Development of Numerical Model of Natural Convection Heat Transfer for Wire-Mesh Vertical Fin

Abdullah F. Ansari[1] Meeta S. Vedpathak[2] Sandeep M. Joshi[3]
[1,2,3]Department of Mechanical Engineering
[1,2,3]Pillai College of Engineering, New Panvel, India

Abstract— The finite difference method in conjunction with least square scheme and experimental temperature data is used to evaluate the approximate value of heat transfer coefficient on the wire-mesh fins in natural convection for various fin spacing and height of the fin. In present study the effect of radiation is neglected and only convection phenomenon is used to predict the heat transfer coefficient in natural convection. Since distribution of temperature on the entire surface is assumed to be uniform, hence the heat transfer coefficient on this wire-mesh fin is assumed to be uniform. Moreover the whole fin surface is divided into several sub-fin regions or discretised in small domain to predict the value of heat transfer coefficient and with the help of governing equation, obtain the value of temperature distribution which then finally compared with the experimental data. The result shows that the value of h (Heat transfer coefficient) increases with increasing the fin spacing between two fins. The fin temperature departs from the ideal isothermal situation and decreases more rapidly away from the base with increasing the fin spacing. In order to validate the accuracy of the present finite difference method, a comparison of temperature value at different location obtained by experiment and by finite difference method on the fin, is made.

Key words: Heat Transfer, Wire-Mesh Fin, Natural Convection

I. Introduction

Natural Convection Heat transfer with heat sink and enhanced surface has been widely used in engineering applications. In recent years, with the rapid development of electronic field, promoting the heat transfer rate under the working process at the desire operating temperature may play an important role to ensure reliable operation of the electronic component. The proper design of heat sink has gradually become attractive for these applications because they provide a more economical and feasible solution for the given problem. This study is slightly different than earlier related topic because in this study the shape of the fin is wire-mesh type and which is different from plate fin type.

A great amount of research has been done to predict natural convection heat transfer between two or more plate-fins. Amruta [1] studied the natural convection heat transfer experimentally for different height and spacing of wire-mesh type fin or approximated pin-fin. Elenbass [2] showed the heat transfer coefficient between two vertical plate-fins with different fin spacing through experiments and conclusion from [4]. Bodia and osterle [3] applied numerical method to study the heat transfer and flow characteristics between two vertical plate-fins. Han-Taw Chen, Chung-Hou Lai, Tzu-HsiangL in, Ge-Jang He [5] used inverse scheme and applied the same to three vertical fins mounted on the heated base plate.

In order to increase the heat transfer rate of the heat sink under natural convection heat transfer, numerous Investigations have been conducted to study heat transfer and empirical correlation of rectangular plate-fins. Han-Taw Chen, Jui-Che Chou [6] investigated natural convection heat transfer coefficient on a vertical square fined tube heat exchanger, and they found the behavior of the fin spacing and efficiency of the system under natural convection phenomenon. Han-Taw Chen, Li-Shie Liu and Shin-Ku Lee [7] they studied the estimation of Heat-Transfer characteristics under natural convection condition and apply numerical scheme to find out the heat transfer coefficient.

For many engineering applications, the heat sink was often placed in a closed enclosure. This has forced many researchers to study the natural convection heat transfer and fluid flow in closed enclosure. Nada [8] obtained empirical relationship of natural convection heat transfer in the horizontal and vertical closed narrow enclosure with the fins on a heated rectangular plate by the experiment. Amruta [1] has also worked in natural convection in closed enclosure for various heights and spacing of wire-mesh vertical fin, she had performed experiment on the wire-mesh fin mounted on the heated horizontal base plate, placed in rectangular enclosure.

The present study applies inverse method and formation of numerical model for the wire-mesh vertical fin which assume to be pin fin with commercial software MATLAB and experimental temperature data to determine the heat transfer characteristics within the fins on a heated horizontal plate for given values of fin spacing and fin height. The value of heat transfer coefficient is obtained by trial and error method. The results also show that the number of the total grid points may slightly increase with the fin spacing. The comparison of the temperature distribution obtained from the numerical data is made, in order to validate the accuracy of the result obtained. Finally by trial and error method the value of heat transfer coefficient is obtained by changing from initial assumed value.

II. MATLAB

MATLAB is a high level computing language. It is widely used in computational analysis, control, signal processing and computational field. Except the field of electronics and telecommunication MATLAB is also playing important role in the field of mechanical engineering.

Numerical computing is done in multi-paradigm numerical computing environment i.e. matrix laboratory (MATLAB). In MATLAB software the required mathematical formulation for free convection is technically computed by performance language. The computation algorithm consist object oriented programme feature as they help evaluate the mathematical expression. Free convection condition are programmed and also an algorithm used for various fin profile i.e. straight rectangular, taper fins, cylindrical pin fins and in-line array or wire-mesh fin for computing the heat transfer characteristics of various fin.

III. MATHEMATICAL FORMULATION OF NUMERICAL SCHEME

The two dimensional inverse heat conduction problems is first introduced to estimate the unknown heat transfer coefficient on the fin of the wire-mesh or approximate pin fin heat sinks for a given values of fin height. The temperature of the fin at the selected measurement locations and the ambient air temperature are measured from the experimental apparatus constructed in a closed rectangular enclosure. The inverse method in conjunction with the finite difference method, the experimental data is used to predict the heat transfer coefficient for the seven array of vertical fin attached to the heated horizontal plate. Due to assumption of uniform distribution of heat transfer coefficient, the entire fin is divided into several sub-fin regions before performing an inverse method.

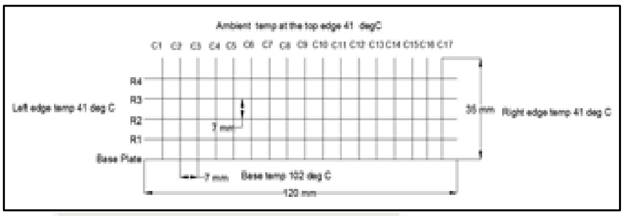

Fig. 2: Physical Geometry of the Wire-Mesh Fin & Sub-Fin Regions

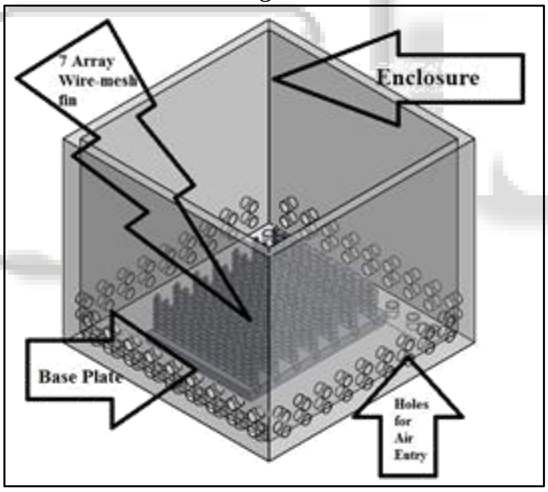

Fig. 3: Seven Parallel Wire-Mesh Fins Mounted On the Top Surface of a Horizontal Plate in a Rectangular Enclosure

Under the assumption of the fin, the temperature gradient in the Z-direction (radial direction or fin thickness) can be neglected and the temperature of the fin is varies only in X and Y directions. Moreover the total surface area of the edge relative to the total surface area of fin is small enough. This implies that the actual heat transfer rate dissipated through the fin tip is much smaller than the total heat transfer rate drawn from the base of the fin. Thus the boundary conditions at the edge surface of the fins may be assumed to be insulated, under the assumption of steady state and constant thermal properties, the heat conduction equation for a thin fin can be expressed as

$$\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 = 4\, h(x,y)/K_f D\,(T_o - T_\infty) \quad 0<x<L,\ 0<y<H \qquad (1)$$

Its corresponding boundary conditions are,

$$\partial T/\partial x \quad \text{at } x = 0 \text{ and } x = L \qquad (2)$$

$$T(x, 0) = T_0 \text{ (Base temperature)} \quad \text{at } y = 0 \qquad (3)$$

and

$$\partial T/\partial y \quad \text{at } y = H \qquad (4)$$

The unknown heat transfer coefficient in each discretized domain or sub-fin region is assumed to a constant. Thus the finite difference form of (1) in different sub-fin region can be expressed as

$$(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})/l_x^2 + (T_{i,j+1} - 2T_{i,j} + T_{i,j-1})/l_y^2 = (4h/K_f D)\,T_{i,j} \qquad (5)$$

Where T denotes the fin temperature, x and y are Cartesian coordinates, L, H and D denotes the length, height and diameter of the fin respectively. h(x,y) is the unknown heat transfer coefficient. K_f is the thermal conductivity of the fin.

T_0 and T_∞ denote the fin base temperature and the ambient air temperature respectively.

For i = 1, 2, …….N_x , j = 1, 2,……..N_y. where N_x and N_y are respectively, the number of nodes in the X-direction and y-direction. l_x and l_y are defined as $l_x = L/(N_x - 1)$ and $l_y = H/(N_y - 1)$.

The finite difference form of the boundary conditions (2)-(4) can be written as

$$T_{0,j} = T_{2,j} \text{ and } T_{Nx-1,j} = T_{Nx+1} \text{ for } j = 1,2\ldots N_y \qquad (6)$$

$$T_{i,1} = T_0 \text{ and } T_{i,Ny-1} = T_{i,Ny+1} \text{ for } i = 1,2\ldots N_x \qquad (7)$$

Rearrangement of (5) in conjunction with their corresponding difference equation can produce the following matrix equation as

$$[K]\,[T] = [F] \qquad (8)$$

Where [K] is the global conduction matrix.[T] is the matrix representing the nodal temperatures. [F] is the constant values depending on the boundary condition. The values of fin nodal temperatures are obtain from equation (8) using gauss elimination algorithm by taking some assumed initial value of heat transfer coefficient.

In order to estimate unknown heat transfer coefficient h, additional information of the measured fin temperature at different locations can be required. The more the number of the analysis sub-fin region are, the more accurate the estimate of heat transfer coefficient may be. However, it might be difficult to measure the temperature distribution on the middle fin of the present problem using infrared thermography. Excessive thermocouples in the fin may also significantly interrupt the flow and heat transfer behaviors within the fins. Thus, the thermocouple may be applied to measure fin temperatures at the selected measurement locations.

Many researchers used various numerical methods to investigate the heat transfer characteristics of plate-fin or pin-fin. However, little information is available in open literature to investigate the effect of the grid point on the numerical result, mainly when the geometry is complex. Therefore, the present study applies MATLAB software to predict the heat transfer behavior and distribution of temperature over the surface of the fin and their variation with respect to change in fin variables i.e. Length, height, spacing, of wire-mesh vertical fin mounted on horizontal heated plate.

Understanding the details of the local heat transfer and fluid flow distributions within the fins can be very important in the design of the heat sink. At the same time in order to validate the accuracy of the results, the numerical technique software MATLAB in conjunction with the experimental temperature data is also used to determine the heat transfer coefficient and fin temperature. The ambient air with constant properties can be assumed to be incompressible.

The flow within the fins of the heat sink may be assumed to be symmetric, steady and no viscous dissipation.

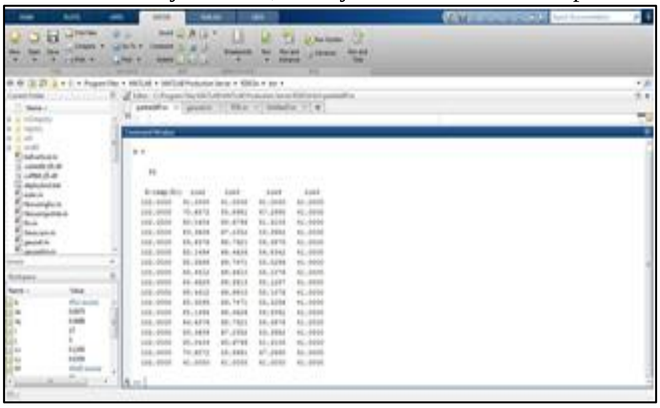

Fig. 4: Distribution of temperature result by MATLAB

IV. EXPERIMENTAL SETUP

The present experiment was conducted in closed rectangular enclosure. The Length, width and height of the enclosure is (240 x 240 x 205) mm respectively. The test fin with 120 mm in length and 35 mm in height and 1mm in diameter made up of steel material is used. The ambient air temperature and the fin temperature are measured with the T-type thermocouple.

Fig. 5: Experimental Setup

The diameter of the T-type thermocouples is about 0.13mm. The limit of its error is (±0.4%) for $0^oC \leq T \leq 350^oC$. The schematic diagram of seven parallel wire-mesh fin mounted on the top surface of heated horizontal plate is as shown in figure 3. In order to heat seven Parallel fins, a 450W electric heating coil having 180mm x 140mm size used as a heat source fixed on the bottom of the plate made up of mild steel material. The test fins and horizontal plate enclosed with brick insulation. Total 29 thermocouples were fixed on the fins and base at different points to measure the temperature at different location. One thermocouple was placed inside the insulating brick, four thermocouples were attached to the base plate to measure the temperature inside the enclosure (ambient Temperature), and other thermocouple was attached to the fin at different point location to measure surface temperature of fin.

V. RESULTS & DISCUSSION

All physical properties are evaluated at the average temperature of the fin base and ambient air temperatures. Thermal conductivity of steel wire-mesh fin K_f = 17 w/m-k, Number of nodes in X-direction is taken as N_x = 17 and in Y-direction N_y = 5 are performed for the inverse method with the help of software MATLAB.

The commercial software MATLAB is used to determine heat transfer characteristics within the fin of the wire-mesh heat sink by using trial and error method. Initially the domain of wire-mesh fin is dividing as an actual physical construction and location of the node is taken at intersection of horizontal and vertical wire. The initial guess of the unknown heat transfer coefficient h, is taken as a unity for the given numerical method and corresponding value of distribution of temperature are compared by measured value of experimental results. The wire-mesh fin divided into 85 regions which actually the hollow space in actual wire-mesh fin and 22 thermocouples are fixed at the different location on the fin surface. T_j^{num} denotes the fin temperature obtained using the MATLAB software.

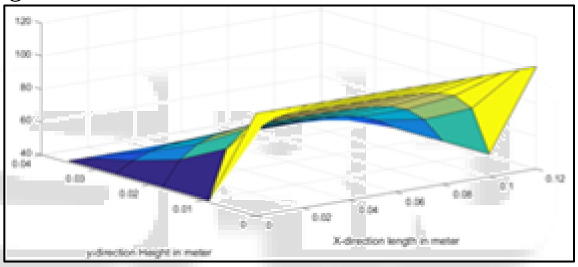

Fig. 6: MATLAB Result of Temperature Distribution of Wire-Mesh Vertical fin for Height is 35 mm Height, 23mm fin Spacing and 40W Heat Supplied

Average Fin temperature at seven horizontal wire position	H=48 mm T_0= 102 ^oC T_∞= 41^0C T_j^{mea} in ^0C (Exp Data)	H=48 mm T_0= 102 ^oC T_∞= 41^0C T_j^{num} in ^0C (Numerical Data)
T1	102	102
T2	84	83.4629
T3	63	69.8913
T4	54	55.1287
T5	41	41
h (w/m^{2}k)	17.208	15
Nu	30.651	25.69

Table 1: Comparison of Tj (Average Vertical Temperature, & Heat Transfer Coefficient)

VI. CONCLUSION

The present study proposes the use of MATLAB software in conjunction with the experimental temperature data in order to determine the heat transfer characteristics within the fins of wire-mesh heat sink. The result shows that the present numerical model and relationship obtain by numerical method are in good agreement with experimental results. Moreover the assumption taken for the given numerical model is also valid for a given system. This implies that the present results are reliable. This implies that the proposed coding to solve the present problem is appropriate. The total number of nodes may vary with the height of the fin in order to obtain the more accurate results. Hence the software MATLAB in conjunction with experimental data can be applied to obtain a more accurate heat transfer characteristics of wire-mesh fin heat sink with appropriate flow model and grid points.

Acknowledgments

The authors gratefully acknowledge the full support of Pillai College of engineering to give me an access of the commercial software. I would also like to thanks all staff at Pillai College of engineering to encourage and supported me in my work.

References

[1] Amruta N. Kalode; March 2016; “Experimental analysis of wire meshes heat sink by natural convection”; “International journal of global technology initiatives”(ICGTI-2016) , ISSN-2320-1207, Volume-5, Issue 1.
[2] W. Elenbass, “Heat dissipation of parallel plates by free convection.” Physical, Vol. 9, app. 2-28,1942
[3] J.R. bodoia, J.F. Osterle, “The development of free convection between heated vertical plate,”ASME j.Heat Transfer vol.84, pp.40-44,1962
[4] E. M. Sparrow, P. A. Bahrami, “Experiments on natural convection between heated vertical plates with either open or cloed edges,”ASME J. Heat Transfer, vol. 102, app. 221-227, 1980.
[5] Han-Taw Chen, Chung-Hou Lai, Tzu-HsiangLin, Ge-Jang He, “Estimation of Natural Convection Heat Transfer from Plate-Fin Heat Sinks in a Closed Enclosure.” International journal of Mechanical, Aerospace, Industrial, Mechatronics and Manufacturing Engineering, vol: 8, no:8, 2014
[6] Han-Taw Chen, Jui-Che Chou “Investigation of natural-convection heat transfer coefficient on a vertical square fin of finned-tube heat exchangers.” International Journal of Heat and Mass Transfer 49 (2006) 3034–3044
[7] Han-Taw Chen, Li-Shie Liu and Shin-Ku Lee “Estimation of Heat-Transfer Characteristics from Fins Mounted on a Horizontal Plate in Natural Convection.”, CMES, vol.65, no.2, pp.155-178, 2010
[8] S. A. Nada, “Natural convection heat transfer in horizontal and vertical closed narrow enclosure with heated rectangular finned base plate,” Int. J. Heat Mass transfer, vol. 50, pp. 667-679, 2007.

