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Design and CFD Analysis of Mini-channel Heat Receiver for CPC based Solar Thermal Absorber Application

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Conventional heat exchangers are bulky in nature. The specific applications like nuclear, submarine, electronic cooling, space cooling, solar thermal absorber etc. requires compact heat exchangers. There is no uniform heat flux input at the surface of mini-channel heat receiver when it is used at solar thermal absorber. For this non- uniform flux input condition, design of heat exchanger is a challenging task. The determination of heat transfer coefficient of such mini-channel heat receiver experimentally is also tedious. This can be made simple and accuracy of the design of heat exchanger can be increased by simulation of performance of the device using suitable software. In this research paper the design of mini-channel heat receiver for solar thermal absorber is done for non-uniform flux input condition. The fluid flow path is also predefined for optimum output temperature. Computational Fluid Dynamic Analysis (CFD) of the mini-channel heat receiver is carried out for determination of convective heat transfer coefficient. This specially designed mini-channel heat receiver for low pressure fluid flow system can be used at low pressure and medium temperature solar thermal systems. The use of mini-channel heat receiver at the solar thermal absorber not only increases the heat extraction rate but also reduce weight and size of the whole system. It indirectly contributes to increase in the overall gain of the solar system.

***Keywords*:** mini-channel heat exchanger, solar thermal system, CFD, medium temperature solar systems.

1. Introduction

Energy is a prime need of the world. The energy demands are increasing due to advancement in human living standards, forthcoming technologies and fourth Industrial revolution. Solar energy is one of the prominent green energy sources, but its effective conversion into usable form is always an issue to proactive research [1]. The non- viability of the solar energy may be due to different technical reasons like, bulky system, improper design of collector and absorbers [2]. The solar thermal absorbers efficiency plays a prime role in the overall efficiency of the solar thermal system. The solar thermal absorber technologies which are used currently limit its performance due to early attaining equilibrium temperature. Equilibrium attainment can be avoided by maintaining temperature difference at the absorbers surface and fluid which is exchanging heat energy. This can be facilitated by using effective and compact heat exchanging device [3]. Mini- channel heat exchanger is better for such applications instead of conventional heat exchangers [4]. Mini-channel heat exchangers advantages in volume (17.2% smaller), weight (2.8% lighter) and heat transfer (4.3% higher), with a little effect on pressure drop [5]. The development and testing of mini-channel heat receiver involves large cost, efforts and time [6]. When these heat exchangers are coupled with concentrating solar systems then the flux input at the receiver where the mini-channel is situated is non-uniform in nature [7]. To absorb this non-uniform flux and to obtain high fluid output temperature the fluid flow path design for optimum condition becomes necessary. This crucial condition of the design has been made more simplified using CFD analysis in this research work.

If the hydraulic diameter of the flow section ranges from 0.01mm to 0.2 mm, then it is called as a micro-channel heat exchanger. If hydraulic diameter of the flow channel r ranges from 0.2 to 3 mm, then it is called as Mini-channel heat exchanger and above 3 mm hydraulic diameter heat exchangers are the conventional type heat exchanger. The ability to produce tubes with external or internal fins and with minimal wall thicknesses allows better heat transfer area per unit volume of a tube. Therefore, mini channel tubes are ideal for use in compact and lightweight heat exchanger. Mini-channel flow governs to accomplish two objectives viz. Keep a fluid into intimate contact with the channel walls, Bring fresh fluid to the heated wall and maintain uniform temperature distribution in the fluid

The result of CFD analysis can be directly used to cross verify the designed parameters. The change in design can be applied which will reduce the cost and time for development of mini-channel heat receiver. The application of this mini-channel analysis for solar thermal system will increase the solar system gain and also help to make the system compact.

2.Material and Method

2.1 Flux Distribution on Surface of heat Receiver

As sun ray incident normally (with 0° angle of incidence) on the receiver, with the help of tracking system. The SolTrace simulation of CPC gives the flux distribution at the receiver surface. There is a formation of the five different flux distribution bands at the absorber surface [7]. Out of these flux bands, the central band has the highest flux density of 7000 W/m2, band in between central band and extreme side way band has lowest flux intensity of 3000 W/m2. The extreme side way band has flux density in the midway of above two as 4000 W/m2 as shown in Figure 2.1. So this variation in flux density will cause variation in surface temperature across the absorber with respect to the flux intensity at that point on absorber.

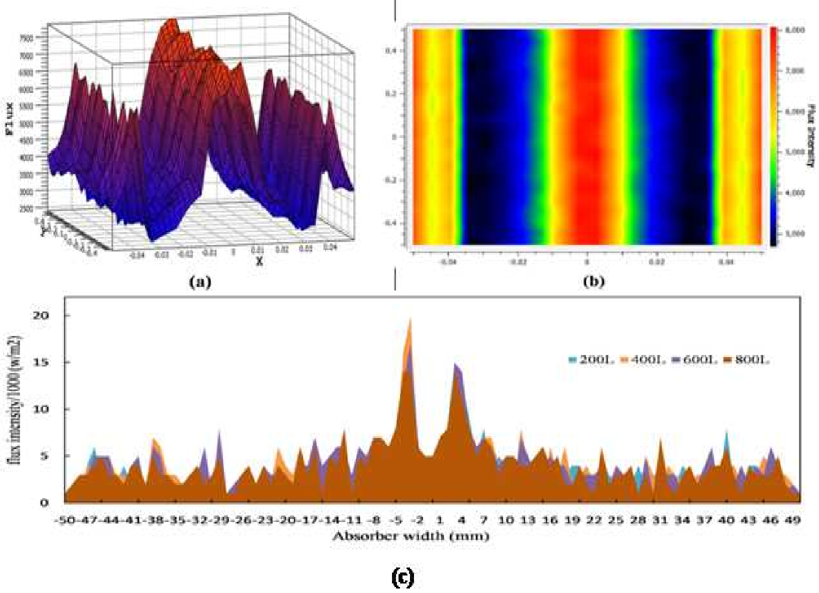

Figure 2.1 Flux distribution at the 4X CPC receiver surface.
a) The contour plot of flux distribution using solTrace software b) Flux plot using SolTrace software along the width of receiver c) The overall pattern of flux distribution on receiver These flux are the input flux for the mini-channel heat receiver situated below solar thermal absorber.[Figure must be printed in Colour]

2.2 Design of Heat Exchanger

Two most common materials can be used as a heat transfer media viz. aluminium and copper. These materials are selected with a compelling combination of durability, corrosion resistance and thermal conductivity. Copper is preferred at heat transfer, and aluminum is preferred at heat dissipation although both are good at its place. It depends on parameters like application, efficiency, and cost to choose the one. When comparing efficiency at the same volumetric heat transfer densities copper is better than aluminium, but the cost of copper is higher than that of aluminium. So for building this solar thermal receiver, the aluminium material is suitable. It can be again manufactured in the form of the mini-channel easily by an extrusion process.

The pressure drop have calculated through following steps

Aspect ratio (A_s) = (H/W)

Flow velocity (v) = (m/N)/(ρ.H.W) in m/s

Hydraulic Dia (D_H) = 4(H.W)/(2(H+w)) in m

Raynold's Number (Re) = ($\rho v D_H L)/\mu$

Poiseuille Number (P_O)

$$P_O = 24[1 - 1.3553As + 1.9467As^2 - 1.7012As^3 + 0.9564As^4 - 0.2537As^5]$$

Friction factor (Fr) = P_O/Re

Pressure Drop (P) = $(2P_O vL\mu)/(D_H)^2$ in N/m^2

By this equation, it comes to know that, by keeping fluid properties constant pressure drop is only depends on the aspect ratio and hydraulic diameter. The length was calculated from the pressure drop by varying the width from 1mm -15 mm & height from 1mm - 9 mm, and keeping the other values (m=0.0001Kg/s, ρ=1000 Kg/m ,μ=0.0008 Ns/m2)as constant .These values are represented by the graph below.

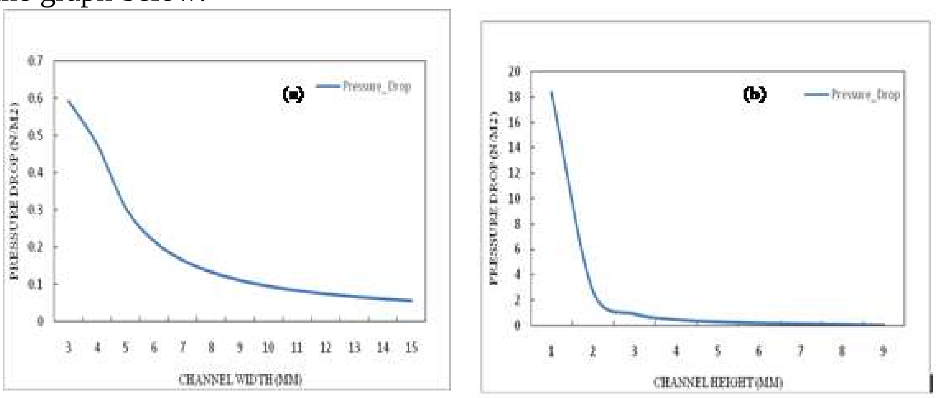

Figure 2.2 Effect of channel dimensions on pressure drop. a)Pressure Drop with Varying Mini-channel Width b) Pressure Drop with Varying Mini-channel Height

From the graph, it can be observed that as the channel width increased the pressure drop decreases. Also as the height of the channel is increased the pressure drop decreases, but the slope of the trend line generated by channel height graph is more as compare to slope of trend line generated by channel width graph. Figure 2.3 shows final dimensions of mini-channel heat exchanger.

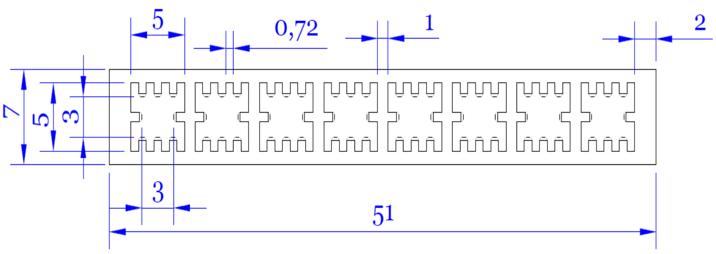

Figure 2.3 Mini-channel heat exchanger cross section

2.3 Fluid Flow path optimization

There are total 5 channels with different flux inputs. These channels with different flux input as mentioned in 2.1 treated as a 5 separate heat exchangers with 7000 W/m^2 one, 4000 W/m^2 two and 3000 W/m^2 two heat exchangers. These heat exchangers can be arranged in total 900 combinations. Some combinations can be mentioned as all heat exchangers in series, all heat exchangers in parallel, Two parallel and Three series, Three parallel and Two series, Four parallel and One series, Three parallel set is in series with two parallel set, Two parallel set 1 and Parallel set 2 in series with one H.E

These combinations are reduced to 350 combinations by permutation- combination law. The Mathematical model was developed for output temperature and efficiency. The MATLAB coding was done to find out output temperature and efficiency of each combination. The Final combination is shown in figure 2.4

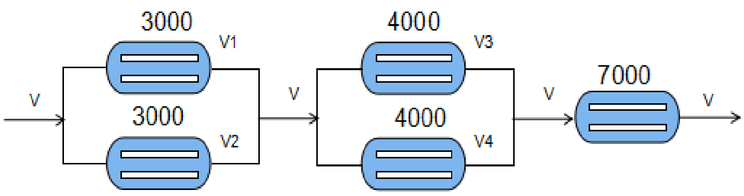

Figure 2.4 Final fluid flow paths

2.4 CFD Simulation of Mini-Channel Heat Receiver

Simulation of performance of mini-channel heat receiver is carried out using Ansys CFD software. The Mini-channel heat exchanger geometry is imported in the CFD and the following input parameters (as given in Table 1) are set for determination of performance of mini-channel heat receiver.

Table 1 Input Parameters for CFD Simulation of Mini-channel heat exchanger

Parameter	Value
Inlet Temperature (Ti)	300 °K
Mass Flow (m)	0.001 Kg/s
Stefan-Boltzmann constant (σ)	5.67×10^{-8}
Emissivity Of Absorber (€)	0.09
Sp. Heat of Fluid (Cp)	2600 J/Kg K

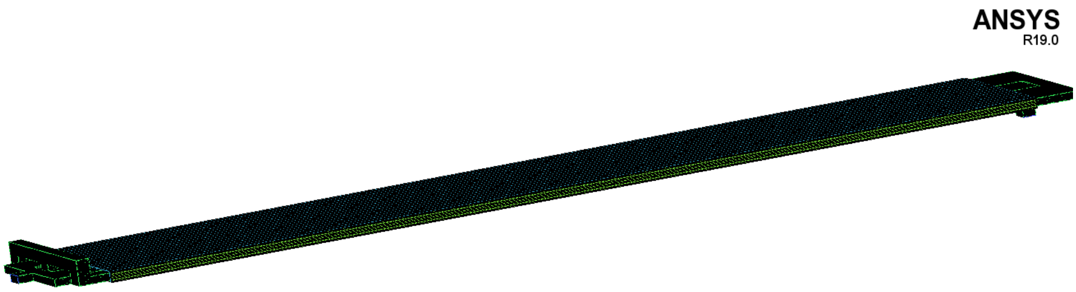

Figure 2.5 Meshing of Mini-channel heat Exchanger

Table 2 Result of CFD Analysis

Sr. No.	Mass Flow	INLET Temp	OUTLET Temp	FLUID Domain (Vol.Wt.)			TOP S/F Temp (Area.Wt.)			S/F Flux	U	Heat Trans
	(Kg/s)	(K)	(K)	Min (K)	Max(K)	Ave(K)	Min(K)	Max(K)	Ave(K)	(W/m2)	(W/m2 K)	Watt
1	0.001	300	346.23	300	352.32	339.61	325.21	352.44	344.04	2067	466.59	124
2	0.0015	300	329.09	300	333.25	324.6	316.15	333.33	328.61	1950	486.28	117
3	0.002	300	319.79	300	322.95	316.51	311.09	323.07	319.97	1767	510.69	106
4	0.0025	300	314.79	300	317.5	312.21	308.38	317.62	315.29	1650	535.71	99
5	0.003	300	311.59	300	314	309.47	306.66	314.126	312.24	1550	559.57	93
6	0.0035	300	308.44	300	310.41	306.85	304.93	310.528	309.11	1317	582.74	79
7	0.004	300	306.92	300	308.71	305.58	304.12	308.82	307.62	1234	605.50	74

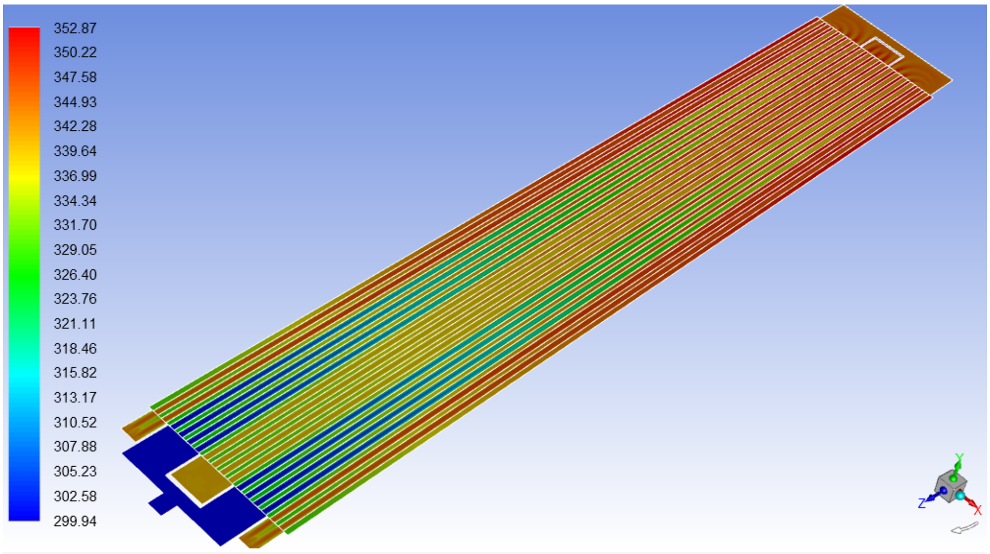

Figure 2.6 Result of CFD Analysis

The CFD Analysis in figure 2.6 shows that the fluid flow temperature can be raised up to 50 K if working fluid is circulated at 0.001 kg/sec with a designed fluid flow path. Table 2 shows that the overall heat transfer coefficient value can be attained up to 605 W/m^2K.

3. Conclusion

The Design of mini-channel heat exchanger for variable flux input condition is presented. The fluid flow path finalization for the variable flux input on the surface of heat exchanger is carried out by optimizing the performance parameters of the mini-channel heat receiver. The average overall heat transfer coefficient value reached up to 600 W/m^2K. The CFD analysis work put forth in this research work help to get investigate the performance of the mini-channel heat receiver. This input is the important step for designing highly efficient solar thermal absorber using mini-channel heat receiver.

4. References

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