Numerical Analysis of Solar Flat Plate Collector for Circular Pipe Configuration by using CFD

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ABSTRACT

In this work experimentally and theoretically investigated results of flow and temperature distribution in a solar collector panel with circular tube configuration is taken and it will be compared with CFD simulated results. Fluid flow and heat transfer in the collector panel are studied by means of computational fluid dynamics. In CFD simulation ICEM CFD for modeling and CFX13 for analysis are used. Results of CFD simulation will be obtained by CFD-POST. The temperature distribution through the absorber is evaluated by means of temperature measurements at the inlet and outlet of absorber tubes. The measured temperatures are compared with the temperatures determined by the CFD analysis. Hence clearly the experimental results are validated through CFD simulations.

Key Points: CFD, Solar flat plate collector, Circular pipe configuration, Numerical studies etc.

1. Introduction

Solar Energy is the energy received from the sun that sustains life on earth. For many decades solar energy has been considered as a huge source of energy and also an economical source of energy because it is freely available. However, it is only now after years of research that technology has made it possible to harness solar energy.

Some of the modern Solar Energy systems consist of magnifying glasses along with pipes filled with fluid. These systems consist of frontal glass that focuses the sun's light onto the pipes. The fluid present in the pipes heats up instantly. In addition they pipes are painted black on the outside so as to absorb maximum amount of heat. The pipes have reflective silver surface on the back that reflects the sunlight back, thus heating the pipes further. This reflective silver surface also helps in protecting everything that is on the back of the solar panel.

The heat thus produced can be used for heating up water in a tank, thus saving the large amount of gas or electricity required to heat the water.

Solar energy is the solar radiation that reaches the earth. Available solar energy is often expressed in units of energy per unit area, such as watts per square meter (w/m^2). The amount of energy available from the sun outside the earth's atmosphere is approximately $1367 w/m^2$. Energy from the sun travels to earth in the form of electromagnetic radiation similar to radio waves, but in different frequency range.

1.1 Solar flat plate collector

Flat plate collectors of the many solar collector concepts presently being developed, the relatively simple flat plate solar collector has found the widest application so far. Its characteristics are known, and compared with other collector types, it is the easiest and least expensive to fabricate, install, and maintain. Moreover, it is capable of using both the diffuse and the direct beam solar radiation. For residential and commercial use, flat plate collectors can produce heat at sufficiently high temperatures to heat swimming pools, domestic hot water, and buildings; they also can operate a cooling unit, particularly if the incident sunlight is increased by the use of a reflector. Flat plate collectors easily attain temperatures of 40 to 100ºC. With very careful engineering using special surfaces, reflectors to increase the incident radiation, and heat-resistant materials, higher operating temperatures are feasible.

A typical flat plate collector is shown in Fig 1.1. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use. The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate, or they can be an integral part of the plate. The liquid tubes are connected at both ends by large diameter header tubes.

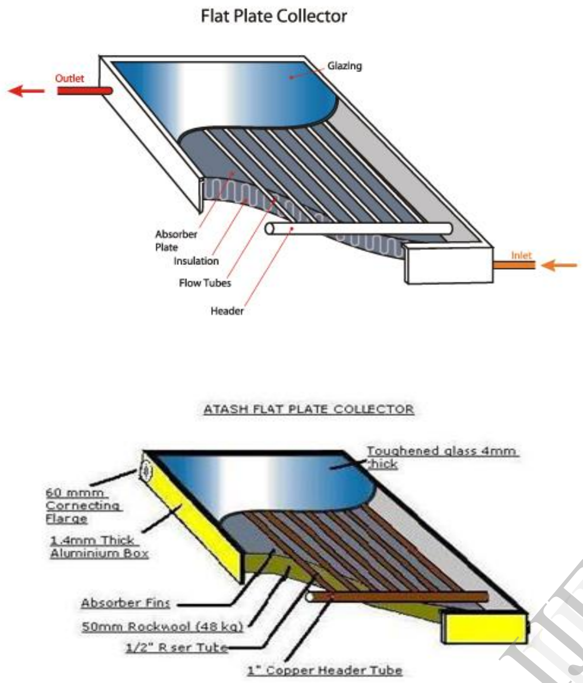


Figure 1.1: Flat plate collector

The main components of a flat plate solar collector are: Absorber plate, Tubes or Fins, Thermal insulation, Cover strip, Glazing, Container or Casing.

1.1.1 Circular tube configuration

The Fig 1.2 shows that the absorber plate and the circular tubes have the line contact between them along the tube axis. The heat energy from the sun is absorbed by the absorber plate and then tubes having line contact and heat is then absorbed by the fluid in circular tubes.

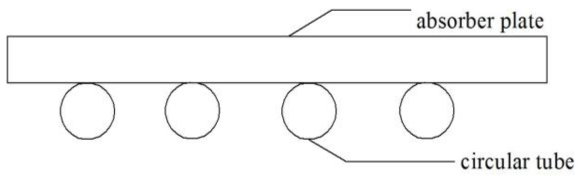
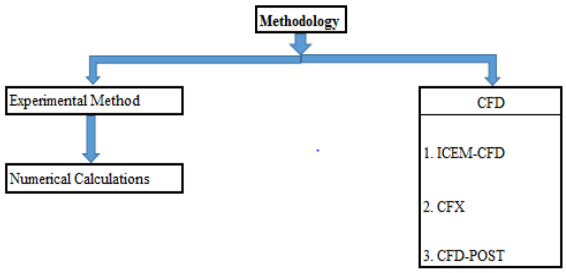


Figure 1.2: Circular tube configuration

2. Methodology



The above flow chart represents the step by step working procedure of this work. Using experimental setup results were obtained and then theoretical calculations are done to calculate the efficiency of circular pipe configuration. The right block shows the standard procedure for CFD work. For the present work, in case of circular pipe configuration creating the geometry then computational domain is constructed around the circular pipe configuration geometry, later set the mesh parameters then generates the mesh. Later this mesh is exported in the CFX readable format. In the CFX, the analysis will be carried out. The post processing is carried according to the requirements.

3. Experimental setup

The natural circulation of the solar water heater is used to conduct the experiment. Each pipe is 0.8 m long and has an inner diameter of 0.0127 m for the corrugated configuration as shown in Fig 2.2. The distances from pipe to pipe are 0.11 m and are gas welded at both the ends to a pipe of 0.0254 m diameter and 0.8m long. The absorber pipe assembly formed an inner box, which in turn is mounted in an outer box, the space between the absorber pipe assembly and the outer box is filled with rock wool an insulating material. To separate these parts an aluminum foil is used, then the box is covered with a 0.004 m thick clear toughened glass and an air gap between the plate and the glass cover is of 0.035 m. The overall dimension of the collector is 1.003*0.503*0.105m and the effective glazing area is 0.5 m^2.

The connection between the flat plate collector and the storage tank are in two parts; the return pipe and the flow pipe. The return pipe connects the outlet of the storage tank and the inlet of the collector together. The flat plate collector is oriented in such a way that it receives maximum solar radiation during the day. The absorbing surfaces are painted with black chrome selective coating. The absorbing plate and the absorbing surface of the pipe absorb solar radiation and absorbed heat is then transferred to the water in the pipes.

To conduct the experiment, the temperature in the tank and temperature of the outlet from the collector and the ambient temperature were recorded using a digital thermometer. To calculate the mass flow rate, water was collected in the measuring flask for time duration of one minute from the outlet of the collector.

Figure 3.1: Experimental setup

4. Results and Discussion

4.1 Experimental results for circular tube absorber configuration

This energy transfer rate is given in terms of overall loss coefficient, U_L (w/m^{2}k). In this work bottom and edge loss is neglected ($U_L = U_t$). Also efficiency is calculated by taking the hourly reading from 8 to 16 hrs. For varying inlet temperature and varying radiation readings and for constant mass flow rate. Hourly radiation data is taken from early researches. [8]

- Geographical location: (13.34°N, 77.10°E)
- Mass flow rate: 0.025 kg/s
- Date: 29th April

Weather Report: The weather was pleasant in the morning. The maximum temperature recorded for the day was 33° C. No rain was observed during the day. The day's readings are listed in below table.

Table 4.1: Experimental results for circular tube absorber configuration.

Time in hrs.	Ambient temp in k	Radiation in w/m^2	Inlet Temp in k	Outlet Temp in k	T_{mean} in k	U_L in w/m^{2}k	F_p	Fr	Qu in w	η
8	299	878.5	306	306	306	4.5995	0.5624	0.5587	187.33	42.64
9	299.5	1125.8	307.3	310.2	308.75	4.7164	0.5562	0.5524	236.70	42.05
10	301.5	1316.8	308.6	312.8	310.7	4.7611	0.5539	0.5502	277.79	42.19
11	303.5	1444.3	310.4	320.6	315.5	4.9011	0.5459	0.5418	303.84	42.07
12	304	1501.3	313.2	326.3	319.75	5.0412	0.5392	0.5350	308.84	42.14
13	304.5	1485.8	315.1	329.3	322.15	5.1121	0.5359	0.5317	301.59	40.59
14	306	1397.3	323	332.3	327.65	5.2619	0.5291	0.5245	269.69	38.60
15	305	1241.3	319.2	330.4	324.8	5.1879	0.5394	0.5279	242.66	39.09
16	304	1025.3	316.5	325.1	320.75	5.0702	0.9550	0.5341	202.12	39.42

4.2 Calculation for circular tube absorber configuration

Top loss coefficient ($\boldsymbol{U_t}$): [13]

$$h_w = 2.8 + 3.0v = 5.8\ w/m^2 k$$

$$f = \left(\frac{9}{hw} - \frac{30}{hw^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091N)$$

$$f = \left(\frac{9}{5.8} - \frac{30}{5.8^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091)$$

f = 0.6793

$$C = \frac{204.429(COS\beta)^{0.252}}{L^{0.24}}$$

$$C = \frac{204.429(COS45)^{0.252}}{0.035^{0.24}}$$

C = 418.82

$$U_t = \left[\frac{N}{\left(\frac{c}{T_m}\right)\left(\frac{T_m - T_a}{N+f}\right)^2} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma(T_m^2 + T_a^2)(T_m + T_a)}{\frac{1}{\epsilon_p + 0.0425N(1-\epsilon_p)} + \frac{2N+f-1}{\epsilon_g} - N}\right]$$

$$U_t = \left[\frac{1}{\left(\frac{418.82}{306}\right)\left(\frac{306-299}{1+0.6792}\right)^{0.252}} + \frac{1}{5.8}\right]^{-1} + \left[\frac{5.7*10^{-8}(306^2+299^2)(306+299)}{\frac{1}{0.9+0.0425*1(1-0.9)} + \frac{2*1+0.6792-1}{0.88} - 1}\right]$$

$$U_t = 4.5995\ w/m^2 k$$

Plate efficiency factor (F_p): [13]

$$a^2 = \frac{U_L}{K_p m_p}$$

$$a^2 = \frac{4.5995}{386 \times 2 \times 10^{-4}}$$

$$a = 7.7187$$

Fin efficiency factor (F): [13]

$$F = \frac{\tan h\left[\frac{a(W-D)}{2}\right]}{a(W-D)/2}$$

$$F = \frac{\tan h\left[\frac{7.7187(0.11-0.0127)}{2}\right]}{7.7187(0.11-0.0127)/2}$$

F = 0.9555

Plate efficiency factor (F_p): [13]

$$F_p = \frac{\frac{1}{U_L}}{W\left[\frac{1}{\pi D h_{fi}} + \frac{m_t}{\pi D K_t} + \frac{1}{C_b} + \frac{1}{U_L[D+(W-D)F]}\right]}$$

$$F_p = \frac{\frac{1}{4.5995}}{0.11\left[\frac{1}{\pi*0.0127*1500} + \frac{5.8*10^{-4}}{\pi*0.0127*386} + \frac{1}{0.69} + \frac{1}{4.5995[0.0127+(0.11-0.0127)0.9555]}\right]}$$

F_P = 05624

Heat removal factor (F_R): [13]

$$F_R = \frac{mc_p}{U_L A_c}\left[1 - exp\left[-\frac{U_L A_c F_p}{mc_p}\right]\right]$$

$$F_R = \frac{0.025*4182}{4.5995*0.5}\left[1 - exp\left[-\frac{4.5995*0.5*0.5624}{0.025*4182}\right]\right]$$

F_R = 0.5587

Actual energy collected (Q_u): [13]

$$Q_u = A_c F_R[I_T(\tau\alpha) - U_L(Ti - Ta)]$$

$$Q_u = 0.5 * 0.5587[878.5(0.8) - 4.5995(306 - 299)]$$

Q_u = 187.33 W

The efficiency of collector (η): [13]

$$\eta = \frac{actual\ useful\ energy\ collected}{solar\ energy\ incident\ on\ the\ collector}$$

$$\eta = \frac{Q_u}{I_T A_c}$$

$$\eta = \frac{187.33}{878.5*0.5}$$

η = 42.64

4.3 CFD Analysis of circular tube absorber configuration

Geometric model and domain of the circular tube absorber is created using ANSYS CFD. The domain created for circular tube configuration shown in Fig 4.1.

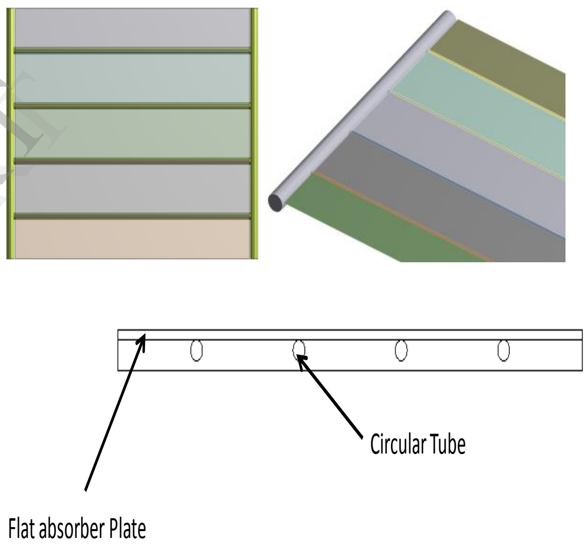


Figure 4.1: Geometric modelling of circular tube-absorber configuration

CFD Meshing Of Circular Tube-Absorber Configuration

The computational model is created in ICEM-CFD as per the dimensions shown in Fig 4.1. CFD meshing of circular tube-absorber are shown in Fig 4.2, it shows absorber plate meshed with hexahedral elements due to small thickness and fluid domain meshed with hybrid mesh consisting of boundary layer prism mesh close to walls and core of the fluid domain filled with tetrahedral mesh. Total number of elements used for this configuration of the absorber is approximately 0.6 millions.

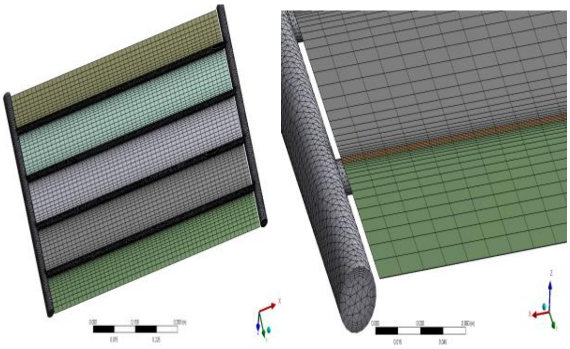


Figure 4.2: CFD meshing of circular tube-absorber configuration

CFD Boundary Conditions

In this analysis mass flow rate of 0.025 kg/s with constant inlet temperature is introduced at the inlet while a pressure outlet condition is applied at the exit. The physical properties of the working fluid (water) have been assumed to remain constant at mean bulk temperature. Impermeable boundary and no-slip wall conditions have been implemented over the channel walls. The time dependent heat flux was given at absorber plate wall while the opposite side was kept at adiabatic wall condition.

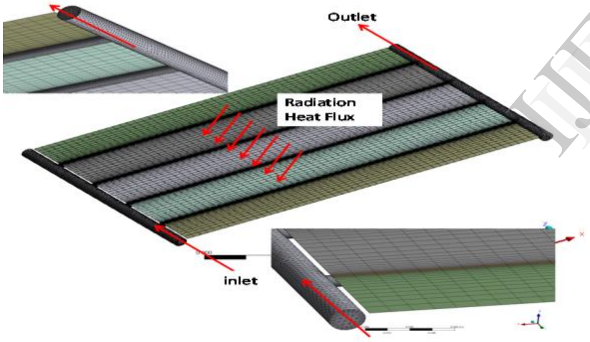


Figure 4.3: CFD boundary conditions

Fig 4.4 shows temperatures at midplane of the absorber plate with a tilt angle of 45º when the collector fluid enters the panel at 0.025 kg/s and 308.6 K, and heated by a solar irradiance of 1316.8 W/m^2 [6]. As seen in the Fig 4.4 the temperature in inlet header corresponds to the ambient temperature and it is very clearly indicated. The rise in temperature of the working fluid as it flows from inlet to exit header due to absorption of solar insolation. As the fluid flows through the tube, the working fluid gains heat and its temperature rises. Similarly Fig 4.6 shows the temperature contours for circular tube-absorber configuration at inlet temperature of 310.4K.

In Fig 4.5 the temperature contour of the absorber plate indicates excess temperature at the edge of the absorber plate. This is due to the fact that this part of the absorber plate doesn’t contain absorber tube which is used to absorb the heat. Thus there is no heat sink at these locations and this result in rise in temperature. There is rise in plate temperature of about 452.91K for inlet fluid temperature of 308.6K. Also, for an inlet fluid Temperature of 310.4K, the plate temperature is 469.21K as shown in Fig 4.7.

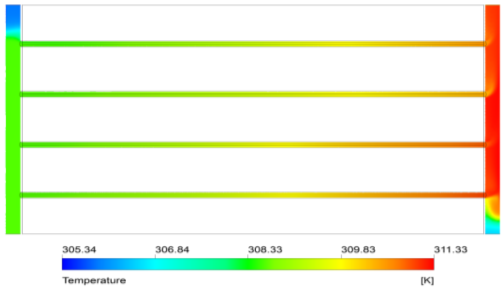


Figure 4.4: Middle plane temp contours at inlet temp of 308.6K

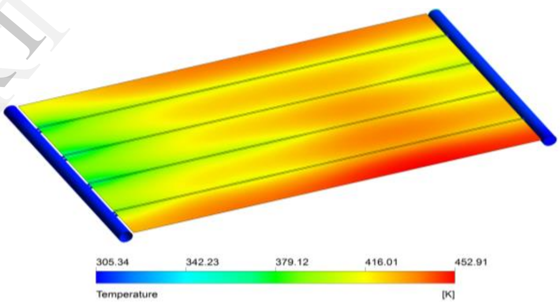


Figure 4.5: Temp contours at inlet temp of 308.6K

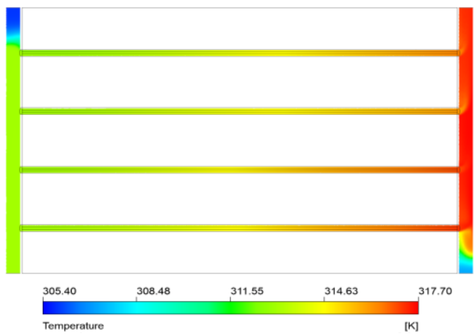


Figure 4.6: Middle plane temp contours at inlet temp of 310.4K

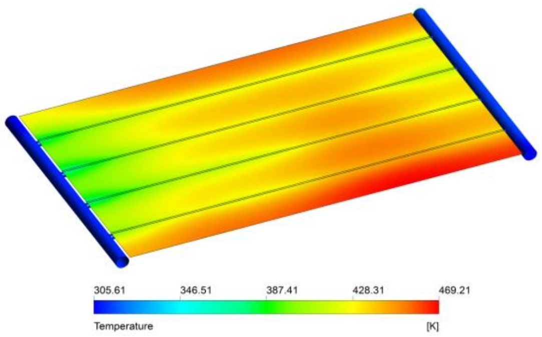


Figure 4.7: Temp contours at inlet temp of 310.4K

5. Validation of experimental and CFD outlet temperature results

Table 5.1: outlet temperature results of circular tube-absorber configuration

Time	Ambient temperature in K	Radiation in w/m^2	Experimental Inlet temperature K	Experimental Outlet temperature K	CFD Outlet temperature K
8	299	878.5	306	306	307.2
9	299.5	1125.8	307.3	310.2	309.5
10	301.5	1316.8	308.6	312.8	311.33
11	303.5	1444.3	310.4	320.6	317.5
12	304	1501.8	313.2	326.3	323.8
13	304.5	1485.8	315.1	329.2	327.1
14	306	1397.3	323	332.3	329.6
15	305	1241.3	319.2	330.4	328.8
16	304	1025.3	316.5	325.1	324.75

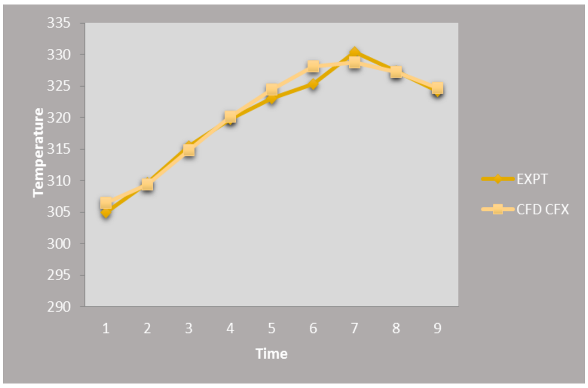


Figure 5.1: Outlet temp from experimatal data and CFD simulation data for circular tube-absorber configuration

The discrepancy obsevered in the outlet temperature of the experimental and CFD results is due to the fact that in experimental observation, the outlet temperature is measured at one particular location of the outlet header, while in CFD analysis the average temperature of the fluid flow through the outlet header is indicated. Hence the observed discrepancy in the outlet temperature. This results in a good comparision between experimental and CFD studies.

6. Conclusion

A numerical and experimental investigation of the flow and temperature distribution in a solar collector was performed. The influence of the tube shape and the absorber plate effect on flow and thermal distribution was investigated with CFD simulations. The CFD model was validated by measurements with the solar collector with circular tube and absorber configurations. Comparison between CFD simulation and the experimental measurements showed that the simulations were quite satisfactory in predicting the outlet temperatures. It shows only 5% deviation. This enhanced heat absorption by the working fluid reduces the overall temperature of the absorber plate while improving the efficiency of the collector.

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