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ENHANCEMENT OF NATURAL CONVECTION HEAT TRANSFER OF PIN FIN HAVING PERFORATED WITH INCLINATION ANGLE

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Abstract: The development of the perforated fin had proposed in many studies to enhance the heat transfer from electronic pieces in modern devices. This paper presents a new design by using inclined perforated for a pin fin. Perforated with rectangular section and different angles of inclination was considered. Signum Function is used for modeling the variable heat transfer area. Set of parameters to handle the conduction and convection area were calculated. Degenerate Hypergeometric Equation (DHE) was used for modeling the Complex energy differential equation and then solved by Kummer's series. In the validation process, the finite element technique was used. The big reliability of the presented model comes from the high agreement of the validation results about (0.3%), therefore, the mathematic model has big dependability to deal with the inclined perforated fin. Two geometric models and range of the Rayleigh number from Ra=1×10^5 to Ra=1×10^6 were considered. The results show the increase of the inclination towards the max angle leads to the enhancement of the temperature difference, heat transfer, and effectiveness with and without the change of other parameters. Improved of Heat transfer ratio and effectiveness are ranging from 18% to 50%.
Keywords: Inclined perforated, Temperature distribution, Signum function, Degenerate hypergeometric equation, Performance enhancement.

KANATTA EĞIM VE PERFORE ETKISI ILE DOĞAL TAŞINIM ISI TRANSFERININ ARTIRILMASI

Özet: Modern elektronik cihazlarda perfore kanatlar kullanılarak ısı transferini artırma konusunda yeni gelişmeler mevcuttur. Bu çalışmada, yeni bir perfore kanat tasarımı sunulmaktadır. Dörtgen kesitli perfore fin değişik eğim açıları için incelenmiştir. Değişken ısı transferi alanı Signum Fonksiyonu ile modellenmiş ve Degenerate Hypergeometric Denklemi (DHE) yöntemi kullanılarak karmaşık enerji diferansiyel denklemi kullanılmış ve Kumner Serisi ile çözülmüştür. Sonuçlar arasında % 0.3 farklılık gözlenmiştir. 10^5 ve 10^6 Rayleigh Sayıları için iki geometrik model kullanılmıştır. Eğim açısının maksimum değerine kadar sıcaklık farkı ve etkenlik değerlerinde artış görülmüştür. Isı transferi oranı ve etkenlik değerleri % 18 den % 50 ye kadar artmıştır.
Anahtar kelimeler: eğimli perfore, sıcaklık dağılımı, Signum Fonksiyonu, Degenerate Hypergeometric Denklemi, performans iyileştirilmesi

NOMENCLATURE

A	Fin cross section area [m^2]
AP	Perforated section area [m^2]
A'	First derivative of area
A''	Second derivative of area
bx	Width of rectangular perforated [m]
by	Height of perforated [m]
Nu	Nusselt Number [=h L/ k_{air}]
$p1,2,...$	Constant of polynomial equation
Pr	Prandtl number [μ c_p/ k_{air}]
Ra	Rayleigh number =(g/T_f)($\bar{T}-T_\infty$)LP^3 Pr/υ^2
T	Temperature [$^\circ C$]
CO	Constant of general solution
g	Gravity [m/s^2]
$h1,2,3$	Convection coefficient of external non-perforated surfaces ,external perforated and inner perforated, respectively [W/m^2 K]
k	Thermal Conductivity [W/m K]
$\bar{T}$	Average Temperature [$^\circ C$]

Subscript

air	Cooling fluid
b	Base
$cond.$	Conduction

$max.$	Maximum
p	perforated
s	solid
∞	Ambient
0	Straight perforated

Greek Letters

β,γ	Inclination angles [degree]
υ	Kinematic viscosity [m/s^2]

INTRODUCTION

Development of the modern devices (communications devices, Mechatronics application, and different electronic devices) depended on the heat sink performance. Therefore, the enhancement of the fin performance based on a novel design is the most important aspirations of the researchers. Perforation fin is the main technique using today to optimizing the fin geometry, which leads to improve the overall performance. Many researchers have studied the effects of the straight perforation parameters (operation conditions and geometric shapes) on the performance of the fin. In experimental studies, models with specified geometry were adopted, (Bayram and Alparslan ,2008[a]) studied the effects of parameters (geometric and fluid flow) on the Nusselt Number and the friction factor for a circular perforated at the straight direction, efficiency, increased by1.1 and 1.9 based on the inter-fin spacing ratio and clearance ratio. (Saurabh and Gosavi , 2014) investigated the influence of metal type on the performance of the circular fin with a straight direction of the perforated, the experimental tests show the higher heat transfer coefficient at a large number of perforated and a copper material having higher thermal conductivity. (Bayram and Alparslan, 2008[b]) proved the efficiency can be increased by 1.4 to 2.6 for circular pin fin with a circular section of perforated by optimized the Nusselt number and friction factor separately and then together. (Elshafei, 2010) presented the study to increase the heat transfer coefficient and heat transfer for the hollow fin with the circular perforated at straight direction by changing the orientation and diameter ratio. Finite volume was used to solve the governing equations at some studies, (Swee et al., 2013) reported the recirculation produced by a circular perforation in multi plans for pin fin with the different specification (number and diameter of perforated). They found the heat transfer increased by 45%, also, the pressure drop of perforated fin decreased by 18%. (Mohamed and Osama, 2014) determined the optimum number of pin fins that associated with a minimum value of thermal resistance to improve the heat transfer by use the circular perforated. (Monoj et al., 2011) presented the numerical study for heat transfer and pressure drop of elliptical pin fin with straight perforated. Results show the enhancement of heat transfer by 5.6%, a pressure drop improvement by 12% and the performance of the fin increased by 23%. (Ashok et al., 2014) obtained a high increase in convection coefficient about (30% to 40%) for a perforated circular section of pin fin with a different number of a circular straight perforated. Other investigations found the temperature distribution of perforated fin by analytical study, (kirpikov and Leifman, 1972) reached to the temperature distribution equation of perforated flat plate based on the mathematical model that solved by Fourier series and Flocke's theory. Finite element techniques were adopted to solve the energy differential equation at some papers, (Abdullah, 2009) reported the decrease of thermal conduction resistance of pin fin due to triangular perforation, which leads to improved the heat dissipation that calculated by use variation approach, finite element techniques. (Kumbhar et al., 2009) concluded to enlarge of perforated size and increase the thermal conductivity leads to augmentation the heat transfer from the rectangular fin. All recent studies worked on the perforated at straight direction with different geometries and various operation conditions to improve the performance of the fin. This study proposes a novel design by using inclined perforated with rectangular section to find the effects of inclination on the temperature distribution, heat transfer, and effectiveness. The goal of current research is using the differential technique to find the general form of the temperature distribution equation based on the accurate analysis of the heat transfer area. Then use the general solution to study the performance of the fin.

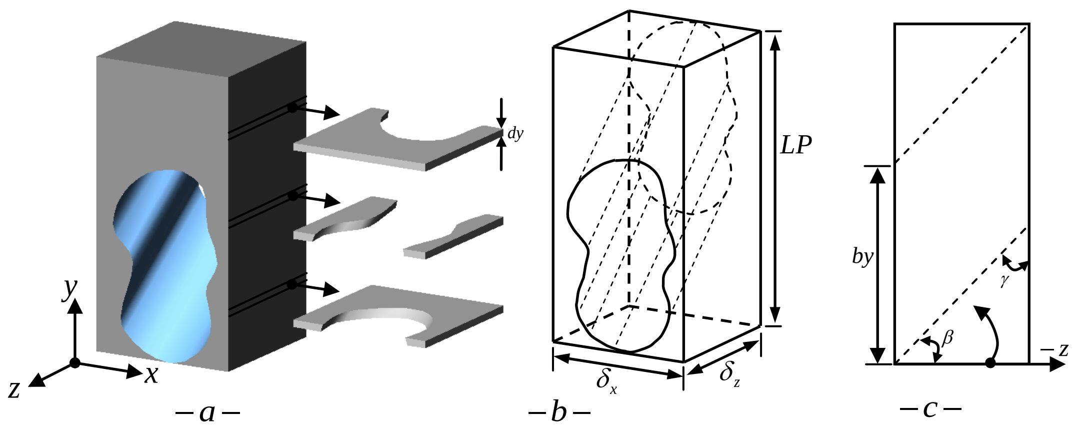

Figure (1) Fin with inclined perforated, a- 3-D model with different layer, b- Illustration diagram, c- Side view.

GEOMETRIC MODEL

The inclined perforated fin is considered in this paper is shown in Figure 1, the model consists of the pin fin with a rectangular section and an undefined section of inclined perforated. Inclination started from ($\beta = 0$) at negative z-axis to maximum angle [$\beta_{max.} = sin^{-1}(by_0 / \delta_z)$].

According to above geometry, the heat transfer area is changing with y-direction as well as change with the angle of inclination.

ENERGY ANALYSIS AND ASSUMPTION

Applied Energy balance to the element shown in Figure 2, to obtain the differential equation of energy in the perforated region.

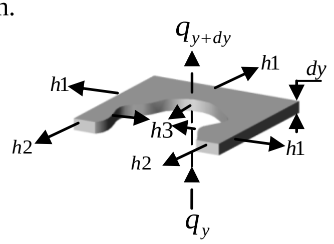

Figure (2) element description

Heat transfer analysis for inclined perforated region relies on a set of assumptions. The flow assumed to be steady heat conduction with no heat generation, constant conductivity, constant base temperature, insulation tip fin, neglected radiation effects, uniform ambient temperature and uniform convection heat transfer coefficient.

Analysis of energy depended on one-dimensional heat transfer because the impairment of the Biot number at z-axis and x-axis compare with y- axis. Convection coefficient is divided into three types (external non-perforated ($conv1$), external perforated ($conv2$) and internal perforated ($conv3$)) when the perforation is inclined. Applied energy balance with assumption gives the differential equation of energy as below:

According to kummer's series (Hazewinkel, 1995), the general solution of (DHE) is:

$$u(\vartheta) = CO_i \, \phi(ku1, ku2, \vartheta) + CO_{i+1} \, \psi(ku1, ku2, \vartheta) \quad , i = 1,3,5,.... \tag{5}$$

Where:

ϕ = confluent hypergeometric function of the first kind.

ψ = confluent hypergeometric function of the second kind.

Boundary conditions according to Eq.(5):

$$\frac{d}{dy}\left(A_{cond.} \frac{d\theta}{dy} \right) dy = [\, h1 P_{conv1} + h2 P_{conv2} + h3 P_{conv3} \,] \frac{\theta \, dy}{k} \tag{1}$$

Where: $\theta = T(y) - T_\infty$

GENERAL SOLUTION

Expanded conduction heat transfer term of Eq.(1) and substitution $\theta = G / \sqrt{A_{cond.}}$ leads to the linear second order differential equation with a variable coefficient.

$$\frac{d^2 G}{dy^2} + \lambda(y) G = 0 \tag{2}$$

Where:

Eq.(2) placed in another form by fitting $\lambda(y)$ using

$$\lambda(y) = -\left[\frac{{A'_{cond.}}^2}{4{A_{cond.}}^2} + \frac{A''_{cond.}}{2A_{cond.}} + \frac{h1 P_{conv1}}{k\, A_{cond.}} + \frac{h2 P_{conv2}}{k\, A_{cond.}} + \frac{h3 P_{conv3}}{k\, A_{cond.}} \right]$$

polynomial function and substitution $\xi = y + p2/2p1$, $d1 = p3 - (p2^2 / 4p1)$.

$$\frac{d^2 G}{d\xi^2} - (\, p1 \xi^2 + d1) G = 0 \tag{3}$$

Can be found Degenerate Hypergeometric Equation (DHE) from Eq.(3) by assuming $\vartheta = \xi^2 \sqrt{p1}$ $, u = e^{\vartheta/2} G$. (Andrei and Valentin, 2003)

$$\vartheta \frac{d^2 u}{d\vartheta^2} + (\, ku1 - \vartheta) \frac{du}{d\vartheta} - (\, ku2) u = 0 \tag{4}$$

Where:

$$ku1 = \frac{1}{2}, \quad ku2 = \frac{1}{4}\left(\frac{d1}{\sqrt{p1}} + 1 \right)$$

$$u\Big|_{\vartheta = \frac{p2^2}{4\, p1^{3/2}}} = \theta_b \sqrt{A_b}\, e^{\frac{p2^2}{8\, p1^{3/2}}} \quad , \frac{du}{d\vartheta}\Big|_{\vartheta = (LP + \frac{p2}{2p1})^2 \sqrt{p1}} = 0$$

The above conditions associated with boundary conditions at original form

$$\theta\Big|_{y=0} = \theta_b \quad , \quad \frac{d\theta}{dy}\Big|_{y=LP} = 0$$

Eq.(5) solved based on the boundary conditions. The general solution can be obtained after rewriting the parameters by re-compensation to all substitutions in original form.

$$\frac{\theta(y)}{\theta_b}=\frac{e^{\frac{-(y+\frac{p2}{2p1})^2\sqrt{p1}}{2}}}{\sqrt{A_{cond.}}}\;\frac{e^{\frac{p2^2}{8\,p1^{3/2}}}\sqrt{A_b}}{\zeta1-\zeta2}[\zeta3\;\;\phi(ku1,ku2,((y+\frac{p2}{2p1})^2\sqrt{p1}))-\zeta4\;\;\psi(ku1,ku2,((y+\frac{p2}{2p1})^2\sqrt{p1}))] \tag{6}$$

Where:

$$\zeta1=[\zeta3\;\;\phi(ku1,ku2,\frac{p2^2}{8\,p1^{3/2}})\;\;]$$

$$\zeta2=[\zeta4\;\;\psi(ku1,ku2,\frac{p2^2}{8\,p1^{3/2}})]$$

$$\zeta3=\psi'[ku1,ku2,((LP+\frac{p2}{2p1})^2\sqrt{p1})]$$

$$\zeta4=\phi'[ku1,ku2,((LP+\frac{p2}{2p1})^2\sqrt{p1})]$$

INCLINED PERFORATED WITH RECTANGULAR SECTION

Fin with inclined perforated is classified into three regions (solid, inclined perforated and solid) as illustrated in Figure 3. ($A_{cond.}$) of inclined perforated region is changing with y-axis from the max value at start region to min value at the point or at the domain and then returned to max value at the perforated region end. Here convection perimeter ($P_{conv.}$) given a good impression about convection area based on the same elements thickness. Figure 3 shows the change of heat transfer area with the inclination angle for two main cases. ($P_{conv.}$) divided into three regions [external non-perforated, external perforated and internal perforated] based on the classification of convection coefficient. Signum function (sgn) (John and Horst, 1998) used to represent the opposite approach of variables ($A_{cond.}$) and ($P_{conv.}$) with the y-axis.

$$A_{cond.}=\frac{\delta_z\,bx}{a}(a_1-y)sgn(a-y)+(\delta_z\,\delta_x)-\delta_z\,bx \tag{7}$$

$$P_{conv1}=2\,\delta_z+\delta x \tag{8}$$

$$P_{conv2}=\delta_x-bx \tag{9}$$

$$P_{conv3}=\frac{-2\delta_z-bx}{a}(a_1-y)sgn(a-y)+2\delta_z+bx \tag{10}$$

Where: $sgn(a-y)=tanh[(N(a-y)],\quad N>>1$

Extreme ends of the ($A_{cond.}$) and ($P_{conv.}$) may be found at locating a point or at a region (several points) depended on the inclined angle. A group of variables ($a, a_1, \delta x$) was calculated to find the heat transfer area at any specification as shown in the table (1).

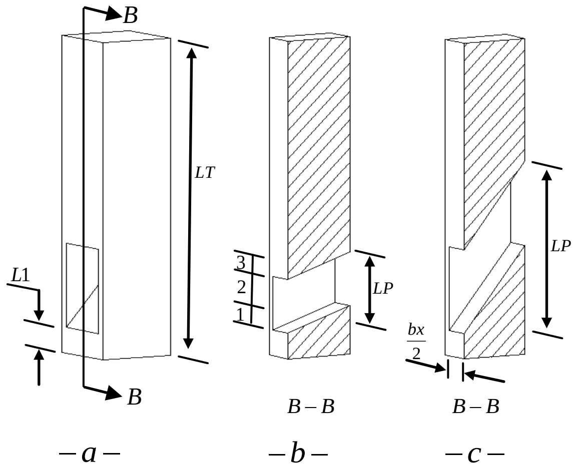

Figure (3) Rectangular perforated with different angle
$a)$ 3-D plot $b)\beta<\beta_{max.}$ $c)$ $\beta=\beta_{max.}$

Table (1) Constant Value

Inclined angle	Domain of region	a	a_1	δx
$\beta=\beta_{max.}$	All inclined regions	$\frac{LP}{2}$	$\frac{LP}{2}$	δ_x
$\beta<\beta_{max.}$	1	$L11$	$L11$	δ_x
	2	$L11$	y	0
	3	$L11$	$L22$	δ_x
$L11=\delta_z\,tan\,\beta$, $L22=LP-L11$				

The equations from (Incropera et al.,2007) and Eq.(6) are used to find the temperature distribution of the solid regions and inclined perforated , respectively.

COEFFICIENT OD THE CONVECTION HEAT TRANSFER

Different effects of inclined perforated appear at two regions of the fin (external and inner surfaces of perforated). Effects of solid faces without perforated represented third region of the fin, thus various convection heat transfer coefficient were considered. Convection coefficient depended on properties of cooling fluid, specifications of the perforated fin and the open perforated ratio (ROP). ROP represents the ratio of actually a perforated area to maximum perforation effects (Incropera et al., 2007; Zan et al., 2012; Raithby and hollands,1998). For presented model, the Nusselt number and Rayleigh number have modified to become useful with inclined perforated.

$$Nu = \frac{h1\,LP}{k_{air}} = \left\{ 0.825 + \frac{0.387\,Ra^{1/6}}{[1+(\frac{0.492}{\Pr})^{9/16}]^{8/27}} \right\}^2 \quad (11)$$

Where:

$$Ra = \frac{g\frac{1}{T_f}(\overline{T} - T_\infty)\,LP^3}{\upsilon^2}\Pr\,, \quad T_f = (\overline{T} + T_\infty)/2$$

$$h2 = (1 + 0.75\,ROP\,)h1 \quad (12)$$

$$Nu = \frac{h3\,Lc}{k_{air}} = \left\{ (\frac{Ra}{14.225})^{-1.5} + [\frac{0.81\,Ra^{0.25}}{[1+(\frac{0.492}{Pr})^{9/16}]^{4/9}}]^{-1.5} \right\}^{1/-1.5} \quad (13)$$

Where:

$$Ra = \frac{g\,(\sin\gamma)\frac{1}{T_f}(\overline{T} - T_\infty)\,Lc^4}{\upsilon^2 \quad \delta_z}\Pr$$

$$Lc = \frac{bx\ by}{by + bx\ \cos\beta}$$

COMPUTATIONAL PROCEDURE

The language of Matlab (R2014a) uses to construct a program for this study. Specify the general dimensions of the fin, types of material, the properties of air and perforated specification are necessary to start the programming. The process of calculation began with determining the convection coefficients and then calculated the variable heat transfer area by applying the numerical integration at desired locations. Curve fitting of the area leads to specify the value of the multi constants. The temperature profile for complete fin can be obtained by solving Eq. (6) with other equations from (Incropera et al., 2007).

VALIDATION

The validation performed by using the finite element techniques that used in articles (Abdullah,2009; Kumbhar et al., 2009). Energy equation (1) is solved numerically by using the Variational approach (Rao, 2011).

$$In = \frac{1}{2}\iiint_V k(\frac{d\theta}{dy})^2\,dV + \frac{1}{2}\iint_{A_{conv1}} k\,\theta^2\,dA_{conv1} \quad (14)$$

$$In = \frac{1}{2}\iiint_V k(\frac{d\theta}{dy})^2\,dV + \frac{1}{2}\iint_{A_{conv1}} k\,\theta^2\,dA_{conv1}$$
$$+\frac{1}{2}\iint_{A_{conv2}} k\,\theta^2\,dA_{conv2} + \frac{1}{2}\iint_{A_{conv3}} k\,\theta^2\,dA_{conv3} \quad (15)$$

Eqs.(14 and 15) represented the Variational statement of elements of solid part and inclined perforated of the fin, respectively. A variational approach is used to derive the finite element equations (Rao, 2011). (Eq.(6) and Eqs.(14,15)) are applying to find the various temperature distributions for thermal conductivity ($k = 222w/m.K$,(A1050)). The Figures (4,5,6 and7) show the comparison results of the square fin section with Ra=1×10^5 , Ra=5×10^5, Ra=1×10^5 and Ra=1×10^6 ,respectively. Rectangular perforated sections with different dimension and variety angles of inclination had adopted. Fin performance factor (m) multiply by (LP) is widely used in the analysis and design of the fin. (m) change with elements, therefore ($m_{max.}$) adopted for each case of operation. Agreements between results are starting from complete resemblance to a maximum difference of (0.3%) for all studied cases.

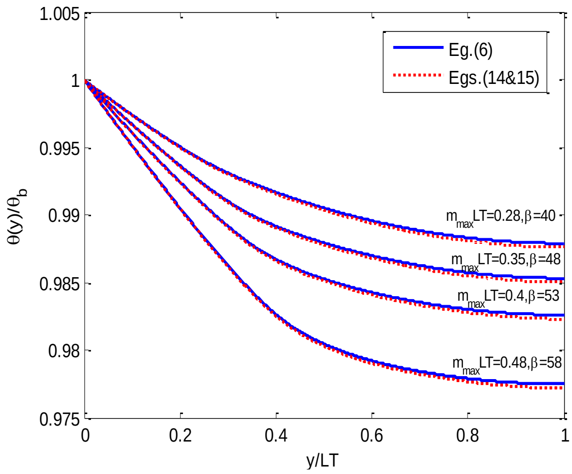

Figure (4) Comparison results of square fin with rectangular perforated.

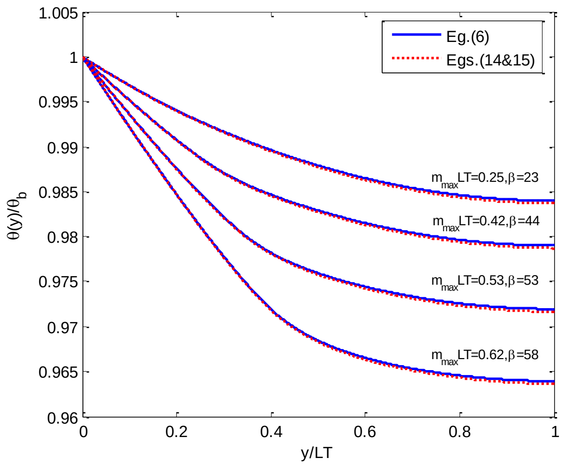

Figure (5) Comparison results of square fin with rectangular perforated.

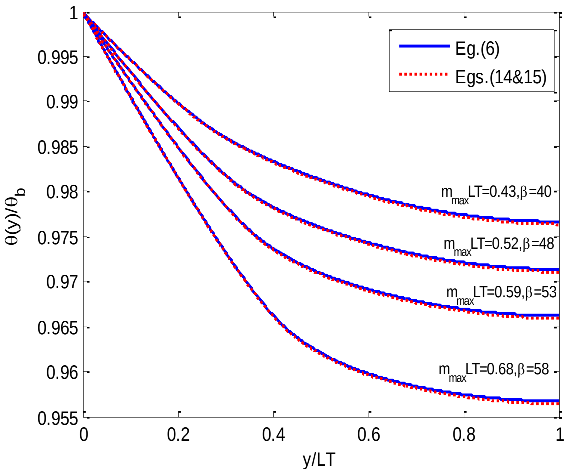

Figure (6) Comparison results of square fin with rectangular perforated.

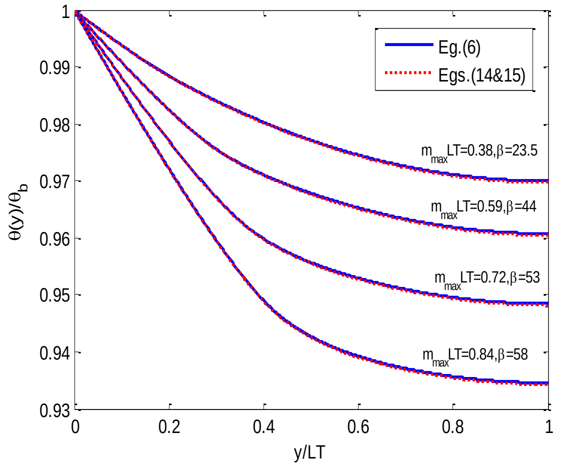

Figure (7) Comparison results of square fin with rectangular perforated.

RESULT AND DISCUSSION

Two different models had adopted to show the effects of the inclined perforation on the fin performance. Models, I and II are described as follows:

$$\delta_x = \delta_z = 0.01\,(m),\, bx = by = 0.007(m),$$
$$LT = 0.05(m), \beta = 0 \rightarrow 44.4^{\circ} \qquad \text{Model I}$$
$$\delta_x = \delta_z = 0.01\,(m),\, bx = by = 0.008(m),$$
$$LT = 0.05(m), \beta = 0 \rightarrow 53.1^{\circ} \qquad \text{Model II}$$

The model I was considered to show the temperature distributions ($\theta(y)/\theta_b$) in Figures (8 and 9) for Ra=1×10^5 and Ra=1×10^6, respectively. In a similar way, the temperature distributions of the Model II are shown in Figures (10 and 11). The results show the increase of the inclination towards the max angle leads to the improvement of the temperature difference along the fin. As well the increase of the Rayleigh number with inclined perforated gives additional improvement to a temperature distribution. The use of the inclined perforation gives more advantages (increase of the inner convection area, distribute the inner convection area on the greater length of the fin, increase of the external perforated area and the recirculations development in y-z as well as the x-z planes), which leads to the best values of the convection coefficient. Heat transfer (q) and effectiveness (ε) for any fin (perforated or solid) can be calculated as below:

$$q_{p\ or\ s} = -k\ A_b \left.\frac{d\theta}{dy}\right|_{y=0} \tag{16}$$

$$\varepsilon = \frac{q_{p\ or\ s}}{q_{no\ fin}} \tag{17}$$

$$HR = \frac{q_p}{q_s} \tag{18}$$

Heat transfer and effectiveness are possible to increase with the improvement of the temperature distributions. Figures (12 and 13) illustrate the heat transfer ratio (HR) for the models I and II, respectively. The range of the Rayleigh number from Ra=1×10^5 to Ra=1×10^6 were considered. The increase of the inclined angle and the Rayleigh number separately or together gives the augmentation to the heat transfer from the perforated fin. Improved of Heat transfer ratio about (18% -27%) for the model I, and (42%-50%) for model II. Enlarge the value of heat transfer leads to improve the effectiveness as shown in Figures (14 and 15) for the model I and II, respectively. Enhanced of the effectiveness about 22% -28% for the model I, and 43%-50% for model II. The Sensitivity of change of the (heat transfer and effectiveness) with a Rayleigh number is large and clear at big values of the inclination.

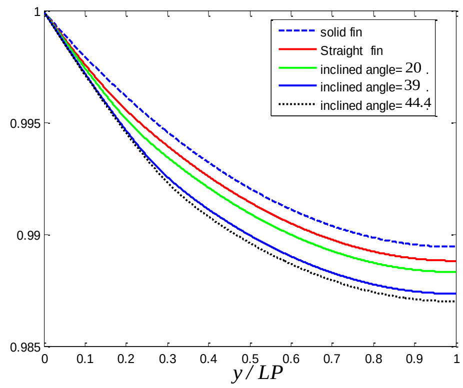

Figure (8) Temperature distribution along the solid and inclined perforated fins

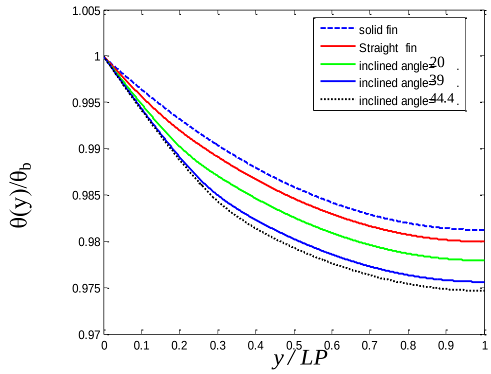

Figure (9) Temperature distribution along the solid and inclined perforated fins

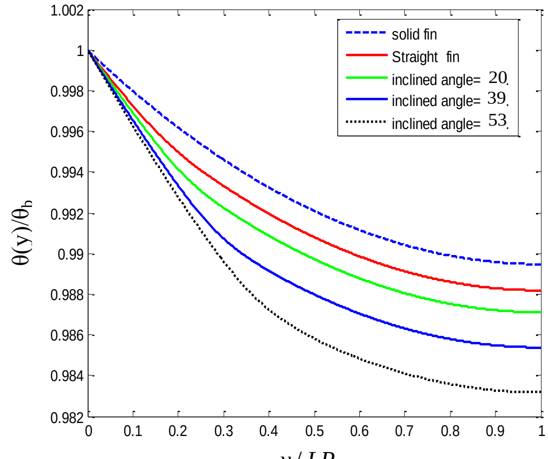

Figure (10) Temperature distribution along the solid and inclined perforated fins

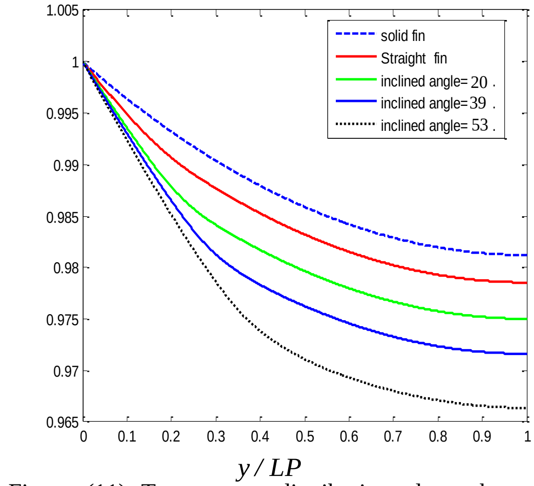

Figure (11) Temperature distribution along the solid and inclined perforated fins

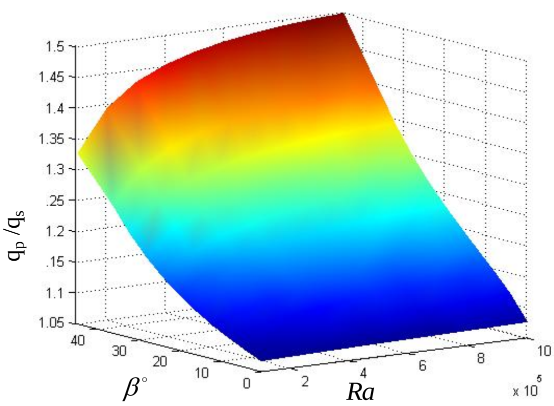

Figure (12) Ratio of heat transfer of perforated fin to solid fin as a function to inclination angle and Rayleigh number

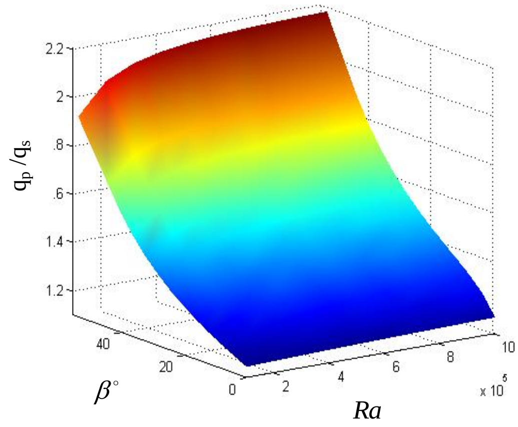

Figure (13) Ratio of heat transfer of perforated fin to solid fin as a function to inclination angle and Rayleigh number

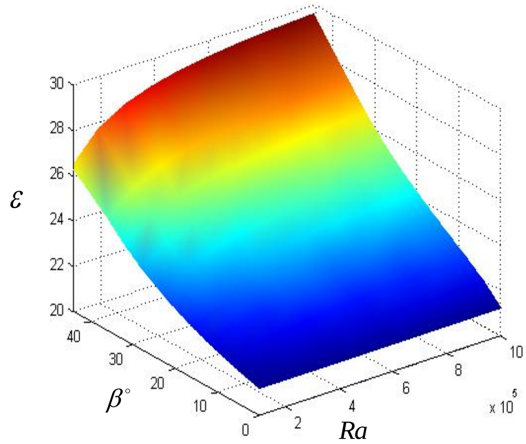

Figure (14) Fin effectiveness for perforated fin as a function to inclination angle and Rayleigh number

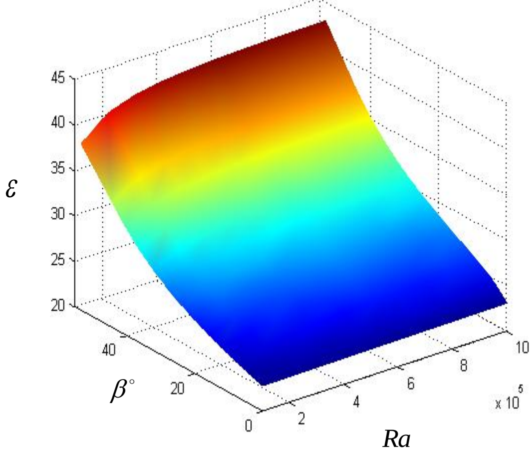

Figure (15) Fin effectiveness for perforated fin as a function to inclination angle and Rayleigh number

CONCLUSION

This paper presented a novel and effective scheme at two major points, *modeling of the variable heat transfer area based on Signum function* and *solves energy differential equation for complex geometry by* (DHE).

The quality of the validation results leads to being sure; the present mathematic model has big reliability. In this study, the use of the common perforated shapes (rectangular) showed the accuracy level and flexibility of the mathematic model. Consequently, general solution for present study taken as the basis to resolve any inclined perforation shape based on modeling of the area.

Fin performance can be improved based on the advantages of inclined perforated. Temperature distribution, heat transfer, and effectiveness are developing towards the positive values for the inclined perforated fin. Increasing the sizes of perforated and Rayleigh number lead to enhance the performance of the fin, on the other hand, all previous enhancements could be better with inclined perforated.

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