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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