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Performance Studies of Sustainable Solar Dryer for Drying Agricultural Products

Nachiketh Ramesh, Moshin Paschapure, Nikhil Nippanikar, Sarvesh Karigoudar, J. R. Nataraj* and K. Badarinarayana

Department of Mechanical Engineering, RVCE, Bangalore - 560059, Karnataka, India; Nataraj_jr@yahoo.in, Moshin.gpt29@gmail.com

Abstract

A large portion of the world agricultural and food market is now dependent on dried fruits and vegetables. Drying of fruits is carried out using many methods, in this paper an approach is made using renewable source of energy to dry fruits and vegetables to reduce food wastage at the same time help the farmers. The solar dryer was fabricated using locally available materials like High quality wood, GI Collector sheet and Baffles etc. Performance studies were made on the solar dryer for different configurations with banana as drying product. Simulation results showed us the improvements in the drying characteristics when baffles were used inside the drying chamber. Through experiments it was evaluated that the efficiency of the solar dryer setup with baffles was 23.4% which was 8% more than efficiency of the solar dryer setup without baffles. The usage of artificial roughness beneath the collector plate and dehumidifier inside the drying chamber further increase the efficiency of the solar dryer system by 4%. It was also found that the drying time decreased by 32% when the solar dryer of configuration with baffles, Ribs and Dehumidifier was used.

Keywords: Artificial Roughness, Baffles, Drying Characteristic, Dehumidifier, Solar Dryer, Simulation

1. Introduction

A large portion of the world agricultural and food market is dependent on dried fruits and vegetables. Agricultural sector in India accounts to 17% GDP. Horticultural produce itself contributes to 30% of it becoming a major player in agricultural production. Preservation is one of the many steps that comes under post-harvesting of agricultural products which reduce post-harvest losses and increases food availability from existing production. In developing nations like India and other countries in Asia, Africa, and South America, it is found that due to lack of proper post-harvest management methods, around 40% of total agricultural products get spoiled[1].

Drying is popular methods of food preservation known to the people in the developing countries. India's geographical location has blessed our country with abundant solar energy to available throughout the year. By harnessing the freely and richly available solar energy using solar dryer, food preservation can be made available to farmers in most economic manner. This can be put to good use in rural areas where electric power supply is limited and discontinuous[2].

The main, concept of drying, is to preserve, the fruits, vegetables and food,materials without allowing them to,undergo further,worsening and lose the,quality of,the product. Several post- process technologies have been,employed on an, industrial scale to preserve,food products. The prime objective of drying apart from extended, storage life can, also be quality enhancement, ease of, handling, further, processing and, preservation. Drying is process, in which moisture is removed from,an object by combination, of Heat and, mass transfer. The removal of,moisture prevents the, growth and, reproduction of micro-organisms, like bacteria, yeasts and molds,causing decay. Thus it minimizes, moisture induced, deteriorative reactions occurring, in the, food product. It, brings about, a substantial, reduction in the, total, weight and, volume of, the item, being dried. It also, results in minimizing, the

Author for correspondence

packing, storage, and transportation, costs and enables, storability of, the product, under, ambient, temperatures.

Donald et al studied challenges of the possibility of using solar drying at individual farm level for food preservation. Solar drying of tomatoes was used as an example. Factors blocking the extensive uptake of food processing technologies and intended short-comings of the adaptation of these technologies to local economies like farm sites are also discussed[3].

Ben Salma Ramdhane et al. researched on solar air collectors with baffles to favour heat transfer[4]. The researcher carried out a project concerning solar air collectors and various techniques to increase the heat transfer co-efficient between the fluid (air) and the absorber such as a fixation of small wings to the absorber, the manner in which the airflows in the absorber, the shape of the collector and those of it inlets and outlets. Study of horizontal and vertical drying chamber positions and observations of nature of varying system efficiencies for different days in drying of bananas was made by Hassanain et al Simple solar drying system suitable for different agricultural fresh commodity was evaluated to dry banana pulp[5].

Vinay Narayan Hegde et al of RVCE designed the solar dryer setup in 13-14. The solar dryer system that has been developed in RVCE was built using locally available and easily biodegradable materials. They studied and compared the performance for top flow and bottom flow air flow in the heating pane[6].

Abhishek Saxena et al conducted research on solar air heaters and prepared a thermodynamic review. In this paper various methods used to improve the thermal performance of solar air heaters are studied like sensible or latent storage media, use of concentrators and integrating photo-voltaic element with the heaters. The results showed that creation of turbulence in the air channels by using obstacles or baffles increased the performance of the solar sir collector[7]. Prasad, H et al conducted experimental analysis of collector plates of solar heater and dryers with small diameter wires for transversal roughness and found out a correlation between heat transfer and the friction factor. This configuration has improved the turbulence of air disturbing boundary layer; hence results in increased heat transfer[8].

2. Design of Solar Dryer

The design procedure of the Solar dryer first involved collecting of the climatic data of the experimental place i.e. Bangalore. Further the other significant data such as isolation was studied and calculated as per the configuration of the collector. For the initial phase in design of dryer, many existing designs were studied and some of the design factors were determined. The performance of the dryer was then analysed[9,10]. Once the design was finalized, the CAD model was prepared to help in the exact visualization and also in fabrication.

2.1 Data Collection

The average solar insolation in Bengaluru is important for the design of the dryer as the study on the dryer is conducted in Bengaluru. Therefore the data pertaining to the amount of solar insolation, sunshine hours and ambient temperature etc. were collected.

Bengaluru is located in Karnataka, India, with a latitude of 120 58’ North and longitude of 770 34’ East[11].

2.2 Design Parameters

The materials used for the construction of solar dryer include plywood, iron rods, stainless steel mesh, clear glass, galvanized iron sheet and axial fan from Crompton Greaves for operation of dryer.

The experiment on dryer is conducted in Bengaluru, Karnataka State, India with latitude of 12°58’ degrees north.

The following were the factors taken into consideration for the design of dryer:

- The metrological data in Bengaluru for the mean solar radiation on horizontal surface was found to be 656.63 W/m^2.
- In this case indirect type of solar dryer was considered as it does not affect the colour and nutrient content of the produce as is the case with direct type. Also the drying is uniform without any localized heating.
- Flat plate collector with ribs fixed over it which resulted in increased turbulence favouring high heat transfer rate.
- For the purpose of experimentation 1.5 kg of banana is used.
- Glass thickness recommended for the collector is 5 mm[12].
- Air, gap-of 5 cm, is recommended, for tropical climate[12].
- The insulating, material was, selected to be plywood as it’s a good insulator as well as environmentally, friendly.
- To further reduce the heat loss by radiation and to avoid moisture absorption by wood aluminium foil wrapped on the inside of the chamber[13].

In a solar dryer baffles are provided to obstruct, control and guide the air flow path, since it is needed to keep the hot air for longer periods inside the chamber, baffles are used.

2.3 Diameter of Wire and Spacing of Ribs (Wires)

Wires are fabricated over the collector in order to increase Artificial Roughness, Verma et al. conducted an,outdoor,experimental, investigating the, thermo-hydraulic, optimization, of the roughness, and flow, parameters, for Reynolds,number (Re),range of 5000–20,000, relative roughness,pitch (p/e) range, of 10–40 and relative, roughness, height (e/D) range of 0.01–0.03.

According to, researches, optimal, parameters for, the Aspect, Ratio are:

Relative,Roughness,Pitch (p/d) varies from 10 to 30. We assumed (p/d) = 20.

Relative,Roughness,Height (e/D) = between 0.01–0.03.

Aspect,ratio = (duct width)/(duct height) = 600/50= 12

Angle of Attack =90 degree

Where,P = Pitch,

D = Depth of Rough surface,

e = Space for air flow

For (p/d) = 20,

If pitch, p = 30mm then,

D = (p/20) = (30/20) = 1.5 mm.

Hence diameter of wire d = 1.5 mm

2.4 Modelling of the Solar Dryer

This Solid Works model depicts the drying chamber with three baffles fitted inside it. The separating distance between each baffle inside the chamber is 150 mm.

The model shown in Figure 2a and 2b depicts the entire solar dryer. It has a drying chamber with trays and baffles fitted, and a solar radiation collector with pebbles and collector. The air enters the solar radiation collector and gets heated up. The presence of black painted corrugated member and pebbles increases the heating rate of air. The air then moves into the drying chamber through the inlet. It then passes inside the chamber in serpentine manner due the presence of the baffles.

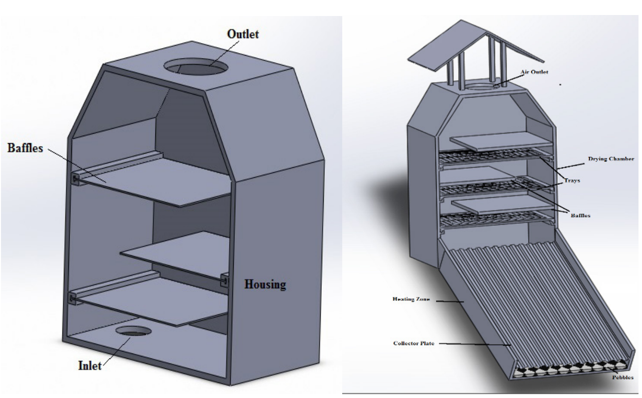

Figure 2. **(a)** Drying chamber with baffles. **(b)** Complete arrangement of solar dryer.

3. Experimental Setup

The Figure 3a shows the solar dryer setup. It has bottom flow configuration. Pebbles and side reflectors are used to increase the collector efficiency. The drying chamber is modifies by incorporating baffles so as to guide the flow inside the chamber. Transverse Ribs (wires) were placed over the collector plate which disturbs the boundary layer and increases friction co-efficient as well as the heat transfer from collector plate to the air[14].

Using the design data and calculations, baffles were designed as per the requirements. Medium Density Fibre (MDF) was chosen as the material for baffles. MDF is less costly and serves the purpose accordingly, resulting in economic System for farmers. MDF was cut to the required dimension. It was then coated with aluminium foil to increase its reflectivity

Roughness to obstruct boundary layer is created using wires attached in transverse direction where, optimum pitch is 30 mm and wire diameter is 1.5 mm that is obtained from the calculations, the ribs were attached to the flat plate solar collector by fixing at both ends. These ribs provided the artificial roughness and created turbulence in the air flow beneath the flat plate solar collector.

The dehumidifier as shown in Figure 3b was placed such that the air entering the drying chamber of the solar

Figure 3a. Solar dryer system.

Figure 3b. Wires attached to the flat collector plate.

Figure 3c. Dehumidifier inside the drying chamber; Electrical dehumidifier.

dryer should pass through it. So, the heated air coming out of the collector chamber was passing through the desiccant material present inside the dehumidifier and was losing its humidity. The Figure 3c shows the positioning of the dehumidifier inside the drying chamber.

3.1 Experimentation Procedure

The drying process of banana (elakki bale) of 1.5 kg containing moisture of 77.2% each was peeled and sliced to 3-4 mm in thickness. It was then placed in the drying and was dried for 16 hours from 9 am-6 pm by forced convention methods during the month of March 2016. Reflectors made up of aluminium foil was inclined at an angle of 60°C, on either side of the collector plate by using a MS plate which was bent and welded to it, to increase heat radiation on the absorber plate and increase the efficiency of dryer. A solar PV cell was integrated to the dryer to make the system sustainable for duration of 8 hours. The drying rate of banana was studied in each case and the best air flow rate and drying time based on the quality, texture, taste, moisture retained and colour of the banana dried was selected.

3.2 Experiments Conducted on Solar Dryer

- Experiment on solar dryer with baffles and without baffles at 2 m/s to study the effect of baffles.
- Experiment on solar dryer with and without baffles at 1.5 m/s to understand effect of velocity.
- Experiment on solar dryer with baffles inside the chamber and incorporating ribs over the collector plate.
- Experiment on Solar dryer for combined setup with baffles, with ribs and the Dehumidifier to work during humid operating condition.

4. Results and Discussion

4.1 Effect of Baffles

Baffles disrupt the flow of fluids and can be used for changing the flow direction at any point. When they were placed inside the drying chamber with a gap of 150 mm between adjacent baffles, the flow of hot air was getting converted from a straight path to a serpentine path. The hot air was covering the entire volume while flowing. Inside the drying chamber, five thermocouples were placed at five different spots. They were named T7, T8, T9, T10, and T11 respectively as shown in Figure 4a – since there were already six thermocouples in the collector chamber of the solar dryer. For various experiments – with and without

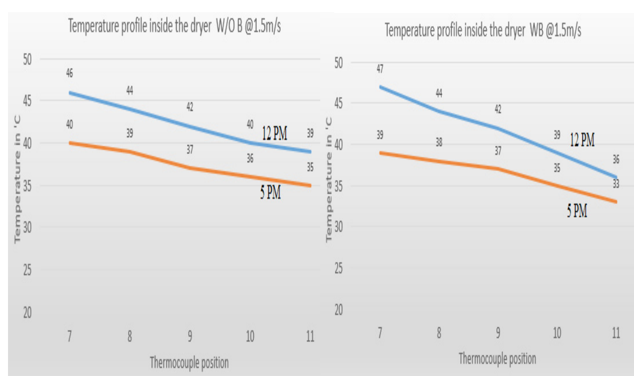

Figure 4a. Comparison of temperature profiles inside the drying chamber without and with baffles.

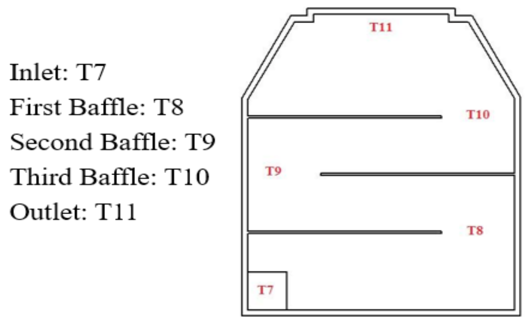

Figure 4b. Position of thermocouples inside the drying chamber.

baffles - the temperature readings were taken on an hourly basis and the data obtained was plotted with temperature on Y-axis and the thermocouple number on the X-axis. This graph gave the temperature reading of each thermocouple at a particular time. Since solar intensity reaches a maximum value at 12 in the noon and it reaches the lowest at 5 in the evening.

At 12 pm, the temperature of the air at the inlet of drying for both without and with baffles is almost equal. But the end temperatures are different. In case of the drying chamber without baffles, the outlet temperature is only 39'C. The inlet temperature is 46'C. So the difference is 7'C. Only 7'C worth of heat has been transferred from the hot air to bananas in order to remove the moisture content present in them. But in the case of the drying chamber having baffles, for the inlet temperature of 47'C, the drop at outlet is 11'C.

So, in comparison to the solar dryer model without baffles, the dryer model with baffles is carrying transferring more heat to the bananas and thus removing more amount of moisture. Accordingly, the drying time should decrease.

4.2 Effect of Artificial Roughness (Transverse Wires)

Initially the atmospheric air enters the collector plate. The six thermocouples – T1, T2, T3, T4, T5 and T6 – are used to note down the temperature readings on an hourly basis. These six values are added and mean value is calculated, which gives the collector plate mean temperature for a particular hour.

The Figure 4c shows the variation of collector plate mean temperature and air temperature from 9 am to 5 pm – in this case, we have baffles placed inside the drying chamber for 1.5 m/s air velocity. Again, at the peak hours, i.e. between 11 am to 3 pm, the plate is getting heated to around 65'C. But the air passing below it is getting heated

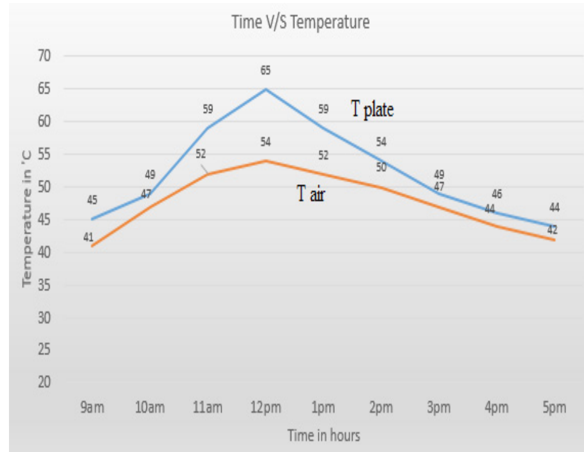

Figure 4c. Graph of collector plate mean temperature and air temperature during various intervals in a day.

to a higher temperature than it was getting heated in the absence of ribs. The mean temperature is around 53'C. Compared to the experiment where ribs are absent, in the present case we are getting an increment of almost 8'C.

Where the air was getting heated to around 45'C, it is now getting heated to around 53'C. This is because of the interaction between the ribs that provide artificial roughness and the air. The boundary layer between the flowing air and the collector gets obstructed by the presence of artificial roughness. This results in turbulence in the flow of air which increases the Reynolds number of the flow.

4.3 Drying Time v/s Weight of Banana

The measure of how good a solar dryer system is shown by its drying. Along X-axis, the drying time, starting from 9 am of first day to 6 pm of the second day has been shown. Along the Y-axis, the weight of bananas has been shown in grams.

The initial weight of banana is 1500 grams. As the drying progresses, the bananas get dehydrated as the hot air removes the moisture content present in them. So we can see a curve indicates the reduction in weight of bananas. Initially, it is very steep. From 9 am to 3 pm – the weight reduction is 859 grams. But from 3 pm to 5 pm of the first day the weight reduction is only 29 grams. Total reduction on the first day is 888 grams.

During day two, the total weight reduction is 76 grams. Cumulatively, the system with baffles and artificial roughness performed better than the system with baffles and without roughness by only a minute amount. It removed around 6 grams of extra moisture. Percentage removal of moisture in comparison to the initial weight is 64.43%.

4.4 Effect of Dehumidifier

Dehumidifier, uses a special, humidity-absorbing, material, called, a desiccant, which is exposed,to the air to be, conditioned. The humidity-saturated, material, is then, moved to a, different location,where it,is,"recharged" to;drive off,the humidity, typically,by,heating; it. The desiccant;can be mounted on;a belt;or other; means of;transporting;it during,a cycle, of operation. Because,of the,lack of compressor,parts desiccant,dehumidifiers are,often lighter, and quieter, than compressor, dehumidifiers. Desiccant dehumidifiers, can also operate, at lower temperatures, than compressor, dehumidifiers as the, unit lacks, coils which, are unable, to extract, moisture from the air at lower temperatures. Since,the dehumidification, is always accompanied,by cooling, or heating, of the air. Dehumidification, process along, with cooling, or heating, is used in number, of air conditioning, applications.

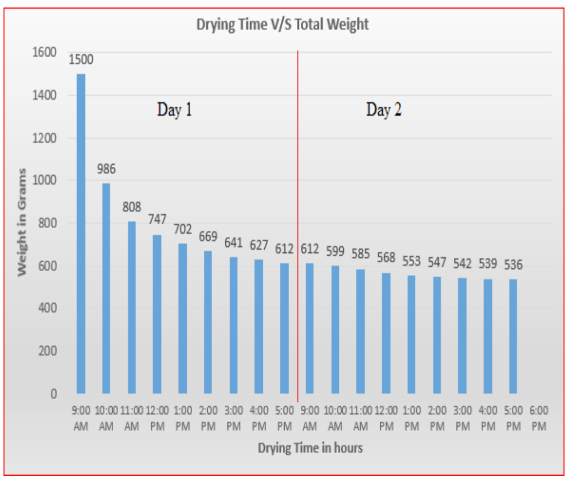

Figure 4d. Drying time v/s Weight of banana for an air velocity of 1.5 m/s with baffles present inside the drying chamber and the use of artificially roughened collector plate.

Table 4. Wet bulb and dry bulb temperatures.

	Wet bulb Temperature				Dry bulb Temperature			
	Tw1	Tw2	Tw3	Tw4	Td1	Td2	Td3	Td4
9:00 AM	31	32	31	32	39	43	42	37
10:00 AM	30	32	31	32	42	48	46	39
11:00 AM	29	32	30	31	40	53	49	42
12:00 AM	30	32	30	32	45	57	55	46
1:00 AM	29	32	31	32	41	54	52	41
2:00 AM	29	31	30	31	40	49	47	40
3:00 AM	29	30	29	31	39	47	46	40
4:00 AM	28	30	29	30	37	44	43	39
5:00 AM	28	29	29	30	37	43	42	37

Psychrometic Analysis

Where,

Tw1 = Inlet of collector

Tw2 = Outlet of collector Before Dehumidifier

Tw3 = Inlet of chamber after Dehumidifier

Tw4 = Outlet of chamber

Figure 4e shows the psychometric analysis done on the solar dryer setup with baffles inside the drying chamber. At the inlet of the collector chamber, the dry bulb and wet bulb reading are 40'C and 29'C respectively. Relative humidity is 46% and humidity ratio is 21.2 grams moisture per kg of dry air.

As the air leaves the collector chamber and just enters the drying chamber, its psychometric co-ordinates are 49'C, 31'C, 29% and 21 grams moisture per kg of dry air.

After passing through the desiccant material present inside the dehumidifier, these values change to 47'C, 29'C, 27% and 18.1 grams moisture per kg of dry air. Checking the humidity ratio of the air coming out at the outlet of the drying chamber gives a clear picture of how much moisture has been absorbed by the air. The humidity ratio at the outlet is 26.5 grams of moisture per kg of dry air. So the air coming out is rich with moisture since it has absorbed some from the bananas.

ΔW (without dehumidifier) = 26.5-21 = 5.5 grams of moisture per kg dry air.

ΔW (with dehumidifier) = 26.5 – 18.1 = 8.4 grams of moisture per kg dry air.

4.5 Drying Time v/s Weight of Banana

To remove the amount of moisture removed by the system without dehumidifier in two days, the one with

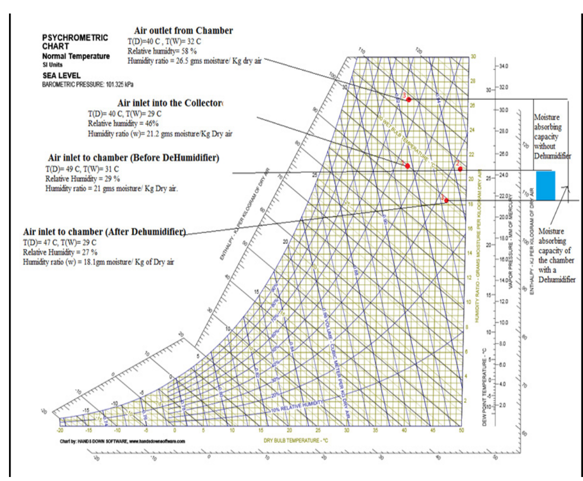

Figure 4e. Psychrometric analysis of Solar dryer with dehumidifier.

the dehumidifier has removed it by taking four hour less. So the modified system is (12-16)/16% quicker than the system without dehumidifier present inside the drying chamber. In simpler words, the solar dryer setup with dehumidifier is 25% quicker compared to the solar dryer model without dehumidifier.

4.6 Net Heat Transfer inside the Drying Chamber for Different Configurations

For 2 m/s air velocity the difference between the net heat utilization of the system with and without baffles is 0.022 kW. For 1.5 m/s air velocity, it is equal to 0.033 kW. This indicates that the system with baffles inside the drying chamber is utilizing more heat in order to remove the moisture content from bananas. In the system without baffles, the hot air is directly moving from the inlet to outlet and not removing enough moisture.

The solar dryer setup with baffles, artificial roughness in the form of ribs and dehumidifier inside the drying chamber, the net heat utilization is 0.124 kW which is again 0.036 kW more than the systems having only baffles. Note that the presence of the dehumidifier doesn't affect the net heat utilization inside the drying chamber. The air undergoes the same temperature drop as it does in the system having only baffles and ribs. But the dehumidifier removes moisture from air and helps it in increasing its moisture carrying capacity.

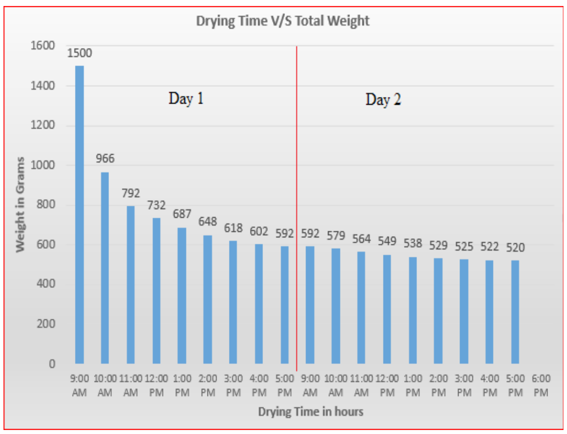

Figure 4f. Drying time v/s Weight of banana for an air velocity of 1.5 m/s with baffles, artificially roughness and a dehumidifier kept inside the drying chamber.

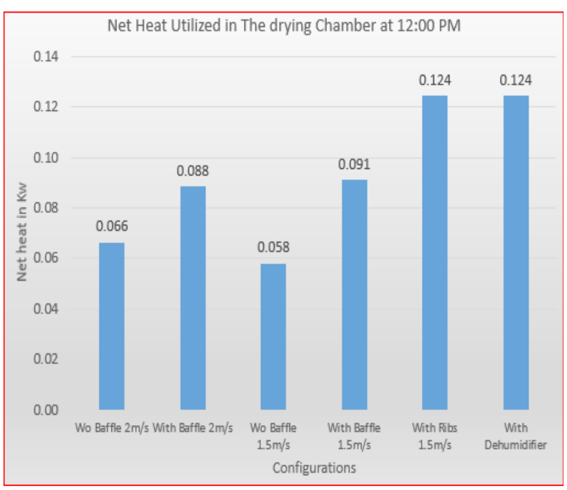

Figure 4g. Net heat utilization inside the drying chamber for different configurations at 12 pm.

4.7 Efficiency of Dryer for Different Configurations

It is clear from the graph that for a given air velocity, the solar dryer setup with baffles inside the drying chamber is always more efficient than the system without baffles inside the drying chamber. Experiments done with 1.5 m/s air velocity are found to have more efficiency than the experiments done with 2 m/s air velocity. The solar dryer setup with baffles and at 1.5 m/s air velocity reaches a maximum efficiency of 23.40%.

In the presence of artificial roughness on collector plate and dehumidifier inside the drying chamber, the solar dryer setup has the highest efficiency of all the cases. It hits a maximum value of 27.27%, which proves that the combined solar dryer setup is the most efficient and using dehumidifier makes it useful in humid regions.

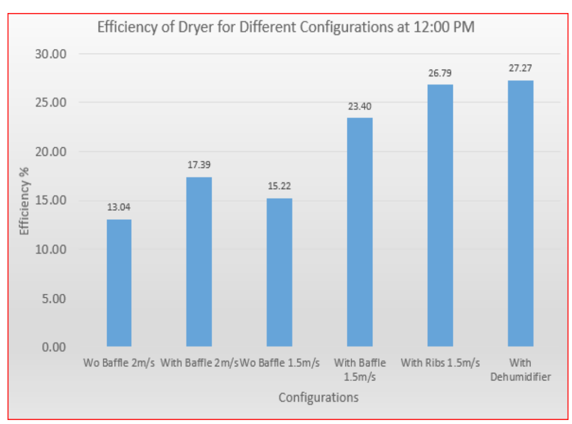

Figure 4h. The efficiencies of different configurations of solar dryer system at 12 pm.

5. CFD Analysis of the solar Dryer for Better Understanding of Temperature Distributions

5.1 Effect of Baffles

Thermal analysis using ANSYS Fluent 15 were made on the drying chamber without baffles, as shown in Figure 5, in order to study fluid behaviour within the system when there was no obstruction to the flow of heated air.

5.2 Drying Chamber without Baffles

Static temperature plot for a drying chamber without baffles for a velocity of 1.5 m/s is shown in Figure 5 and Figure 5a from the plot it can be seen that temperature of air at the outlet of the chamber is 320 K. The ΔT is small and the temperature distribution is highly localized in certain regions between the inlet and outlet. Since there is no obstruction to the flow effective utilization of the heated air for drying was not appreciable.

5.3 Drying chamber with Baffles

Figure 5c shows Static temperature plot for a drying chamber with baffle for a hot air velocity of 1.5 m/s. From the plot it is seen that temperature of air at the outlet of the chamber is 312 K. Since the air is properly guided within the system by the use of baffles effective utilization of the heated air is possible and the air temperature within the system reduces gradually as the flow progresses as seen in the above plot. This reduces the loss of heat within the system and increase the efficiency of the heating chamber. This in turn reduces the dying time.

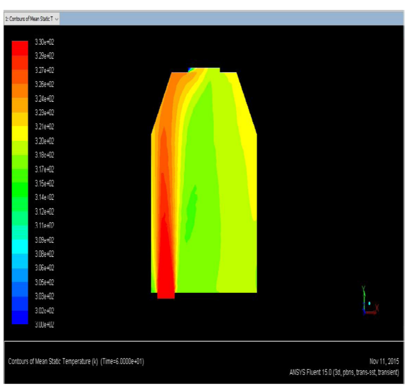

Figure 5. Static temperature distribution.

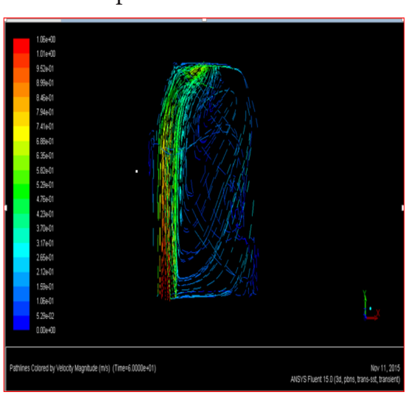

Figure 5a. Flow path line of hot air inside the chamber.

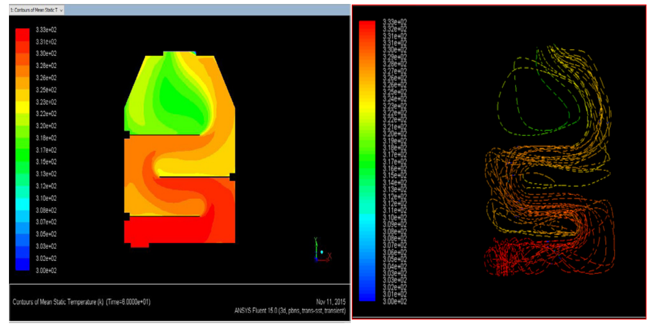

Figure 5c. Mean static temperature distribution plot in the chamber with baffles (in K).

6. Conclusion

Incorporation of reflectors at an angle of 60° increased the solar intensity falling over the collector throughout the day. Experimental analysis of the solar dryer setup without any baffles at 2 m/s velocity had a drying efficiency of 13.04%. The experimental analysis of the solar dryer system with baffles at 2m/s air velocity showed an efficiency of 17.39%.

- At 1.5 m/s air velocity, drying rate in the solar dryer with baffles was quicker than the system without baffles by 23.53%.
- Experimental analysis of the solar dryer setup with baffles and artificial roughness at 1.5 m/s velocity had a drying efficiency of 26.79% which was more than the solar dryer system with baffles but without any artificial roughness. Net heat transfer was 0.124 kW.
- Experimental analysis of the solar dryer setup with baffles, artificial roughness and a dehumidifier at 1.5 m/s velocity had a drying efficiency of 27.27% which was more than all the previous setups.
- Thermal analysis made on both the cases (With and without baffle) where temperature and velocity plots were obtained, it was seen that the dryer efficiency depends on the temperature of the air exiting the chamber and in the system with baffles ΔT is larger hence more heat is being utilised in the drying chamber**.**

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