A CFD Study of a rectangular fin having different geometry exposed to natural convection

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***Abstract*— The purpose of the paper is to investigate the heat transfer from a longitudinal fin by varying geometrical configurations. In this problem, heat from the base wall which is made of mild steel, is transferred through conduction and conducted heat is interacting with atmosphere through natural convection by the extended surface to enhance the heat transfer rate. Two different profiles are chosen for the study namely rectangular profile with single step change (RFSSC) and rectangular profile with double step change (RFDSC). Convective heat transfers, End-tip temperatures and Effectiveness are calculated for the chosen profiles and compared with the orthodox CRF profile. The best profile based on the application is identified to increase heat transfer is shown in this paper. ANSYS 19.0 is used to design the different configurations and to carry out the simulation to get the results. The simulated data have been verified analytically using Finite Difference Method and the equations are solved in MATLAB to get the desired data to be compared with fluent data. Few exhortations have been made about the possible application areas of the identified profiles.**

Keywords*— *Fin; CRF; RFSSC; RFDSC; CFD; Finite Difference Method; MATLAB; Convective heat transfer; Effectiveness.

I. Introduction

Heat transfer domain deals with generation of heat, absorption of heat and transportation of heat. Fin is nothing but the extended surface which helps to enhance the heat transfer by providing extra area. Application of fins are huge in mechanical devices such as IC engines, compressors, heat exchangers etc., even it is being used in space vehicles and in cooling of electronic components. The geometrical configurations are crucial since the volume and weight of the devices increase, consequently manufacturing cost raises when fins are used. For this reason only, fins with different geometry have been used to get the best profile which can save some manufacturing costs. Cuce E. et al.[1] investigated the effect of concavity level on performance parameters of a parabolic fin under the influence of natural convection and radiation. Total heat transfer, effectiveness and fin efficiency were calculated and this has been observed that heat loss due to convection and radiation decreases exponentially with the concavity of the profile. The volume of the profiles decreases with the concaveness of the profile as well. They have concluded that profiles with higher concavity provide the cheap and effective profile in terms of heat loss. Aziz A. [2] et al. applied finite element method to investigate the 2D performance of rectangular, trapezoidal, triangular and concave parabolic profile based fins under the mutual effect of convection and radiation. They have identified few parameters on which the total heat transfer rate is dependent, these parameters are fin size parameters, Biot number, radiation-conduction parameters and environment temperatures. Observations were done for each and every profiles and it was observed that profile with concave parabolic shape provided the best heat transfer rate and lowest was achieved for rectangular profile. Few assumptions were made in this study such as uniform convective heat transfer coefficient, constant base temperature and absence of radiative interaction between the fin profile and base surface. Kraus D. [3] reviewed the literatures of fins in the period of 1922-1987. The review was commenced with the NACA report of Harper & Brown and it was winded up with the work of Marto Wanniarachchi, Rose, Mitrou, and Razelos. The review was done based on non-uniform heat transfer coefficient, heat transfer solely on radiation, combined mode: Convection and Radiation, non-steady state heat transfer, non-homogeneous fin material, heat sources within the fin etc. Ullmann A. [4] et al. studied the efficiency and optimized dimensions of annular fins using different cross section areas. They took a constant mass system for different profiles and heat transfer rate was observed. Fin efficiency was calculated for the optimized profile and practical applications were discussed. Fabbri G. [5] developed a genetic algorithm for fin profile optimization. 2D distribution of temperature on the longitudinal section was observed using finite element method. Heat transfer was compared for generic profile with the rectangular profile with same length and volume. Generic algorithm was applied on polynomial profiles to determine polynomial parameter values which optimize the fin effectiveness. Azarkish H. [6] et al. worked on the geometry optimization of a longitudinal fin with volumetric heat generation under the influence of convection and radiation. The main objective was to investigate the maximum heat loss for a given volume of fins. Maximize object function was achieved corresponding to the optimized profile applying modified generic algorithm. The effect of the base temperature, heat transfer coefficient, temperature distribution along the fin length, fin efficiency etc. were calculated in this study. Finite volume method was applied to solve the 1D heat transfer problem and B-spline curves are used to generate the profile and optimal shape was found by optimizing the locations of a few control points by applying generic algorithm. Malekzadeh P. [7] et al. used differential quadrature element method (DQEM) for shape optimization of fins exposed to radiation and convection. In this study, thermal conductivity is assumed to be varied linearly with temperature and optimization of fins with uniform and stepped cross section was investigated. Accuracy of the work was measured by Adomian's decomposition technique, Taylor transformation technique and finite difference method. It was observed that DQEM happens to be the propitious technique in practical engineering simulations where complex boundary conditions are imparted.

The objective of the work is to investigate the two novel profiles exposed to natural convection only. The two novel geometrical configurations are shown in figure 1, namely rectangular fin with single step change (RFSSC)and rectangular fin with double step change (RFDSC). Heat loss due to convection, End-tip temperatures and Fin-effectiveness have been investigated and based on the results, the profile has been identified. The results have been compared with common rectangular profile (CRF) and the verification of the computational result has been verified using finite difference method. The obtained equations from FDM have been solved using MATLAB.

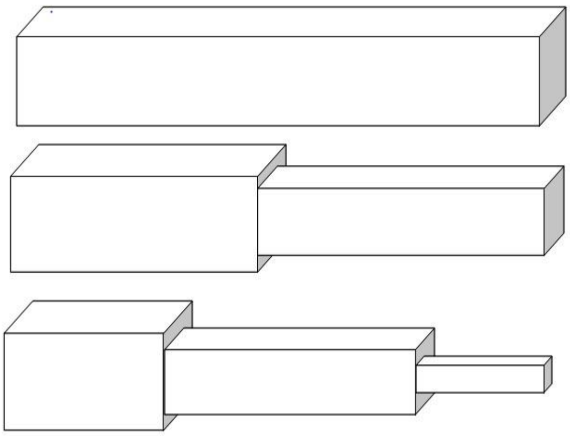


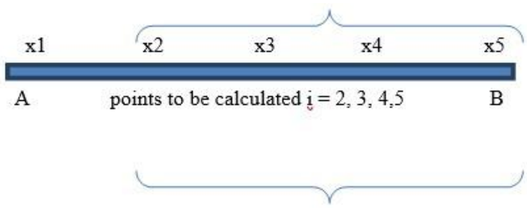
Fig. 1. fin profiles investigated in the study (Upper: CRF, Middle: RFSSC and Lower: RFDSC)

II. Mathematical Analysis

The general energy equation for a fin profile exposed to natural convection, can be written as –

$$\frac{d^2T}{dx^2} + \frac{hp}{kA}(T-T_s) = 0$$

Boundary condition: $T(0) = T_A$



Finite difference form of the energy equation is –

$$\frac{T_{i-1} - 2T_i + T_{i+1}}{h^2} - \beta(T_i - T_s) = 0, \text{ where } \beta = \frac{hp}{kA}$$

$$T_{i-1} - (2 + h^2\beta)\, T_i + T_{i+1} = -h^2\beta T_s$$

When i=2

$-(2+h^2\beta)\, T_2 + T_3 = -(h^2\, \beta T_s + T_1)$

When i=3

$T_2-(2+h^2\beta)\, T_3 + T_4 = -h^2\, \beta T_s$

When i=4

$T_3-(2+h^2\beta)\, T_4 + T_5 = -h^2\, \beta T_s$

When i=5

$T_4-(2+h^2\beta)\, T_5 + T_6 = -h^2\, \beta T_s$ (T_6 is the atmospheric temperature)

These equations can be presented in matrix form as [a][T] = [c]; the system can be written as –

$$\begin{bmatrix} -(2-h^2\beta) & 1 & 0 & 0 \\ 1 & -(2-h^2\beta) & 0 & 0 \\ 0 & 1 & -(2-h^2\beta) & 1 \\ 0 & 0 & 1 & -(2-h^2\beta) \end{bmatrix} \begin{bmatrix} T_2 \\ T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} -(h^2\beta T_s) + T_1 \\ -(h^2\beta T_s) \\ -(h^2\beta T_s) \\ -(h^2\beta T_s) + T_6 \end{bmatrix}$$

III. Problem Statement

Common rectangular fin (CRF) made of aluminium having length (L) = 80 mm and width (w) = 25 mm has been taken for the reference and other profiles namely RFSSC and RFDSC are being used to investigate the change in different parameters compared to CRF. Optimization will be done by taking five different cases for RFSSC and RFDSC which is illustrated in table 1.

Atmospheric temperature has been taken as 293 K.

Three different cases (in mm) for optimization are illustrated as table 1.

Cases	L1	L2	L3	L4	L5	L6	t1	t2	t3	t4	t5	t6
1	80	50	30	30	20	30	3	3	2	3.6	2.4	1.8
2	80	40	40	40	20	20	3	3	2.2	2	3	4
3	80	25	75	20	30	50	3	2.5	4.5	2.3	3.5	4

In this study, the temperature of the base wall has been taken as 373 K and aluminium has been chosen as fin material. Thermal conductivity and heat transfer coefficient have been taken as 240 w/m/K and 40 w/m^2/k. Step length of the FDM analysis has been taken as 0.016.

IV. Verification of Computational Results

The accuracy of the FLUENT results will be verified using finite difference method (FDM) for a specific case (CRF). Finite Difference Method will be used to find out the temperature distribution of the fin. We will find the temperature distribution at i-1, i, i+1, i+2… nodes. These values will be compared with the FLUENT data. The FDM generated equations have been solved using MATLAB after representing those into matrix format and we will generate a graph between temperature and fin length.

Above matrix form is being used to get the different temperatures along the fin length. After putting the values of input parameters, the matrix can be represented as –

$$\begin{bmatrix} -2.052 & 1 & 0 & 0 \\ 1 & -2.052 & 1 & 0 \\ 0 & 1 & -2.052 & 1 \\ 0 & 0 & 1 & -2.052 \end{bmatrix} \begin{bmatrix} T_2 \\ T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} -388.23 \\ -15.23 \\ -15.23 \\ -308.23 \end{bmatrix}$$

This system has been solved in MATLAB and the data have been captured for the temperatures where T2 = 352.503 K, T3 = 335.106 K, T4 = 319.604 K and T5 = 306.108 K. These values have been compared with the fluent data for verifying the fluent result.

These graphs show the similarity of trends of the temperature distribution using FLUENT and MATLAB. It indicates that the distribution which we have got using computational technique, has been verified using the analytical method. It can be surmised that computational method can be used for other profiles in order to get different outcomes. This comparison has been done just to check whether the computational method can be used for further analysis or not.

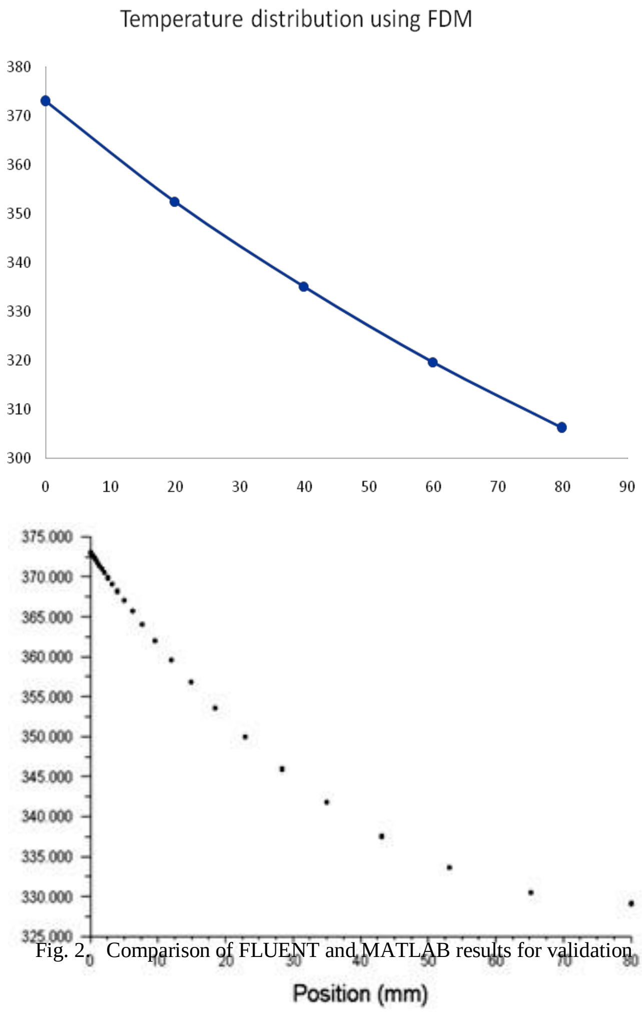


Fig. 2. Comparison of FLUENT and MATLAB results for validation

V. Analysis of Rectangular Fin with Single Step Change (RFSSC)

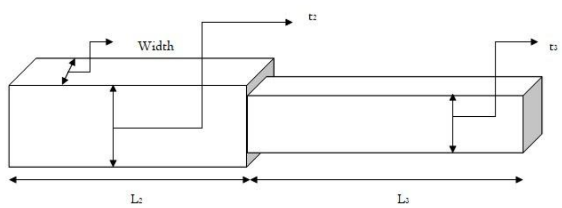


Fig. 3. Schematic diagram of RFSSC

CFD analysis has been performed on RFSSC profile using three different geometrical configurations. Heat loss due to convection, End-tip temperatures and fin effectiveness.

Different Configurations for RFSSC are shown in table 2:

Case	L_2 (mm)	L_3 (mm)	t_2 (mm)	t_3 (mm)
1	50	3	3	2
2	40	40	3	2.2
3	25	55	2.4	1.8

After doing analysis on RFSSC, three output parameters such as total convective heat transfer and end-tip temperature, have been analysed and represented for every case.

VI. Analysis of Rectangular Fin with Double Step Change (RFDSC)

CFD analysis has been performed on RFDSC profile using three different geometrical configurations. Heat loss due to convection, End-tip temperatures and fin effectiveness.

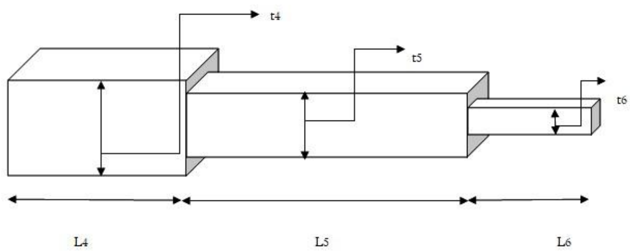


Fig. 4. Schematic diagram of RFDSC

Different Configurations for RFDSC are shown in table 3:

Case	L_4 (mm)	L_5 (mm)	L_6 (mm)	t_4 (mm)	t_5 (mm)	t_6 (mm)
1	30	20	30	3.6	2.4	1.8
2	40	20	20	3.4	2.2	1.6
3	20	30	30	3.2	2.0	1.2

After doing analysis on RFDSC, three output parameters such as total convective heat transfer and end-tip temperature, have been analysed and represented for every case.

VII. Results

After analysing the two novel profiles namely RFSSC and RFDSC, all the data associated to heat loss and end-tip temperature have been tabulated and represented to identify the best profile depending upon the applications.

Table 4 Convective heat transfer through different profiles

Profile	Convective Heat Transfer (10^5 W/m^2)
CRF	1.05
RFSSC1	1.25
RFSSC2	1.48
RFSSC3	1.42
RFDSC1	1.00
RFDSC2	1.04
RFDSC3	1.02

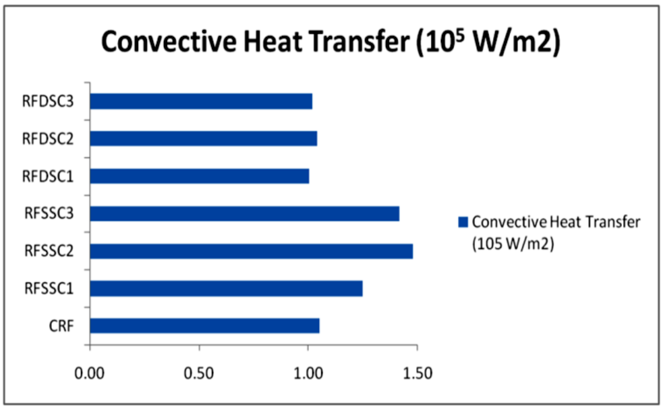


Fig. 5. Convective heat transfer through different profiles

Table 5. End-tip temperatures of different profiles

Profile	End tip temperature (Degree Centigrade)
CRF	67.62
RFSSC1	70.15
RFSSC2	68.28
RFSSC3	66.86
RFDSC1	43.73
RFDSC2	43.59
RFDSC3	38.34

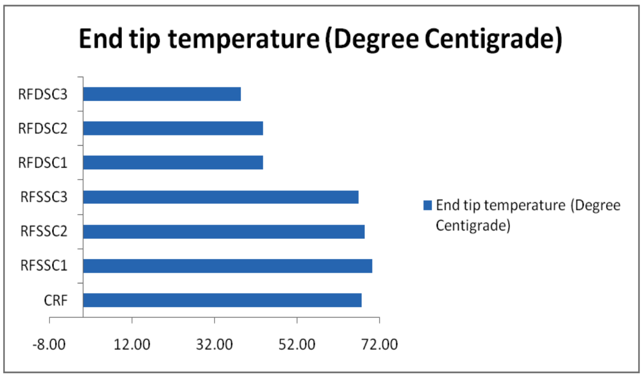


Fig. 6. End-tip temperatures of different profiles

Table 6. Fin effectiveness of different profiles

	Fin effectiveness
CRF	5.44
RFSSC1	6.47
RFSSC2	7.67
RFSSC3	7.34
RFDSC1	5.19
RFDSC2	5.40
RFDSC3	5.28

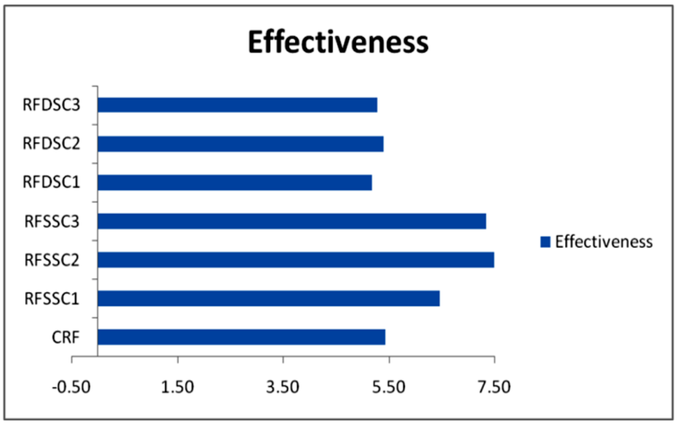


Fig. 7. Fin effectiveness of different profiles

VIII. Comparative Results

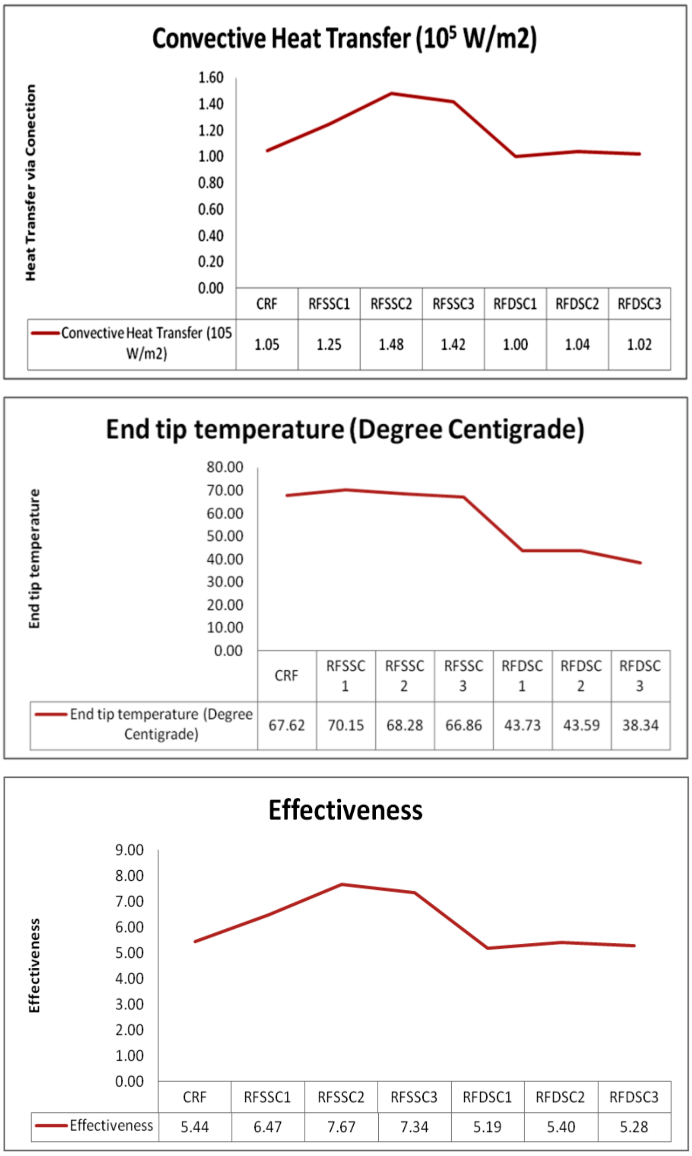


Fig. 8. Comparative results of different output parameters

In this work, CFD study was done on two novel profiles with different geometrical configurations to identify the best profiles based on the application. Here we have observed –

Rectangular fin with single step change (Case2) is showing the best result based on the heat loss due to convection which is 1.48 X 105 W/m^2.

Rectangular fin with double step change (Case3) is showing the best result based on the end-tip temperature which is 38.340 C where the base temperature was 1000 C and ambient temperature was 200 C

Rectangular fin with single step change (Case2) is showing the best result based on the fin effectiveness which is 7.67.

Based on the previous observation, this can be concluded that Rectangular fin with single step change (Case2) (RFSSC2) is to be identified as the best profile with the specific geometrical configurations for overall applications.

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