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Optimization of Inclination Angle of Cavity and Characteristics of Attached Fins on the Absorber for Performance Enhancement of Solar Collectors

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Abstract

This research investigation was undertaken in ANDUAT, Kumarganj, Ayodhya, Uttar Pradesh, India to study the numerical optimization of natural convection heat suppression in a solar flat plate collector with straight fins. Optimal characteristics of an array of thin fins attached on the absorber plat were obtained by Particle Swarm Optimization algorithm (PSOA). Free convection considered dominant in the cavity. Governing equations contained continuity; momentum and energy are discretized by finite volume method. The medium is considered incompressible, whose free convection is dominant and Boussinesq approximation is applied. A simplified model of real systems is applied with free convection. Free convection problem is solved by SIMPLER algorithm. Two confined cavities with aspect ratios 30 and 60 are considered as flat plate solar collectors. The results indicate that significant reduction on the free convection heat loss can be obtained from solar flat plate collector by using plate fins, and an optimal plate fins configuration exit for minimal natural convection heat loss for a given range of Rayleigh number. Reduction of up to a maximum of 25% at 0 inclination angle was observed in aspect ratio 30. Results showed PSOA is able to obtain characteristics of attached adiabatic fins on the absorber plate also it can obtain optimal inclination angle of cavity to decrease heat losses from solar collectors. The results obtained provide a novel approach for improving design of flat plate solar collectors for optimal performance.

Keywords: Particle swarm optimization algorithm, solar collectors, natural convection

1. Introduction

Flat plate solar collectors are technique to utilizing solar energy. The flat plate absorbs incoming solar radiation and converts it in to heat and also transfers this heat to a fluid flow. Glazing cover plate prevents from heat loss by force convection but when temperature difference between flat plate and glazing cover plate exceeds to a critical value, natural convection will exist between absorber and cover plate. In present work of heat loss from absorber plate is reduced by investigating optimal characteristics of an array of thin fins are considered. Grossman et al. (1977) expanded a model for heat transfer in a flat plate solar collector with a rectangular channel for water or air fluid flow. The analysis was performed for temperature and heat flow distributions in both dimensions of the collector to investigate the thermal boundary layer development. Overall efficiencies are calculated for uniform solar

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heat influx with variable heat losses from plate. The thermo-syphonic effect attributable to free convection, is appraise, collector geometry is optimized with respect to this effect. The definitions of various relations that are required to determine the useful energy collected and the interaction of the various constructional parameters on the performance of a solar collector are justly complex. To overcome this complexity, artificial neural network (ANN) models have been developed to handle practical problems. Several studies were performed on ANN modeling of solar thermal systems in the literature. Kalogirou (2001) presents applications of neural networks for modelling and design of a solar steam generating plant. Kalogirou (2004) optimize a solar-thermal system using a TRNSYS computer program. Mellit et al. (2006) applied adaptive wavelet-network architecture for predicting the daily total solar-radiation. Sozen and Arcaklıoglu (2007) applied artificial neural network approach a solar pond coupled to an EAHT. Recently Gupta and Varshney (2017) optimize SAH for THPP (Thermo-hydraulic performance parameter) using Ansys simulation with SIMPLE algorithm, Singh and Singh (2018) also use same algorithm to solve governing equations for simulation , Saravana kumar et al. (2019), Bezbaruah et al. (2020), Kumar and Verma (2020), Masoumi et al. (2020), Yadav and Saini (2020), Ammar et al. (2020), Bezbaruah et al. (2020), Nidhul et al. (2020), also reported similar work for solar collector are with similar algorithm for heat transfer enhancement. The numerical algorithms gives vary acceptable results as experimental investigation are found Ngo et al. (2015) obtains an optimal length and an optimal space for an array of thin fins in to receiver cavity. In this work length of all fins are considered same (equal length) and space between them areequal. Therefore, for an array of thin fins both length of thin fins and space between them are unknown. As seen from above literatures, no optimization problem is not applied for obtaining characteristics of an array of adiabatic thin fins for decrease of heat losses from solar collectors. In this paper, numerical modeling and optimization of natural convection heat suppression in a solar flat plate collector with adiabatic thin fins is studied. The use of adiabatic thin fins attached on the absorber plate is presented as a possible low cost means of depression natural convection heat loss in a solar flat plate collector. In this paper, Particle Swarm Optimization is applied for obtaining length and location each thin fin on the absorber plate of a flat plate collector.In the first part of the study a two-dimensional numerical model for obtaining free convection heat transfer from a rectangular cavity with attachment of very conductive thin fins on the hot wall is analyzed. Characteristics of two fins and inclination angle are obtained by optimization algorithm. In the second part, flat plate collectors with aspect ratios 30 and 60 are considered for analysis.

2. Materials and Methods

This work details the numerical optimization of natural convection heat suppression in a solar flat plate collector with straight fins. Following sections described the Methodology adopted in present work.

2.1. Description of problem

Figure 1 shows a two-dimensional solar collector. The enclosure contains an incompressible medium, whose free convection is dominant and Boussinesq approximation was applied it. Horizontal walls are cold and hot and vertical walls are insulated. The aim of the optimization problem was to find the characteristics of one fin or an array of straight thin fins on the hot wall such a way that heat transfer rate from cold wall minimize. This problem can be imagined as a simplified model in the design of real systems with free convection.

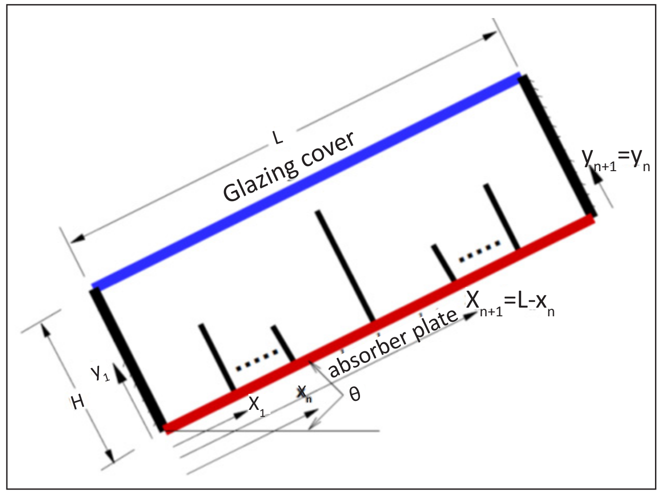


Figure 1: Schematic figure of a solar collector with optimal characteristics of fins array attached on the absorber plate

As seen in Figure 2a PSOA selects a pair of (x,y) for each fin that x is length of each fin and y is its location. These variables are selected from continues space between minimum and

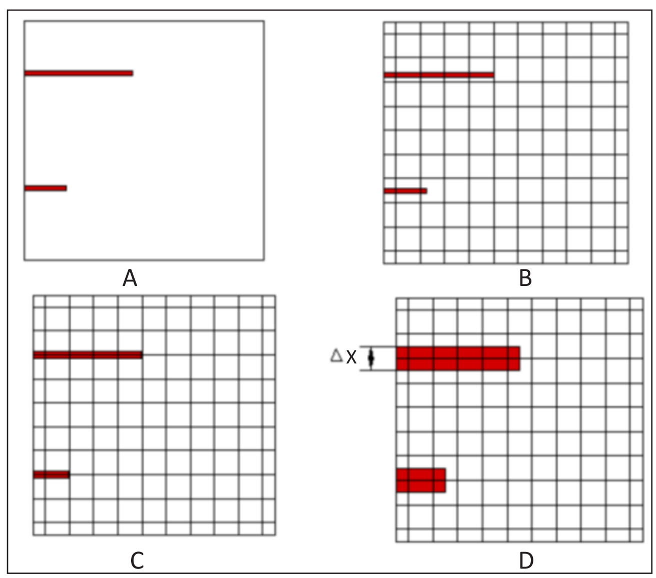


Figure 2: schematic figure a) select of a pair of (x, y) for each fin by PSOA b) difference between PSOA grid and free convection grid c) set of obtained fins in nearest grids of physical domain d) placing infinite orfinite values in to non-dimensional diffusion coefficients of momentum

maximum values. Figure 2b, shows a grid distribution for a square cavity but as seen the fins may be not locate on the grids. Figure 2c, shows how a subprogram can match location and size of each fin in to the nearest grid. As shown in Figure 2d. non-dimensional diffusion coefficients in both momentum and energy equations for all grids placed into each fin are considered as infinite value (for very conductive thin fins) or non-dimensional diffusion coefficients in momentum equation for all grids placed into each fin are considered as infinite value and those in energy equation for all grids placed into each fin are considered as small finite value (for adiabatic thin fins), Finally. The transformation of fluid to the solid is performed by this simple model.

2.2. Direct problem

Natural convection heat transfer is governed by a set of non-linear partial differential equations, namely the continuity, momentum, and energy equations. For the case of natural convection problems, the energy equation is coupled with the momentum equations through Boussinesq approximation

$$\rho = \rho_0[1-\beta(t-t_0)] \text{ Where } t_0 = \frac{t_h + t_c}{2} \tag{1}$$

The non-dimensional form of governing equations is given by

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2a}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \Gamma\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + GrT\sin\theta$$

$$\text{Where} \begin{cases} \Gamma = 1 \quad for\ Fluid \\ \Gamma = \inf inite \quad for\ Solid \end{cases} \tag{2b}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \Gamma\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + GrT\cos\theta$$

$$U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = -\frac{1}{p}\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) \text{for Fluid}$$

$$k^*\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) = 0 \qquad \begin{cases} k^* = \infty \quad for\ very\ conductive\ solid \\ k^* = 0.0 \quad for\ very\ insulative\ solid \end{cases}$$

Where non Dimensional Variable are

$$X = (x/H);\ Y = (y/H);\ U = \frac{u}{\nu/H};\ V = \frac{V}{\nu/H};\ P = \frac{p + \rho_0 gy - p_0}{\rho_0(\nu/H)^2};\ T = \frac{t - t_c}{t_H - t_c};\ k^* = \frac{k_{Solid}}{k_0} \tag{3}$$

and the non-dimensional groups Gr and Pr and Ra are the Grashof, the Prandtl and Rayleigh numbers, respectively, defined by

$$Gr = \frac{g\beta(T_H - T_c)H^3}{\nu^2} \tag{4a}$$

$$\Pr = \frac{\nu}{\alpha} \tag{4b}$$

$$Ra = Gr\Pr \tag{4c}$$

The set of Equations (2) with the associated boundary conditions provide a complete mathematical formulation of the problem. The boundary conditions are defined by

$$U = 0, V = 0, T(X) = 1.0 \qquad over\ the\ hot\ surfaces \tag{5a}$$

$$U = 0, V = 0, T(X) = 0.01 \qquad over\ the\ cold\ surfaces \tag{5b}$$

$$U = 0, V = 0, T(X) = 0.0 \qquad over\ the\ other\ surfaces \tag{5c}$$

The set of equations (2) is solved by the finite-volume method. A staggered grid is used for discretization of the velocity field to consider the influences of the pressure field. The power-law differencing scheme is used to interpolate the convective terms. The problem associated with the pressure-velocity linkage is resolved by adopting an iterative solution strategy such as the SIMPLER algorithm. The method is described in detail by Patankar (2018).

2.3. Optimization problem

For the optimization problem considered here, the size of straight fins ($X_{f,i}$), position of them ($Y_{f,i}$) and inclination angle (θ) are regarded as unknowns and the average Nusselt number over the cold surface, B$\overline{Nu_d}$, is available for the analysis. To solve such a problem, we consider the unknown coordinates of ($X_{f,i}$, $Y_{f,i}$) for*ith* fin on the hot wall in a cavity with inclination angle (θ). These fins attach in nearest position corresponding with grids

for solving governing equations using control volume approach. In convection program finite non- dimensional diffusion parameters change to infinite values and replace in to the governing equations for producing very conductive thin fins. Therefore convection problem solve for the interaction of fluid and very conductive solids

$$X_{f,m} = \left\{X_{f,1},\ X_{f,2},............X_{f,i}, X_{f,M_f}\right\} \tag{6a}$$

$$X_{f,m} = \left\{Y_{f,1},\ Y_{f,2},............Y_{f,i}, Y_{f,M_f}\right\} \tag{6b}$$

$X_{f,m}$ is size and $Y_{f,m}$ispostion parameters of unknown type

$$\overline{Nu_d} = \frac{1}{L}\sum_{nd=1}^{R} Nu_{d,nd}\Delta X\delta(\chi_c - \chi_{c,nd}) \ where\ Nu_d = \left.\frac{\partial T}{\partial Y}\right|_{Y=1} \tag{7a}$$

$$\overline{Nu_e} = \frac{1}{L}\sum_{nd=1}^{R} Nu_{e,nd}\Delta X\delta(\chi_c - \chi_{c,nd}) \tag{7b}$$

Where and $Nu_{e,nd}$ is estimated nodal Nusselt numbers over the cold surface when a fin or an array of fins attached on the hot wall and $Nu_{d,nd}$ is local Nusselt Number over the cold wall when no fin is attached on the hot wall. Here R is the number of nodes on the cold surface, c,ndχ is the nodal position over the cold surface and XΔ is grid size in X direction. δ (x−x_0) is known Dirac delta function. The solution of this problem is based on the minimization of an objective function given by

$$G(X_{f,m}, Y_{f,m}, \theta) = \left\|B\overline{Nu_d} - \overline{Nu_e}X_{f,m}, Y_{f,m}, \theta)\right\|$$

Where $\overline{Nu_d}$ is an average Nusselt number over cold wall and B is a constant value that is greater or smaller than 1 if aim of optimization is increase or decrease of heat transfer, respectively. B would be selected by designer.

3. Results and Discussion

Nusselt number or rate of heat transfer in this mode was less than other modes of convection heat transfer as usual. Although, rate of heat transfer was low but it exists naturally.

Therefore, when it founded to be favorable, to minimize operating (increase of heat transfer) cost, natural convection was preferred to other modes of heat transfer. In such case it was desirable to decrease heat transfer from a system. In these cases, with increase of temperature difference, heat loss from cavities increase that it was not favorable. In this section one examples was considered to determine optimal size and position of the fin or characteristics of an array of thin fins that those decrease rate of heat transfer from the cavity. At first, a simple m odel was applied to fluid for transforming it to solid thin fins. This simple model was validated with Shi and Khodadadi (2003) work. Next, Optimal characteristics of fins for range of Rayleigh numbers 10^5-10^6 for a horizontal cavity with aspect ratio 2 was obtained PSO algorithm. Also, it obtained both characteristics of fins and optimal inclination angle for two Rayleigh numbers 10^5 and 10^6 in a cavity with aspect ratio 2. Afterward, two cavities with aspect ratios 30 and 60 were considered. These cavities were similar to solar collectors that up wall is as a glazing cover (cold wall) and down wall is as a absorber plate (hot wall). Although, very conductive thin fins were attached on the absorber plate firstly, but decrease of heat loss was very small therefore adiabatic thin fins are attached on the absorber plate. Finally, for two Rayleigh numbers 10^4 and 10^5 in a solar collector with aspect ratio 30 optimal inclination angle and characteristics of thin fins was found with maximum constrain length 0.9L and angle 300.

3.1. Validation of a simple model

In this case a square cavity shown in Figure 3 is considered with vertical hot and cold walls and horizontal insulation walls. Rayleigh numbers and Prandtl number are 1.0E+4 and 1.0E+7 and 0.707 respectively. In corrent studies, the comparison

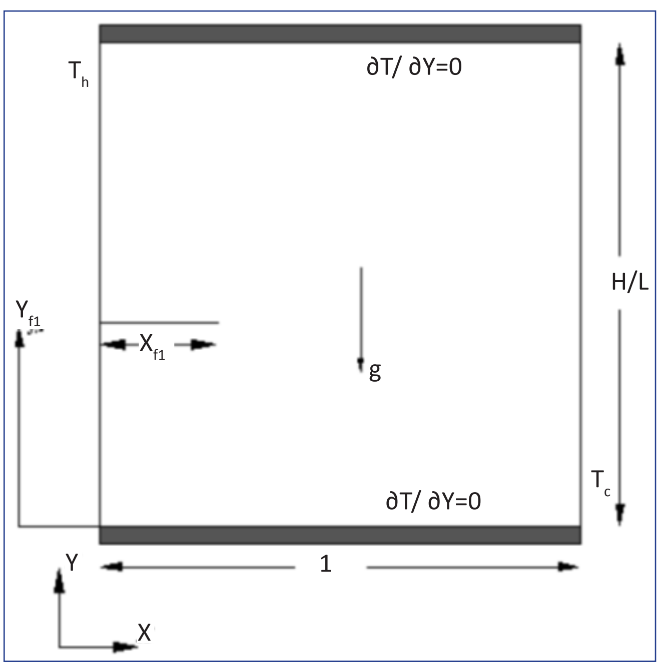


Figure 3: Schematic figure of a square cavity with a fin attached on the hot wall

of results obtained was done with similar work of Shi and Khodadadi (2003) At this part 21 cases ($X_{f,m}$=0.2L, 0.375L, 0.5L and $Y_{f,m}$=0.125H, 0.25H, 0.375H, 0.5H, 0.625H, 0.75H, 0.875H) for each Rayleigh number are considered. In first stage results are compared with Davis (1983) work, Shi and Khodadadi (2003) and presented in Table 1.

Table 1: Comparison of average nusselt numbers

Ra	10^4	10^5	10^6	10^7
Davis (1983)	2.243	4.519	8.800	-
Shi and Khodadadi (2003)	2.247	4.532	8.893	16.935
Present study	2.245	2.529	8.880	16.883

Comparison of results obtained from present modeling Shi and Khodadadi (2003) work for Rayleigh number 10^4 and 10^7 are shown in Figure 4a and Figure 4b respectively. Obtained results are shown acceptable accurate when a simple model is used.

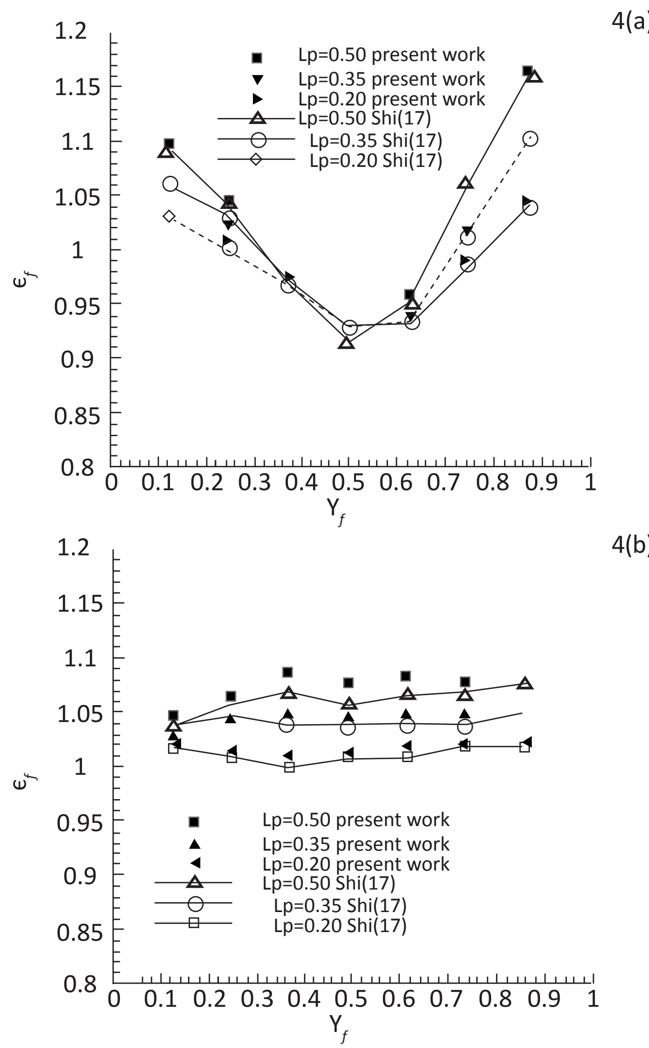


Figure 4: Comparison of fin effectiveness between present work and Shi and Khodadadi (2003) works, a) Ra=1.0E+4; b) Ra=1.0E+7

3 2. Example problem 1

Now we consider a horizontal cavity shown in Figure 5 with up cold wall and down hot wall. In this optimization problem size and location of a very conductive thin fin is obtained for Rayleigh numbers 10^5 and 10^6. The aim of this problem is decrease of heat transfer from the cold wall. The maximum constrain length is 0.1L for the thin fin. Locations and sizes of the thin fins for all desired Rayleigh numbers are shown in Table 2.

Table 2: Comparison of average nusselt number optimal size and position of a fin and without fin

Ra	Aim	εf, present work	X	Y	$\overline{Nu}$ Hasnaoui	$\overline{Nu}$ Present Work
10^5	Declination	0.937	0.232	0.038	4.78	5.12
10^6	Delineation	0.656	0.694	0.087	-	9.29

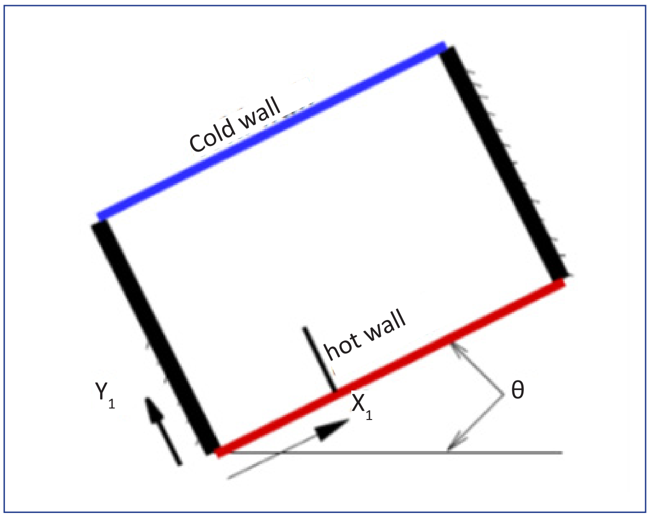
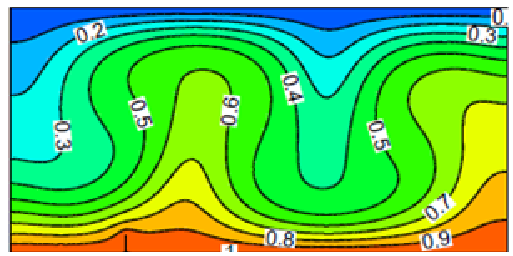


Figure 5: Schematic figure of a rectangular cavity with inclination ɵ heated from bellow with a fin attached on the hot wall



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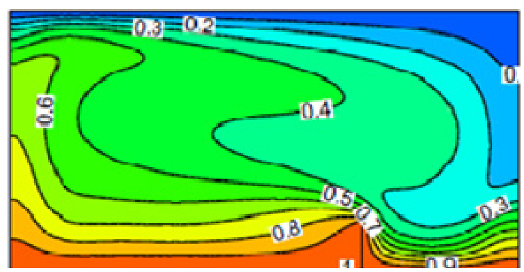


b

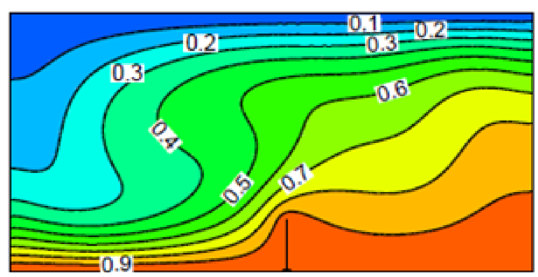
Figure 6: Velocity vectors with an attached fin with constrain 0.1L for decrease of heat transfer using PSOA for with a attached fin for horizontal cavity a) Ra=10^5 b)Ra=10^6

Also Nusselt number obtained from present work without any fin with Hasnaoui et al. (1992) are compared in last column of Table 2. Obtained results from PSOA are shown in Figure 6. Next PSOA is applied for obtaining optimal inclination angle and characteristics of a very conductive thin fin for a cavity with aspect ratio 2. Results are shown in Table 3.

Table 3: Optimal size, and position of a fin also εf and optimal inclination angle of a rotated cavity heated from bellow with aspect ratio 2

Ra	Aim	εf, present work	X	Y	θ
10^5	Declination	0.820	0.532	0.1	10.47
10^6	Delineation	0.655	0.302	0.1	1.487

As seen for Rayleigh 10^5 inclination angle 11 was found when a very conductive thin fin with length 0.06L is attached on the hot wall. These results show PSOA is able to find optimal size and position of very conductive thin fins on the hot wall also it is able to obtain optimal inclination angle of cavity. Velocity vectors are shown in Figure 7. Results obtained from this part showed that very conductive thin fins have a few



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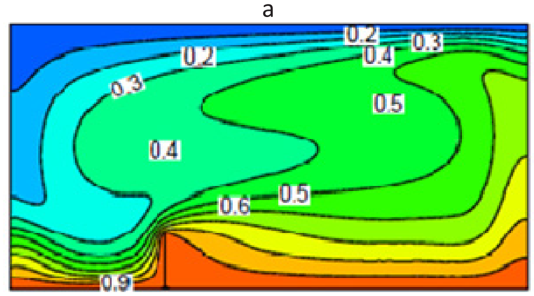

b

Figure 7: Velocity vectors with an attached fin with constrain 0.1L for decrease of heat transfer using PSOA for with a attached fin for rotated cavity a)Ra=10^5 b) Ra=10^6

effects on the decrease of heat losses from solar collectors therefore adiabatic thin fins were attached on the absorber plate. Attachment of adiabatic thin fins caused decrease of heat transfer between 13% – 25%. Also, results obtained from this paper showed for high aspect ratio in Rayleigh number 104 optimal inclination angle is equal to maximum angle. Maximum angle is maximum constrain in PSO algorithm.

4. Conclusion

Very conductive thin fins could not decrease heat transfer from solar collectors very well. The results showed adiabatic thin fins can decrease heat transfer from horizontal flat plate collectors for both optimal inclination angle and characteristics of an array of adiabatic thin fins for a solar collectors or each rectangular cavity.

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