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CFD Modelling And Validation Of Solar Flat Plate Collector Subjected To Natural Convection

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ABSTRACT

Computational Fluid Dynamics (CFD) is used to model optimal design in various fluid flow situations and heat transfer processes for the prediction of heat, mass and momentum transfer. The present study reveals an investigation on the collector efficiency of a solar water heater with and without fins attached internally in the riser tubes by CFD So as to reduce cost, time and to optimize the behaviour of the solar collector without performing the expensive experimental and complicated tests that generally done. A modern CFD code (ANSYS FLUENT v12.1) is used to simulate fluid flow through solar water heater. The numerical results obtained from the experimentally measured temperature readings and the results are compared to the temperatures obtained by CFD modelling. Finally an error analysis is done for the experimental and CFD values and the results are compared, it was observed the error varies from 0.536% to 1.282% with the average being 0.78675%.

KEYWORDS: CFD-Computational Fluid Dynamics, FPC-Flat plate collector, LPD- litres per day.

1. INTRODUCTION

Solar energy is one of the solution and future way for the world's abundant energy requirements. Renewable energy utilization is synonymous with solar energy as Sun is the main source. The transition to solar energy economy has begun all over the world and the renewable energy sector has profusely moved to the centre stage of the energy mix along with energy policies of the developed and developing nations of the world. The easiest way of harnessing abundant solar irradiance on earth is to directly convert it into useful thermal energy. To produce hot water, solar flat plate water heating systems are encouraged which can heat the water from ambient temperature to over 90°C. Solar hot water systems are normally designed for a definite temperature at the outlet of the collector bank. Efficiency factor of FPC depend on local conditions like solar radiation, temperature, wind velocity, relative humidity and other climatic conditions. Designing a solar water heating system is always as easy from the efficiency point of view as it may appear but it’s merely a matter of optimization rather than simply maximizing efficiency.

2. DESIGN OF 25LPD SOLAR FLAT PLATE COLLECTOR

A 25 LPD experimental collector set up is fabricated with Heat Exchanger as primary and hot water storage tank as secondary loop.

Fig.1. 25 LPD collector with primary riser tube and secondary storage tank

The energy balance of the absorber plate yields the following equation for steady state

$$q_u = (Ap\ \ S) - q_l = \dot{m}\ \text{LPD- litres per day, } C_p\ \Delta T$$

q_u = Useful heat gain, i.e. the rate of heat transfer to the working fluid

S = Incident solar flux absorbed in the absorber plate/m

Ap = Area of absorber plate, m^2

q_l = Rate at which heat is lost by convection and re-radiation from the top and by convection from the bottom and sides.

$$\text{Area of plate } Ap = \left[\frac{m\ Cp\ \Delta T}{S\ \eta}\right]$$

$$= \left[\frac{25 \times 4187 \times 35}{680 \times 60 \times 60 \times 7 \times 0.4}\right] = 0.534 \text{ m}^2$$

For this area & design purpose, efficiency of the collector is assumed as 40%. Total temperature difference across the storage tank is assumed over the day is 35^{o} C. For this collector area, available length (L) & breadth (W) are calculated as the effective length of the collector is 0.945m & Effective Width of the collector plate is 0.535m with 4 riser tubes placed in 100 mm pitch each other.

3. METHODOLOGY

The basic procedure adopted for CFD modelling is

- Geometry (physical bounds) of the problem is defined.
- Volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or non-uniform.
- Physical modelling is defined into the equations of motion + enthalpy + radiation + species conservation
- Boundary conditions are defined. This involves specifying the fluid behaviour and properties at the boundaries of the problem. For transient problems, the initial conditions are also defined.
- Simulation is initiated and the equations are solved iteratively as a steady-state or transient.
- Finally a postprocessor is used for the analysis and visualization of the resulting solution.

4. MODEL OF THE SYSTEM BY Pro-E

The geometrical model of the system is created by Pro-E with following data as input for design and saved in IGS format.

- Diameter of tube (OD) = 12.5 mm
- Diameter of main header (OD) = 25.4 mm

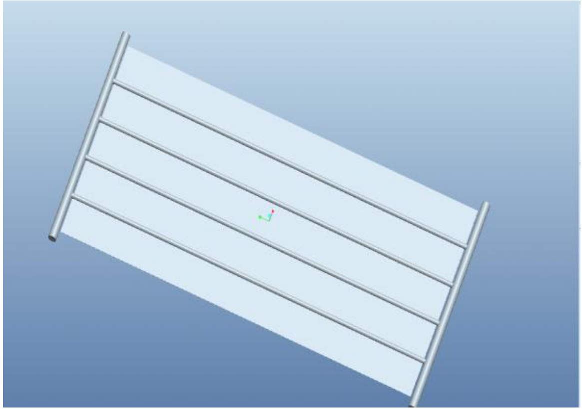
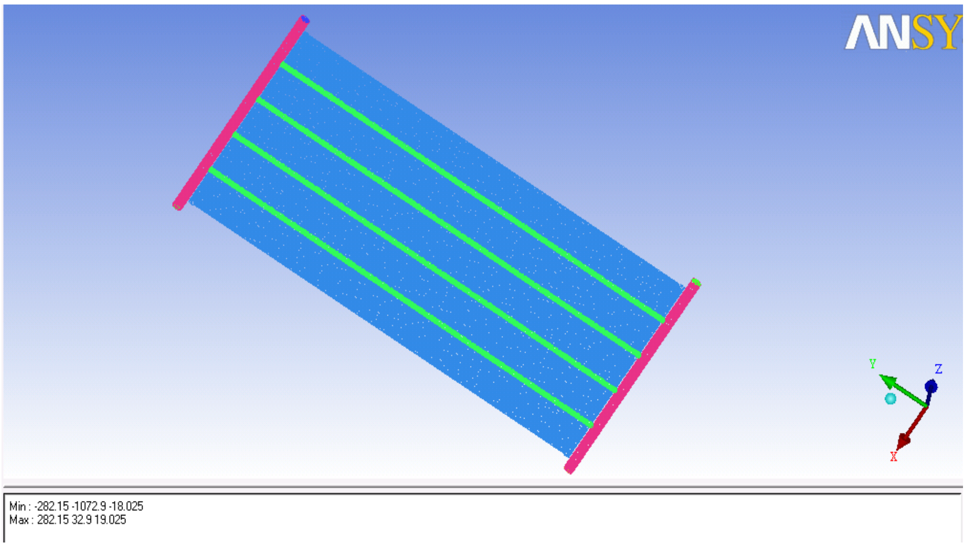


Fig.2. Model of Solar Flat Plate Collector

4.1. MESHING THE MODEL

The meshes are built up of tetrahedral cells and are thus unstructured meshes. In order to better predict the internal flow field behaviour, the optimized solution-adaptive mesh refinement is used. More cells are added at locations where significant flow changes are expected, for example near the tube walls and inlet/outlet ports.

The resulting mesh enables the features of the flow field to be better represented. The symmetric solver selected here accounts for the three-dimensional effects, and the calculation domain was half of the physical body, based on symmetry considerations. The model which is in IGS format is imported to Ansys Fluent (ICEM CFD) for meshing is shown in fig.3.



```
Min : -282.15 -1072.9 -18.025
Max : 282.15 32.9 19.025
```

Fig.3. Meshed model

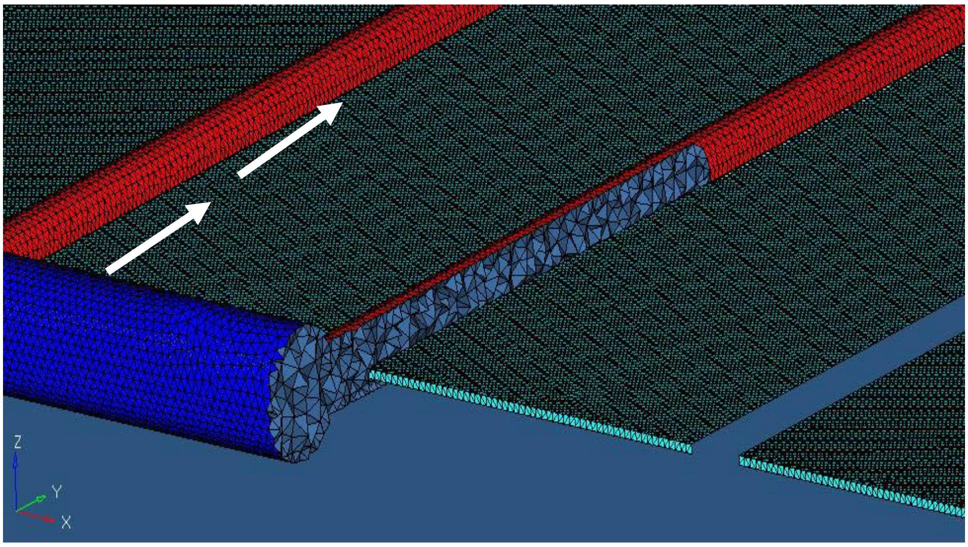


Fig.4. View of Meshed model

4.2 GOVERNING EQUATIONS

Continuity Equation

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho V) = 0$$

Momentum Equations

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu\left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_j}\right] - \overline{\rho U_i U_j}$$

Energy Equation

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

4.3. MESH DETAILS

The model that is meshed using ANSYS ICEM CFD had the following properties are shown in table.1. $_j$

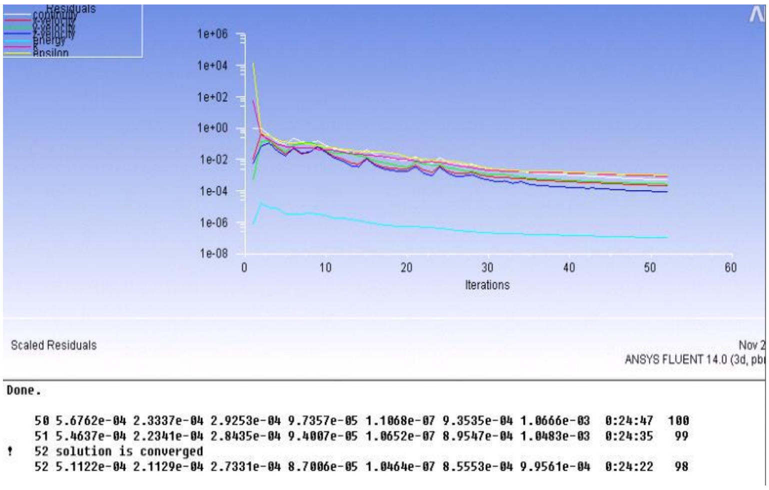
DETAILS	MESH TYPE	COUNT
Surfaces	Tri-Elements	1589406
Volumes	Tetra-Elements	2778375
Nodes	----------	690309

5. RESULTS AND DISCUSSION

The model which is designed is simulated by using ANSYS Fluent. 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.

5.1. SOLUTION CONVERGENCE

The solution of the CFD analysis is found to converge.



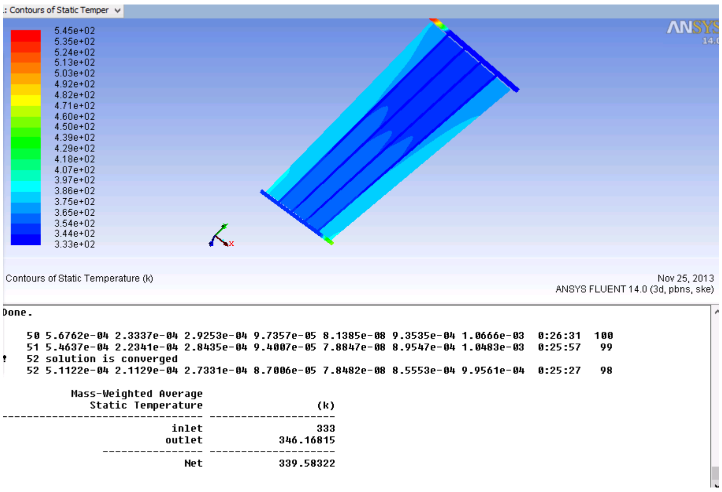
```
Done.

   50 5.6762e-04 2.3337e-04 2.9253e-04 9.7357e-05 1.1068e-07 9.3535e-04 1.0666e-03  0:24:47  100
   51 5.4637e-04 2.2341e-04 2.8435e-04 9.4007e-05 1.0652e-07 8.9547e-04 1.0483e-03  0:24:35   99
!  52 solution is converged
   52 5.1122e-04 2.1129e-04 2.7331e-04 8.7006e-05 1.0464e-07 8.5553e-04 9.9561e-04  0:24:22   98
```

Fig.5. Convergence Diagram of SFC by using ANSYS FLUENT

5.2. TEMPERATURE DISTRIBUTION ALONG THE COLLECTOR

The temperature distribution along the Solar Flat Plate collector obtained using CFD analysis is shown below.



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Done.

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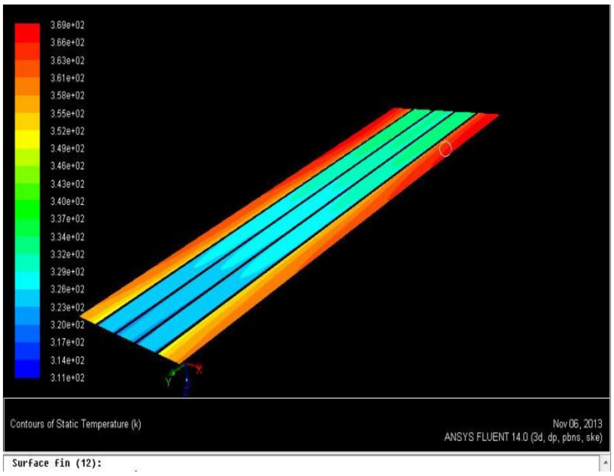
   51 5.4637e-04 2.2341e-04 2.8435e-04 9.4007e-05 7.8847e-08 8.9547e-04 1.0483e-03  0:25:57   99
!  52 solution is converged
   52 5.1122e-04 2.1129e-04 2.7331e-04 8.7006e-05 7.8482e-08 8.5553e-04 9.9561e-04  0:25:27   98

              Mass-Weighted Average
                 Static Temperature                  (k)
-------------------------------- --------------------
                              inlet                  333
                             outlet            346.16815
                 ---------------- --------------------
                                Net            339.58322
```

Fig.6. Temperature Distribution Along riser tube of the collector

5.3. TEMPERATURE VARIATION ALONG THE CENTRAL FIN

The variation of temperature along the central fin the of the solar flat plate collector using CFD is shown below.



Surface fin (12):

Fig.7. Temperature variation along central fin of the collector

5.4. VALIDATION OF EXPERIMENTAL RESULTS WITH CFD

The Outlet temperature obtained from the CFD simulation is validated with the experimental outlet temperature and error analysis is done. The error analysis is conducted for the experimental results and CFD results. It is found that the error varies from 0.536% to 1.282% with the average being 0.78675%. The outlet temperature of the CFD is higher by 2-3 K compared to experimental values.

Table.2. Comparison with CFD Outlet Temperatures

time (hr)	inlet temp. (k)	solar insolation (w/m2)	experiment outlet temp. (k)	cfd outlet temp.(k)	error analysis (%)
8	306	249	307.48	309.1	0.53
9	313.4	362	316.08	318.1	0.66
10	318.3	582	324.22	327.4	0.99
11	322.2	772	328.71	330.6	0.59
12	325.3	869	332.69	334.9	0.68
13	328.7	886	333.43	336.6	0.96
14	329.2	903	335.07	339.3	1.28
15	328.8	738.1	333.28	335.2	0.58

5.5. EXPERIMENTAL & CFD MODELLED OUTLET TEMPERATURE Vs SOLAR INSOLATION

The experimental outlet values of Solar Flat Plate Collector are compared with the CFD values. The fig.8 shows the variations for outlet temperature for the experimental and CFD analysis with respect to the solar insolation. It was inferred that outlet temperature for the CFD is higher than the experimental values. The outlet of the SFPC system increases as the solar insolation increases and found to have a peak value at 14:00 hrs. The CFD outlet is found to have same curve behaviour as that of the experimental value when it is plotted between temperature and solar insolation.

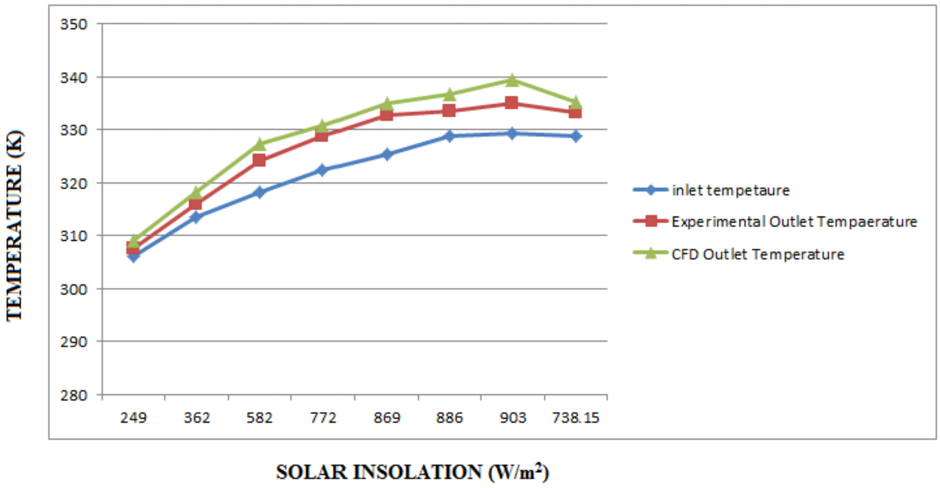


Fig.8. Comparison of Outlet Temperature for Experimental & Model Vs Solar Insolation

5.6. EXPERIMENTAL & CFD MODELLED OUTLET TEMPERATURE Vs TIME

The fig.9 shows the outlet temperatures of the SFPC system for both experimental and CFD model is plotted versus the time. For instance during peak hour of insolation for the experimental temperature difference for the inlet to the outlet of the collector system is nearly 5.8^{0}C and for CFD model for the same is 10.1^{0}C.So it is proven that a better heat enhancement was taking place by the CFD analysis.

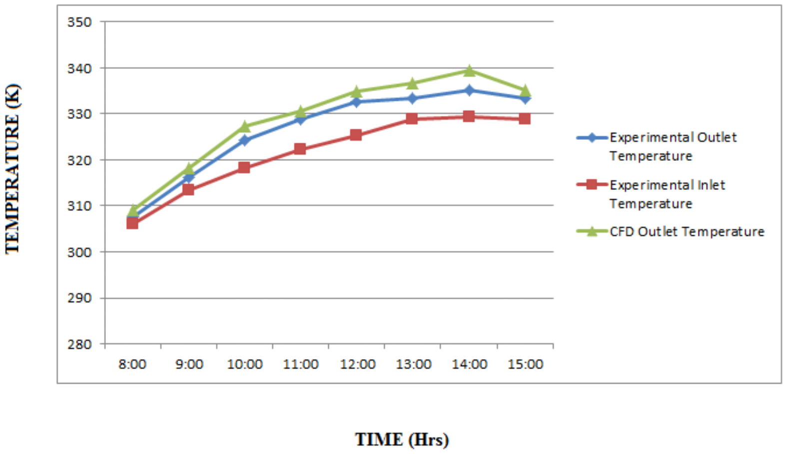


Fig. 9. Comparison of Outlet Temperature for Experimental & Model Vs Time

TABLE3: Process details of Solar FPC

PARTICULARS	DIMENSION/UNIT	VALUES
Velocity in riser	m/s	0.034
Velocity in main header	m/s	0.031
Total mass flow rate in riser	Kg/s	0.29
Initial temperature	^{o}C	30
Final Temperature	^{o}C	70
Total flux received (S)	W/m^2	600
Re Number in Riser	-	693
Re Number in main header	-	1385

6. CONCLUSION

The solar flat plate collector was modelled and CFD analysis is carried out. The results obtained from the CFD is validated with the experimental values and found that there is good agreement lies between experimental and CFD result. Based on this an error analysis is carried out and found to lie in the range between 0.536% and 1.282% with the average being 0.78675%.

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