Three Dimensional Numerical Analysis of Conjugate Heat Transfer for Enhancement of Thermal Performance using Finned Tubes in an Economical Unglazed Solar Flat Plate Collector

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Abstract: **Flat plate solar collectors are the most common thermal collectors used among the various solar collectors for domestic and industrial purposes. This is mainly due to simple design as well as low maintenance cost. But an attempt is being made in this paper to design low cost but comparatively efficient, maintenance free flat plate collector. The greater affordability in terms of cost is the most important objective of the present paper. In general, flat plate collectors have lower efficiency as large heat losses occur from the collector surface by convection and re-radiation. In the present work an unglazed solar collector is designed with an innovative serrated fined tube design as well as another designing with diametrically placed planar fin bifurcating the absorber tube passage. The idea behind these two designs is that greater heat transfer by convection is possible from the unglazed collector to the absorber tubes.**

The numerical results obtained using Computational fluid dynamics by employing conjugate heat transfer show that for lower flow rates the heat transfer flux increases as compared to the base model for both the configurations.

Index Terms--- **Conjugate Thermal Analysis, Unglazed Solar Collector, Finned Tube, CFD Simulation.**

I. INTRODUCTION

SOLAR energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. Of all the solar thermal collectors, the flat plate collectors though produce lower temperatures, have the advantage of being simpler in design, having lower maintenance and lower cost.

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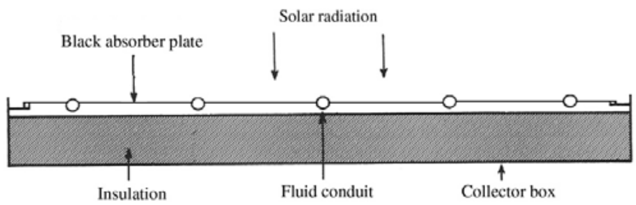

Fig.1 Cross-sectional view of an unglazed solar flat-plate collector

While most of the solar collectors have a transparent cover to help reduce re-radiation and convection losses, it is found from the literature that there is a dearth of technical papers on unglazed solar collectors with improvements for thermal efficiency. But there is a host of literature on glazed solar collectors.

Sopian et al. [2] conducted an experimental study on the thermal performance of a non-metallic unglazed solar water heater integrated with a storage system. Gorla [3] performed an analysis based upon the two-dimensional finite element method to characterize the performance of solar collectors. Selmi et al. [5] performed a CFD simulation of flat plate solar energy collector with water flow. The CFD model was validated with experimental results. Janjai et al. [7] developed a mathematical model for simulating the performance of a large area plastic solar Collector. Lecoeuche and Lalot [9] applied neural network technique to predict the thermal performance of a solar flat plate collector. Collector efficiency improvement using recyclic double-pass sheet-and-tube solar water heaters with fins attached have been reported by C. D. Ho and T. C. Chen.

In consideration of the above it was decided to conduct a three dimensional numerical study on unglazed solar collector with improvements for thermal efficiency.

II. NOMENCLATURE

T Temperature
x Distance along the absorber plate
L Length of the collector
X Non-dimensional collector length (x/L)
U Velocity

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ρ Density
μ Viscosity
Pr Prandtl Number

Subscripts
i inlet
bi base model inlet

III. THEORETICAL FORMULATIONS

A. Problem statement and assumptions

The flow domain consists of a flat plate absorber plate with circular absorber tube connected below the absorber as shown in Fig. 1. Water is supplied at the inlet of the absorber tube. The following assumptions are made in the analysis.

(1) Water is a continuous medium and incompressible.
(2) The flow is steady and possesses laminar flow characteristics.
(3) The thermal-physical properties of the absorber plate, water and the absorber tube are independent of temperature.

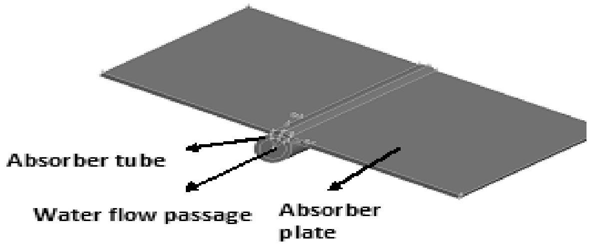

Fig. 2. Geometry of the unglazed collector and absorber Tube without fin (Base model)

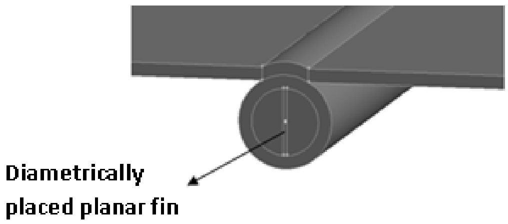

Fig. 3. Geometry of the unglazed collector with Diametrically placed planar fin

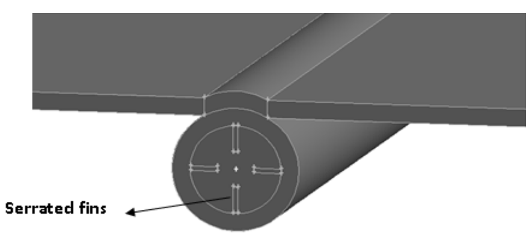

Fig. 4. Geometry of the unglazed collector and absorber Tube with serrated fins.

B. Collector configurations for the analysis

The collector absorber plate length and width for all the design is taken as 0.5m and 0.14m respectively. The absorber tube diameter is 0.01m with a thickness of 0.002m. The diametrically placed planar is placed all along the length of absorber tube and has a thickness of 0.0005m.The serrated fins also are placed all along the length of the absorber tube and have a thickness of 0.0005m.

C. Numerical model

To conduct numerical simulation, the computational domain is meshed with control volumes built around each grid using GAMBIT (version 2.4.6), which is the preprocessor for FLUENT (version 6.3.26). Numerical simulation was carried out using steady state implicit pressure based solver which is an in-built in the commercially available software FLUENT (version 6.3.26). The governing partial differential equations, for mass and momentum are solved for the steady incompressible flow. The velocity-pressure coupling has been effected through SIMPLE algorithm (Semi Implicit Method For Pressure-Linked Equations) developed by Patankar S.V [1]. Second order upwind schemes were chosen for the solution schemes. Laminar flow condition was used.

D. Mean Flow Equations

All the equations are presented in Cartesian tensor notation.

Continuity:

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0 \qquad (1)$$

Momentum equation

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\overline{u_i u_j}\right] \qquad (2)$$

Energy equation

$$\frac{\partial}{\partial x_j}(\rho U_i T) = \frac{\partial}{\partial x_j}\left[\frac{\mu}{\Pr}\frac{\partial T}{\partial x_j} - \rho\overline{u_i t}\right] \qquad (3)$$

(3)

IV. METHOD OF SOLUTION

A. Numerical scheme

Conservation equations were solved for the control volume to yield the velocity and temperature fields for the water flow in the absorber tube and the temperature fields for the absorber plate. Convergence was effected when all the residuals fell below 1.0e-6 in the computational domain.

Computational domain was modeled using the pre-processor routine called GAMBIT and meshing was also done using appropriate grid cells of suitable size available in the routine. A three dimensional computational domain is built used as shown in Figure 2 and Figure 3.

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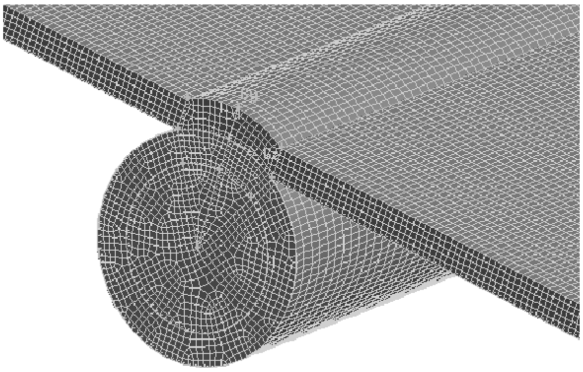

Fig.5. Mesh of the computational domain

The grid independence test was performed to check validity of the quality of mesh on the solution. The influence of further refinement did not change the result by more than 0.75% which is taken here as the appropriate mesh quality for computation.

B. Boundary conditions and Operating parameters

Appropriate boundary conditions were impressed on the computational domain, as per the physics of the problem.

Inlet boundary condition was specified as velocity inlet condition. Outflow boundary condition was applied at the outlet. Wall boundary conditions were used to bound fluid and solid regions. In viscous flow models, at the wall, velocity components were set to zero in accordance with the no-slip and impermeability conditions that exist there.

The interface between the water and the absorber tube is defined as wall with coupled condition to effect conjugate heat transfer from absorber tube to the water.

A constant heat flux equivalent to the solar insolation is applied at the top surface of the absorber plate. The bottom and side surfaces of the absorber plate and the outer surface of the absorber tube are defined as wall with zero heat flux condition to effect insulated conditions. The material used for both absorber plate and the water tube is copper. The input parameters used in the analysis are as shown in TableI.

TABLE I
INPUT PARAMETERS FOR SIMULATION.

Parameter	Value
Density (Copper)	8978 kg/m^3
Specific heat (Copper)	381 J/kg-K
Thermal conductivity (Copper)	387.6 W/m-K
Density (Water)	998.2 kg/m^3
Viscosity (Water)	0.001003 kg/(m.s)
Specific heat (Water)	4182 J/kg-K
Thermal conductivity (Water)	0.6 W/m-K

V. RESULTS AND DISCUSSION

To assess the thermal performance of the unglazed solar collector with improvements in design, a base model with only cylindrical absorber tube is analyzed and the results are as shown in Fig. 6 and 7. It is observed that there is a decrement in the plate temperature with a consequent increase in the mass flow rate for the condition of a simulated constant solar heat flux of 800W/m^2. This is because, as the mass flow rate increases, the heat is carried away from the plate due to convection at a faster rate within the tube.

Above is corroborated by the temperature gradient plots for the water passing through the absorber tubes. It is seen from Fig. 7 that there is a gradual increase in the temperature of water along the length of the tube. As explained earlier, the temperature increase is due to the heat transfer at the absorber plate all along its length due to conjugate heat transfer.

But it is observed that with increase in mass flow rate, there is a relative decrease in the temperature rise of water. This can be explained by the fact that as the velocity is increased due to increase in the mass flow rate, the fluid particles are carried forward at a faster rate thereby a perceptible lower temperature rise is observed for the water.

In the foregoing analysis, three different mass flow rates are employed to bring out the effect clearly. As seen from the Fig. 6 and 7, the trend lines match the physical explanation given above. To improve the heat transfer rate to the water in the absorber tube, two innovative designs have been tried.

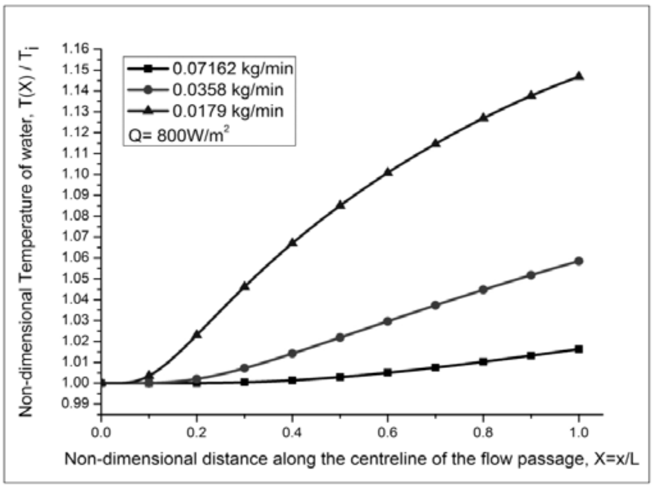

Fig. 6. Temperature plots for three different mass flow rates for the absorber plate without fins in the absorber tube

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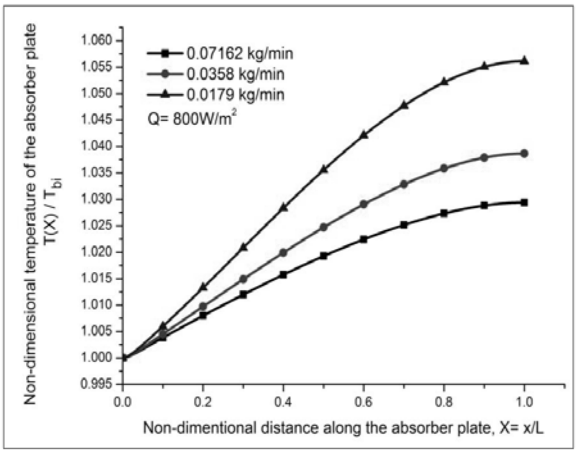

Fig. 7. Temperature plots for three different mass flow rates for the absorber plate without fins in the absorber tube

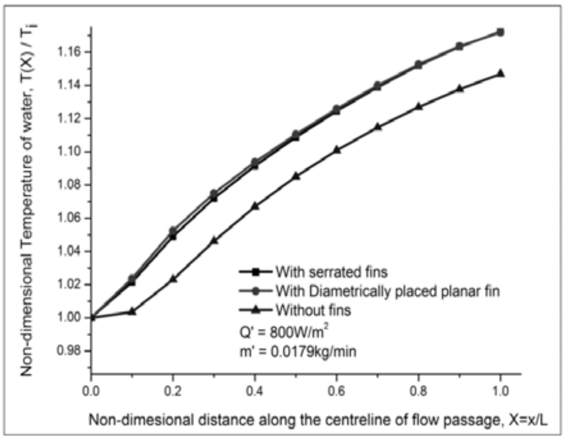

Fig. 8. Comparison of the temperature plots along the centerline of the water flow passage in the absorber tube with and without fins

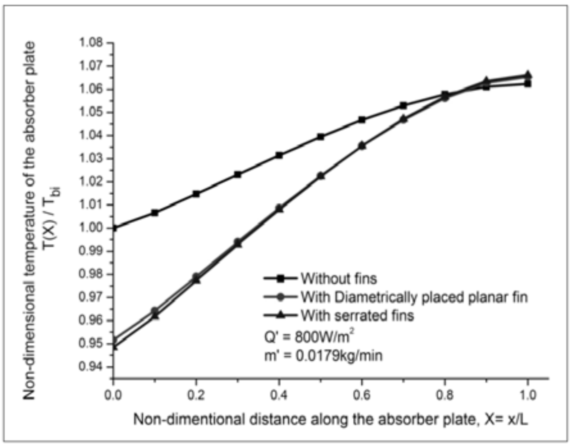

Fig. 9. Comparison of the temperature plots along the length of the absorber plate having absorber tube with and without fins

The configuration involving the serrated finned tube shows a significant improvement in heat transfer from the absorber plate to water in the absorber tube as shown in Fig. 8. This is clearly due to the fact that a larger convective area is available for the heat transfer from the absorber plate to the water in the tube using this new design. The serrated fins within the flow passage enhance heat dissipation all along the length of the tube.

Another design involving a diametrically placed planar fin which splits the flow passage into two parts is found to posses the same characteristics as that of the serrated fin due to almost the same surface area available for convective heat transfer. The temperature distributions of the absorber plate as obtained from the simulation for flow without fins and with fins are shown in Fig. 10, 11 and 12.

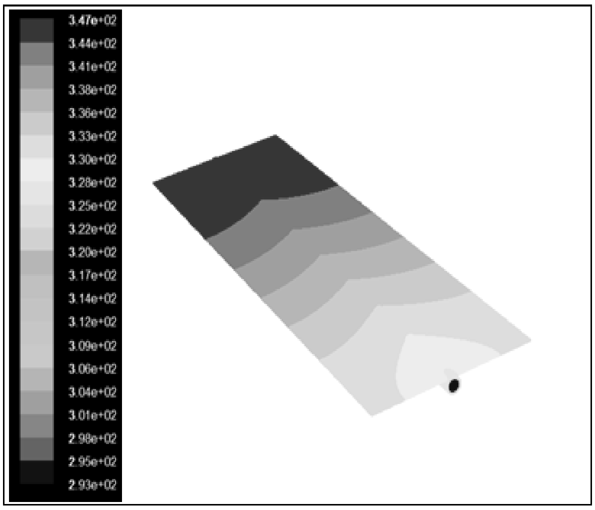

Fig. 10. Temperature plots for unglazed collector without fin for a heat flux of $800W/m^2$ and mass flow of 0.0179kg/min

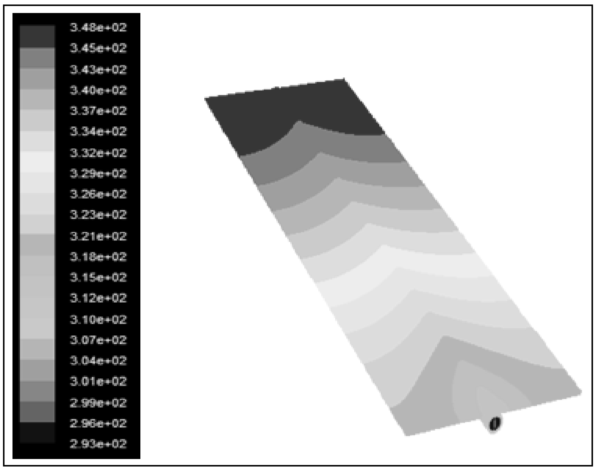

Fig. 11. Temperature plots for unglazed collector with diametrically placed planar fin for a heat flux of $800W/m^2$ and mass flow of 0.0179kg/min

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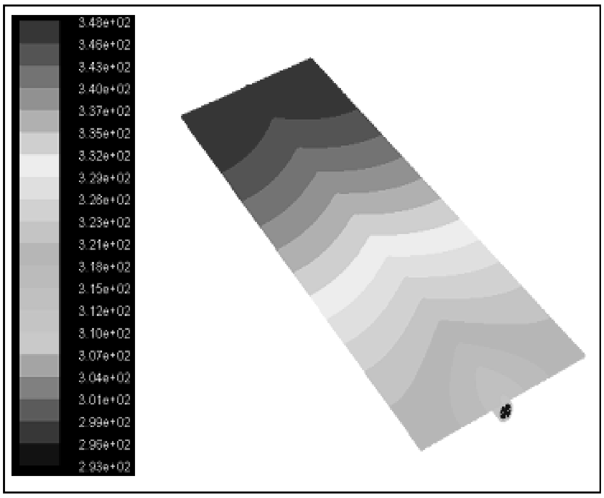

Fig. 12. Temperature plots for unglazed collector with serrated fin for a heat flux of 800W/m^2 and mass flow of 0.0179kg/min

VI. Conclusion

The following conclusions are deduced from the above numerical simulation:

- There is a decrement in the plate enthalpy with a consequent increase in the mass flow rate of water through the absorber tube for all the three designs.
- Use of serrated fins enhances the heat transfer from the absorber plate to the water in the absorber tube and improves the overall thermal performance of the collector.
- Use of diametrically placed planar fin is found to posses the same characteristics as that of the serrated fin due to almost the same surface area available for convective heat transfer.
- Use of optimal number of fins in the serrated fin configuration may further increase the heat transfer from the absorber plate to the water in the absorber tube due to increased surface area for convective heat transfer.

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References

[1] Patankar S.V. and D.B. Spalding, "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows", International Journal of Heat Mass Transfer, 1972, vol. 15, p. 1787.

[2] K. Sopian, M. Syahri, S. Abdullah, M.Y. Othman, B. Yatim," Performance of a non-metallic unglazed solar water heater with integrated storage system", *Renewable Energy*,vol. 29, 2004, pp. 1421–1430.

[3] Gorla, R.S.R, "Finite element analysis of a flat plate solar collector", *Finite Elements in Analysis and Design*, vol.24, 1997, pp. 283-290.

[4] Turgut, O. & Onur, N, "Three dimensional numerical and experimental study of forced convection heat transfer on solar collector surface", *International Communications in Heat and Mass Transfer*, vol. 36, 2009, pp. 274-279.

[5] Selmi, M., Al-Khawaja, M.J., and Marafia, A., "Validation of CFD simulation for flat plate solar energy collector", *Renewable Energy*, vol.33, 2008, pp. 383-387.

[6] Khoukhi Maatouk, "Non-gray radiative and conductive heat transfer in single and double glazing solar collector glass covers", *International Journal of Thermal Sciences,*Vol.45, 2006, pp. 579-585.

[7] S. Janjai, A. Esper, W. Muhlbauer, "Modelling the performance of a large area plastic solar collector", Renewable energy, vol. 21, 2000, pp. 363-376.

[8] K.P. Gertzos, S.E. Pnevmatikakis and Y.G. Caouris,"Experimental and numerical study of heat transfer phenomena, inside a flat-plate integrated collector storage solar water heater (ICSSWH), with indirect heat withdrawal", *Energy Conservation and Management*, vol.49, no.11, 2008, pp. 3104-3115.

[9] S. Lecoeuche and T, S. Lalot, "Prediction of the daily performance of solar collectors", *International Communications in Heat and Mass Transfer,*vol.32, 2005, pp. 603–611.

[10] Fluent user's guide, Volume I to IV