Simulation Studies on Porous Medium Integrated Dual Purpose Solar Collector

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Abstract- Solar air heating is a sustainable option for obtaining thermal energy over a varying temperature range. Design and operation of such systems must focus on the energy performance for their wider acceptability. The present work concentrates on the incorporation of porous medium to improve the thermal performance of a dual purpose solar collector. Dual purpose solar collectors can be used for heating air and water simultaneously using incident solar radiation resulting in optimum usage of energy and space. A simulation study is undertaken to investigate the integration of a porous matrix to dual purpose collectors. The porous matrix is incorporated below the absorber plate of the collector to improve the thermal performance of the overall system. The total thermal efficiency of the modified collector is found to vary from 34.60% to 46.03% over inlet water temperature range of 30°C to 90°C. Comparison of the proposed dual purpose solar collector with an existing design clearly indicates the advantage of incorporating the porous medium in terms of enhanced heat delivery and thermal efficiency.

Keywords- Dual Purpose Solar Collector, porous medium, air heater, water heater, fluent.

1. Introduction

Solar air heating is a sustainable option for meeting thermal energy demands for low temperature drying applications. Studies on performance analysis of varied designs of such systems have been extensively reported. Chamoli et al. [1] had presented a review on the performance on double pass solar air heaters. It has been observed that amongst various methods adopted for augmenting the heat transfer, incorporation of porous media had resulted in significant improvements in the thermal performance of the collectors. Mohamad [2] investigated heat transfer in single-pass, two cover solar air heater integrated with porous matrix and had reported collector efficiency of 75% under normal operating conditions. Naphon [3] developed mathematical model for two-pass air heaters with porous media and proved analytically that system thermal efficiency increases by 25.9% with the porous media insert. Parametric investigations on the effect of porous medium on double pass solar collectors had been reported by Sopian et al. [4]. Languri et al. [5] studied two pass heaters with and without porous medium. Results of their study showed that the incorporation of porous medium resulted in an increase of 30% in thermal efficiency.

It is observed that in many fluid heating applications, it is desirable to have options for simultaneous heating of air and water streams. A dual purpose solar collector is a novel solar energy conversion device which can be used for simultaneous heating of water and air streams [6]. The system essentially relies on a basic flat plate collector with appropriate design changes to accomplish these tasks. Adequate heat delivery and optimisation of space are possible with this type of integrated system. Dual purpose solar collectors have the potential to find applications in diverse areas like building air and water heating, process heating applications etc. Assari et al. [7] had presented basic theoretical and experimental investigations on dual purpose solar collector. The focus of the present work is on the performance enhancement of a dual purpose solar collector integrated with a porous matrix. Numerical simulations of the modified system are undertaken to suggest the design improvements for the system. With the help of illustrative examples, the proposed system is compared with existing design of a dual purpose solar collector.

2. Modified Dual Purpose Solar Collector

The thermal performance of a dual purpose solar collector (DPSC) may be improved by incorporating a porous matrix into the collector system. To illustrate the advantages of such a modification, an existing dual purpose solar collector is numerically analysed for its thermal performance after incorporating the modification through system simulation approach. The basic collector design as detailed by Assari et al. [7] is utilized in the current study. The schematic diagram illustrating the basic dual purpose collector is given in Figure 1.

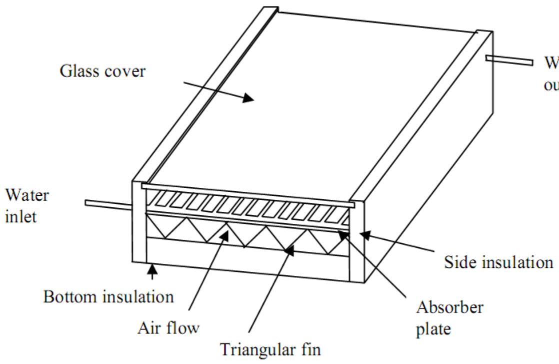

Fig. 1. Schematic of a basic Dual Purpose Solar Collector

The DPSC is essentially a flat plate collector made up of two sections, one for water heating and other for air heating. The liquid collector part consists of a set of parallel pipes bonded above the absorber plate and connected to two main inlet and outlet ports. There are three fluid streams through the collector, comprising of water flowing through the collector tubes and two air streams above and below the absorber plate. For a proper comparison, the dimensions of the modified collector are maintained exactly as reported in a basic study of DPSC by Assari et al. [7]. The schematic diagram of the modified dual purpose collector is shown in Figure 2.

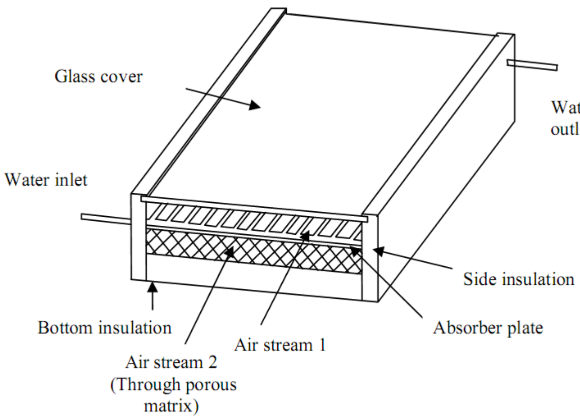

Fig. 2. Schematic of the proposed Dual Purpose Solar Collector

The proposed dual purpose solar collector has additionally a matrix of porous medium below the absorber plate. Two streams of air flow above and below the absorber plate while water circulates through the collector tubes. It may be noted that the proposed system is modified with respect to the original system in terms of the porous matrix and the additional air stream above the absorber plate. The air stream above the absorber plate is indicated as air flow 1 and that through the porous matrix is indicated as air flow 2. The cross sectional view of the proposed dual purpose collector is given in Figure 3.

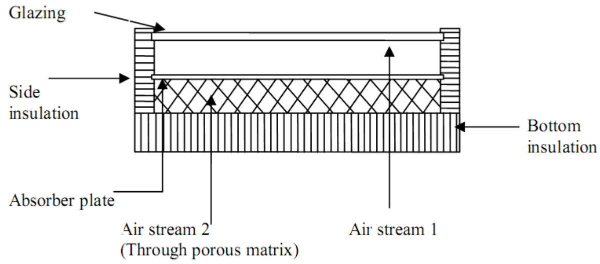

Fig. 3. Cross sectional view of the proposed Dual Purpose Solar Collector

Table 1 gives the details of the materials used for the collector.

Table 1. Collector component materials

Collector component	Material
Main frame	Stainless steel
Absorber plate	Aluminium
Glazing	Float glass
Side insulation	Silicon rubber
Bottom insulation	Glass wool

3. System Modelling and Simulation

System modelling and simulation of the proposed dual purpose collector was carried out using the software ANSYS 13 [8]. The pre-processor GAMBIT [8] was used for creating the geometry and for meshing. The computational analysis has been carried out using the Fluent [8] solver available in ANSYS 13 [8]. The major steps involved in simulation are indicated through a flowchart in Figure 4. In the meshing step, higher mesh density was applied to those regions where greater gradient of the parameters were expected. The continuum and boundary conditions were then appropriately defined. The export of the mesh to Fluent [8] solver and checking the mesh for errors was carried out in the problem set up stage. The solution step involved appropriate model selection for the problem, selection and definition of the material properties, defining of the boundary conditions and operating conditions. The computational domain considered for the analysis is illustrated in Figure 5.

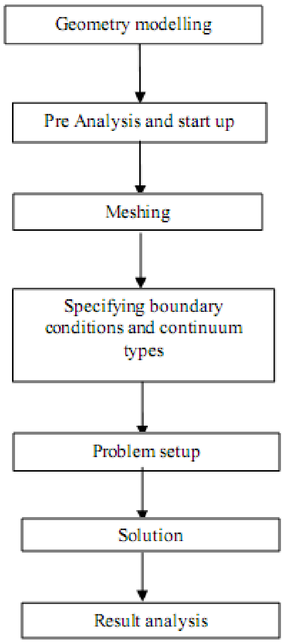

Fig. 4. Simulation methodology

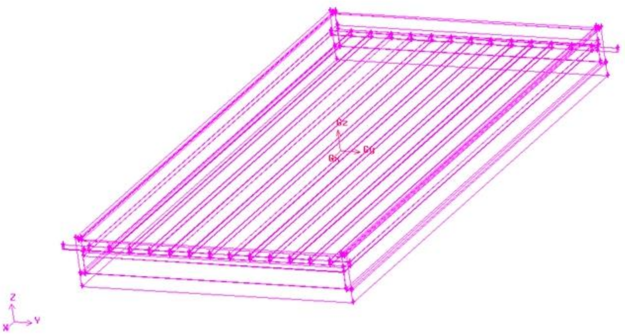

Fig. 5. Computational domain

3.1. Numerical Model

The fluid flow has been modelled using the incompressible Navier-Stokes equation. The relevant governing equations of mass and momentum are given as:

$$\frac{\partial}{\partial t}(\rho)+\nabla.\left(\rho\vec{v}\right)=0 \quad (1)$$

$$\frac{\partial\left(\rho\vec{v}\right)}{\partial t}+\nabla.\left(\rho\vec{v}\vec{v}\right)=-\nabla p+\nabla.\left(\bar{\bar{\tau}}\right)+\vec{F} \quad (2)$$

where ρ is fluid density (kgm^{-3}), $\vec{v}$ is velocity vector (ms^{-1}), p is static pressure (Pa), $\bar{\bar{\tau}}$ stress tensor and $\vec{F}$ external body force (Nm^{-3}). For the porous medium, (assuming isotropic porosity γ and single phase flow), the volume averaged mass and momentum conservation equations are as follows:

$$\frac{\partial}{\partial t}(\gamma\rho)+\nabla.\left(\gamma\rho\vec{v}\right)=0 \quad (3)$$

$$\frac{\partial\left(\gamma\rho\vec{v}\right)}{\partial t}+\nabla.\left(\gamma\rho\vec{v}\vec{v}\right)=-\gamma\nabla p+\nabla.\left(\gamma\bar{\bar{\tau}}\right)-\left(\frac{\mu}{\alpha}+\frac{R\rho}{2}\left|\vec{v}\right|\right)\vec{v} \quad (4)$$

where μ is fluid viscosity (Pa.s), α is permeability (m^2) and R the inertial factor (m^{-1}). Fluent [8] solves the energy equation in the following form (without porous media):

$$\frac{\partial\left(\rho E_f\right)}{\partial t}+\nabla.\left(\vec{v}\left(\rho E_f+p\right)\right)=\nabla.\left(k_{eff}\nabla T-\sum_j h_j\overline{J_j}+\left(\tau_{eff}.\vec{v}\right)\right)+s \quad (5)$$

Here E is total fluid energy (J), k_{eff} is effective thermal conductivity (Wm^{-1}K^{-1}), T is temperature (K), h sensible enthalpy (Jkg^{-1}), J is diffusion flux (mols^{-1}m^{-2}) and s is fluid enthalpy source term (J). The energy equation corresponding to the porous medium is given by:

$$\frac{\partial\left(\gamma\rho E_f+(1-\gamma)\rho_s E_s\right)}{\partial t}+\nabla.\left(\vec{v}\left(\rho E_f+p\right)\right)=\nabla.\left(k_{eff}\nabla T-\sum_j h_j\overline{J_j}+\left(\tau_{eff}.\vec{v}\right)\right)+s \quad (6)$$

It may be noted that subscripts f and s refer to fluid and solid respectively and j refers to species in equations 5 and 6. Following are the simplifying assumptions considered for the analysis: (i) prevalence of quasi-steady state for the system (ii) negligible convection losses from glass cover to atmosphere and radiation losses from glass cover to sky. The standard viscous-turbulent (k-epsilon model) and the SIMPLE solution algorithm was used for the numerical simulations [8]. The solar irradiance on the absorber plate S (Wm^{-2}) has been estimated by the following relation:

$$S=I_T(\tau\alpha)_{av} \quad (7)$$

where I is solar irradiance on the glass cover (Wm^{-2}) and $(\tau\alpha)_{av}$ represent the average transmissivity-absorptivity product of the glass cover.

4. Simulation Results

The simulation results for the modified dual purpose collector are presented in this section. The plot showing the magnitudes of velocity for the two air streams and the water stream along the x direction is given in Figure 6.

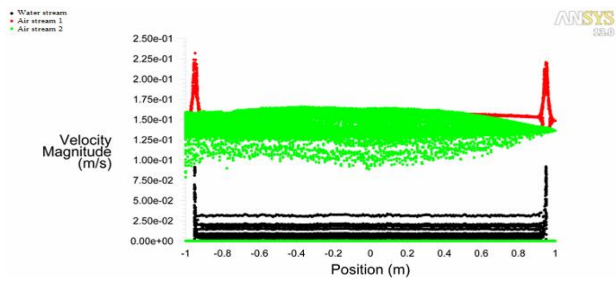

Fig. 6. Velocity variation for the fluid streams along the flow direction

The axis is assumed to be at the centre of the computational domain. The total length of collector is 2 m and position 1 on the plot corresponds to the flow inlet position while -1 indicates the flow outlet. As the circulation of water is due to natural convection, the magnitude of water velocity is low along the tubes. For the air stream through the porous matrix, velocity magnitude increases as the flow progresses until it becomes fully developed. The air stream above the absorber plate shows an increase in velocity near the inlet and outlet owing to reduction in cross sectional area of flow passage due to the presence of header pipes.

It is of interest to study the temperature variation of the fluid streams along the collector in the flow direction. The temperature distributions for the three streams are plotted separately in the form of contour plots. The system simulation is carried out for the following conditions specified: solar irradiance on the collector plane: 700 W/m2, mass flow rate of air: 0.01 kg/s, mass flow rate of water: 0.01 kg/s, inlet air temperature: 27°C and inlet water temperature: 27°C. The temperature distribution for the air stream above the collector plane is given in Figure 7. For a clearer understanding of the temperature variation, the view as observable from the bottom plane is also illustrated in Figure 8.

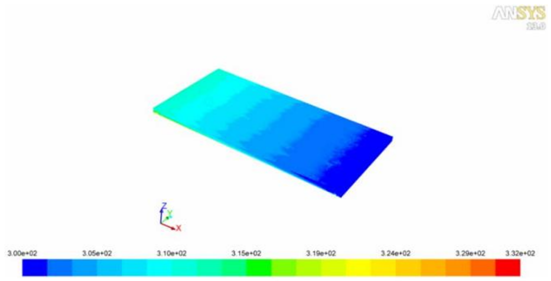

Fig. 7. Temperature contour plot for air stream 1 (view from top)

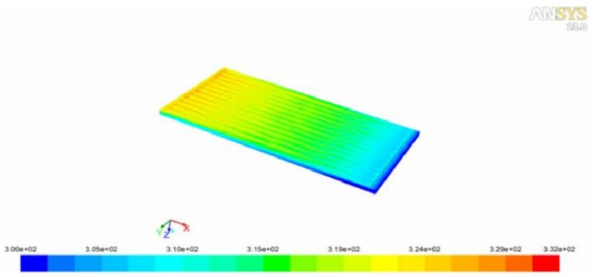

Fig. 8. Temperature contour plot for air stream 1 (view from bottom)

A net temperature rise of 14.3°C is obtained for this stream under the given conditions. The temperature contour shows variation along the z direction. Higher temperature is obtained along the absorber plate along the region where the tubes are present. This is attributed to the superior thermal properties of the absorber plate. Lower temperature is observable along the glass cover. The variation of the temperature of air along the bottom of the absorber plate through the porous medium matrix is illustrated in Figure 9.

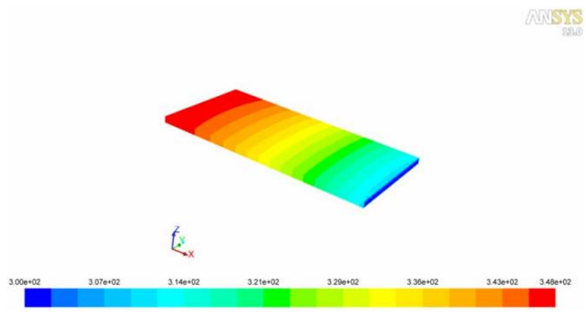

Fig. 9. Temperature contour plot for air stream 2

A value of 0.7 is taken for the porosity for this simulation run. A higher temperature rise of 48 °C is obtained for this air stream indicating clearly the advantage of the porous matrix. The temperature variation across the z direction is not significant. The variation of temperature for water in the tubes is illustrated in Figure 10. About 11.1 °C rise in water temperature is obtained for the specified simulation conditions.

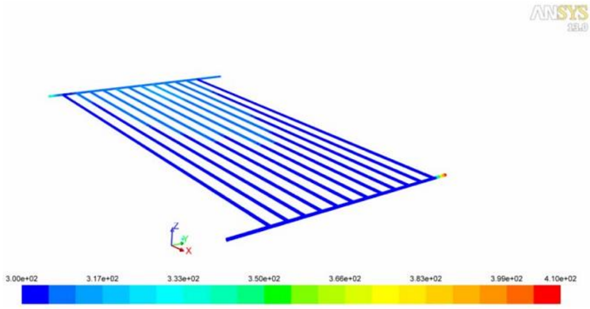

Fig. 10. Temperature contour plot for water flowing through tubes

4.1. Comparison with an Existing Dual Purpose Solar Collector

The performance of the modified dual purpose collector is compared with the available data for an existing design [7]. The temperature rise of the air stream (air stream 2) for the proposed system and the existing system are shown in Figure 11.

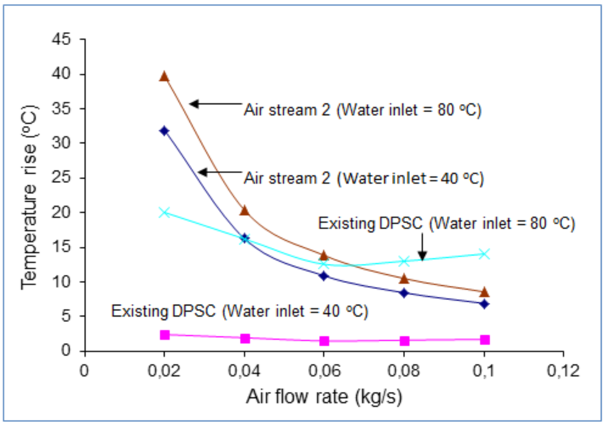

Fig. 11. Air stream tempertaure rise for different inlet water temperatures (comparison with existing DPSC)

It is observed that for specified inlet water temperatures, the temperature rise is significantly higher for the dual purpose collector. In the proposed design there is an additional air stream above the absorber plate (air stream 1). The temperature rise variations with mass flow rate of air for both the streams are shown together in Figure 12.

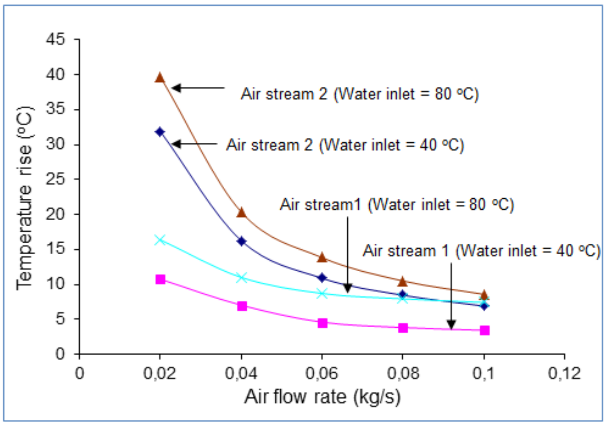

Fig. 12. Air stream tempertaure rise for different inlet water temperatures

It is desirable to study the effect of major factors influencing the collector performance. For a given dual purpose collector, the major parameters which affect the performance are (i) global solar irradiance (ii) water inlet temperature and (iii) flow rate of air. To investigate the effect of these parameters on heat delivery and efficiency of the collector, each of them is varied, keeping the other parameters constant. The results of this analysis are presented in Figures 13 to 17.

4.2. Effect of Solar Irradiance

The effect of solar irradiance (on the collector plane) on the temperature rise of the fluid is illustrated in Figure 13. The variation corresponds to mass flow rate of air: 0.01 kg/s, mass flow rate of water: 0.01 kg/s, inlet air temperature: 27 °C, inlet water temperature: 27 °C and porosity of 0.7. The rise in temperature is expressed in terms of the difference of outlet temperature and inlet temperature of the respective fluids.

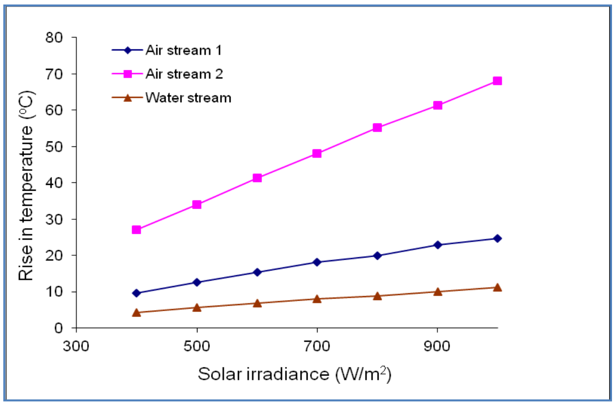

Fig. 13. Variation in temperature rise of fluid streams with solar irradiance

For the air flow through the porous matrix, significant rise in temperature is obtained with increase in solar irradiance. The rise is up to 68 °C which is due to the enhanced heat transfer through conduction and convection. Temperature rise up to 24.7 °C in the upper air stream is observed for a solar irradiance of 1000 W/m^2. For the same condition, an increase of 11.1 °C is obtained for the water stream.

4.3. Effect of Inlet Water Temperature on Water Heat Gain

The variation of useful heat gain of the water stream with inlet water temperature is illustrated in Figure 14. The simulation results correspond to air mass flow rate: 0.01 kg/s, inlet temperature of air: 27 °C and water flow rate: 0.02 kg/s. Water heat delivered $(\dot{Q}_u)$ is evaluated by:

$$\dot{Q}_u = \dot{m} C_p (T_o - T_i) \tag{8}$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat at constant pressure, T_o is outlet temperature and T_i the inlet temperature of the respective fluid. A comparison of the water heat gain with existing DPSC is given in Figure 14. The useful heat gain decreases with inlet water temperature as expected. For the modified DPSC the water heat gain is slightly lower as compared to the original design due to the additional heat extraction by the air stream flowing through the top of the absorber plate (air stream 1).

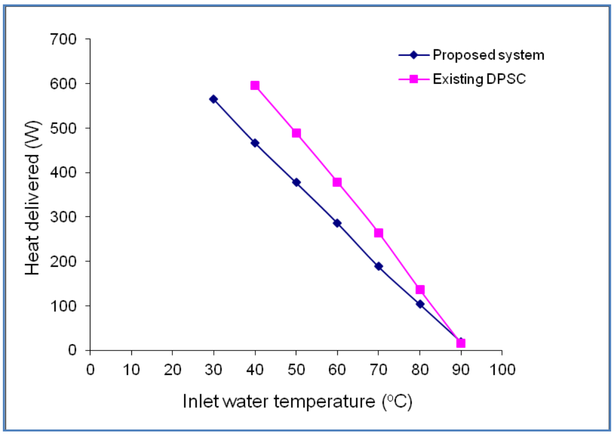

Fig. 14. Variation in water heat gain with inlet water temperature

4.4. Variation of Air Heat Gain with Flow Rate

The variation in air heat gain is simulated for different values for air flow rates for the specified conditions of solar irradiance: 700 W/m^2, water flow rate: 0.02 kg/s, water inlet temperature: 27°C, inlet air temperature: 27°C and porosity: 0.7.The corresponding variation is illustrated in Figure 15. The trend is similar to the reported results of the existing DPSC [7]. It is observed that the modified DPSC delivers higher quantity of thermal energy for lower water inlet temperature. For water inlet temperature of 40°C the system can deliver 1043 W against 172 W delivered by the existing DPSC [7]. This is also true for higher water inlet temperatures. The simulation results indicates that the new DPSC can deliver 1611 W of heat at water inlet temperature of 80°C and 0.1 kg/s flow rate, but the existing design can deliver only 1428 W of heat under the same conditions [7]. This clearly justifies the application of porous media insert in the system.

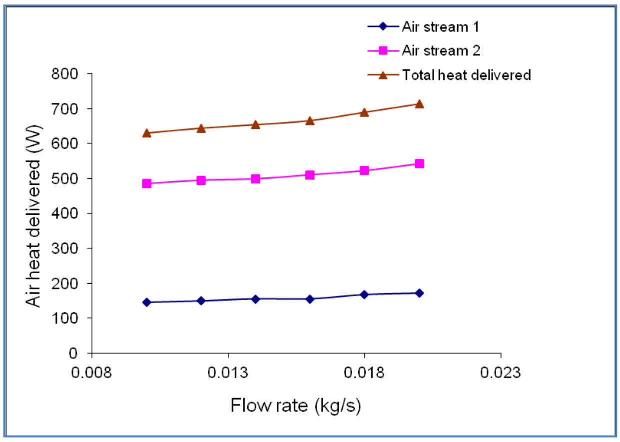

Fig. 15. Variation of air heat delivered with air flow rate

4.5. Optimizing Mass Fraction

The thermal efficiency (η) of the system for the air and water heating are evaluated individually using the following relation:

$$\eta = \frac{\dot{Q}_{u,f}}{I_T A_c} \tag{9}$$

Here, $\dot{Q}_{u,f}$ is the useful heat gain by the fluid (air or water), I_T is the irradiance on the collector plane and A_c is the collector area. It is of interest to consider the variation in the total thermal efficiency of air heating with the mass fraction. Mass fraction is defined as the ratio of the mass of the individual air stream to the total mass of air circulated through the system. Illustrative variation is shown for the conditions of solar irradiance: 700 W/m^2, water mass flow rate: 0.01 kg/s, inlet water temperature: 27°C, inlet air temperature: 27°C, total mass flow rate of air stream: 0.02 kg/s and porosity of 0.7. Mass fraction of air stream 1 is considered. Air heating efficiency for air stream 1 is found to increase with mass fraction (Figure 16). For air stream 2, due to the reduced flow rate, the air heating efficiency drops down with the mass fraction. For the two streams together, the combined efficiency is found to be 43.03% corresponding to mass fraction value of 0.5. It is to be noted that the total air heating efficiency is showing only a slight variation for mass fraction values ranging from 0.1 to 0.5.

4.6. Performance of the System in Combined Mode

The overall performance of the system and its comparison with the existing design is illustrated in Figure 17. The simulations are carried out for specified conditions of air flow rate: 0.01 kg/s, inlet temperature of water: 30°C to 90°C, flow rate of water: 0.02 kg/s and solar irradiance of 900 W/m^2. With the increase of water inlet temperature, water heating efficiency decreases and air heating efficiency increases. Comparison of the performance of the modified system with that of the existing design shows that air heating efficiency of the modified DPSC has increased than the existing DPSC while the water heating efficiency has not declined significantly.

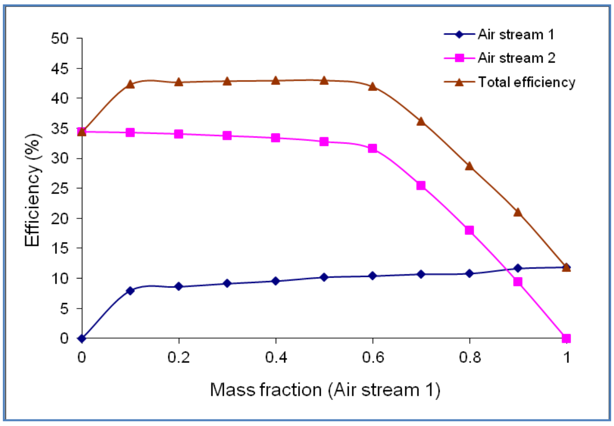

Fig. 16. Variation of air heating efficiency with mass fraction of air stream 1

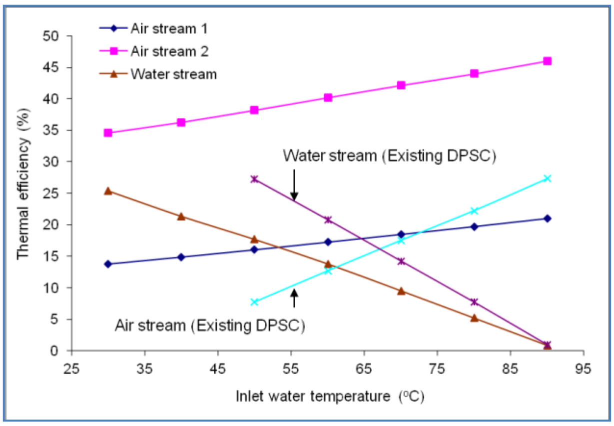

Fig. 17. Performance of DPSC in combined mode

5. Conclusion

Theoretical investigation on the performance improvement of a modified dual purpose solar collector is considered in this paper. Thermal performance of the collector is improved by integrating a porous matrix in the absorber plate of the system. Modelling and simulation studies of the system are carried out using software ANSYS 13 and associated Fluent CFD package. Velocity and temperature distribution of the fluid streams are obtained under quasi-steady state situation. Significantly higher temperature rise is obtained for air and water streams under various operating conditions as compared to the original system without the porous medium. Parametric studies on the system are carried out to obtain the effects of fluid flow rates, total solar irradiance on the collector plane and water inlet temperature. With representative illustration, the range of mass fractions favourable for the system operation is found out. The simulation results clearly indicate that the modified

DPSC is more efficient than existing DPSC at low and high inlet temperatures of water. Performance plots in combined mode prove that modified DPSC is thermally more efficient in terms of air heating efficiency and water heating efficiency has not declined significantly. This owes to the presence of porous media insert which increases the heat transfer area with air. The numerical simulations thus provide useful guidelines for the optimal system design of the dual purpose collector.

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