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Research Article

THERMAL PERFORMANCE ANALYSIS OF A PACKED BED SOLAR AIR HEATER HAVING ROUNDED TIP V-GROOVED ABSORBER

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ABSTRACT

The thermal efficiency of conventional solar air collectors is found to have low thermal efficiency mainly due to higher top losses and low heat transfer rate from absorber plate to flowing air due to low specific heat of air. Use of packed bed solar collector helps in reducing the top layer temperature by absorption of heat energy in depth, thus minimizing the top losses. Also, heat transfer coefficient between the packing element and flowing air is increased as a result of air flows through the tortuous path. Heat transfer area is also increased in packed bed air heaters. Overall effect is the enhanced thermal efficiency of the collector along with increased pressure drop. Rounded V-grooved absorber plate have also been used for increasing the thermal efficiency of conventional smooth collectors taking advantage of large amount of intercepted radiation on the absorber plate, without any increase in the pressure drop. Use of rounded V-grooved absorber plate is made in packed bed air heaters in the present investigation which is found to further increase thermal efficiency of a packed bed collector, without additional pressure drop penalty in packed bed.

Experiments are conducted on a solar collector under simulated conditions using wire screen matrices in its air flow duct for varying operating parameters. It has been observed that the maximum thermal efficiency of 85.2% with outlet temperature of 56.1 oC is obtained at a mass flow rate of 0.035 kg/s.m2 and a fixed insolation of 1100 W/m2. These results in thermal efficiency enhancement by approximately 65% compared to the conventional smooth collector. For a mass flow rate of 0.015 kg/s.m2, the increase in efficiency has been found to be 46% higher compared to conventional collector for same value of insolation with air outlet temperature of 68.9 oC

It is seen that the efficiency of the collector increases with increase in mass flow rate and insolation. It has been found that geometry of absorber plate significantly affects the performance of the collector.

INTRODUCTION

The fast depleting conventional energy resources and problems regarding pollution and global warming have made it inevitable to think about cleaner and sustainable form of energy. One such form of energy is solar energy, which has got great potential especially for countries like India because of abundant insolation available due to their geographical location. The utilization of this form of energy can easily be achieved for low temperature applications using flat plate solar collectors, which have a wide range of applications viz. domestic and industrial water heating, drying of agricultural products such as fruits and grains, green house chambers, space heating, solar refrigeration and air conditioning etc. Conventional solar air collectors have inherent disadvantages viz low thermal efficiency due to low value of specific heat of air. In order to increase the thermal efficiency of conventional collectors different techniques have been proposed for thermal performance improvement [1-6]. These techniques include enhancement of heat transfer coefficient between absorber plate to working fluid and reduction of top losses etc.

The enhancement of heat transfer coefficient can be achieved in several ways, such as the use of artificial roughness which disturbs the viscous boundary layer of the flowing fluid and thus augmenting the heat transfer rates. Use of finned plate absorber surface causes an increase in the turbulence of air flowing through the duct, increasing the thermal performance with limited increase in pressure drop. Use of rounded tip V-grooved absorber plate proves to be beneficial in increasing the effective absorbing area as compared to the conventional collectors. This effectively increases the absorbing area and the amount of incident solar radiations collected by the absorber plate. Use of packed bed solar air heaters is another approach to

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obtain deeper absorption of heat and thus achieve reduction in top losses [8-18]. Although, no such work has been conceded out yet, taking up the arrangement having corrugated absorber plate along with packing of the duct with porous material, which is expected to yield still better performance compared to the packed bed alone. The introduction of corrugation on absorber plate in packed bed collectors requires insignificant modification as only the smooth plate is replaced by rounded tip V-grooved absorber plate.

Design and Validation of Experimental Setup

The experimental set up configured in accordance with the ASHRAE standards [19] is shown in Fig. 1. The collector has

Been Tested with Following Three Different Configurations

1. Collector having rounded tip V grooved absorber plate with wire screen mesh packing.
2. Collector having rounded tip V grooved absorber plate without wire screen mesh packing.
3. Flat absorber plate solar air collector.

Before collecting the actual experimental data, the calibration of the experimental setup for heat transfer coefficient and friction factor values have been performed using the standard correlations [20-22]. These values are determined for the experimental data taking the mass flow rate ranging from 0.015 kg/s.m^2 – 0.035 kg/s.m^2.

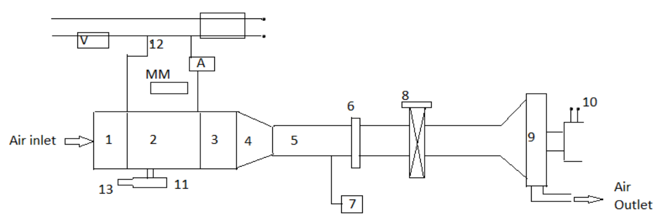

Figure 1 Detailed Parts of Experimental Setup

The Labeled Components are Listed Below

1. Entry section, 2. Test section, 3. Exit section, 4. Mixing plenum, 5. G. I. pipe, 6. Orifice plate, 7. U-tube manometer, 8. Control valve, 9. Centrifugal blower, 10. Electric motor, 11. Selector switch, 12. Voltage variac, 13. Temperature Indicator, V = Voltmeter and A = Ammeter

The experimental values of heat transfer coefficient and friction factor are compared with those obtained from the predicted values of Nusselt's number after using Dittus- Boelter's correlation published in hand book [23].

$$Nu_s = 0.023\ Re^{0.8}\ Pr^{0.4} \quad (1)$$
$$f_P = 0.085\ Re^{-0.25} \quad (2)$$

The graphs are drawn between the predicted values taken on abscissa vs experimental values taken along ordinate axis, for the values of Nusselt's number in Fig.2 and for friction factor in Fig. 3 respectively. From the Fig. 2, it is observed that the experimental values of Nusselt's number lie in the range of ± 10 % of the predicted values of Nusselt's number, and from Fig. 3 it is evident that the values of friction factor obtained experimentally lie within ± 7 % of its predicted values.

After satisfactory calibration of the system, actual tests were performed on the setup to obtain data for studying the effects of various operating parameters on the thermal performance of packed bed solar air collectors with rounded tip V-grooved absorber plate.

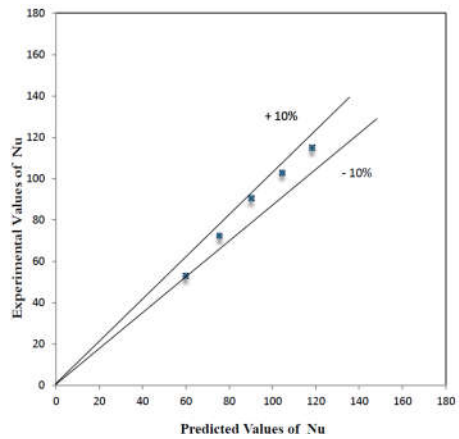

Figure 2 Comparison of Experimentally And Analytically Predicted Values of Nusselt's Number

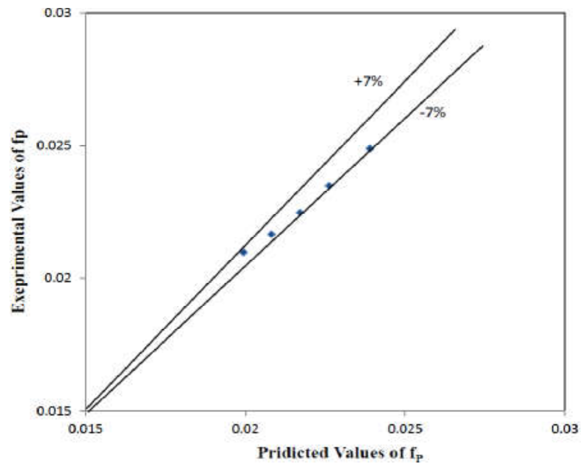

Figure 3 comparison of experimentally and analytically predicted values of friction factor

Thermal Performance Analysis

The following equations and correlations are used for determining values of various parameters in the analysis of thermal performance of rounded tip V-grooved solar air heater using packing in the duct flow passage. The steady state thermal efficiency of the solar air collector is given by:

$$\eta = \frac{Q_u}{IA} \quad (3)$$

Where Q_u = the useful heat gain is given by

$$Q_u = \dot{m} c_p \Delta T \quad (4)$$

The effective efficiency of the solar air collector is calculated using the following relation:

$$\eta_e = \frac{Q_u - \frac{P_m}{C}}{IA} \quad (5)$$

The mechanical power, P_m, required to force air through the duct is given by

$$P_m = Q_u . \Delta p \quad (6)$$

Here, the pressure drop, Δp, across the duct of length, L, can be determined from the following expression:

$$\Delta p = \frac{f_p \rho V^2}{2 r_h} \quad (7)$$

where, f_p has been calculated using the correlation reported in [14].

$$f_p = 2.484 \left[\frac{1}{nP}\left(\frac{P_t}{d_w}\right)\right]^{0.699} Re_p^{-0.44} \quad (8)$$

$$r_h = \frac{P d_w}{4(1-P)} \quad (9)$$

and

$$P = \frac{(V_o - Vs)}{V_o} \quad (10)$$

RESULTS AND DISCUSSION

In order to study the effect of operating parameters on the collector efficiency, various plots have been drawn between the collector efficiency and operating parameters. In order to arrive at some profound results, these are compared with corresponding results for conventional smooth duct collector.

Effect of Mass Flow Rate on Thermal Efficiency

The thermal efficiency plots are drawn taking efficiency along ordinate axis and mass flow rate on abscissa for rounded tip V-grooved absorber plate solar air collector with and without packing and are compared along with those of conventional flat plate collector. Fig. 4 represents the effect of mass flow rate on thermal efficiency for a fixed value of insolation taken to be I = 1100 W/m^2. It is observed from the graph that the thermal efficiency increases with increase in mass flow rate. This effect can be attributed to the fact that at higher mass flow rates turbulence increases causing increase in heat transfer rate, resulting into increased thermal heat gain.

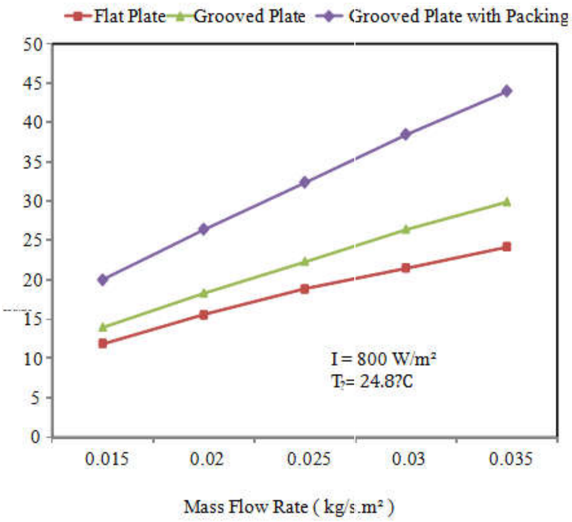

Figure 4 comparison of efficiency of solar air collector having grooved absorber plate with and without wire mesh packing along with flat plate collector at i = 1100 w/m^2.

It may be noticed that maximum efficiency of V-grooved solar collector with wire matrix packing is found to be 44.01% at mass flow rate 0.035 kg/s.m^2, compared to 29.92% for V-grooved absorber solar collector without packing, against 24.18 % for flat plate collector. Similarly, graphs are plot for similar configurations at I = 1200 W/m^2 in Fig. 5 where maximum efficiency is obtained as 52.43 % at mass flow rate 0.035 kg/s.m^2, which is 24.46 % greater than that for without packing.

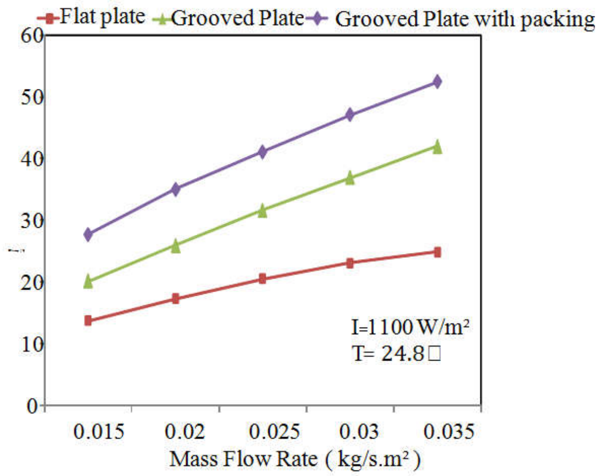

Figure 5 comparison of efficiency of solar air collector having grooved absorber plate with and without wire mesh packing along with flat plate collector at i = 1100 w/m^2.

Effect of Insolation on Thermal Efficiency

In order to evaluate the effect of insolation, Fig. 6 is drawn showing the effect of insolation on the efficiency of solar air collector having grooved absorber plate with and without packing for half groove angle $\psi = 50^o$ and its comparison with the efficiency of packed bed solar air collector having grooved absorber plate with $\psi = 30^o$. This behaviour of increase in efficiency in packed bed collector using grooved absorber plate with $\psi = 30^o$ is due to the fact that the incident energy gets absorbed to deeper bed depth there by keeping the top layer temperature low and hence reducing top losses. This energy absorbed to greater depth is utilized for heating the air which flows through the duct. It can be concluded from this figure that V- grooved collector with packing is more efficient than that without packing for both mass flow rates. This is obvious because the packed bed V-grooved collector is able to minimize losses as compared to the other configuration.

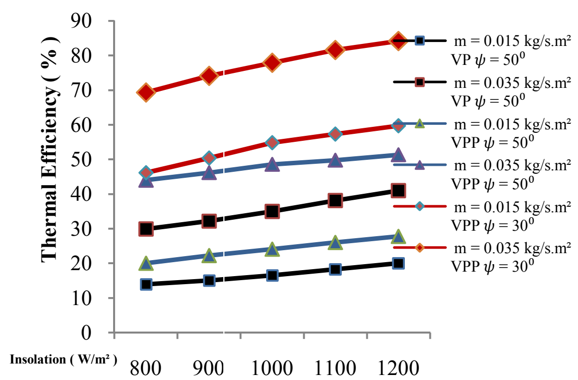

Figure 6 Effect of insolation W/m^2 on the efficiency of solar air collector having grooved absorber plate with and without packing

Effect of Mass flow rate on Effective Efficiency

In order to study the effect of mass flow rate on the effective efficiency, Fig. 7 and Fig. 8 have been drawn representing the efficiency along ordinate axis and mass flow rate on abscissa.

As observed from the graph that the thermal efficiency keeps on increasing with mass flow rate whereas effective efficiency first increases then decreases with mass flow rate. This is evident from the fact that with increase in mass flow rate, pumping power increases, causing an increase in losses. Thus the useful efficiency gain starts decreasing after attaining an optimum value.

Fig. 7 has been drawn on same basis for packed bed solar air collector using grooved absorber plate having $\psi = 30^0$. Here the optimum value of effective efficiency reaches 57.5% compared to thermal efficiency of 67.08% at mass flow rate of 0.02kg/s.m^2. Similarly, Fig. 4.8 depicts the efficiency plot for packed bed solar air collector having grooved absorber plate with $\psi = 50^0$. The best effective efficiency obtained is 29.45% at mass flow rate of 0.025 kg/s.m^2

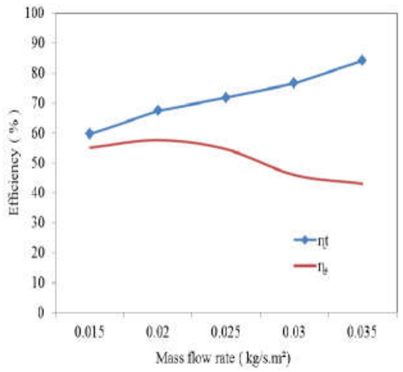

Figure 7 Effect of Pumping Power on Efficiency of Packed Bed Grooved Absorber Solar Air Heater With Absorber Plate Having $\psi = 30^0$

Effect of Mass Flow Rate on Outlet Temperature

In the Fig. 9, plot has been drawn to represent the effect of mass flow rate on air outlet temperature for plates with different geometrical parameters and compared with that of without packing. The maximum temperature is observed as 69.2^{0}C for packed bed solar air collector having grooved absorber plate with $\psi = 30^0$ at mass flow rate 0.015 kg/s.m^2 followed by 46.7^{0}C

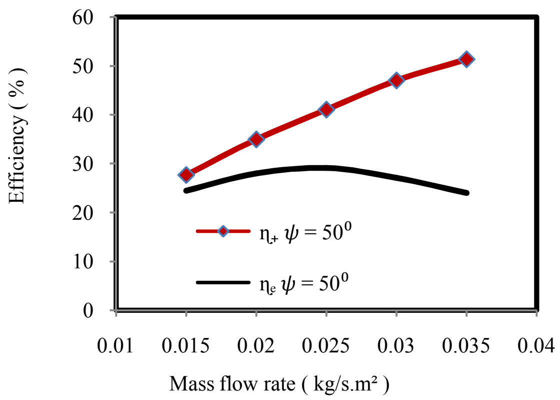

Figure 8 Effect of Pumping Power On Efficiency of V-Grooved Absorber Solar Heater With ABSORBER PLATE HAVING $\psi = 50^0$

for packed bed grooved solar collector having $\psi = 50^0$, against 41.2^{0}C for that without packing. Thus it can be inferred from the figure that deep grooves provide higher temperatures and better efficiency than shallow grooves due to increase in heat intercepting area. Further, packing improves both efficiency and outlet temperature. It is obvious that the air outlet temperature falls with increase in mass flow rate because of increase in air velocity; air takes lesser time to travel through the duct. The results obtained can be utilised for design considerations as elaborated in earlier literatures [25].

Effect of Geometry of Corrugation on Efficiency

The efficiency of packed bed solar air collector having V-grooved absorber plate with half V-angle $\psi=30^0$ is compared with the packed bed collector plate having half V-angle $\psi=50^0$, in Fig. 10 by drawing plot between efficiency vs mass flow rate. Here the former plate with $\psi=30^0$ is found to be more efficient than the plate having $\psi=50^0$. This can be understood from the fact that lesser angles provide deeper grooves on absorber plate, causing an increase in the effective heat transfer area, by allowing an increased access of useful heat gain to deeper bed depth. Increasing effective heat transfer area is one of the renowned methods for enhancement of collector efficiency.

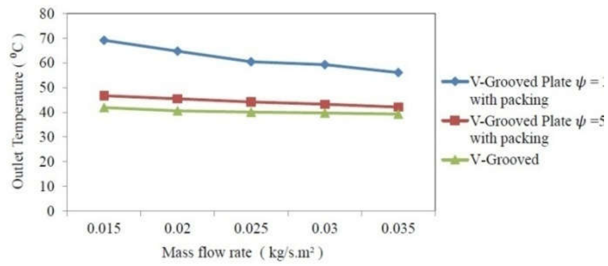

Figure 9 Effect of Mass Flow Rate on Outlet Temperature of Packed Bed V-Grooved Solar Sir Collector For Different Configurations At Air Inlet Temperature $T_i = 24.8^0C$

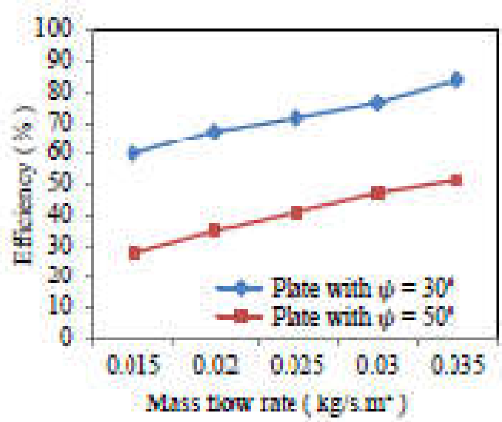

Figure 10 Effect of Mass Flow Rate on Efficiency of Packed Bed Solar Air Solar Air Having V-Grooved Absorber Plate With $\psi=30^0$ And $\psi=50^0$

CONCLUSIONS

The thermal performance of V-grooved absorber plate solar air collector having wire mesh matrix packing comes out to be higher than that compared to one without packing. However, the efficiencies obtained in these two configurations are much better than that of conventional collector. For mass flow rate 0.035 kg/s.m^2 the efficiency of collector having V-grooves varies from 29.01 % to 41.20 %, whereas efficiency of collector with groove and packing in the duct bed varies from 44.3 % to 51.7 %, corresponding to even lower efficiency of smooth collector. The percentage enhancement in efficiency of grooved absorber plate solar air collector lies in the range of 45.27 % to 68.4 % for the set of operating parameters, with air inlet temperature 24.8^0 C, in comparison to conventional collectors. The percentage enhancement in efficiency of grooved absorber plate with packing, as compared to without packing is observed to be 38.1 % at mass flow rate 0.015 kg/s.m^2 and insolation 1100 W/m^2, whereas for mass flow rate 0.035 kg/s.m^2 and insolation 1100 W/m^2 the efficiency increment is observed to be 24.9 %. Efficiency has also been found to be affected by the rate of incident solar radiation. It has been noticed that the efficiency increases with increase in value of insolation for all the collector configurations.

For packed bed grooved collector, efficiency increases from 44.01 % to 51.34 % as the insolation increases from 800 W/m^2 to 1200 W/m^2. Similarly, the grooved collector without packing shows efficiency increment from 29.92 % to 41.95 %, within the same insolation range, against the corresponding average value for smooth collector as 24.18 %. It has been observed that efficiency of collectors for all the configurations (ie., smooth, grooved without packing and grooved with packing) , the efficiency is dependent on mass flow rate.

The maximum efficiency obtained for grooved absorber plate ($\psi = 30^0$) solar air collector with duct bed packing is found to be 84.15 % as compared with that of 51.7 % for packed bed collector having grooved absorber plate with $\psi = 50^0$. This increment of 32.45 % in the collector efficiency is attributed to the combined yield effect of corrugations on absorber plate and duct packing.

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