Numerical investigation on flat plate collector with struts for drying of fruits and vegetables

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Abstract: The demand for quality food product is growing all around globe due to population explosion. Drying is one of the ancient technique to preserve the fruits and vegetables. Indirect solar drying system with flat plate collector is used in this experiment for drying operation. V-shaped struts on top of the absorber plate to augment the thermal performance of the dryer. CFD study on the influence of V-shaped struts and its relative roughness pitch parameter on the thermal efficiency, Nusselt number and friction factor was performed. Providing V-shaped struts improved the thermal efficiency of the collector also increased the friction factor. Thermal efficiency improved by 47% while the Nusselt number increased by 2.1 times for plate with V-shaped strut of relative roughness pitch 10 compared to the plain tube.

Keywords: Solar Dryer, Air Collector, V-shaped struts, Numerical Simulation, Thermal efficiency.

1. Introduction

The balance between population growth and food supply is maintained by reducing the loss of fruits and vegetables during post harvesting and marketing process [1]. The loss during post harvesting and marketing process contributes to nearly 40 to 50% of the total production. The loss occurs because of improper processing methods and non-availability of storage spaces. The loss can be avoided by solar drying. Drying is one of the early and traditional technique used to preserve fruits and vegetables. Drying is the process which removes excess water in the fruits which would reduce the growth of bacteria. Thus the fruits and vegetables are preserved for a stretched time. Solar drying uses solar energy to dry the fruits and vegetables. The drying process happens in two different ways namely direct and indirect
drying. In the direct drying process, the fruits and vegetables will be kept in the container enclosed with glass. In indirect solar heating process, the drying unit is separated from the collecting unit. The hot air from the collecting unit enters the drying chamber to dry the fruits and vegetables and exits out through a chimney. In-direct solar drying is preferred over direct solar drying as it has superior control on drying and quality compared to direct drying. Many researchers are trying to augment the thermal performance of the indirect solar drying by improving the performance of the collector.

Investigation with different glazing material namely glass and polycarbonate sheets were performed for solar flat plate collector [2]. The efficiency increased using both the material, while glass had better efficiency compared to the other. Solar collecting unit fitted with reflectors also improved the efficiency of the dryer [3]. The performance of the collector can be improved by breaking the laminar sub layer by providing artificial roughness. Placing U-shaped corrugations over the absorber plate of the collector improves the energy transfer [4]. V- Shaped roughened absorber plate is used by Abhay et al to dry banana [5]. The drying container had four trays placed one above the other. The Moisture content of banana reduced from initial 79% to nearly 14%. A numerical model to estimate the air velocity and temperature inside the drying unit was performed [6]. Numerical simulation for collector, drying unit and chimney were separately performed by Tedesco [7]. V- Grooved collector fitted drying unit using forced convection yielded better performance of the dryer. It is also observed that drying phase can be minimized by boosting the flow rate [8]. The drying phase can also be minimized by slicing the fruits and vegetables into small pieces and by providing pre-treatment to it without affecting the flavor of strawberry [9]. Drying unit combined with chimney fitted with evacuated tube collector improved the drying rate. Also, the quality of the product dried using the set-up was observed to be superior to the Open Sun drying [10]. Akbulut and Durmus performed first and second law analysis of the collector for mulberry slices using seven different mass flow rates. Increase in flow rate reduced the exergy loss of the collector [11]. Apart from these innovations, provision of artificial roughness on the top of the absorber plate in the collector to improve the efficiency and also to reduce the drying time. Roughness like U shaped ribs, V- Groove, V- shaped ribs, V- corrugation and square shaped ribs are provided to improve the efficiency [5, 9, 12 – 13]. This paper provides roughness in the form of inverted v and studies the improvement in the efficiency by varying the relative roughness pitch.

2. Test set-up

The Illustrative diagram and 3D model of the test set-up is shown in figure. The test set-up comprised of two different units' namely solar collecting unit and drying unit. The collector is exposed to the incident radiation. The air which enters the collector at certain mass flow rate gets heated by the incident solar radiation. Due to the change in the density, the heated air flows towards the drying chamber. The drying chamber consist of wire mesh tray which holds the fruits and vegetables. As the heated air move in the drying unit, the vegetables gets
dried and air is out of the drying unit through a chimney. The flat plate solar absorber surface is made of steel and 5 mm thick galvanized iron frame is used to construct the drying unit. Rock wool insulation was placed at the bottom of the absorber plate. More details about the experimental set-up is given in the table1. The experiment is conducted by varying the pitch distance between two consecutive inverted V-struts for Reynolds number between 4000 and 12000. The height of the rib is kept constant as 5 mm and width 30 mm. The Relative roughness pitch is varied as 10, 15 and 20

Figure 1 a. Illustrative Diagram b. 3D Model of the test set-up
Table 1. Details of the Test set-up

| Parameter                     | Value                  |
|-------------------------------|------------------------|
| Solar Air heating Collector   | 1000X300               |
| Size (mm)                     |                        |
| Size of the storage box (mm)  | 6000X600X600           |
| Glazing thickness             | 4 mm                   |
| Insulating material           | Rose wool              |
| Absorber plate material       | Copper (t = 10mm)      |
| Frame                         | Galvanized steel       |
| No. of Trays                  | 2                      |

Figure 2. Schematic of the test Section

3. Theatrical Analysis

The performance of the collector will be determined by the term thermal efficiency. Collector’s thermal efficiency is influenced by Solar radiation, Collector area and outlet temperature.

\[
\eta = \frac{mc_p(T_{out} - T_{in})}{I Ac}
\]  

(1)

The energy rate is formulated as

\[
Q = mc_p(T_{out} - T_{in})
\]  

(2)

The deviation of Nusselt number is given by Dittus-Boelter equation

\[
Nu = 0.023Re^{0.8}Pr^{0.3}
\]  

(3)
The frictional resistance caused by the artificial roughness and the linkages is calculated by the parameter called frictional factor and it is given by

$$f = \frac{\Delta P}{\left(\frac{L}{D_h}\right)\left(\frac{\rho V^2}{2}\right)}$$

(4)

4. Numerical Model and Boundary Conditions

The Numerical model of the collector with different roughness is shown in the figure. Academic Licensed ANSYS 17.0 software was used to simulate the numerical model. Double Precision Pressure based CFD solver is used for simulation. The solution is assumed to be converged only after the residuals for energy and momentum fall below $10^{-6}$ and $10^{-5}$ respectively. Mass flow rate is given as the inlet condition and the outlet is set as pressure outlet with atmospheric pressure as value. External boundary conditions are set as adiabatic conditions. Heat flux is given at the top of the absorber plate as the heat input.

Figure 3 Numerical Model of the Absorber plate with relative roughness pitch 10 and 15

5. Mesh Independence Test

Mesh independence is performed to make certain the mesh quality and to optimize the number of control volumes for better results. The meshed view of the absorber plate is given in the figure 4. The simulation is performed at Reynolds number 7500 to ensure the mesh quality. An optimized control volume of 2.05 million is chosen to perform the analysis.
6. Result and Discussion

6.1 Thermal Efficiency

Thermal efficiency is influenced by factors like flow rate and incident radiation. As the flow rate rises the rate at which energy transfer happens between the radiation and air increases. The increase in energy transfer improves the efficiency of the collector. Improving turbulence in the collector will also improve the efficiency of the collector. Though solar air collector works in turbulent region, formation laminar sub layer reduces the energy transfer rate which in turn reduces the efficiency of the collector. So artificial roughness is being provided atop the absorber plate to improve the turbulence. Turbulence improvement due to the provision of roughness on the plate is shown in the figure. Streamline traced by the air particles after getting hit by the V- shaped strut shows that turbulence increases. Because of the improved turbulence, the amount of heat extracted and the rate of heat extraction increases which eventually increases the efficiency. Figure shows the outlet temperature of the collector. The improvement in the efficiency of the collector is shown in figure.

Fig 4 Meshed view of the absorber plate

Fig 5. Streamline traced by the air particles
Figure 6. Temperature variation along the absorber plate for different relative roughness pitch

Figure 7. Outlet temperature of the collector for different Reynolds number
6.2 Nusselt Number

Nusselt number increases with rise in Reynolds number. Due to the presence of roughness on the absorber tube, turbulence gets improved. Due to improvement in turbulence, the Nusselt number increases. Nusselt number improved 2.1 times in the highest mass flow rate while at the lowest mass flow rate, the improvement was about 1.33 times for the plate with relative roughness pitch 10. The improvement in Nusselt number is shown in figure 9.
6.3 Friction factor

The term friction factor determines the frictional resistance happening in the absorber plate with ribs. Because of the ribs on the absorber plate, turbulence created which resist the air particles to move further on it. This resistance is called as frictional resistance. Absorber plate with less relative roughness pitch produced higher frictional resistance compared to plate with plate with higher relative roughness. Maximum enhancement of about 3.48 times was observed for plate with relative roughness pitch 10 at high mass flow rate.

![Friction Factor Vs Reynolds number](image)

Figure 10. Friction Factor Vs Reynolds number

7. Conclusion

Solar dryer with flat plate collector was numerically simulated. V-Strut were given as the artificial roughness on the absorber plate. Providing roughness improved the performance of the collector. Following were found as observation as the result of the simulation

1. Thermal efficiency of the collector improved by 47% compared to the plain plate. The improvement is attributed to the turbulence caused by the roughened plate
2. Maximum Nusselt number enhancement of about 2.1 times for plate with relative roughness pitch 10 compared to plain plate
3. Friction factor also increased by 3.4 times for plate with relative roughness pitch 10 compared to plain plate
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