Experimental and Numerical Analysis of Heat Transfer Through Various Types of Fin Profiles

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ABSTRACT

Employing extended surfaces, or 'fins', are, undoubtedly the most widely used method for dissipation of excess heat generated in reciprocating and rotary machine components. Moreover, the amount of heat extracted by a fin from the machine surface depends, to a great extent, on the cross-sectional shape. This paper aims at studying the said dependence of a fin's thermal dissipation capacity on its geometry. Experimental analysis and computer simulation were employed to verify and corroborate already established results. For simplicity, the most commonly used cylindrical pin fin, or spine, was used as a standard and the characteristics of three alternative shapes were compared against those of the former. Furthermore, to prove the consistency of the trend, experiments were carried out on two materials-aluminum and copper. Numerical simulation included the CFD analysis of the problem using ANSYS Fluent 13. The results obtained through both the approaches were compared against each other.The investigation helps understand how fin shapes affect their behaviour and could lend an insight into realizing the utility of each fin from a designer's perspective.

Keywords - Effectiveness, Enhancement, Fin length, Nusselt number, Rectangular fin.

INTRODUCTION

In the study of heat transfer, a fin is a surface that extends from an object to increase the rate of heat transfer to or from the environment by increasing convection.. Increasing the temperature difference between the object and the environment, increasing the convection heat transfer coefficient, or increasing the surface area of the object increases the heat transfer. Sometimes it is not economical or it is not feasible to change the first two options. Adding a fin to an object, however, increases the surface area and can sometimes be an economical solution to heat transfer problems. Typically fin material has high thermal conductivity and so they are made up of materials like copper, aluminum and iron. The fin is exposed to flowing fluid which cools or heats with high thermal conductivity allowing the heat being conducted from the wall through surface. Thus fins are used to enhance convective heat transfer in a wide range of engineering applications, and offer a practical means for achieving a large total heat transfer surface area without the use of an excessive amount of primary surface area. Fins are commonly applied for heat management in electrical appliances such as computer power supplies or substation transformers. Other applications include IC engine cooling, such as fins in a car radiator and compressors. Fins are also used in newer technology such as hydrogen fuel cells.

1.1ANALYTICAL STUDY OF CYLINDRICAL FIN

To create a simplified equation for the heat transfer of a fin, many assumptions need to be made:

1. Steady state
2. Constant material properties (independent of temperature)
3. No internal heat generation
4. One-dimensional conduction
5. Uniform cross-sectional area
6. Uniform convection across the surface area

With these assumptions, the conservation of energy can be used to create an energy balance for a differential cross section of the fin,

$$\frac{d^2T}{dx^2} = -\left(\frac{1}{A_c}\frac{dA_c}{dx}\right)\frac{dT}{dx} + \left(\frac{1}{A_c}\frac{h}{k}\frac{dA_s}{dx}\right)(T - T_\infty) \quad (1)$$

This is the general equation for convection from extended surfaces.
Thus, the general equation for Convection from extended surfaces with constant cross-sectional area simplifies to

$$\frac{d^2T}{dx^2} = \frac{hP}{kA_c}(T - T_\infty) \quad (2)$$

Similarly the rate of heat transfer from a surface at a temperature "T_s" to the surrounding medium at "T_0" is given by the Newton's law of cooling as:

$Q = h\ A_S\ (T_s - T_0)$ (3)

Where:

A_S - heat transfer surface area and

h -is the convection heat transfer coefficient.

- Temperatures T_s and T_0 are fixed by design considerations. The various dimensionless numbers like Reynolds number,Prandtl number(Pr) ,Nusselt Number (N_u),Grashoff number (Gr) are required for analysis of heat transfer rate. Similarly the fin effectiveness calculation is also required.

Literature Review

Literature survey has been done in order to study the research done by various researchers on the heat transfer analysis of heated plates by using fin .The few of the articles chosen for review work are stated below.

Baskaya S, Sivrioglu M., and Ozek M. [1] carried out parametric study of natural convection heat transfer from the horizontal rectangular fin arrays. They investigated the effects of a wide range of geometrical parameters like fin spacing, fin height, fin length and temperature difference between fin and surroundings; to the heat transfer from horizontal fin arrays. However, no clear conclusions were drawn due to the various parameters involved. M.J. Sable, S. J. Jagtap, P.S.Patil, P. R. Baviskar, and S.B.Barve [2] investigated heat transfer enhancing technique for natural convection adjacent to a vertical heated plate with a multiple V- type partition plates (fins) in ambient air surrounding. They concluded that as compared to conventional vertical fins, the V-type partition plates work not only as extended surface but also as flow turbulator.The work by R.S.Prasolov , Heya, Fujii , Bhavnani and Bergles [3] suggest that the roughness elements whose height is less than the boundary layer thickness will have no appreciable influence on the heat transfer of natural convection and these elements will work as flow retarder rather than the heat transfer promoter.Misumi and Kitamura [4] have reported an experimental work on enhancement of natural convection heat transfer from vertical plate having a horizontal partition plate and V-plates in the water ambience. An extensive review and discussion of work done on the convective heat transfer in electronic equipment cooling was presented by Incropera [5], summarizing various convection cooling options.. Jones and Smith [6] studied the variations of the local heat transfer coefficient for isothermal vertical fin arrays on a horizontal base over a wide range of fin spacing.For a wide range of temperatures Rammohan and Venkateshan [7] made an interferometric study of heat transfer by free convection and radiation from a horizontal fin array. Correlations useful for thermal design were presented .S.S.Sane,N.K.Sane, and G.V. Parishwad [8] established a match between the experimental results and the results obtained by using CFD software for a horizontal rectangular notched fin arrays dissipating heat by natural convection. Both the flow patterns as well as the trend of heat transfer coefficient are found to be within 5% range.Kharche and Farkade ,[9] used fin with notch and with-out notch of copper as a fin material on vertical heated plate for the experimental work. They compared the effect of heat transfer coefficient for notch and without notch fins. From the experimental study it was found that the heat transfer rate in notched fins was more than the unnotched fins..Matthew Christensen [10] does his investigation on the Static Heat Transfer analysis of Fins, for the analysis he considered a plate with fin & without fin, and he compared them, It was determined that fins are extremely effective in situations where Heat Transfer Coefficients (h) is low, but as h rises the effect of a fin will decrease. R. L. Edlabadkar [11] did their research work on single V-type partition plate with different included angles, in air as ambience in the laminar air flow over a vertical base plate with length 0.3m, width 0.3m, and V shape fin (the fin limb length is 0.15m and width 0.05m) attached to it .Results were numerically tested using Computational Fluid Dynamics (CFD) software of FLUENT with laminar viscous model. Wankhede [12] developed an experimental setup to carry out the investigation on horizontal rectangular fin array with and without inverted notch under natural and forced convections..Barhatte [13] did the work on heat transfer rate with V-fins with bottom spacing and vertical plate with different V-type fins. It is further observed that the base heat transfer coefficient (hb) of V-type fin array is better than all other configurations. T. Aberra, S.W. Armfield [14] studied numerically the stability of the natural convection boundary layer on an evenly heated vertical plate for a Boussinesq fluid with Prandtl numbers of Pr= 0.733 and 6.7.

METHODOLOGY

3.1 Experimental set-up

The experiment is carried out to find out the actual temperature profile for each fin and subsequently, compare them for their effectiveness. For this, the setup is constructed as explained in the following section. Four fins of different cross-sections are attached to a base plate of the same material. The base plate is assumed to be the machine or application from which heat is to be removed. The base plates will be heated to a convenient, predetermined temperature and various drafts will be made incident on the fin assembly and their response to each of those drafts will be recorded and analyzed for the amount of heat removed from the base plate. To achieve this, three thermocouples are mounted on each fin at distances of 50mm, 100mm and 150mm from the fin base and the temperatures recorded by each is documented and the resulting variation of temperature along the length of the fin is plotted. The slope of the graph at the fin base, i.e. at x= 0, is an indication of the amount of heat conducted from the base plate to the fin base. $Q_{cond} = k\, A_{c/s}\, (dt/dx)$ Once the values of heat conducted from the base plate are obtained, they can be directly compared to find which fin shape conducts the greatest amount of heat from the base plate. Likewise, the heat transfer through each fin can be then divided by the heat transfer through equivalent area of the base plate, to find the fin effectiveness.

3.2 DESIGN OF APPARATUS

For verifying the results obtained in CFD analysis the results are compared with experimentation results. The experimental setup consists of the following components:

- 2 nos. Single Phase 230V AC supply
- 2 nos. Heating apparatus (350W, 230V, 1.515A)
- 27 nos. Thermocouples (PT-100)
- Electrical Panel
- Galvanized Iron Duct
- Base plate and fin assembly
- Blower

Details of apparatus are as follows:

3.2.1 BASE - FIN ASSEMBLY

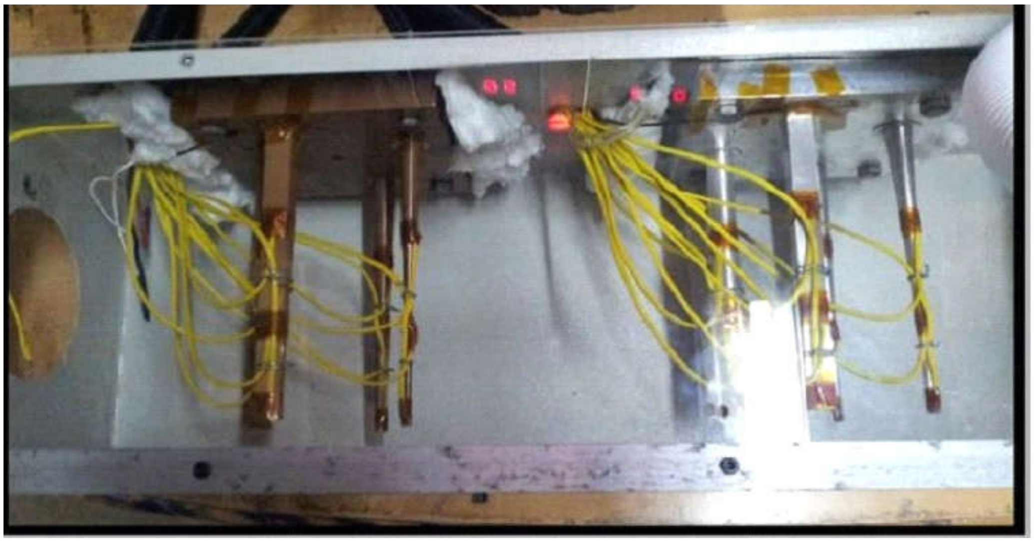


Figure 3.1: Base - Fin Assembly

For the study of heat transfer through fins using different surfaces and cross section four 3D shapes have been taken and are manufactured. The shapes are Cylindrical,Conical,Concave, ,parabolic &Trapezoidal. For the consideration of change of heat transfer due to conductivity two materials are used. The materials are: Aluminium (Lower conductivity) & Copper (Higher conductivity).

3.2.3 ELECTRICAL PANEL

The electrical panel consists of the display of the Thermocouple Temperatures (PT-100). The temperatures can be viewed by using two displays each with 12 channel selector switch .Heating element 1 is attached to the base plate made of copper and element 2 is attached to the base plate made of aluminium. The top left display show the temperatures of the copper fins while the top right display shows the display of aluminium fins. The panel is provided with three display screens to view temperatures of the ambient air and of the two base plates. There are two temperature controllers attached to each of the heating element. A predetermined temperature can be set in these controllers. If the temperature of the base plate is less than the predetermined temperature then the relay in the controller starts heating the element. As soon as the temperature of the base plate reaches the determined temperature the relay turns the heating off, thus maintaining a constant temperature at the base plate. There are two ammeters and a voltmeter to display the voltage across the heating element and the current through the element.

3.2.4 DUCT

Fins are mounted inside a duct with the help of bolts. Front and top faces of the duct are covered using acrylic sheets for protection and visibility. The duct dimensions are: 200 mm x 200 mm x 800 mm. The material of duct is Galvanized Iron.

3.2.5 HEATING APPARATUS

A flat plate heating element is used to heat the base plates. The resistance of coil is very high giveing a high temperature rise. The heating plate is connected between the base plate and duct. To insulate the duct ceramic wool is used. Ceramic wool consists of fine ceramic particles which are bad conductor of heat and act as thermal insulator. Two Mica sheets hold the conductor sandwiched. The mica is a bad conductor of electric current, thus acts as an electric insulator. The thermocouple numbers on the electrical panel for each fin at distances, 50mm, 100mm and 150mm from the fin base, respectively, are as shown in the following table:

Table 3.1: Thermocouples Numbering – Copper

	Fin	Distance from Fin Base		
		50mm	100mm	150mm
Channel 1 (Copper)	Trapezoidal	1	2	3
	Parabolic	4	5	6
	Conical	7	8	9
	Cylindrical	10	11	12

Similarly numbering has been done for aluminium

3.3 PROCEDURE

- Switch on the mains and the power supply to the heating elements and set the desired base plate temperatures.
- Note down the voltage and current readings for each channel from the voltmeter and ammeters.
- After both the base plates attain the set temperatures, start noting down the temperatures recorded by the thermocouples along the lengths of the fins at regular time intervals, say of two minutes each.
- Once at least two subsequent readings agree, it can be assumed that the steady state has been attained and the last noted reading can be used for calculations.
- Note down the twelve temperatures on the fins and those of the ambient air and base plates.
- Switch off the power supply.
- Fill out the observation tables and carry out the relevant calculations.
- Plot the temperature distribution of each fin along its length.
- Estimate the slope of each graph at the fin base, i.e. at x=0.
- Find the heat transfer rate at the base of each fin using the formula:
- Find out the value of the surface heat transfer coefficient for the base plate.
- Calculate the fin effectiveness for each fin and compare the results with those obtained through CFD analysis.

3.4 RESULTS

Experimental Results and Discussion for Cylindrical Fin Copper :

Plate temp $T_{out}=37\ ^0C$
Length L = 150 mm
$t_f = (37+28)/2 = 32.5\ ^0C = 305.5$ K
The thermo physical properties of air at 305.5 K are,
Density of air :(ρ_a) = 1.1614 kg/m$^{3`}$
Thermal conductivity of air: (k) = 0.0263 W/m K
Kinematic Viscosity of Air (ν) = 184.6 * 10^-7 Ns/m2
Dynamic viscosity of air (μ) = 15.89*10^-6 m2/sec

Prandtl No= 0.707

- Heat Supplied Q = V*I (4)
- Experimental Convective Heat Transfer Coefficient (h_{exp})=Q/(A_{fin}(T_s-T_{atm})) (5)

For Laminar Flow Nusselt Number is

$$Gr = \frac{\rho^2 \beta g \Delta t L^3}{\mu^2}, \quad (6)$$

β= 1/ T (7)

For Laminar Flow,

Nu = 059 * (Gr * Pr)(1/4) (8)

Since ,Nu = h L/k

$$\text{Effectiveness of Fin} = \frac{\text{Q fin}}{\text{Q without fin}} \quad (9)$$

By using above standard formulas and standard values the calculation is done and value are tabulated in table 4.3

4.4.1 NATURAL CONVECTION

Table-3.3: For Cylindrical Fin

Cylindrical Fin for Copper					
Temp.	**Mean film temp. Tf C^0**	**Grashloff Number (Gr)**	**Prandtl Number (Pr)**	**Nusselt Number (Nu)**	**Heat transfer Coeff. (h) W/m2 K**
352 **Copper**	305	68.007 * 10^6	0.707	49.129	8.614

Table 3.4: Experiment Temperature Readings - Natural Convection

	Copper			Aluminium		
	50mm	100mm	150mm	50mm	100mm	150mm
Trapezoidal	364	359	358	363	356	355
Cylindrical	362	360	354	367	354	352
Conical	358	354	351	366	353	349
Parabolic	362	353	345	357	348	340

Table-3.5 Effectiveness Comparison for Cylindrical Fin of Aluminum and Copper

Fin data for Cylindrical Fin Type				
Temperature of fin ^{0}C	**h W/mm^2 K**	**Q without fin(W)**	**Q for fin**	**ε fin**
352 Copper	8.614	104.82	251.108	2.39

PLOTS For Copper

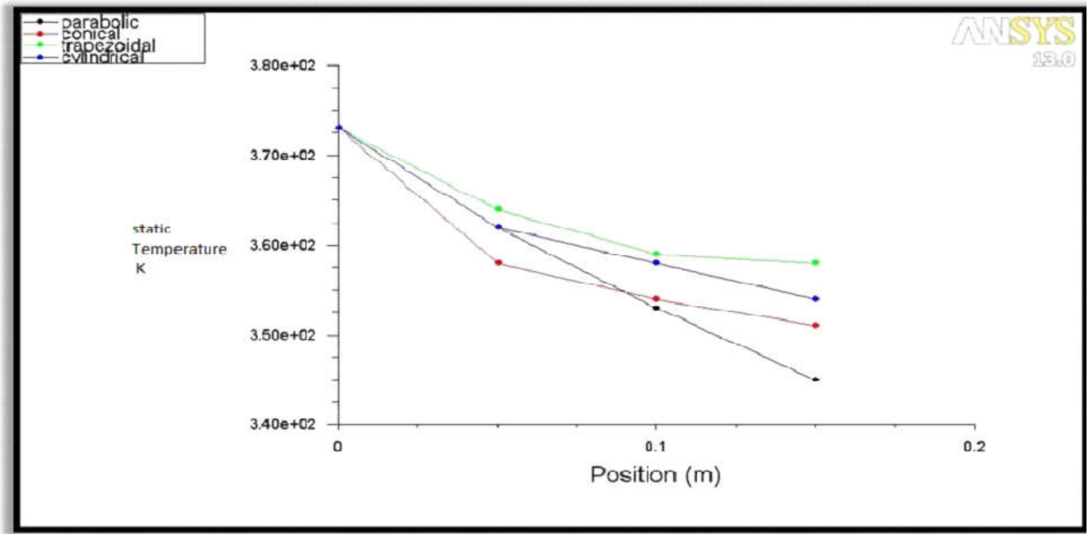


Figure 3.2: Experiment Pressure Plot - Copper - Natural Convection

For Aluminium

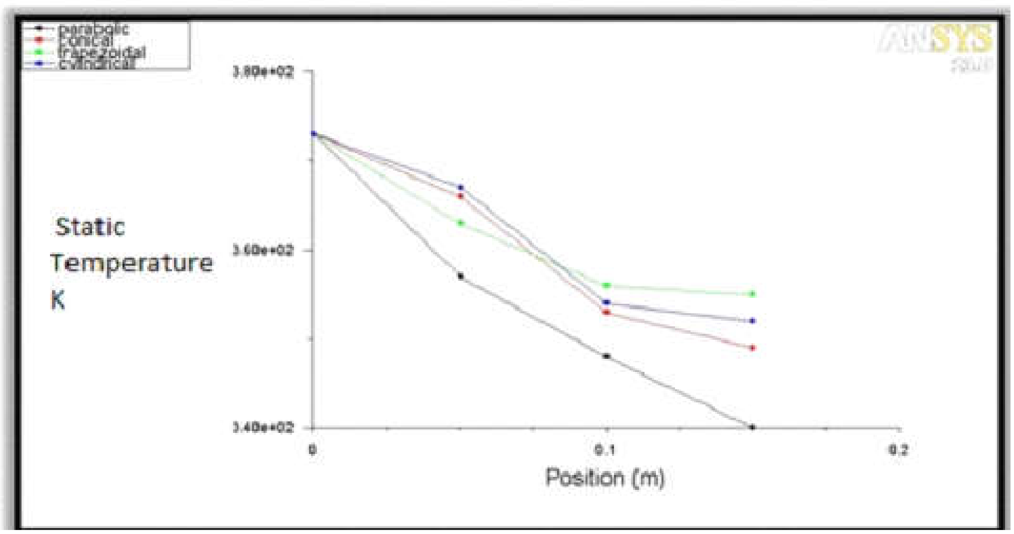


Figure 3.3 : Experiment Temperature Plot - Aluminium - Natural Convection

4. COMPUTATIONAL FLUID DYNAMICS

4.1 GENERAL

Computational fluid dynamics, abbreviated as CFD, uses numerical techniques and algorithms to solve fluid flow and heat transfer problems. Being a numerical approach to solving problems involving complex differential equations, CFD yields only approximate solutions. CFD problems are solved in the following fundamental steps Pre-Processing, Processing, Post-Processing&Meshing**,**After the meshing and applying the necessary boundary conditions the solver needs to solve all the general differential equations on every grid points. Here we have considered K-€ turbulence model. This model focuses on the mechanisms that affect the turbulent kinetic energy per unit mass (k). The instantaneous kinetic energy k(t) is the sum of the mean kinetic energy K and the turbulent kinetic energy k.€ is the rate of dissipation of the turbulent kinetic energy.By the application of the k - € model the solver has to solve:1 equation of continuity,3 equations of momentum,1 equation of kinetic energy &1 equation of € that is dissipation of kinetic energy.Hence the solver solves 6 equations on every grid point. After solving these equations at every point the temperatures obtained are plotted along the length of the fins. The variation of temperature is the expressed as XY plots and contours.

4.2 RESULTS

PLOTS

For Copper

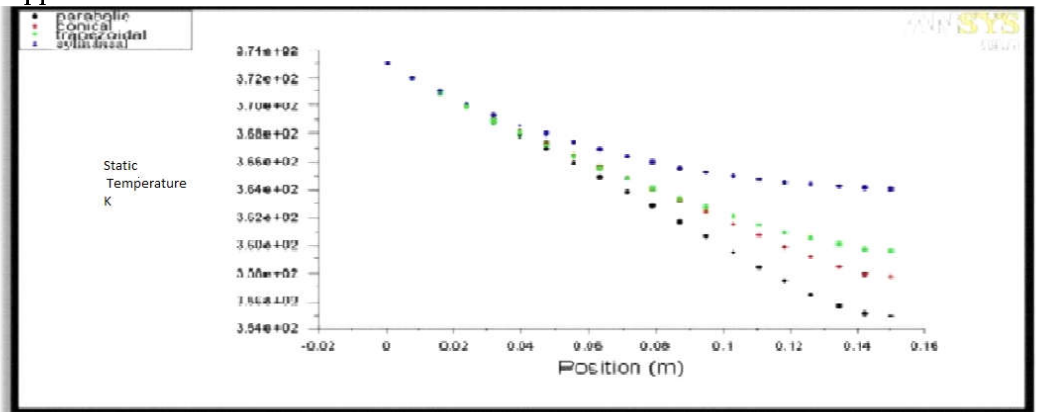


Figure 4.1: CFD Analysis Pressure Plot - Copper - Natural Convection

For Aluminium

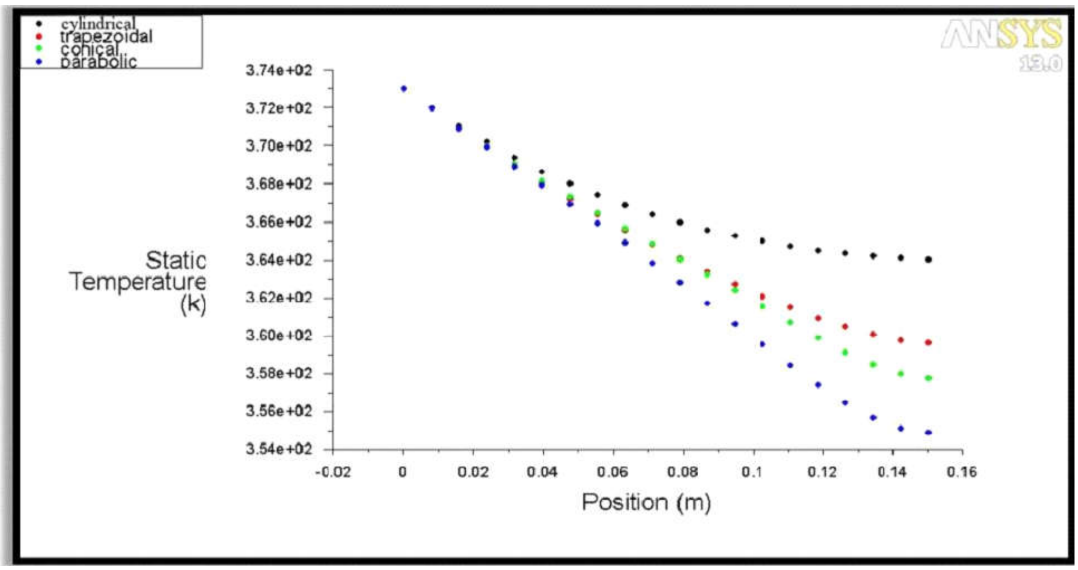


Figure 4.2: CFD Analysis Temperature Plot - Aluminium - Natural Convection Table 5.1:

Table 4.1: CFD Analysis Temperature Readings - Natural Convection

	Copper			Aluminium		
	50mm	100mm	150mm	50mm	100mm	150mm
Trapezoidal	362	355	353	360	350	350
Cylindrical	362	355	350	362	350	348
Conical	355	350	345	360	348	345
Parabolic	360	353	340	355	348	335

4.3. FINITE ANALYSIS USING C++

4.3.1 FINITE ELEMENT METHOD

In this method the entire domain is divided into a large number of elements. Depending on the nature of the problem these elements can be linear, 2-D or 3-D. Then for any one such element the differential equation is solved by Rayleigh-Ritz method to obtain an 'Element Matrix Equation (EME)'. All such element matrix equations are added together to obtain a 'Global Matrix Equation (GME)'. Then applying appropriate boundary conditions the global matrix equation is solved.

4.3.2 FINITE VOLUME METHOD

This is the most widely used method in CFD programming mainly because it combines the advantages of both the above methods. In this method the system is divided into a large number of finite volumes and the fluxes are calculated over these small volumes using integral form of energy, momentum and continuity equations. The value at any node is then calculated depending on the adjacent nodes and using various upwinding schemes. It takes into account the physics of the system as well as uses finite difference approximation to solve the problem. In our case we have used Finite Element Method for solving Cylindrical Fin and Finite Difference Method for the other fins. 'C++' is chosen as the language for executing these codes precisely because ANSYS uses 'C++' at its back - end.

COMPARISION BETWEEN EXPERIMENTAL AND THERMAL ANALYSIS

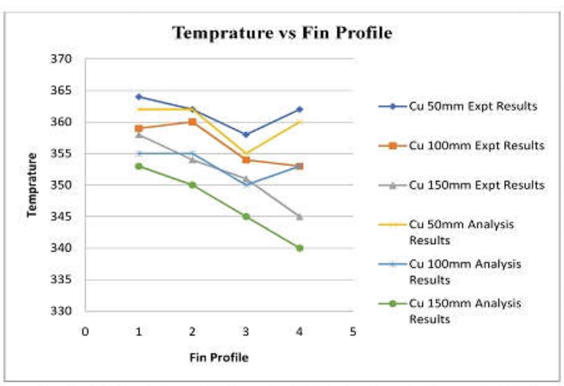
5.1 Experimental and Analysis Results

5.1.1 Natural Convection For Copper

Table 5.1: Experimental And Analysis Results – Natural Convection

	Experimental Results			Thermal Analysis Results		
	50mm	100mm	150mm	50mm	100mm	150mm
Trapezoidal	364	359	358	362	355	353
Cylindrical	362	360	354	362	355	350
Conical	358	354	351	355	350	345
Parabolic	362	353	345	360	353	340

On X Axis-1- Trapezoidal, 2- Cylindrical, 3- Conical, 4- Parabolic On Y-Axis-Temperature in C^0



Graph 6.1: Experimental And Analysis Results – Natural Convection for Copper

Similarly the experimental and analytical result for aluminium can be compared and plot can be generated (which is not shown here to page limitation)

5.2 DEVIATION OF EXPERIMENTAL OBSERVATIONS

We have now seen how the experimental analysis and numerical simulation of the problem were conducted to obtain harmonious results. However, getting there was not easy and despite best efforts to obtain matching results, some deviations in the answers obtained from the two approaches was inevitable.

CONCLUSION

- The experimental and numerical analysis of heat transfer through fins of four cross sections was carried out and the results from both the approaches were obtained and compared.
- From the results, it is observed that for the same fin material, the trapezoidal fin experienced the least temperature drop over its length, while the parabolic pin fin consistently had the largest temperature drop.
- Also, as heat flux entering each fin is same owing to their equal base area, parabolic fins are able to achieve least tip temperature for the same material. Hence, the parabolic fin is the most efficient in dissipating heat to its surroundings.
- Due to their greater thermal conductivity, copper fins are, in general, more efficient than aluminium fins.
- However, a designer must consider the trade-off between the greater conductivity and the larger density of copper before selecting it to fabricate fins.

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