Thermal performance analysis of perforated pin fin solar air heater

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Abstract. The present paper presents the thermal performance analysis of a perforated pin fin solar air heater. The width of channel is 1000mm and the height is 30mm. The analysis covers the following ranges: Fin spacing 40mm - 80mm, mass flow rate 30kg/hour – 180kg/hour and solar intensity 600 – 900 W/m². A comparative study has been carried out between the conventional solar air heater and perforated pin fin solar air heater. A mathematical model has been developed to find out the solution. Programming has been done using Mat lab software to obtain the results too find out the solution. The effects of mass flow rate of air on the outlet temperature and thermal efficiency were studied. The results have been compared with that of a conventional solar air heater. The results show substantial enhancement in the performance of the solar air heater with the addition of fins on the absorber plate. The maximum efficiency obtained for a conventional single pass solar air heater with mass flow rate of 30kg/hour was 19.22%. While the maximum efficiency obtained for a single pass solar air heater with perforated pin fin was 46.65%. The outlet temperature of 340.17K was obtained for conventional solar air heater and 393.22K was obtained for perforated pin fin solar air heater.

1. Introduction

Energy is the prime mover of economic growth and is vital to the sustenance of a modern economy. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible and environmentally friendly technology.

Apart from being freely available in nature, renewable energy resources can be used in a decentralized manner, reducing the cost of transmission and distribution of power. Conventional solar air heater consists of a flat plate collector with an absorber plate, transparent cover system at the top and insulation at the bottom and on the sides. Whole assembly is enclosed in a sheet metal container. Working fluid is air and the passage for its flow varies according to the type of air heater [1]. Materials for the construction of air heater are similar to the liquid flat plate collectors. Transmission of solar radiation through the cover system and its subsequent absorption in the absorber plate can be taken into
account by expressions identical to those of liquid flat-plate collectors. In order to improve collection efficiency, selective coating on the absorber plate can be used.

Bayram Sahin et al. [2] in their paper describe the heat transfer enhancement and corresponding pressure drop over a flat surface equipped with circular perforated pin fins in a duct of rectangular cross-section having sectional area of duct 100-250 mm². The experiment insures the following ranges; Reynolds number 135002-42000, clearance ratio (C/H) 0, 0.33 and 1 and inter fin spacing ratio (S/D) 1.208, 1.524, 1.944 and 3.417. The heat transfer, friction factor and efficiency of enhancement has been carried by correlation equations. The experimental results show that, the heat transfer enhancement lead by using circular cross section pin fins. The clearance ration and inter fin spacing ratio is based on the efficiency of enhancement varied between 1.4 and 2.6. An overview of the fin optimum shaping issue has been depicted by Snider and Kraus [3]. Meyer [4] in his famous book with a simple manner describes the temperature distribution in conventional fins. But in the recent years, porous fins have become an excellent passive means to provide high heat transfer rate for electronic components in a small, lightweight, low maintenance and energy free package. A good insight into the subject is given by Pop and Ingham [5], Nield and Bejan [6]. A simple method has been developed by Kiwan [7] to analyze the performance of porous fins in a natural convection environment. Bassam and Hijleh [8] investigated a problem of natural convection from a horizontal cylinder with multiple equally spaced high conductivity permeable fins on its outer surface. They concluded that porous fins provide much higher heat transfer rate than traditional fins. Gorla [9] and Kiwan [10] investigate thermal analysis of natural convection and radiation in porous fins of rectangular shape. Yu and Chen [11] performed a study on optimization of circular fin with variable thermal parameter. Saedodin and Olank [12] investigated the temperature distribution over fin surface and compared the results with conventional fins. For the analysis they have selected a pin fin subject to heat transfer in natural convection condition. From the through literature survey summarized above, it is apparent that a very few work is present about porous pin fin. In the present work it is intended to investigate the heat transfer enhancement of perforated pin fin and comparison of this with conventional solar air heater, investigate the enhancement of heat transfer and to investigate the effect of change in the efficiency of the system, useful heat gained by the system and the outlet temperature of air of the system due to change in the mass flow rate and solar flux.

2. Data processing

The convective heat transfer has been calculated using the energy balance equations. We assume that (i) the bulk mean temperature of the air changes from T₁ to (T₁ + dT₁), as it flows through the distance dx. (ii) the air mass flow rate is m. (iii) the mean temperature of the plate below are Tₚ and Tₚ respectively and their variation may be neglected. (iv) side losses and bottom losses is neglected.

Energy balance equations of perforated pin fin for the absorber plate, bottom plate and air stream can be written as:

For absorber plate:

\[
SA_p = U_t A_p \left( T_p - T_a \right) + h_r A_p (T_p - T_b) + h_f A_p (T_p - T_f) \frac{N_A f^p f i n}{A_p} \tag{1}
\]

For bottom plate:

\[
h_r (T_p - T_b) A_p = h_f (T_b - T_f) + U_b (T_b - T_a) \tag{2}
\]

For air stream:

\[
\frac{Q_u}{A_p} = h_f (T_p - T_f) + h_f (T_b - T_f) + \frac{N_A f^p f i n}{A_p} (T_p - T_f) \tag{3}
\]

After solving these equations, we find the collector efficiency factor F’ as

\[
F' = \frac{h_f \varphi (h_r + h_f) h_f h_r}{h_f (U_t + 2 h_r + h_f \varphi) + h_r U_t}
\]
Where \( \varphi = 1 + \frac{N A_f}{A_p} \)

The Nusselt Number correlation for the case without fin and with fin is taken as reference from Sahin [2]. It is as follows:

For smooth face, the Nusselt Number correlation is as follows;

\[
N_u = 0.077 R_e^{0.716} P_r^{0.33}
\]

For perforated pin fin the Nusselt Number correlation is as follows:

\[
N_u = 45.02 R_e^{0.390} (1 + \frac{C}{H})^{-0.556} (S y / D)^{-0.452} P_r^{0.33}
\]

3. Result and Discussions:

In Fig. 1 the effect of solar intensity on the outlet temperature of the system has been studied. The values of solar flux on the X-axis are being increased in step size of 50 from 600W/m² to 900W/m². The corresponding values of the outlet temperature have been plotted in the Y-direction. Outlet temperature values have been taken for three different configurations of the perforated pin fin and also the condition of conventional solar air heater. All the other factors have been kept constant. As seen in the graph, the temperature of air at the outlet rises in a linear pattern. This is because increase in solar flux intensity means increased useful heat gain. This implies that the outlet temperature is also increased as it is directly proportional to useful heat gain. The temperature of outlet air keeps on increasing at higher rate than the ambient temperature due to high absorption rate of solar radiation.
In Fig. 2, the effect of increasing mass flow rate on the outlet temperature of air has been studied. The values of mass flow rate on the X-axis are being increased in step size of 30 from 30 kg/hour to 200 kg/hour. The corresponding values of outlet temperature have been plotted in the Y-direction. Outlet temperature values have been taken for three different configurations of the perforated pin fin and also the condition of conventional solar air heater. Solar air heaters heat the air much more at the lower air rates, because the air has more time to heat up inside the collector. The curve of outlet temperature tends to increase with decreasing air mass flow rate. For a specific air mass flow rate at a constant ambient temperature, the outlet and inlet temperature increase with increasing solar intensity. The thermal efficiency of the heater improves with increasing air flow rates due to enhanced heat transfer to the air flow, while the temperature difference of fluid decreases.
In Fig. 3, the effect of mass flow rate on the top loss of the solar air heater has been studied. The top loss of the system at different values of mass flow rate of air has been calculated at different values of inter fin spacing. The values of mass flow rate on the X-axis are being increased in step size of 30 from 30kg/hour to 200kg/hour. The corresponding values of outlet temperature have been plotted in the Y-direction. Outlet Temperature values have been taken for three different configurations of the perforated pin fin and also the condition of conventional solar air heater. The reason for the significant decrease in outlet temperature with increase in mass flow rate can be attributed to changes in flow condition from laminar to turbulent. It could also be attributed to the fact that the lesser the duration that the air remains in the air heater, lesser is the top loss.
In Fig. 4, the effect of mass flow rate on the efficiency of the solar air heater has been studied. The efficiency of the system at different values of mass flow rate of air has been calculated at different values of inter fin spacing. The values of mass flow rate on the X-axis are being increased in step size of 30 from 30kg/hour to 200kg/hour. The corresponding values of efficiency have been plotted in the Y-direction. Efficiency values have been taken for three different configurations of the perforated pin fin and also the condition of conventional solar air heater. The reason for the significant increase in efficiency with increase in mass flow rate can be attributed to changes in flow condition from laminar to turbulent. It could also be seen that the slope of the efficiency curve decreases, meaning decrease in loss coefficient, with increase in mass flow rate the change in different values of fin spacing has relatively less effect on the efficiency of the system. This is because the increase /decrease in the fin spacing will result in the increase/decrease of the total fin area for heat transfer. This value is very small as compared to the total area exposed to heat transfer. The efficiency is highest for the least fin spacing and lowest for the highest value of fin spacing. This is because lesser spacing means more fins. More fins bring about more surface area and turbulent flow, thus higher efficiency.

4. Conclusion:
This paper reports a comparative theoretical analysis of a conventional solar air heater and perforated pin fin solar air heater. This paper focuses on efficiency enhancement with respect to varying mass flow rate under different scenario, variation in top loss and outlet temperature at different mass flow rate and variation in outlet temperature with varying solar intensity. Our findings can be summarized as follows:

- The indicated results show that the efficiency always increases with increasing the mass flow rate for the range of the flow rate used in this work. The maximum efficiency obtained for a conventional solar air heater with mass flow rate of 30kg/hour is 19.22% and for 180kg/hour is 47.061%.
• While the maximum efficiency obtained for a solar air heater with perforated pin fin at 30kg/hour is 46.96% and for 180kg/hour is 75.105%
• The outlet temperature of conventional solar air heater is 340.17K 30kg/hour of mass flow rate and 318.17K for 180kg/hour of mass flow rate.
• For solar air heater with perforated pin fin the outlet temperature at 30kg/hour is 393.84K and 327.21K for 180kg/hour of mass flow rate. There is a decrease in outlet temperature because at higher mass flow rate the air has less time to heat up.
• The collector efficiency factor for solar air heater with perforated pin fin at 30kg/hour is 0.9895 and for 180kg/hour is 0.9970. For conventional solar air heater, the collector efficiency factor at 30kg/hour and 180kg/hour is 0.28932 and 0.6128 respectively.
• The top loss at 30kg/hour for conventional solar air heater is 7.7409W/m² and top loss for perforated pin fin solar air heater is 6.9786 W/m².
• The outlet temperature of conventional solar air heater increased from 329K to 340K due to increase of solar intensity from 600W/m² to 900W/m². The increase in outlet temperature of perforated pin fin solar air heater is from 364.75K to 393.95K due to increase of solar intensity from 600W/m² to 900W/m². In both the cases the mass flow rate has been kept at 30kg/hour.

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