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CFD and Taguchi Analysis on Tree Fin for Natural Convection

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Abstract:
In Natural convection process fins are extensively used for cooling of devices generating heat either internally or externally. In the present analysis, a tree shaped fin having three branches is designed in CATIA and CFD analysis (ANSYS15) is performed on it, when placed in an enclosure using FLUENT. Heat input is given to the bottom of the fin in the form of temperature. The heat t ransfer characteristics are calculated for various temperature inputs with simultaneous changes in the orientation. The analysis attained better results for temperature input and orientation 363K and 90o respectively. Taguchi analysis, which is performed to analyse the system performance, concludes that parameter temperature is having more impact on the system performance.

Keywords: Heat Transfer Characteristics, Taguchi, Tree Fin.

1. INTRODUCTION

Devices generate heat while operating, the heat generated should within the recommended working temperatures for the appropriate functioning of the system, cause it may leads to faulty functioning and overheating. The space allocated for heat dissipation units reduced, as the devices are going to be diminutive in the upcoming days. Research is being done to increase the effectiveness in heat transfer by reducing the volume to weight ratio of the heat exchanging bodies. This resulted in use of fins, which enhance the heat transfer rate. Fins find its use in many modern engineering applications like refrigeration and air conditioning, power plants, electric industry, transformers, air compressors etc., the optimal combination of fin geometry and orientation is necessary for the enhancement of heat transfer rate. Forced convection requires auxiliary deices for heat dissipation which leads to economic constraints, space, power consumption etc., To maximize the heat emancipation and to minimize the mass in natural convection process, fins design is to be optimized. The tree shaped flow paths are common ones in engineering as well as the real world entity propagation. The realistic view inherited from the natural sciences is, the tree shaped flows are examples of self organization and self optimization. The flow connection from a source to infinity of points (or areas or volumes) is the function of a tree network. Optimization of global flow performance subjected to constraints represents the tree architecture [1]. The fixed volume of the system and the fixed space of heat dissipation units are the global constraints from which the utmost global performance is to be achieved. Various parameters like bifurcation angle, surface emissivity, material, width to thickness ratio and base heat rate are studied in MATLAB software for tree lie fins and the same is compared with other configurations, concluded that parabolic fins can be adapted like tree fin to amplify the heat transfer rate [2]. The heat transfer rate and effectiveness of a vertical fin array are influenced by system parameters like base temperature, fin height and fin spacing. It is concluded that optimal performance cannot be attained by concentrating on one or two parameters [3, 4]. The heat transfer characteristics like fin spacing and Grashoff number plays a significant role in natural convection process. Also acquired a relation between fin spacing and Nusselt number for triangular fin array and the result is compared with rectangular fin array, achieved good results [5]. The dependency of Nusselt number on Reynold,s number is experimentally investigated under forced convection environment by performing analysis on pin-fin arrays [6]. Tree shaped fins attached to a flat and wedge shaped base plate are analysed in forced convection environment and it was proved that tree fins attached to wedge shaped base plate yielded the high heat dissipation rates [7]. The amount of fin, the gap between fin, area and its peripheral design has an exhaustive relationship in enhancing the convection effect and in increasing the heat sink ability [8, 9]. The selection of geometry and the optimal design of the fin module became the major problem of the electronic industry; therefore the statistical analysis is performed to attain the best results [10]. In the current issue tree fin placed in a cuboidal enclosure is studied by varying the inputs, temperature and orientation of the fin by using CFD analysis (FLUENT) under natural convection. Taguchi analysis is done to analyse the the effect of parameters on the system.

2. SOLUTION PROCEDURE

The current study explains the heat transfer through a tree shaped fin placed in an enclosure under natural convection. Conservation of mass, momentum and energy are considered in the analysis therefore the properties of the fluid are assumed to be constant. Equations (1-5) represent the governing equations. The Boussinesque approximation equation is considered [11]. The governing equations are:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\mu\nabla^2 u+\rho g_x \quad (2)$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\mu\nabla^2 v+\rho g_y \quad (3)$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial P}{\partial z}+\mu\nabla^2 w+\rho g_z \quad (4)$$

$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha\nabla^2 T$ (5)

where, y is taken along the gravitational acceleration direction and x and z are taken normal to the gravitational acceleration, the three fluid velocity components along the x, y and z directions are u, v and w respectively.

2.1 Design and Modeling

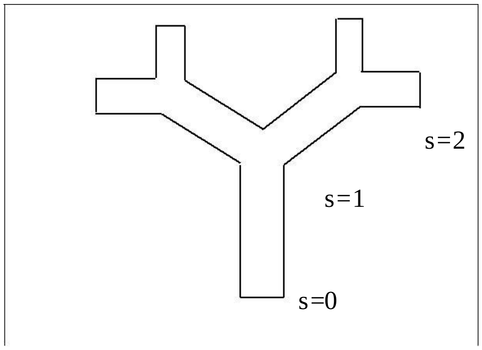

Figure. 1. sketch of the proposed tree fin [7]

Table. I. Dimensions given to the tree fin

Stem Numbers(s)	Length(cm)	Width(cm)	Depth(cm)
0	2.5	1	0.5
1	1.77	0.71	0.5
2	1.25	0.5	0.5

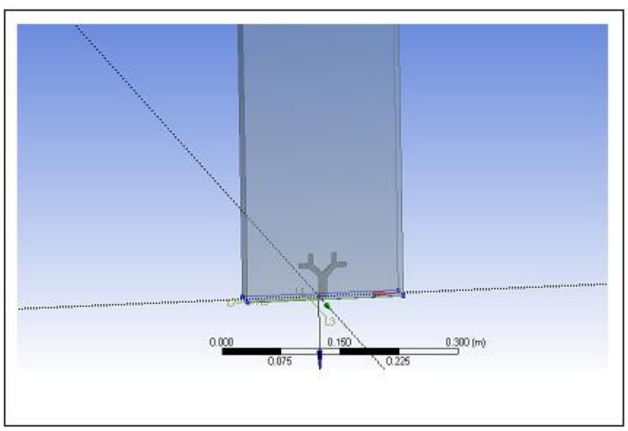

Figure. 2. Modeling of tree fin with enclosure

A Tree fin (Figure 1) having three branches with an included angle of 90^0 between them and height of the fin 5.52cm is designed in CATIA. The fin is imported to ANSYS and an enclosure of dimensions 0.2X0.025X0.495m is generated in such a way that the tree fin base and the enclosure base are in contact shown in figure2. The material of the fin is chosen as aluminium and air as the surrounding medium. The heat input, temperature is given to the base of the fin (323K, 333K, 343K, 353K and 363K) and the orientation (0^0, 45^0, 90^0, 135^0 and 180^0) is also varied simultaneously. For each temperature input the heat transfer characteristics are calculated for all orientations. The buoyancy forces are developed due to the temperature gradient between the fin and the air thus creating density differences which sets up free convection currents inside the enclosure. The heat transfer mostly depends on fluid motion which is governed by balanced buoyancy and viscous forces. The orientation plays a major role in the current analysis, as the air contact time with the fin is varied with the change in orientation. The direction of air is along the gravitational acceleration and the orientation is also chosen along the gravity but in opposite direction for 0^0.

2.2 Grid Independent Study

Meshing is the process of discretisation of volume in which flow takes place. The enclosure and the tree fin are discretized into tetrahedral and hexahedral elements respectively.

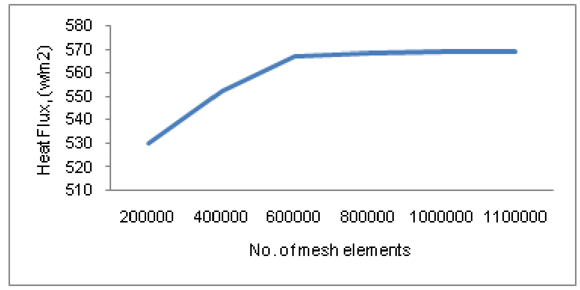

Figure.3. Graph showing the variation of heat flux and the number of mesh elements

The above Figure 3 explains the variation of heat flux with the no. of mesh elements. It is observed that the refinement of solution is attained at 1100000 mesh elements in the graph. Even with further increase in no. of mesh elements there is no detectable change in the value of heat flux.

2.3 Boundary Conditions

The heat input in the form of temperature is supplied at the base of the fin, the enclosure wall is maintained at 300K atmospheric temperature, with the density considered as buoyant and coefficient of thermal expansion for air as 0.0032. The buoyancy force develops fluid motion or circulation within the enclosure.

2.4 Results and Discussion

The temperature inputs at the base of the fin are 323K, 333K, 343K, 353K and 363K. With the corresponding change in the orientation 0^0, 45^0, 90^0, 135^0 and 180^0 for each temperature input the heat transfer characteristics Nusselt number, convective heat transfer coefficient, heat flux, wall shear stress, enthalpy and entropy are computed in all cases and tabulated. The fin material is chosen as aluminium.

Convection heat transfer is governed by Newton's law of cooling, and the relation is

$Q = h A (T_s - T_a)$ (6)

The above equation states that the rate of heat transfer depends on, surface area, the temperature difference between the surface temperature and the ambient temperature and the convective heat transfer coefficient.

The flow of air in the enclosure is assumed to be laminar basing on the relations given below,

$Ra = Gr. Pr$ (7)

$Ra = \frac{g\beta(Ts-Ta)l^3}{\alpha\upsilon}$ (8)

The Rayleigh number (Ra) is less than 10^9 ($Ra < 10^9$), hence the flow of fluid in the enclosure is taken as laminar. The Nusselt number is a function of Grashof number and prandtl number in natural or free convection.

Nu = f(Gr , Pr) (9)

The Nusselt number can be calculated using the below equation.

$$Nu = \frac{h * d_{hydraulic}}{K} \quad (10)$$

$$Gr = \frac{g\beta(Ts - Ta)l^3}{\upsilon^2} \quad (11)$$

$$Pr = \frac{\mu C_p}{K} \quad (12)$$

The Grashof number is the ratio of the buoyancy force to the viscous force in the fluid. The buoyancy force develops acceleration to the particles of the fluid thereby increasing the velocity of fluid in the enclosure.

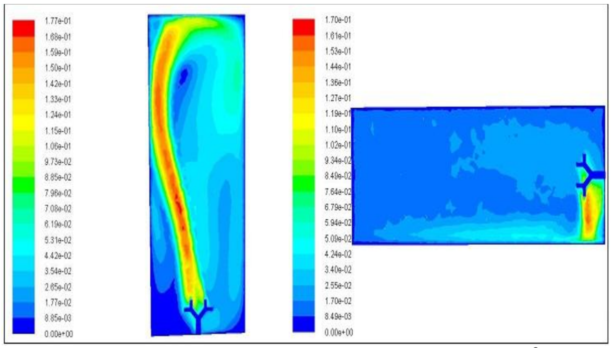

Figure.4.Velocity Contours Of Orientation 0^0 And 90^0 For 333k Base Temperature

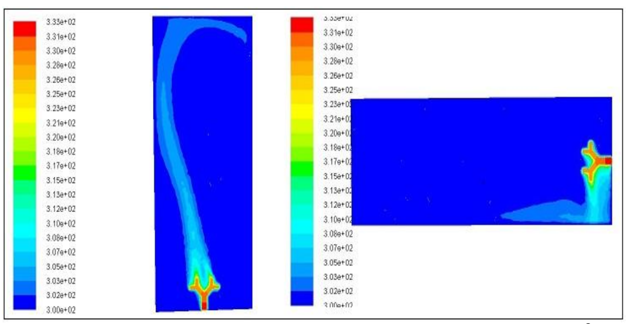

Figure.5.Temperature Contours Of Orientation 0^0 And 90^0 For 333k Base Temperature

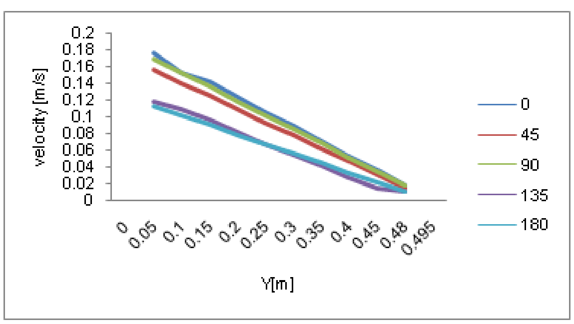

Figure.6. Graph showing the velocity along a vertical line for the different angles

The heat transfer rate from the fin increases with increase in velocity if the particles. It is clear from the Figure 6 that the velocity of the fluid is elevated when the fin is placed in the orientation 90^o. The convection currents developed carries away the heat from the source more effectively. Hence the heat dissipation rate in this case is more when compared to other cases.

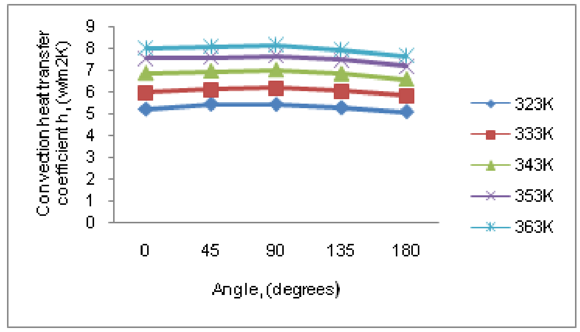

Figure. 7. Graph showing the convection heat Transfer coefficient on the vertical line For different orientations and base temperatures

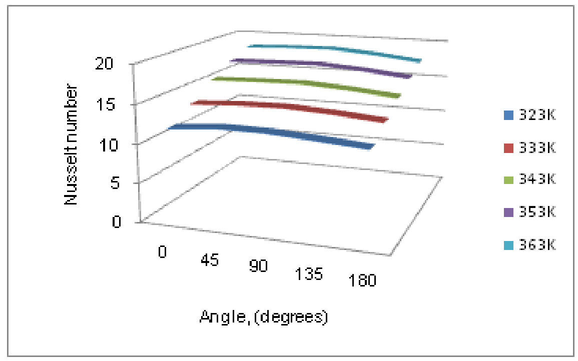

Figure. 8. Graph showing the nusselt number along a vertical line for different orientations and base temperatures.

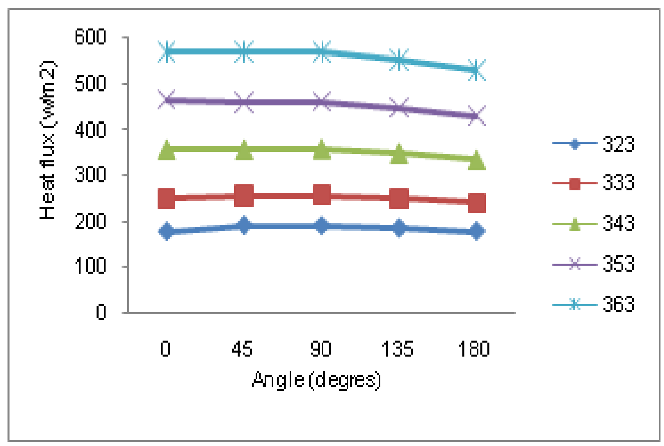

Figure.9.graph showing the heat flux along a vertical line for the different orientations and base temperatures.

Convective heat transfer coefficient is mostly influenced by the parameter temperature applied at the base rather than orientation (Figure 7). The air heated circulating around the tree fin and in the enclosure confining the air near the fin, resulting in increase in the convective heat transfer coefficient for 363K and 90^0 orientation as shown in Figure 4. The high temperature air is been more stagnant near tree fin for 90^0 angle as shown in Figure 5 which again affirms that heat transfer coefficient to be maximum for 363K and 90^0 orientation. he maximum heat transfer rate is observed at 90^0, as the Nusselt number is maximum for each base temperature in that case as shown in Figure 8. Nusselt number has an increasing and decreasing tendency starting from 0^o to 180^0. As the heat flux is directly proportional to convective heat transfer coefficient, the heat flux also increases with increase in heat transfer coefficient shown in the Figure 9.

2.4.1 Taguchi Method

Taguchi is one of the best statistical methods as it combines both the statistics and engineering for achieving rapid improvements in product design and the process. It is a quality based approach which improves the fineness of the parameters and the process. The effect of various parameters on the process is studied by laying the investigative experiments objectively to solve the problems. Design of Experiments using the Taguchi approach has become more attractive tool and is proven to be the best method in getting optimized results. The parameter which is having either more or less impact on the heat flux of the fin is to be determined and the performance of individual parameters is analysed. To ascertain the robust design, experiments are conducted to reduce the noise by considering various noise factors. An "Orthogonal Array" is used to reduce the number of noise conditions obtained by the combination of various noise factors. Five levels and two parameters were taken basing on the Taguchi design of experiments (DOE) L25 orthogonal array as in Table 2. 25 experiments were conducted. The values of heat flux are evaluated by varying the orientation and temperature simultaneously and these are taken as input for statistical analysis. In conducting the experiment the data is to be represented in table format as shown in Table 3.

2.4.1.1 Signal to Noise ratio

Taguchi's emphasis on minimizing deviation from target led him to develop measures of the process output that incorporate both the location of the output as well as the variation. These measures are called signal to noise ratios. The signal to noise ratio provides a measure of the impact of noise factors on performance. The larger the S/N, the more robust the product is against noise. Calculation of the S/N ratio depends on the experimental objective. The main aim is to increase the heat transfer rate from the tree fin placed in an enclosure. The heat flux should be high for the efficient heat transfer. Hence S/N ratio calculated should be bigger in order to get the better results. The expression for S/N ratio is selected based on the above perception.

$$MSD = \left\{ \frac{1}{Y_1^2} + \frac{1}{Y_2^2} + \frac{1}{Y_3^2} + \ldots\ldots\ldots + \frac{1}{Y_n^2} \Big/ n \right\} \quad (13)$$

For BIGGER IS BETTER

S/N = - 10 x Log (MSD) for all characteristics. (14)

Where, MSD is Mean Squared Deviation

TABLE.2.CONTROL FACTORS AND LEVELS

Item	control factor	units	level1	level2	level3	level4	level5	
T	Temperature	Kelvin	323	333	343	353	363	
A	Angle	Degrees	0	45	90		135	180

TABLE.3.HEAT FLUX AND S/N RATIO VALUE FOR TREE SHAPED FINS

Exp No	Coded values		Heat Flux (w/m^2)	S/N ratio
	Temperature	Angle		for heat flux
1	1	1	178.320	45.0240
2	1	2	192.270	45.6782
3	1	3	191.600	45.6479
4	1	4	185.890	45.3851
5	1	5	179.090	45.0614
6	2	1	250.418	47.9733
7	2	2	256.550	48.1834
8	2	3	258.380	48.2452
9	2	4	251.490	48.0104
10	2	5	241.670	47.6645
11	3	1	355.580	51.0187
12	3	2	355.680	51.0212
13	3	3	357.590	51.0677
14	3	4	347.760	50.8256
15	3	5	333.850	50.4710
16	4	1	465.560	53.3595
17	4	2	459.450	53.2448
18	4	3	461.530	53.2840
19	4	4	448.410	53.0335
20	4	5	430.300	52.6754
21	5	1	569.380	55.1080
22	5	2	567.430	55.0782
23	5	3	569.400	55.1083
24	5	4	552.950	54.8537
25	5	5	530.260	54.4898

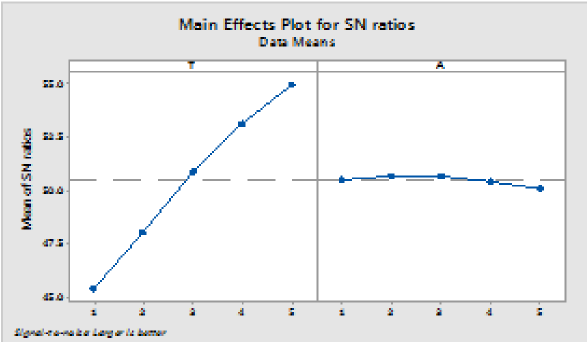

Figure.10. Factor effect diagram s/n ratio for tree shape fin heat flux

Level 5 of T and level 3 of A indicates the maximum effect of temperature and Angle on the heat flux.. Captivatingly, T5 and A3 is the best combination. At temperature 363K and orientation 90^0 heat flux attained maximum value. From the graphical analysis as shown in fig. 10, the factor temperature is having more influence on heat flux. Based on the experiments, the optimum parameters of design are T5A3. In the current analysis Of tree fin, the factors are temperature and angle, among these two factors, temperature ranked one, which is having more influence on the heat transfer characteristic, heat flux.

TABLE .4. S/N RATIO EFFECT FOR HEAT FLUX

Factor	Level1	Level2	Level3	Level4	Level5	Delta	Rank
Temperature	45.36	48.02	50.88	53.12	54.93	9.57	1
Angle	50.50	50.64	50.67	50.42	50.07	0.60	2

3. CONCLUSION

The heat transfer characteristics of the fin like heat flux ($569.4 w/m^2$), convective heat transfer coefficient ($8.1894 w/m^2K$) and Nusselt number(18.612) has obtained high values for temperature 363K and orientation 90^0 which signifies that in this case the heat dissipation rate is more. From the analysis it is concluded that the performance of the fin is affected by both the parameters. With the increase in temperature the heat transfer characteristics increased, but in the case of orientation the characteristics increased up to $90^0$and declined, as the restriction caused to the fluid is optimum at 90^0, with further increase in orientation the air between the enclosure and fin is immobile at the root of the fin due to more obstruction, which led to the limiting of heat dissipation rate and gradual decrease in the values is observed. From Taguchi analysis, it is inferred that the temperature shows more influence on the system performance.

Nomenclature

A	Surface area
C	Specific heat
$d_{hydraulic}$	Hydraulic diameter, m
g	Acceleration due to gravity, m/sec^2
h	Convection heat transfer coefficient, W/m^2K
K	Thermal Conductivity, W/mK
l	Distance, m
n	no. of experiments
p	pressure, Pa
Q	Rate of heat transfer
T	Temperature, K
u	flow velocity in x direction, m/s
v	flow velocity in y direction, m/s
w	flow velocity in z direction, m/s
x	direction normal to the fin surface
y	direction along the fin surface
Y	response value
z	direction normal to the fin surface

Greek Symbols

μ	fluid viscosity, kg/ms
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
β	coefficient of volume expansion, 1/K
ν	kinematic viscosity, m^2/s

Subscripts

a	ambient
p	constant pressure
s	surface

Notations

$\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}, \frac{\partial}{\partial T}$ partial derivatives

Non-dimensional Numbers

Nu	Nusselt number
Ra	Rayleigh Number
Gr	Grashof number
Pr	Prandtl number

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5. ACKNOWLEDGEMENT

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