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CONSTRUCTAL DESIGN OF FLAT PLATE SOLAR COLLECTOR

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Abstract. This paper presents a geometric optimization of flat plate solar collector for water heating using constructal design method. In this case, the objective is to identify an optimized geometric configuration of flat plate collector with the minimum entropy generation subject to global constraints (fixed area of the collector surface and fixed volume of the riser tube). The length of the absorber plate equivalent to the length of the riser tubes (*L*), the spacing between the risers (*W*) and the diameter of the riser (*D*) are free to morph with respect to the degree of freedom provided by the area of the collector surface and the volume of the riser tube until an optimal geometric configuration is obtained at minimum entropy generation or maximum conductance. The heat flux (equivalent to solar radiation) applied on the top surface area of absorber plate; the inlet velocity and the inlet temperature of water were all considered constant. With the simulation results obtained a modified Reynolds number was computed and some useful correlations of the modified Reynolds number with the optimal geometrical parameters (Lopt, Wopt and Dopt), minimum entropy generation and maximum conductance were established. The effect of the volume of fluid in the riser tube with respect to optimal geometrical parameters was also studied at constant modified Reynolds. It was observed that the optimal length increases with increase in the volume of the fluid while the optimal riser tube diameter and riser tube spacing slightly decrease with increase in the volume of the fluid. The minimum entropy generation also slightly decreases as the volume of fluid in the riser tubes increases. The numerical results obtained using computational fluid dynamics (CFD) code were verified with the experimental data reported in the open literatures and there was a good agreement with the experimental data.

Key words: Geometric, Constructal method, Entropy generation, Flat plate collector, Modified Reynolds number.

1. INTRODUCTION

Flat plate collector (FPC) is one the solar collectors developed to harness solar energy. It is a special type of exchanger that transforms solar radiation into heat unlike the convectional heat exchangers which usually accomplish a fluid-to-fluid exchange with high heat transfer rate [1, 2]. It is simple and inexpensive to fabricate, install, and require little maintenance [3].

In an attempt to improve the thermal performance of FPC, various researches have been conducted, some of the works done are as follows: Bejan *et al*. [4] conducted an exergy analysis of a solar collector using second law of thermodynamic and found that the amount of exergy delivered by solar collector system is affected by heat transfer irreversibility occurring between the sun and the collector, between the collector and the ambient air and inside the collector. The effect of irreversibility on the performance of FPC was studied by Saha and Mahanta [5]. Luminosu and Fara [6] analysed the optimal operation mode of FPSC by mean of exergy analysis using numerical solution under the assumption that the fluid inlet temperature is equal to the ambient temperature. In the exergetic optimization of FPC carried out by Farahat *et al*. [7] of which the optimum values of parameters such as mass flow rate, the absorber plate area and the maximum exergy efficiency were obtained. The design method of FPC based on minimum entropy generation was carried out by Torre-Reyes *et al.* [8]. Maha *et al*. [9] examined the effect of geometrical design parameters of FPC on energy and exergy efficiencies. The used converging lenses mounted at the glass cover of FPC was carried out by Alkhair *et al.* [10] and found out that the temperature of the water increases as the number of lenses increase. In a similar vein, different geometry configurations of FPC has been used to improve its performance as shown by Sivakumar *et al.* [11], Sanke *et al*. [12], Kumar [13]. The work on fluid flow and heat transfer in FPC has been investigated by Fan *et al*., [14] and Marroquin-De *et al*. [15].

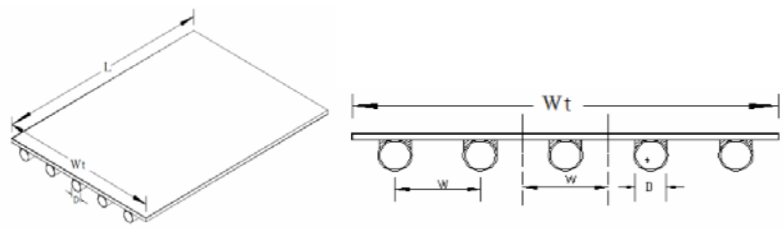
It is apparent that much study has done to improve the thermal performance of the flat plate solar collector ranging from energy and exergy optimization to the use of various geometric configurations of the collector. However, based on available literatures there is lack of information on the geometric optimization of FPC where optimal parameters such as length of the absorber plate, spacing between the risers and the diameter of riser tubes are simultaneously obtained.

In this paper, a geometric optimization of the unglazed flat plate collector using constructal design method with the global objective function of minimization of entropy generation which is equivalent to the maximization of exergy is carried out. In this case, the external irreversibilities due to temperature difference between the sun and the collector and between the collector and environment are fixed. The focus is to minimize the internal irreversibility which is due to fluid flow friction and heat transfer as result of temperature difference between the collector and the fluid. The global objective is to determine the optimal size of the collector which destroys least exergy.

2. PHYSICAL MODELLING

Figure 1 is 3D geometric of unglazed flat plate collector (FPC) which consists of three basic parameters which includes: the length of the absorber plate equivalent to the length of the riser (*L*), spacing between the riser tubes and diameter of the riser (*D*). The riser tubes bonded below the absorber plate are usually connected to the header tube which conveys and distributes water into the riser tubes. The water enters from one end of the riser tubes through the header pipe and gets heated in the collector area and the hot water is given out at the other end. But for the simplicity of the geometric, the header tube connected to the riser tubes is not considered.

The riser tubes bonded to absorber plate are of equal diameter and are uniformly spaced. Hence, it can be assumed that the flow rate in all riser tubes is constant and fluid is uniformly distributed in all the riser tubes from the header tube. Therefore, it is only a symmetric of the collector that is modelled for simplicity of the analysis as seen in the computational domain in Fig. 2. The fluid (water) used was assumed to be a continuous medium and incompressible which possesses laminar flow characteristics. Thermo-physical properties of the material (copper) for both absorber plate and riser tube are constant with respect to the operating temperature. The bottom side of the absorber tube and the absorber plate as well as sides of the absorber plate was assumed to be adiabatic. In order to eliminate the drawbacks arising from the random variation of inlet temperature, it was also assumed that the inlet temperature is equal to environment temperature.



a) 3D view b) front view

Fig. 1 – The FPC with five (risers) tubes bonded below the absorber plate.

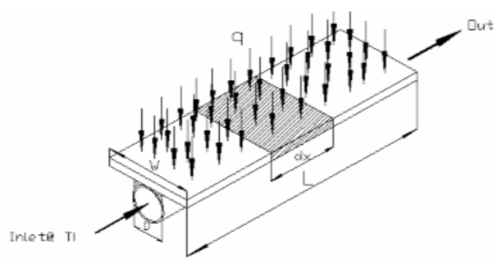


Fig. 2 – The 3D view of FPC with five (risers) tubes bonded below the absorber plate

3. GOVERNING EQUATIONS

The three dimensional, laminar, incompressible and steady viscous Newtonian flow in the collector is governed by the continuity, momentum and energy equations as follows [16]

$$\nabla \cdot \mathbf{U} = 0, \tag{1}$$

$$\rho \frac{D\mathbf{U}}{Dt} = \rho g - \nabla P + \mu \nabla^2 \mathbf{U}\,, \tag{2}$$

$$\frac{D\mathbf{U}}{Dt} = \mu \nabla^2 T\,, \tag{3}$$

where $\mathbf{U} = [u, v, w]$ is velocity field and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$.

4. NUMERICAL MODELLING

The 3D computational domain of the geometric of flat plate collector was modelled in SoldWorks and then imported into ANSYS-fluent R16.0. The grid was generated using appropriate meshing parameters and techniques. The materials for absorber plate and fluid were selected and the boundaries conditions applied on the computational domain. The governing equations for mass, momentum and energy integrated on every control volume were solved using Computational Fluid Dynamics (CFD) code for steady flows. To ensure the accuracy of the numerical results, several grid refinement tests were conducted, of which the outlet temperature of water was monitored. The convergence was established based on the criterion

$$\gamma = \left| \frac{T_{outlet,i} - T_{outlet,i-1}}{T_{outlet,i}} \right| \le 0.001\,, \tag{4}$$

where i is the mesh iteration index such that i increases when the mesh is more refined. When the criterion is satisfied, then i–1 mesh is selected as the convergence mesh. The temperature profile of the computational domain is shown in Fig. 3.The numerical results were verified with the experimental data. The numerical results of the present work show a good agreement with the experiment results.

5. OPTIMIZATION

In the geometric optimization of flat plate solar collector, the external irreversibilities are fixed. The focus is to minimize the internal irreversibility, which is due to fluid flow friction and heat transfer between the collector (absorber plate) and the fluid.

The global objective function is the minimization of entropy generation due to internal irreversibility in the collector, given by [5]

$$S_{gen} = \frac{\dot{m}}{\rho T_{\max,c}} \left(-\frac{\mathrm{d}P}{\mathrm{d}x} \right) + \frac{\Delta T}{T^2_{\max,c}} \left(\frac{q'}{1 + \Delta T / T} \right). \tag{5}$$

In the numerical simulation for the optimization, the heat flux $\left(500\,\mathrm{W/m^2}\right)$ applied on the top surface of absorber plate area and inlet temperature of water (300 K) were all considered constant. The optimization was subjected to fixed area of the collector surface and fixed volume of the riser tube. The length of the absorber plate equivalent to the length of riser (L), the spacing between the riser tubes (W) and the diameter of the riser (D), were free to morph with respect to the degree of freedom provided by the area of the collector surface and the volume of the riser until an optimal geometrical configuration was obtained which gives the minimum entropy generation.

6. NUMERICAL RESULTS AND DISCUSSION

The simulation results obtained are presented in the graphical form as shown in Figs. 3–11. The basic geometric parameters for FPC considered are the length of the absorber plate/length of riser tubes, the spacing between the riser tubes and the diameter of the riser tube. Figures 4–6, show entropy generation as the function of the length of the absorber plate/length of riser tubes, spacing between the riser tubes and the diameter of the riser tube for different modified Reynolds number (Re_m). The entropy generation is highest at the minimum value of length of the absorber plate/riser tubes and at the maximum value of spacing between the riser tubes and at maximum value of the diameter of the riser tube. It reduces as the length, the spacing between the riser and the diameter of the riser increase from left to right hand side of the graph, this is due to improvement in heat transfer between the collector and the fluid and consequently the entropy generation attain the minimum value and start increasing again as the length, the spacing between the riser and diameter keep increasing, as a result of increase of irreversibility due to fluid flow. This indicates that the collector gives the best performance at the minimum value of entropy generation.

Figure 7 shows the variation of the three geometric optimal parameters with the modified Reynolds number of which the optimal length of the absorber plate/riser tubes increase with increase in modified Reynolds number while the other parameters; the optimal spacing between the riser tubes and the optimal diameter of the riser tube decrease as the modified Reynolds number increase. Figure 8 shows the minimum entropy generation as a function of modified Reynolds number of which increase in modified Reynolds number give rise to decrease in the minimum entropy generation. In terms of maximum conductance, the modified Reynolds number increases with increase in the maximum conductance as shown in Figure 9.

The numerical result was used to develop some correlations for the three geometric parameters; optimal length of the absorber plate/riser tubes, optimal spacing between the riser tubes and the optimal diameter of the riser tube as well as the minimum entropy generation and the maximum conductance with respect to the modified Reynolds number as follows:

$$L_{opt} = 0.1294\,\mathrm{Re}_m^{1/3},\ W_{opt} = 1.5456\,\mathrm{Re}_m^{-1/3},\ D_{opt} = 0.0392\,\mathrm{Re}_m^{-1/6},$$

$$S_{gen.\min} = 0.2155\,\mathrm{Re}_m^{-2/3},\ C_{\max} = 0.0021\,\mathrm{Re}_m^{1/2}.$$

Figure 10 shows the effect of volume of the fluid on the optimal parameters of the collector at constant modified Reynolds number. The optimal length increases with increase in the volume of the fluid while the optimal riser tube diameter and riser tube spacing slightly decrease with increase in the volume of the fluid. The minimum entropy generation also slightly decreases as the volume of fluid in the riser tubes increases as shown in Fig. 11.

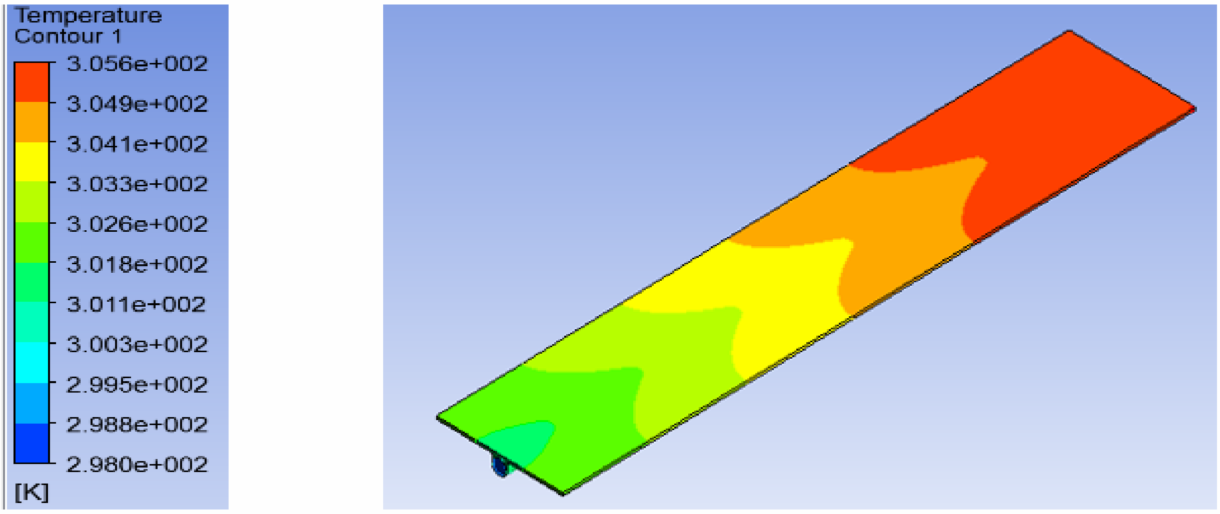


Fig. 3 – Converged solution; temperature profile of the computational domain.

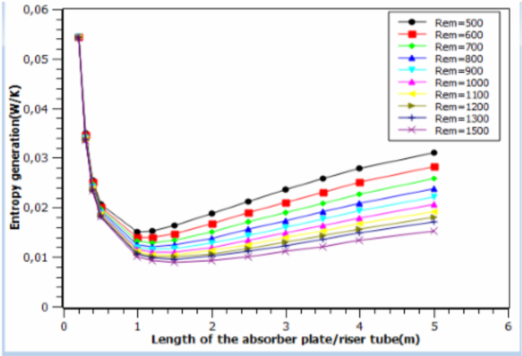


Fig. 4 – Variation of the entropy generation with the length of the collector.

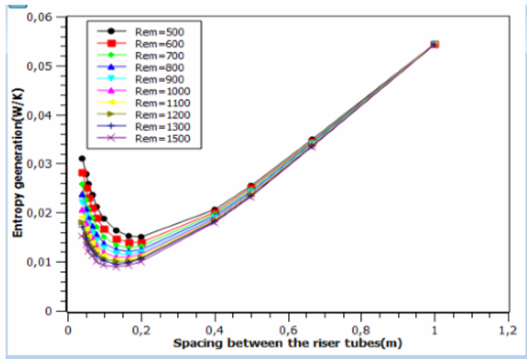


Fig. 5 – Variation of the entropy generation with the spacing between the riser tubes.

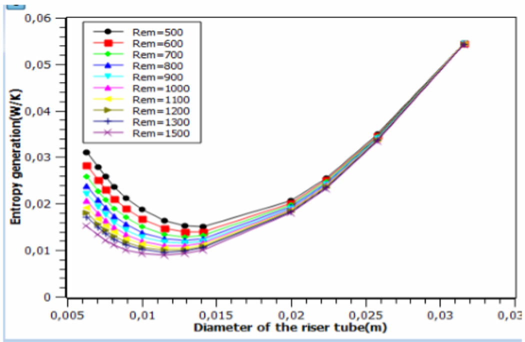


Fig. 6 – Variation of the entropy generation with the diameter of the riser tube.

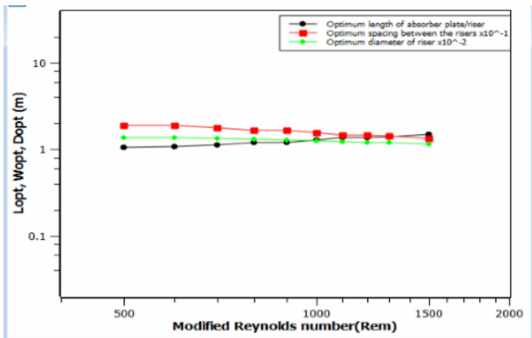


Fig. 7 – Variation of the optimal geometric parameters with the Reynolds number.

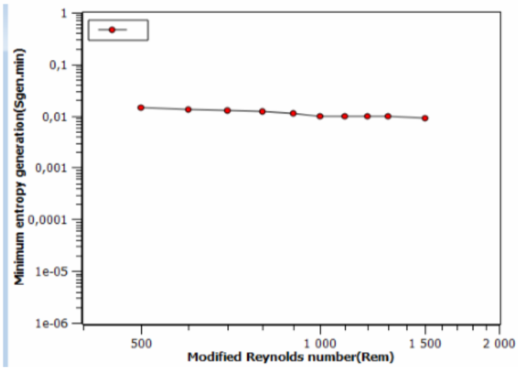


Fig. 8 – Variation of the minimum entropy generation with the modified Reynolds number.

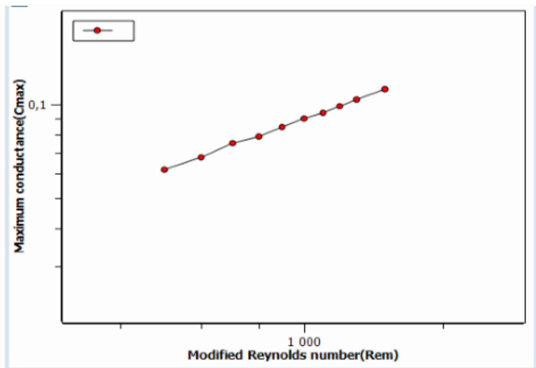


Fig. 9 – Variation of maximum conductance with the modified Reynolds number.

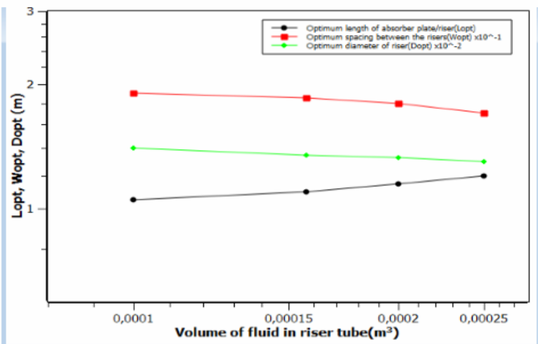


Fig. 10 – Effect of volume of the fluid in the riser tube on the optimal geometrical parameters.

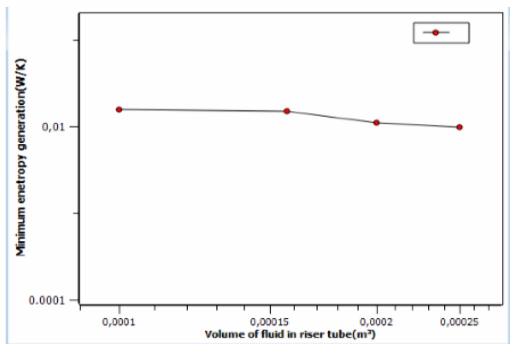


Fig. 11 – Effect of volume of the fluid in the riser tube on the minimum entropy generation.

6. CONCLUSION

The optimal geometric parameters such as the length of the absorber plate/riser tubes, the spacing between the riser tubes and the diameter of the riser tube were achieved at the minimum value of entropy generation.

The performance of optimal geometric parameters as the function of modified Reynolds number was investigated and it was shown that the optimal length of the absorber plate increases with increase in modified Reynolds number while the optimal spacing between the riser tubes and the diameter of the riser tube decrease with the increase of the modified Reynolds number. It was also observed that the modified Reynolds number increased as the maximum conductance increased while the minimum entropy generation decreased. This means that internal irreversibilities are minimized at the higher modified Reynolds number thereby resulting to better performance of the collector.

Also, the performance of optimal geometry parameters with respect to the volume of fluid in the riser tube was investigated and it was observed that the optimum length of absorber plate/riser tube increases as the volume of the fluid increase. For the optimal riser tube spacing and the diameter as well as the minimum entropy generation slightly decreases with increase in the volume of the fluid.

Some useful correlations were developed to help predict the performance of the collector with respect to modified Reynolds number for the optimal geometric parameters. The correlations could be very useful in the design of the flat plate collector and also to predict the performance of the collector for different modified Reynolds number.

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