HEAT TRANSFER ANALYSIS IN COMPOUND PARABOLIC COLLECTOR: A CFD APPROACH

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Abstract: In this paper, a 2D compound parabolic collector (CPC) numerical modelhas been developed on ANSYS 16.0 software to analyze the heat transfer phenomenon inside the CPC air cavity, which is used to design efficient solar collectors. A steady-state CFD simulation was done to analyze, the complex process of heat transfer by considering materials, fluid physical properties and boundary conditions at the walls of the CPC. Simulated results of the temperature distribution over the CPC surface and collector efficiency were validated with the experimental values from literature. To increase the thermal efficiency of the solar collector, the glass baffle was used as convection suppression device. The baffle of size of 40 mm × 3 mm was placed at four different positions above the receiver surface in the air cavity of CPC. The total heat losses from the receiver surface to the CPC air cavity and outer environment were obtained and collector efficiency was calculated. The percentage reduction of heat losses were observed as 4.19, 4.44, 5.4 and 9.36 for 15 mm, 10 mm, 5 mm and 1 mm respectively as compared to the original CPC without baffle arrangement. The baffle arrangement at position 1 mm showed maximum suppression to convection heat loss. The glass baffle ceased the passage of hot air inside and obstructs its circulation from receiver tube to CPC glass cover surfaces separating out the convection phenomenon. It also prevents the heat losses to the environment and increased the collector efficiency up to 88.78%.

***IndexTerms* -** CFD, Compound Parabolic Collector (CPC), Convection, Radiation.

I. INTRODUCTION

The sun is the most important renewable energy source, with its endless supply of high-energy radiations to the earth. Solar energy has been used from many years by converting it into usable form. Today, there are numerous types of solar collectors are abundantly available, which convert solar energy into heat energy. Solar collectors are used to capture optimum amount of solar radiation according to the suitability of the collectors and geometric locations. These collectors are of different types like Flat plate, Fresnel, parabolic, compound parabolic collector, etc.

Recently, the use of Compound Parabolic Collector receiving more attention in industrial applications. The CPC has high optical efficiency and lower initial cost by removing the solar tracking mechanism for certain applications. CPC is a concentrating type of solar collector which focused all incident radiations to the smaller receiver surface. The geometric shape of CPC is obtained by intersection of the two parabolic curves, which can be designed by ray tracking method [1].

The overall efficiency of solar collectors depends on the radiative and convective heat losses from the surface of the CPC to the environment. The literature showed that the heat losses phenomenon inside the CPC solar collector was complex process of convection and radiation, which depends on the collector orientation, geometric parameters, aspect ratio, boundary condition at wall surfaces and operating fluid property [2, 3]. Aguilar et al. [3] had studied the effect of CPC orientation on the heat losses from collector. The heat losses were higher for East-West CPC orientation than the North-South and these losses were due to heat losses at collector end, solar incident angle and fluid flow mechanism inside the cavity of CPC. Li et al. [4] had done an investigation on heat loss mechanism in Cross Compound Parabolic Collector air cavity. The total loss of energy from the receiver surface was about 60 % of the total solar irradiation and that should be had more attention to design thermally efficient CCPC solar collector. Ch. Reichal *et al.* [5] showed the overall heat transfer phenomenon inside CPC. The various heat transfer processes were involved in the heat loss phenomenon from the receiver surface. The main heat loss mechanism obtained in CPC air cavity was convective heat transfer. Antonelli *et al*·[6] analyzed the effect of tilt angles concentration ratios of CPC on the heat loss mechanism with circular and rectangular receiver. This study showed, the correlation to determine the natural convective heat loss in air cavity and thermal efficiency of the CPC solar collector. Osorio et al. [7] had used the double glass envelope over the receiver surface of parabolic collector, to reduce the heat losses. At low operating temperature, collector efficiency reduced due to attenuation of radiation through envelope but for higher temperature collector efficiency were increased. Francesoni *et al.* [8] were used evacuated pipe in air cavity of the CPC. For temperature range above 440K, the evacuated pipe were best suited to suppress the natural convective heat loss from the receiver tube surface.

Nomenclature

A_p	Entrance aperture area (mm^2)
A_r	Receiver area (mm^2)
C	Concentration ratio
C_p	Specific heat (J/Kg K)
D_i	Inner receiver diameter (mm)
D_o	Outer receiver diameter (mm)
H	Total height of CPC system (mm)
H'	Height of CPC (mm)
h	Heat transfer coefficient (W/m^2 K)
I	Solar radiation intensity (W/m^2)
K	Thermal conductivity (W/m K)
L	Length of CPC (mm)
N_u	Nusselt number
Q_{loss}	Total heat loss from receiver (W)
T	Temperature (K)
V	Velocity (m/s)
W	Entrance aperture width (mm)

Greek Letters

α	Absorptivity
Υ	Reflectivity
θ_a	Half acceptance angle (°)
θ	Angle of inclination (°)
δ	Thickness (mm)
τ	Transmitivity
ε	Emissivity
σ	Stephens Boltzmann constant (W/m^2K^4)
η	Efficiency
ρ	Density (Kg/m^3)

Subscripts

a	Acceptance
abs	Absolute
amb	Ambient
gc	Glass Cover
ins	Insulation
rec	Receiver
ref	Reflector

Abbreviations

CFD	Computational Fluid Dynamics
CPC	Compound Parabolic Collector
S2S	Surface to Surface

II. METHODOLOGY

2.1Geometric Model Description

The geometric model of CPC was developed on the ANSYS software. The specifications of the CPC are shown in Table 2.1, which are taken from the literature [5] for analysis. To get desired temperature distribution over the CPC surface and heat losses from the receiver, k-type thermocouples (0.5K tolerance) were mounted on the reflector and glass cover surface. Fourthermocouples are mounted on right half of reflector surface where, hot air comes in contact and one at left half surface, where cold air circulation occurred. Five thermocouples are mounted over the glass cover surface. The outer surface of receiver was coated with a non-selective lacquer to reduce the heat losses.

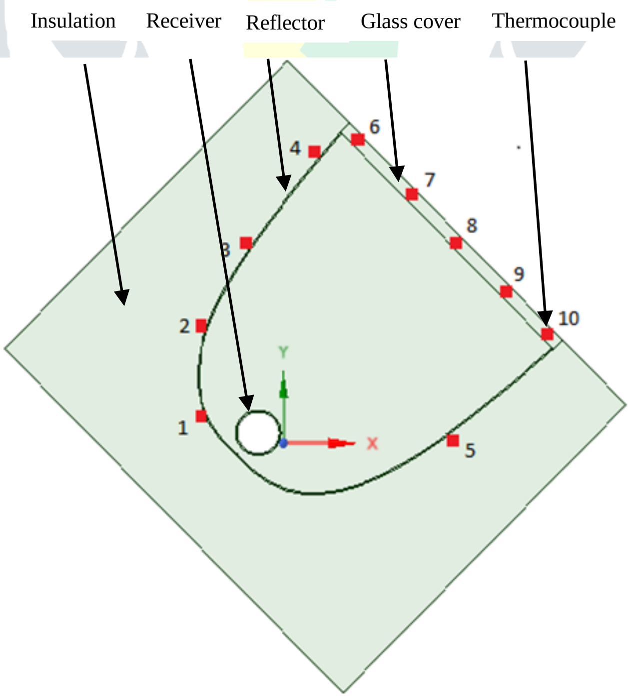


Fig. 2.1: Geometric model of CPC

Table2.1: Specification of CPC

Parameters of CPC	Values
Height (H')	100 mm
Receiver outer diameter (D_O)	15 mm
Receiver thickness (δ_{rec})	1 mm
Reflector thickness	0.5 mm
Glass cover thickness (δ_{gc})	4 mm
Insulation thickness (δ_{ins})	30 mm
Acceptance angle (θ_a)	20°
Receiver emissivity (ε) with coating	0.86
Slope (θ)	45°

2.2 Numerical model and solution method

The governing equation of mass, momentum and energy were solved by ANSYS Fluent software,

- **Conservation of mass:**

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}+\frac{\partial p}{\partial t}=0 \quad (2.1)$$

- **Conservation of momentum:**

X-momentum equation

$$\rho\left(u\frac{\partial u}{\partial x}+\right. \quad (2.2)$$

Y-momentum equation

$$\rho\left(u\frac{\partial v}{\partial x}+\right. \quad (2.3)$$

Z-momentum equation

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}\right. \quad (2.4)$$

- **Conservation of energy:**

$$\frac{\partial}{\partial} \quad (2.5)$$

The two equations k-ε model uses the following transport equations for k and ε:

$$\frac{\partial}{\partial t}(\rho k)+ \quad (2.6)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\mathrm{div}(\rho\varepsilon U)=\mathrm{di} \quad (2.7)$$

2D numerical model of CPC was generated as computation domain for analysis. The meshed quality of the model solely done using quarts, which improved the accuracy of the simulation. The area at bottom, between the CPC involute and receiver tube and between reflector surface and glass cover at the top, are important for numerical computation. In these regions careful meshing required, because there strong gradient of velocity and temperature occurred. The meshed quality should resolve the $y^+ \leq 1$ at surfaces near receiver, glass and reflector. The meshing of the CPC model done very fine about 85000 cells, to capture the radiation and convection phenomenon accurately

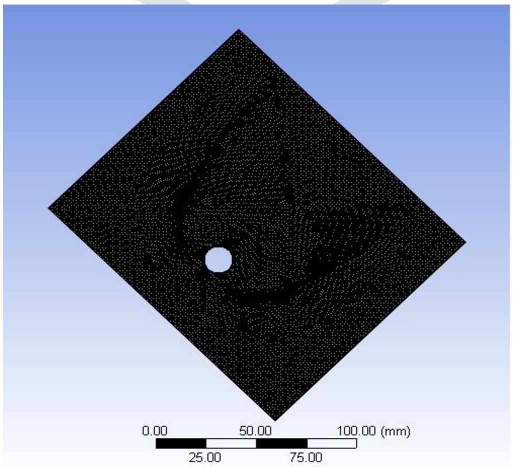


Fig. 2.2: Meshed model of CPC

All calculations were obtained on the ANSYS 16.0 code with double precision option enabled. In general setting, pressure-based, absolute and steady options were done. The model includes energy model, k-ε viscous model and Surface to Surface model were employed. In k-ε viscous model wall enhance treatment and full buoyancy effect were used to capture viscosity effect at the walls and buoyancy effect in air cavity of CPC respectively. Surface to Surface (S2S) model was employed to consider all incident radiations which were transferred to the receiver, without interfering of the intermediate medium.

2.3 Boundary conditions

The thermophysical properties of the CPC materials are shown in Table 2.2. The air inside the CPC cavity were modeled to be incompressible ideal gas. The constant wall temperature were considered at receiver surface and it had given as input. The boundary conditions for glass cover, reflector and insulation were employed as convection and radiation by considering natural convective heat transfer coefficient 5 W/m^2 K, 300 K ambient temperature and at 1 atmospheric pressure.

Table 2.2: Thermophysical Properties of CPC Materials

Materials	**K(W/m^2 K)**	**ρ (Kg/m^3)**	**C_p(J/Kg K)**	**ε**
Glass	1	2530	840	0.9
Polysterol	0.034	30	1300	-
Copper	387.6	8978	381	0.9
Aluminium	222	2739	381	0.05
Air	0.0242	-	1006.43	-

The calculation were done by employing couple algorithm for pressure velocity coupling. In spatial discretization, body forced weighted was empowered for pressure and for momentum and energy Second Ordered Upwind option were enabled. Pseudo-transient option were enabled to speed up the calculation process. The simulation have been allowed to converge using 2500 iteration, to reach the conservation criteria of residual for energy 10^{-7} and for others 10^{-3} were considered.

2.4 Validation of results

The 2D simulation results of CPC model were validated with the experimental values [5] from literature. The temperature distribution over surfaces of reflector and glass cover, for receiver surface temperature 65°C is shown in Fig.2.3. The Fig. 2.3 showed, the temperature distribution curves of experimental and numerical values followed the same trend.Variationof numerical results from experimental values are under the tolerance range. The error tolerances were due to assumptions made in numerical simulation that, the all incident solar rays directed to the receiver surface and there was no heat energy loss to intermediate air medium and outside environment.

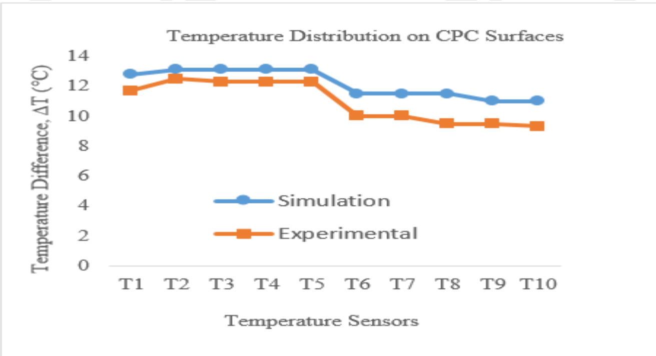


Fig.2.3: Temperature distribution over reflector and glass cover surface at temperature, T_{abs} = 65°C

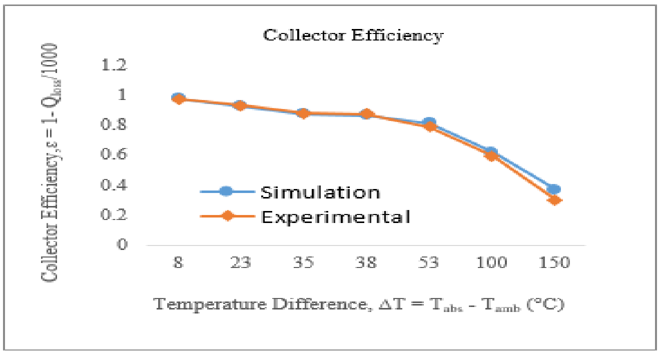
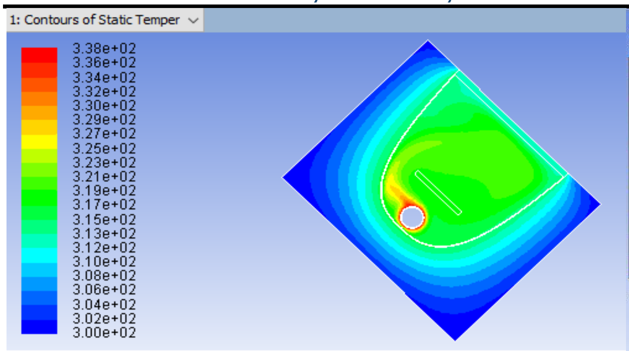


Fig.2.4: Collector efficiency

Fig.2.4 shows, collector efficiency of CPC at corresponding receiver temperature. The results of the simulation and experimental data are quite promising at lower receiver temperature, as the heat losses from the receiver were minimum. Thehigher receiver surface temperature increased the heat losses from receiver and it influenced to the thermal efficiency of solar collector.

III. RESULTS AND DISCUSSION

The glass baffle of geometric size 40 mm × 3 mm was used as convective heat transfer suppression device. It was placed at 15 mm, 10 mm, 5 mm and 1 mm positions above the receiver tube in CPCair cavity. The heat loss analysis was done for above four cases of baffle arrangements, for 65°Creceiver surface temperature and for same environmental conditions of original CPC system.



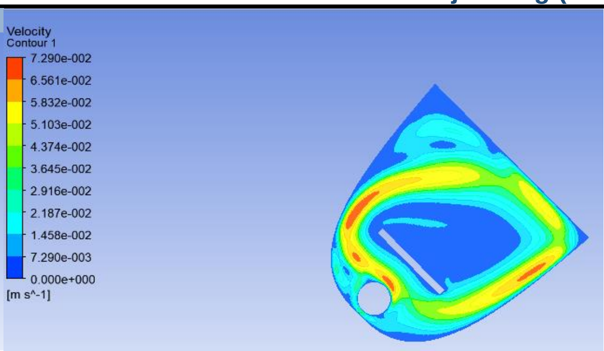
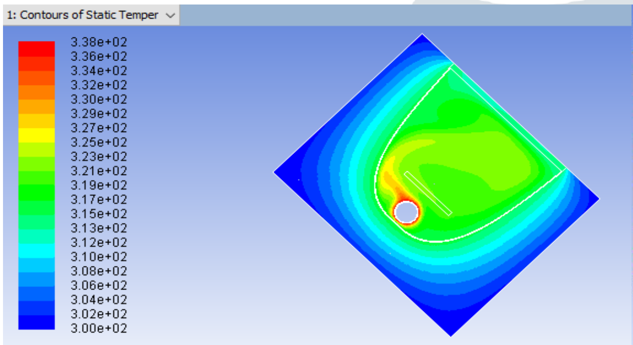


Fig.3.1: Temperature contour at, Tabs = 65°C, baffle at 15 mm above receiver tube

Fig.3.2: Velocity contour at, Tabs = 65°C, baffle at 15 mm above receiver tube

For case I, where glass baffle was placed at 15 mm away from the receiver surface. The temperature distribution contour and velocity contour are shown in Fig.3.1 and 3.2. The Fig 3.1 showed the variation of temperature over the surfaces of reflector and glass cover. With the glass baffle arrangement, the variation of average surface temperature of CPC system was reduced by 0.5°C than the original system. The velocity contour showed, the circulation of hot air from heated receiver surface to the top portion of CPC and cold air from top to bottom of CPC. The air density difference in CPC air cavity became the main driving component of air circulation, which facilitatedthe convection heat transfer phenomenon. But in case of baffle arrangement in CPC, baffle opposed the air circulation and suppressed convection heat transfer process.



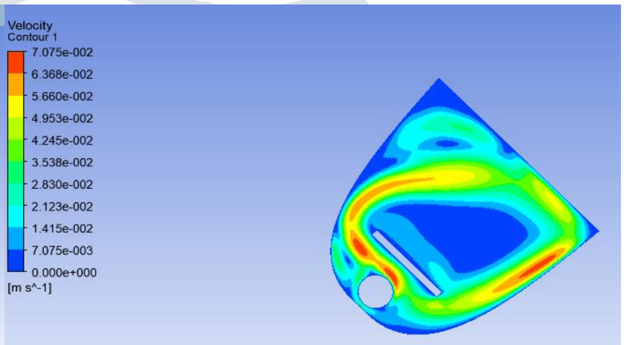
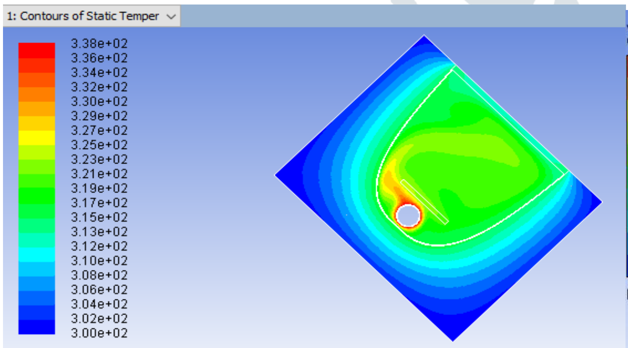


Fig.3.3: Temperature contour at, Tabs = 65°C, baffle at 10 mm above receiver tub

Fig.3.4: Velocity contour at, Tabs = 65°C, baffle at 10 mm above receiver tube

For case II, the glass baffle at 10 mm above the receiver surface. The temperature and velocity contours are shown in Fig.3.3 and 3.4. From above velocity contour it is observed that, the cold air circulation from right reflector surface to the left surface was divided in to two parts. The large portion of air flow passed over receiver surface and influenced the convection heat transfer process and remaining portion of air flow was untouched to the receiver surface and passed over baffle surface.



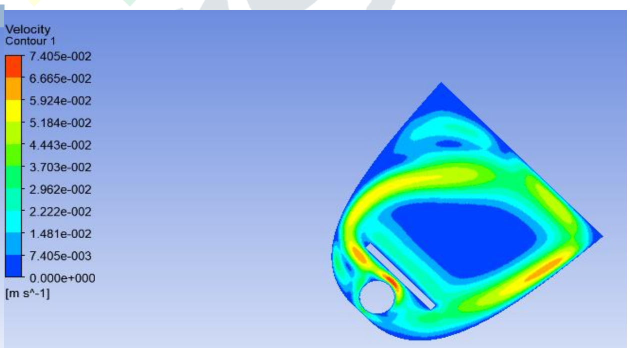
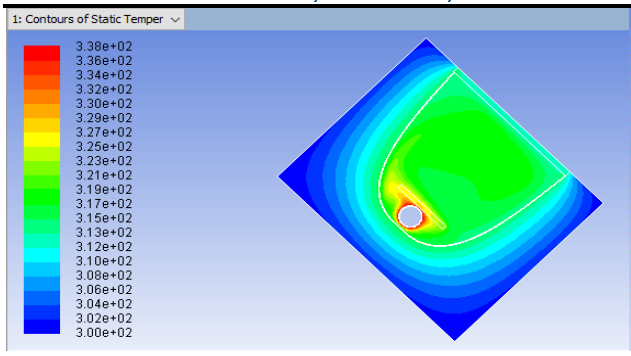


Fig.3.5: Temperature contour at, T_{abs} = 65 °C, baffle at 5 mm above receiver tube

Fig.3.6: Velocity contour at, T_{abs} = 65 °C baffle at 5 mm above receiver tube

For case III, the temperature and velocity contour for the baffle arrangement at 5 mm above receiver surface are shown in Fig.3.5 and 3.6. In this case, the maximum portion of cold air flow was bypass over the baffle surface and very less quantity of air was touched to the receiver surface.The bypass portion of air flow affected the convection heat transfer phenomenon from the receiver surface. In this baffle arrangement, the heat loss from the receiver surface was suppressed by 5.4%.



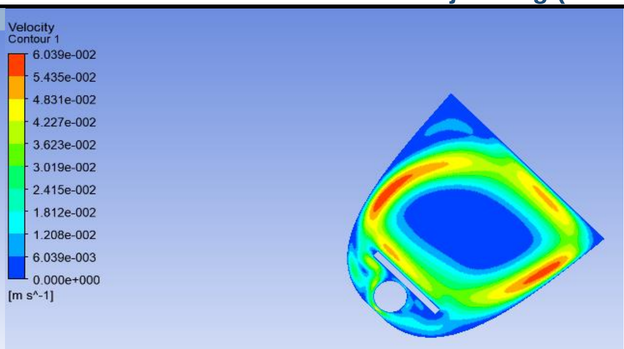


Fig.3.7: Temperature contour at, Tabs = 65°C, Fig.3.8: Velocity contour at, Tabs = 65°C,
baffle at 1 mm above receiverbaffle at 1 receiver mm above tube

For case IV, the baffle is placed at the 1 mm above the receiver tube. Both temperature and velocity contour, which are shown in Fig3.7 and 3.8, displayed temperature distribution and circulation of hot air in air cavity of CPC. The circulation of air was separated out from the receiver wall surface and it bypass over the baffle surface. In this case, the direct convection of heat from receiver surface to circulating air was ceased. So, the convection of heat transfer happened as, firstly from receiver surface to the baffle surface and then it was convected to the upper portion of the air cavity through the glass baffle.

Table 3.1: Results of glass baffle arrangement

Baffle position above receiver surface	Average surface temperature drop of CPC in ℃	Reduction of heat transfer loss in %	Collector efficiency in %
15 mm	0.5	4.19	88.136
10 mm	0.8	4.44	88.17
5 mm	1.5	5.4	88.29
1 mm	2	9.36	88.78

IV. CONCLUSION

In this 2D compound parabolic collector (CPC) numerical model, the heat transfer phenomenon inside the CPC air cavity have been studied. The total heat losses from the receiver surface to the CPC air cavity and outer environment for the above four cases of baffle arrangementwere analyzed on ANSYS Software. The following conclusions are made from numerical results:

- The average temperature distribution over reflector and glass cover surface was reduced by significant level for above four cases of baffle arrangement. It actually helped to reduce the convection heat losses from CPC surfaces to the outside environment.
- The total radiative and convective heat losses from the receiver surface to CPC walls and environment were reduced maximum in case of baffle arrangement at 1mm above receiver surface.
- The baffle arrangement at 1 mm above receiver surface had suppressed the convection heat transfer phenomenon and improved the collector efficiencyof the CPC solar collector to 88.78%, which is quite high among existing solar collectors.

With the glass baffle arrangement in air cavity of CPC, it separate out the air flow from receiver wall and it bypass over the baffle surface. So, the natural convection heat transfer phenomenon was suppressed. The total heat losses from the receiver surface reduced to significant level and increased the overall efficiency of solar collector. The glass baffle arrangement is a cost wise very cheap solution, to improve the efficiency of solar collector, it will be used as prominent option for design of efficient solar collectors.

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