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Effect of depth ratio on the thermal performance of double flow packed bed solar air heater

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Abstract

In this paper double flow packed bed solar air heater has been investigated theoretically. The effect of air mass flow rate, porosity and different depth ratios at study state conditions on the thermal performance of a double flow packed bed solar air heater is found by using the alternative simulation system. Comparisons between the measured thermal and effective thermal efficiency of the double flow packed bed and double flow without packed bed solar air heaters were also presented. The problem has been solved by the Finite Difference Method. The results showed that the thermal efficiency increases by 78.8 % in double flow mode with porous media than double flow without porous media at the mass flow rate of 0.05 kg/s at the bed porosity of 92%.

Keywords- Packed bed; Porosity; Heat Transfer; Thermal efficiency; double flow solar air heater

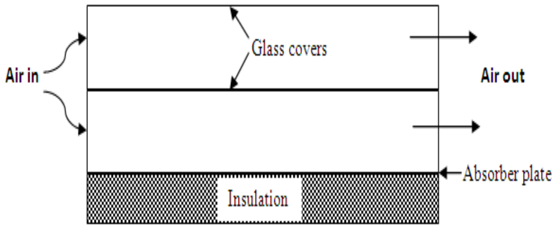
Introduction

Conventional type solar air collectors are designed to provide maximum amount of heat at lower cost. These types of solar air collectors collect solar energy and because of low operating and maintenance cost, they are widely used as a heating media. Useful heat energy from flat plate solar air heaters can be used in many thermal applications in drying agricultural products such as in seeds, fruits, and vegetables and residential also some time in industries and as a auxiliary heater for heating building in winter time. Mohammad [1] presented an analysis for novel type solar air heater. Study by Ramani, B.M. et al.[2] demonstrates that double pass counter flow solar air heater with porous material in the second air passage is one of the important and attractive design improvement that yields better thermal performance. Thermal performance of a double-pass solar air heater with packed bad above the heater absorber plate was investigated experimentally and theoretically by Ramadan et al. [3]. The thermal performance of a double glass, double pass solar air heater with a packed bed in the lower channel was investigated experimentally and theoretically by EI-Sebaii, et al. [4], Aldabbagh et al. [5]. To study the heat transfer characteristics and performance of the double pass flat plate solar air heaters with or without porous media numerically Naphon, P et al.[6]. In the present work, a mathematical model capable of providing the numerical solution to predict the thermal performance of a double flow solar air heater with or without packed bed is developed. Materials such as wire mesh screens, iron scrap are considered. Therefore, mathematical model is solved by use of forward difference technique of finite difference scheme and examined by using a constructed computer program that uses an iterative solution procedure.

Mathematical model

In the present work double flow with or without packing solar air heaters are discussed. Packing is considered in the lower channel. Models consist of two glass covers and an insulated absorber or back plate. Double flow passage is made through between two glass covers (upper and lower) and between lower glass covers and absorber or back plate as shown in fig.1. In the present study first a mathematical model is obtained by the application of the governing conservation laws.

The heat balance is accomplished across each component of a given air heater, i.e., the glass covers, the air streams in both of the upper and lower channels, for the absorber plate in case of double flow without packing and for the back plate in case of double flow with packing in the lower channel. It is assumed that air velocity in the channel at any section is constant, the flow of heat is one-dimensional and steady, heat loss across the sides of the duct is very small and hence neglected, no conduction inside the heater, the porous absorber and the air stream are in thermal equilibrium because the value of volumetric heat transfer coefficient in the pores of the porous matrix is very high.



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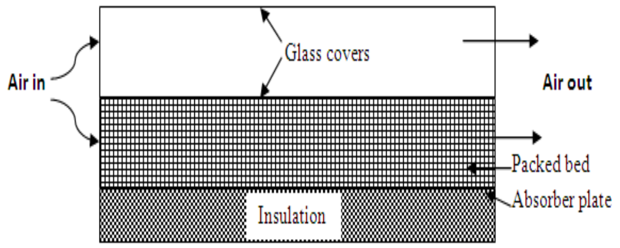
Model of double flow solar air heater without porous media or packing (DFSAHWOP).



(B)
Model of double flow packed bed solar air heater (DFPBSAH) in the lower channel.

Fig.1 (A) Model of double flow solar air heater without porous media, (B) Model of double flow solar air heater with porous media.

Hence the energy balance equations for solar air heater models are written as.

2.1 Energy balance equation for double flow solar air heater without porous media.

For upper glass cover

$$I\alpha_{gu} = [h_{r(gu-a)} + h_w](T_{gu,i} - T_a) + h_{r(gu-gl)}(T_{gu,i} - T_{gl,i}) + h_{c(gu-fu)}(T_{gu,i} - T_{fu,i}) \quad (1)$$

For lower glass cover

$$I\alpha_{gl}\tau_{gu} = [(h_{r(gl-gu)} + h_{c(gl-gu)})](T_{gl,i} - T_{gu,i}) + [h_{r(gl-p)}(T_{gl,i} - T_{p,i})] + h_{c(gl-fu)}(T_{gl,i} - T_{fu,i}) \quad (2)$$

For flow in upper channel

$$\frac{mC_p}{w}\frac{(T_{fu,i+1} - T_{fu,i})}{\Delta x} = h_{c(gl-fu)}T_{gl,i} + h_{c(gu-fu)}T_{gu,i} - (h_{c(gl-fu)} + h_{c(gu-fu)})T_{fu,i} \quad (3)$$

For flow in lower channel

$$\frac{mC_p}{w}\frac{(T_{fl,i+1} - T_{fl,i})}{\Delta x} = h_{c(b-fl)}(T_{p,i} - T_{fl,i}) + h_{c(gl-fl)}(T_{gl,i} - T_{fl,i}) \quad (4)$$

For absorber plate

$$I\alpha_p\tau_{gu}\tau_{gl} + h_{r(gl-p)}(T_{gl,i} - T_{p,i}) = h_{c(p-fl)}(T_{p,i} - T_{fl,i}) + U_p(T_{p,i} - T_a) \quad (5)$$

Energy balance equation for double flow solar air heater with porous media in lower channel.

Equations (1) and (3) are same for double flow solar air heater with packed bed in lower channel. So the energy balance equations for packed bed, flow in lower channel and for absorber plate are written as.

For lower glass cover

$$I\alpha_{gl}\tau_{gu} = [(h_{r(gl-gu)} + h_{c(gl-gu)})](T_{gl,i} - T_{gu,i}) + [h_{r(gl-m)}(T_{gl,i} - T_{m,i})] + h_{c(gl-fu)}(T_{gl,i} - T_{fu,i}) \quad (6)$$

For porous matrix (packed bed)

$$I\alpha_m\tau_g\tau_{gl} = h_{r(m-p)}(T_m - T_p) + h_{r(m-gl)}(T_m - T_{gl}) + h_{c(m-fl)}(T_m - T_{fl})A_m \quad (7)$$

For flow in lower channel

$$\frac{mC_p}{w}\frac{(T_{fl,i+1} - T_{fl,i})}{\Delta x} = k_p\delta_p\frac{(T_{fl,i+1} - 2T_{fl,i} + T_{fl,i-1})}{\Delta x^2} + h_{c(gl-fl)}(T_{gl,i} - T_{fl,i}) + h_{c(p-fl)}(T_{p,i} - T_{fl,i}) + h_{c(m-fl)}(T_{m,i} - T_{fl,i}) \quad (8)$$

For absorber Plate

$$h_{r(p-m)}(T_{m,i} - T_{p,i}) = h_{c(p-fl)}(T_{p,i} - T_{fl,i}) + U_p(T_{p,i} - T_a) \quad (9)$$

Calculation methods

The above assumptions are based upon the fact that the volumetric heat transfer coefficient in solid matrix is very high. Effective thermal conductivity (k_p) value changes from 5-20 times the air thermal conductivity, but the effect on the results of simulation is significant. Hence, k_p is set to 0.3 W/mK (Mohamad [1]).The meanings of all symbols and notations of various heat transfer coefficients in equations (1) – (9) of the different elements of the solar air heater given as: $h_{r(gu-gl)}, h_w, h_{r(gl-gu)}, h_{c(gl-fu)}, h_{r(gl-m)}, h_{r(p-m)}, h_{r(p-b)}, h_{c(p-fl)}$ and $h_{c(b-fl)}$, and calculated using the correlations given in literature Garg et al. [7].

The convective heat transfer coefficient for air flowing over the outside surface of the glass cover is proposed by McAdams [8] as follows:

$$h_w = 5.7 + 3.8V \quad (10)$$

Nu_m is the Nusselt number for the packed bed and is given by

$$Nu_m = 0.2Re_m^{0.8}Pr^{1/3} \quad (11)$$

Equations (1), (2), (5), (6), (7) and (9) are solved simultaneously to give the expressions for nodal temperatures, $T_{gl,i}, T_{gu,i}, T_{m,i}$, and $T_{p,i}$ respectively. Guass elimination technique is used to solve the Equations for $T_{gu,i}, T_{gl,i}, T_{m,i}$ and $T_{p,i}$ as given in Boyce et.al. [9].

Following boundary conditions (B.C.) were applied:

B.C. for double flow solar air heater with or without packed bed in lower channel

$T_{fu}|_{x=0} = T_a$, $T_{fl}|_{x=0} = T_a$,

Following parameters are considered;

length of solar air heater, L = 2.2 m, width of solar air heater, W = 0.45 m

depth of the upper channel, d_u = 0.025 m, 0.04 m, 0.06 m depth of the lower channel, d_l= 0.025 m,

Channel depth ratio, $r\left(\frac{d_u}{d_l}\right)$ = 1.0, 1.6, 2.4 transmissivity of the glass covers, τ_{gu}, τ_{gl} = 0.92

absorptivity of the glass covers, α_{gu}, α_{gl} = 0.05, absorptivity of the porous material, α_m = 0.95

absorptivity of the absorber plate, α_p = 0.95, Total air mass flow rate, m = (0.02kg/s -0.1 kg/s) porosity of the porous media, ϕ = 0.92 to 0.96

conductivity of the wire mesh screens, k_m = 0.3W/m-k

Results and discussions

Thermal performance of double flow solar air heaters with or without packing are investigated theoretically. All of the models are predicted for various mass flow rates ranging from 0.01 to 0.05 kg/s and for various ranges of porosity 92-96%. Obtained results then compared with each others to check the best performance among all of the heaters models. Thermal performance for double flow with or without porous media is checked on $m_{fu} = \frac{m}{2}, m_{fl} = \frac{m}{2}$ $and\ m = m_{fu} + m_{fl}$.

Fig. 4.1 shows the comparison of thermal efficiency of DFPBSAH having bed porosity of 92% for the different depth ratios and with DFWOPSAH. It is found that the thermal efficiency of DFPBSAH is higher at the particular mass flow rate when the depth ratio is 1 in comparison to the other values of depth ratios i.e. 1.6 and 2.4 of DFPBSAH and DFWOPSAH and found to be 77.6 and 43.4 % respectively. At the lower value of depth ratio, the average velocity/ Reynolds No. increases result in increase in heat transfer coefficient between the surface and the fluid leading to higher thermal efficiency. Similarly, the Figs. 4.2 to 4.5 show the comparison between the DFPBSAH and DFWOPSAH for varying bed porosities ranging from 93 to 96%. It is noted that the thermal efficiency of the DFPBSAH decreases with increase in bed porosity at particular mass flow rate and depth ratio. It is observed that thermal efficiency of DFPBSAH is significantly higher compared to plain collector, DFWOPSAH and also observed that the thermal performance of DFWOPSAH is greatly influenced by porosity.

The effect of equal mass flow rate on the effective thermal efficiency of DFPBSAH and DFWOPSAH is presented in Figs. 4.9 to 4.13. It is observed that the increase in effective thermal efficiency of DFPBSAH is insignificant at the higher mass flow rate depending upon the bed porosity and depth ratio. The maximum effective thermal efficiency is predicted to be 64.9% at the mass flow rate of 0.02 kg/s (total mass flow rate of 0.04kg/s) and depth ratio of 1 when the bed porosity is 92% as shown in Fig. 4.9 and the corresponding thermal efficiency is 66.5% as shown in Fig. 4.1 for the same operating conditions. As the mass flow rate increase beyond this value, the effective thermal efficiency of DFPBSAH starts decreasing. This may be due to the reason that energy required to overcome the friction losses increases sharply with the increase in mass flow rate; the rate of increase of thermal energy gain and friction losses are, not proportional, i.e. the heat transfer coefficient increase being proportional to a power less than one of the mass flow rate, while the friction losses increasing with the square of the mass flow rate. Consequently, at higher mass flow rate, the rate of increase of thermal energy gain is lower in comparison to the rate of increase of friction losses, i.e. a region where the actual thermal energy gains are not commensurate with the expenditure in power losses [10].

Similarly, the maximum effective thermal efficiency of DFPBSAH is predicted to be 64.5% at the mass flow rate of 0.03 kg/s (total mass flow rate of 0.06 kg/s) and the bed porosity is 92% when depth ratio of 1.6 as shown in Fig. 4.9 and the corresponding thermal efficiency is 68.7% as shown in Fig. 4.1 for the same operating conditions whereas, the effective thermal efficiency of DFWOPSAH for the same operating conditions is predicted as 41.7%. For the higher bed porosity of 96%, the maximum effective thermal efficiency of DFPBSAH is obtained as 52.7% for total mass flow rate of 0.06 kg/s and depth ratio of 1 as shown in the Fig. 4.13.

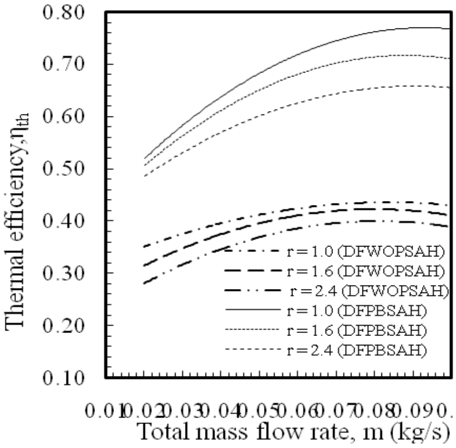


Fig.1 Effect of mass flow rate on the thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 92%)

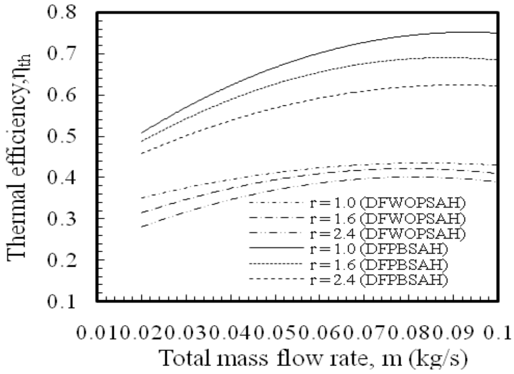


Fig.2 Effect of mass flow rate on the thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 93%)

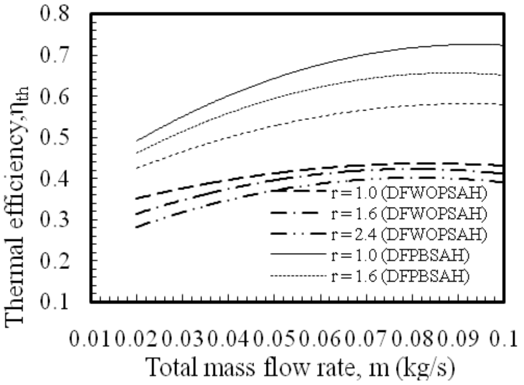


Fig.3. Effect of mass flow rate on the thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 94%)

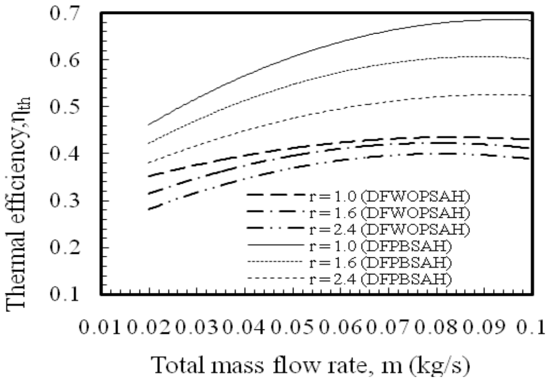


Fig.4 Effect of mass flow rate on the thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 95%)

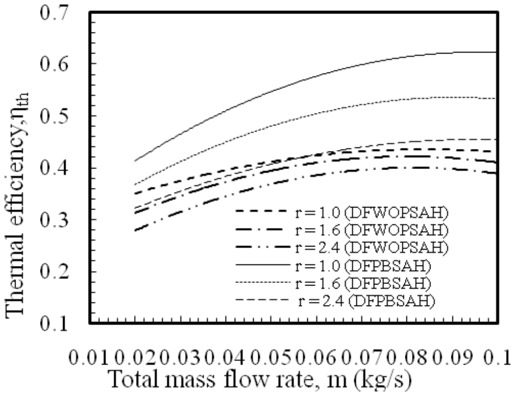


Fig.5 Effect of mass flow rate on the thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 96%)

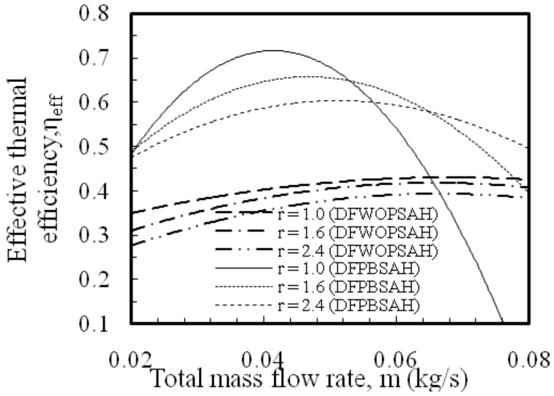


Fig.9 Effect of mass flow rate on the effective thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 92%)

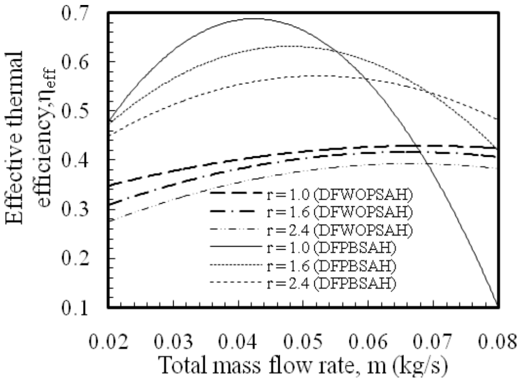


Fig.10 Effect of mass flow rate on the effective thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 93%)

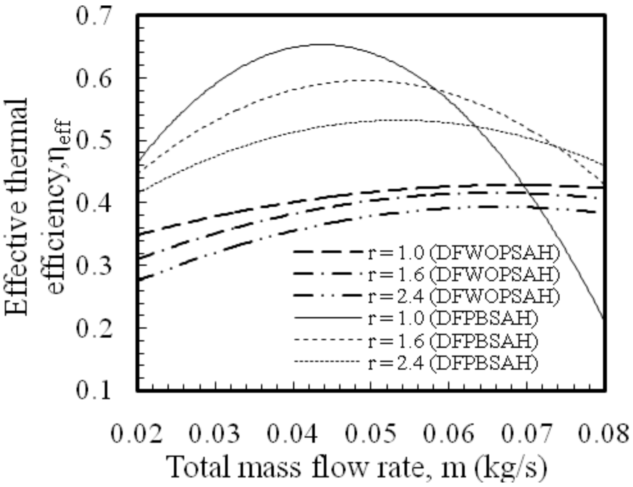


Fig.11 Effect of mass flow rate on the effective thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 94%)

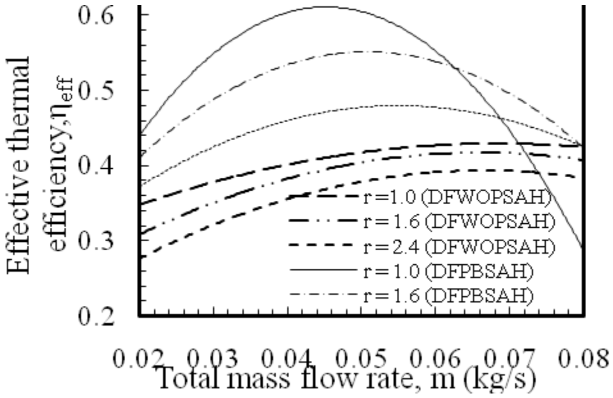


Fig.12 Effect of mass flow rate on the effective thermal performance of DFPBSAH and DFWOPSAH (r = 1.0, 1.6 and 2.4, ϕ = 95%)

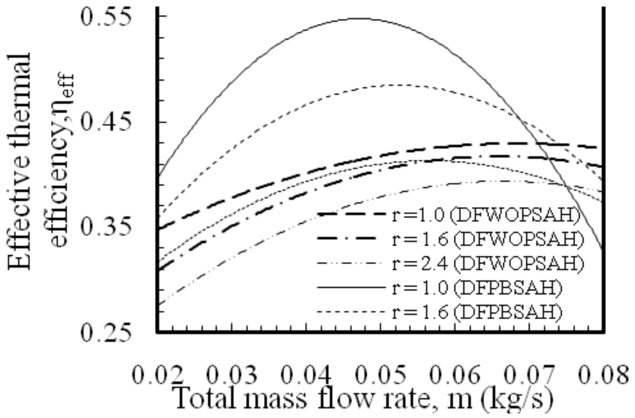


Fig.13 Effect of mass flow rate on the effective thermal performance of DFPBSAH and DFWOPSAH at (r = 1.0, 1.6 and 2.4, ϕ = 96%).

Conclusion

The advantages of present numerical simulation for investigating the performance of double flow packed bed solar air heater are that it can produce extremely large volumes of results at virtually no added expense and it is very cheap to perform parametric studies to optimize equipment performance. In the present study an attempt has been made to optimize the thermal performance of double flow packed bed solar air heater. Thermal efficiency of double flow solar air collector with porous absorbing material is about 78.8% higher than that of double pass solar air collector without porous absorbing material at the mass flow rate of 0.05 kg/s, bed porosity of 92% for the range of parameter investigated. Effective thermal efficiency of DFPBSAH is obtained maximum at the mass flow rate 0.02 kg/s (total mass flow rate of 0.04 kg/s) and starts decreasing beyond this mass flow rate. It is recommended to operate the system with and without packed bed with values of mass flow rate of 0.02 kg/s or lower to have a lower pressure drop across the system and therefore, a reasonably high effective thermal efficiency.

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