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ANALYSIS OF HEAT TRANSFER THROUGH FINS

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ABSTRACT

Fins is an integral part of any heating or cooling system. It is primarily responsible for improving heat transfer. The different characteristics of fins such as fin tip, base temperature, fin array, fin efficiency, fin effectiveness amongst others were studied in order to understand how they affect fin effectiveness and fin efficiency and propose a working algorithm which will be capable of flexible analysis and design which can be used in refrigerators and transformers. The result of numerical computation showed that the fin effectiveness and heat transfer through fins increases as the length and width increases. Though, efficiency increases with thickness and fin effectiveness decreases. The heat transfer surface area is a function of fin dimensions and fin shape, as the surface area increases the amount of heat transferred increases. Also, copper material had highest fin effectiveness and heat transfer. The fin efficiency can be improved by using a material with higher conductivity.

1. INTRODUCTION

Extended surfaces, commonly known as fins, often offer an economical and trouble-free solution in many situations demanding natural convection heat transfer (Baskaya *et al.*, 2000). Heat sinks in the form of fin arrays on horizontal and vertical surfaces used in variety of engineering applications, studies of heat transfer and fluid flow associated with such arrays are of considerable engineering significance. The main controlling variable generally available to designer is geometry of fin arrays. Considering the above fact, natural convection heat transfer from vertical rectangular fin arrays with and without notch at the center have been investigated experimentally and theoretically (Garriga and Ritort, 2001). Moreover, notches of different geometrical shapes have also been analyzed for the purpose of comparison and optimization (Kundu and Das, 2007). In a lengthwise short array where the single chimney flow pattern is present, the central portion of fin flat becomes ineffective due to the fact that, already heated air comes in its contact (Dixit *et al.*, 2013).

Barhatte et al. (2011) and Kiwan and Al Nmir, (2001) conducted thermal analysis of natural convection through porous fins. The geometric and flow parameters that influenced the temperature distribution were combined into one parameter. Nagarani and Mayilsamy (2010) and Kadbhane and Palande (2016) analyzed the heat transfer rate and efficiency for circular and elliptical annular fins for different environmental conditions. It was found that elliptical fin efficiency was higher than that of circular fin. Bassam (2003) investigated the problem of cross-flow forced convection heat transfer from a horizontal cylinder with multiple, equally spaced, high conductivity permeable fins on its outer surface numerically. Permeable fins provided much higher heat transfer rates compared to the more traditional solid fins for a similar cylinder configuration. The investigation was conducted on 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. Conclusively, it was not possible to obtain optimum performance in terms of overall heat transfer by only concentrating on one or two parameters. Nguyen and Aziz (1992) compared the heat transfer rates from convecting-radiating fins for different profile shapes. Rectangular, trapezoidal, triangular and concave parabolic shapes were used to compare heat transfer rates. They identified that heat transfer rate for a profile was function of ratio of length to one half base thickness, Biot number, radiation-conduction number, dimensionless convective environment temperature and dimensionless sink temperature for radiation. It was observed that heat transfer rates were higher for rectangular fins than those for triangular fins. Kundu and Das (2003) reported the performance of an elliptic disc fin using a semi analytical technique. They found that optimum elliptical fin dissipated heat at a higher rate compared to annular fin when space restriction exists on both sides of the fin. Babu and Lavakumar (2009) studied heat transfer in aluminium Alloy 204, aluminium alloy 6061 and Magnesium alloy materials of varied geometries and thickness and concluded that aluminium alloy 6061 with cylindrical shape and 2.5 mm thickness had highest heat transfer rate. Raju et al. (2002) and Sobamowo et al. (2016) investigated the maximization of heat transfer through fin arrays of an internal combustion engine cylinder, under one dimensional, steady state condition with conduction and free convection modes. The results showed that the fin temperature distribution, the total heat transfer, and the fin efficiency are significantly affected by the thermo-geometric of the fin. Cha'o-Kuang et al. (1989) studied the optimization of rectangular profile circular fins with variable thermal conductivity and convective heat transfer coefficients by solving the nonlinear conducting-convecting-radiating heat transfer equation using the differential transformation method. The authors concluded that if the thermal conductivity and heat transfer coefficient were taken as constants for a given fin volume, the optimum fin length would be independent of the fin base temperature for pure convection. Sharma and Sharma (2013) presented the results of computational numerical analysis of air flow and heat transfer in a light weight automobile engine, considering three different morphology pin fins. The results indicated that the drop shaped pin fins gave highest heat transfer rate and pressure drop when compared with other fins.

In present study, the fin flats were modified by removing the central fin portion and cutting a notch. This paper presents a numerical analysis of the results obtained over a range of different dimensions and heat dissipation rate of a fin.

2. METHODOLOGY

2.1. Heat Transfer Through Fins

A differential element of fin (Figure 1) with thickness dx, at a distance x from the base in steady-state has a rate of heat flow into the element equals to the rate of heat flow out of the element.

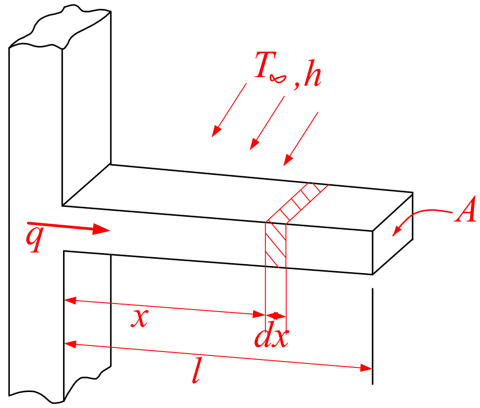

Figure 1: A straight rectangular fin with uniform cross section

This can also be expressed as:

(Rate of heat flow by conduction into the element at x) = (Rate of heat flow by conduction out of the element at x+dx) + (Rate of heat flow by convection from the surface between x and x+dx)

$$- KA\frac{dT}{dx} = - kA\frac{dT}{dx} + \frac{d}{dx}(-KA\frac{dT}{dx})\, dx + hPdx\,(T - T_\infty) \quad (1)$$

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

$$m = \sqrt{\frac{hP}{KA}} \quad (3)$$

where A=*heat transfer* area, P=Perimeter of the fin, h=convective transfer coefficient, K=thermal conductivity, T_∞= airstream temperature and T=temperature

The rate of heat transfer q from the fin to fluid can be estimated as:

$$q = \int_0^\infty hP\,(T - T_\infty)dx = \int_0^\infty hP\,(T_s - T_\infty)dx\, e^{-mx}\, dx \quad (4)$$

$$[-\frac{hP}{m}(T_s - T_\infty)\, e^{-mx})\,]_0^\infty = \frac{hP\,(Ts - T_\infty)}{\sqrt{hP/KA}} \quad (5)$$

$$q = \sqrt{hPKA}\,(Ts - T_\infty) \quad (6)$$

where T_s=suface temperature

The temperature distribution and the rate of heat flow obtained can be used in practice for a fin of finite length if the length is very large compared to its cross-sectional area

2.2. Finite Length Fin with Insulated Tip

A fin of finite length with its end insulated so that there is no heat loss through it has secondary boundary condition given by:

$$\frac{dT}{dx} = 0 \text{ at } x = l \tag{7}$$

where l=length of the fin

The rate of heat flow can be estimated from the relation as:

$$q = -(KA\frac{dT}{dx})\ \ x = 0 \tag{8}$$

Differentiating

$$[\frac{dT}{dx}]_{x=0} = -\ m\ (T_s - T_\infty)\tanh(ml) \tag{9}$$

Substituting Equation (9) into Equation (8) to obtain:

$$q = mkA(T_s - T_\infty)\tanh(ml) = \sqrt{hPKA}(T_s - T_\infty)\tanh(ml) \tag{10}$$

2.3. Finite Length Fin with Convection Heat Transfer at The End

A finite length fin with an insulated end which loses heat from its end by convection has the rate of heat flow by conduction to the face at x=l equals the rate of heat flow by convection from the end to the fluid. In other words, the secondary boundary condition is given by

$$[-kA\frac{dT}{dx}]_{x=l} = hA\ (T_{x=l} - T_\infty) \tag{11}$$

The rate of heat transfer is therefore given according to Bergman *et al.* (2011) as:

$$q = \sqrt{hPKA}\ (T_s - T_\infty)\frac{\sinh(ml) + \frac{h}{km}\sinh[m(l-x)]}{\cosh(ml) + \frac{h}{km}\sinh(ml)} \tag{12}$$

2.4. Fin Efficiency

Fin efficiency, η, is the ratio of heat transfer from the fin, q_f, to the maximum heat that can be transferred from the fin, q_{max}, which is expressed in Equation (13).

$$\eta = \frac{q_f}{q_{max}} \tag{13}$$

The maximum heat, q_{max} , is an ideal state in which the entire surface of the fin and base are of equal temperature.

Thus:

$$q_{max} = hA_S\ (T_0 - T_\infty) \tag{14}$$

Where $A_S = total\ surface\ area$ of the fin

$$\eta = \frac{q_f}{hA_S\ (T_0 - T_\infty\ )} \tag{15}$$

2.5. Development of the Software

An algorithm (Figure 2) was developed for the heat transferred through different fins considering the three conditions (convective heat transfer, insulated tip fin and infinitely long fin), fin effectiveness, fin efficiency, perforated rectangular fins. The developed algorithm also allows the user to calculate the amount of heat rejected in a refrigerator and the number of fins that would be required in a refrigerator. A user-friendly software was developed based on the algorithm using MATLAB.

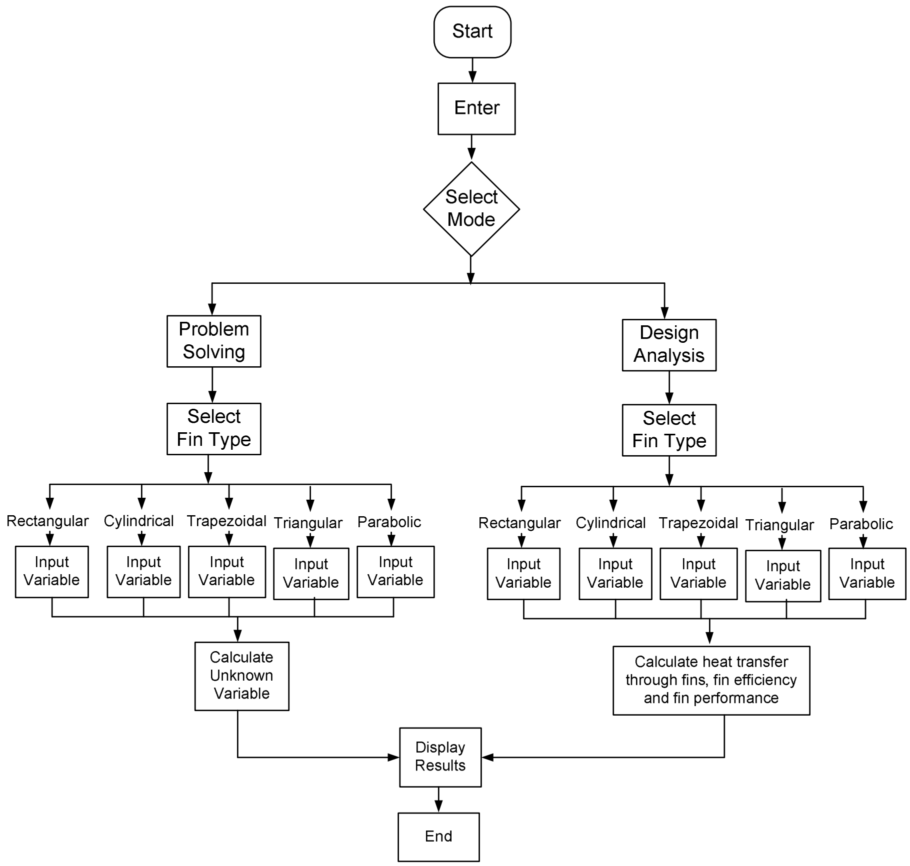

Figure 2: Flow chart for the algorithm

3. RESULTS AND DISCUSSION

3.1. Results of Varying Fin Length with Heat Transfer and Fin Effectiveness

In this present simulated study, three different materials were investigated using a solid fin with a fin length of 120 mm, fin width of 62 mm and a thickness of 3 mm while keeping the environment temperature at 20^{o}C and base temperature of 50^{o}C with a conductive heat transfer coefficient of 45 $Wm^{-2}K^{-1}$ and simulating for the following materials: Aluminum, Copper, and Iron. Figures 3 and 4 show the heat transfer and fin effectiveness when varying the fin length from 90 mm to 180 mm and keeping the fin width constant at 62 mm when using aluminum, copper and Iron. Fin made of the iron has the lowest heat transfer rate, followed by aluminum and the highest was obtained with Copper. This could be due to the fact that iron has low thermal conductivity compared to copper with the highest thermal conductivity. The fin effectiveness which is the ratio of heat transferred when a fin is used to heat transfer without a fin increased with an increase in the fin length or height. The effectiveness of a fin also increases as the thermal conductivity increases with copper having an effectiveness of 72.05, aluminum having 51.15 and iron 35.19 (Figure 4).

The effect of heat transfer through fin with different fin length is shown in Figure 3. It showed that heat transfer increases as the length increases. Fin made of copper material had highest heat transfer and least was observed in iron. Figure 4 shows the relationship between the fin effectiveness and fin length. It could be seen that as the fin length increases the fin effectiveness increases. The fin made of copper material had highest fin effectiveness values considering different length.

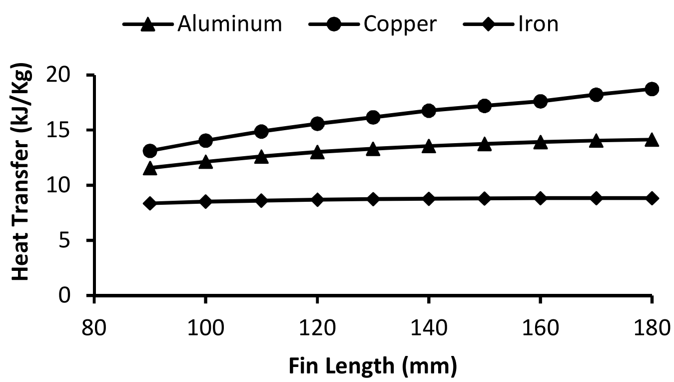

Figure 3: Effect of fin length on heat transfer

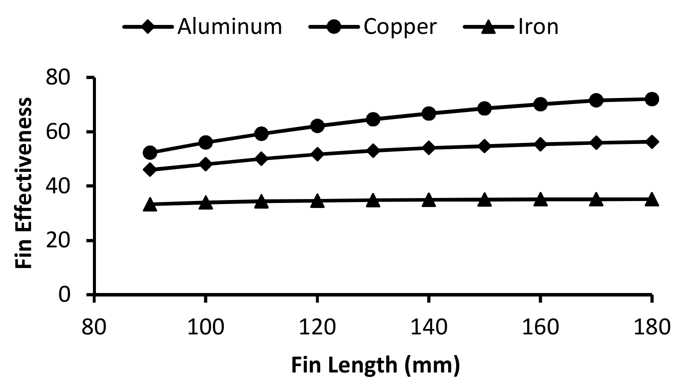

Figure 4: Variation of fin effectiveness with length

3.2. Results of Varying Fin Width with Fin Effectiveness

Three different materials were investigated using a solid fin with a fin length of 102 mm, fin width of 62 mm and a thickness of 3 mm while keeping the environment temperature at 20ºC and base temperature of 50ºC with a conductive heat transfer coefficient of 45 $Wm^{-2}K^{-1}$. The Figure 5 shows the heat transfer, effectiveness and when the fin breadth was varied from 12 mm to 102 mm and keeping the fin length constant at 102 mm when using aluminum, copper and Iron material. The fin effectiveness decreased with an increase in the fin width. Though, heat transfer increased with an increase in width, both fin effectiveness and heat transfer were highest in Copper material and the least was observed in iron.

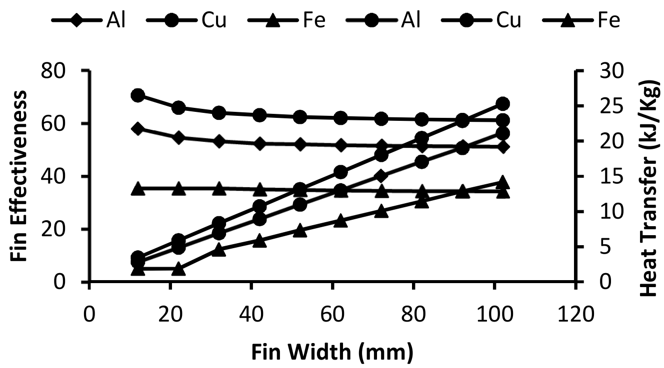

Figure 5: Effect of fin width on fin effectiveness and heat transfer

As the fin width increases the fin effectiveness decreases which implies that the extra 10 mm added to increase the fin width did not improve the fin transfer but only added to the weight of the fin system and design cost of the fin. Even though there is an increase in heat transfer due to the increase width that resulted in higher surface area, it can better be achieved with an increase in fin length with lesser weight and design cost. Therefore, in order to achieve optimum fin effectiveness, the fin width should be designed as small as possible with the fin length as long as possible.

3.3. Effect of Fin Thickness on Fin Effectiveness and Efficiency

An aluminum fin of length 120 mm and width 62 mm (Model 1) and a second fin having dimension of fin width 150 mm and width 80 mm (Model 2) were simulated. The thickness of the fin was varied from 1 mm to 6 mm while keeping the ambient temperature at 20^{o}C and base temperature at 50^{o}C. The following results were obtained. The fin effectiveness decreased with an increase in thickness while the fin efficiency increased. When a fin thickness of 1mm was used in both fin models, the effectiveness was as high as 94 in the first fin model and 95.47 in the second fin model but with a low efficiency of 0.34 and 0.31, respectively (Figure 6). The main aim of using fin is to increase heat transfer and having the fin effectiveness as high as possible. Though very little inference is gained from fin efficiency, it is advisable to select 3 mm as the standard fin thickness because in both fin models, the fin effectiveness is still as high 50.8 and 53.3 and the efficiency is above 0.5 in both fins. The fin efficiency can be improved by using a material with higher conductivity such as copper.

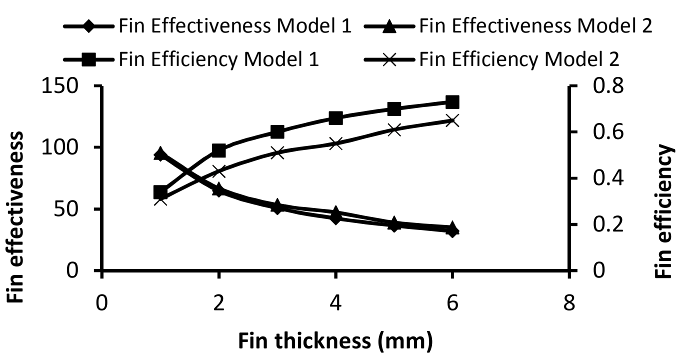

Figure 6: Effect of fin thickness on fin effectiveness and efficiency for fin models 1 and 2

3.4. Effect of Perforation Dimensions on Heat Transfer in a Fin

Fin perforations increases the amount of heat transfer but in this work the effect of variation of the fin perforation dimensions (for both circular and rectangular) were studied. Using a solid aluminum fin of width 62 mm and fin length of 120 mm with a thickness of 3mm with ambient temperature of 20ºC and base temperature of 50ºC while assuming the convective heat transfer coefficient to be 45 $Wm^{-2}K^{-1}$. Nine different variations of fin perforation from 2 to 10 mm were investigated. The result of effect of perforations on the fin effectiveness considering different configuration was shown in Figure 7. The circular perforations only increased the amount of heat transferred when the perforation diameter was increased to 17 mm with 5 perforations on the x axis with a very low fin effectiveness of 6.8. The square perforations on a fin do not affect the amount of heat transferred in the fin which means a square of 1 mm and square of 7 mm would give you the same quantity of heat transfer while when a circular perforation is used, the heat transfer increases as the diameter increases. From the results, the heat transfer surface area is a function of fin dimensions and fin shape, as the surface area increases the amount of heat transferred increases. When a circular perforation is used, the amount of heat transferred increases as the perforation diameter increases and small circular diameters renders the perforated fin ineffective as the amount of heat transferred without a fin is still higher than the heat transferred when a fin with small circular perforation is used. When a square perforation is used, the amount of heat transferred is not a function of the square dimensions. It can be implied that heat transfer in a perforated fin is higher than heat transferred in a solid fin.

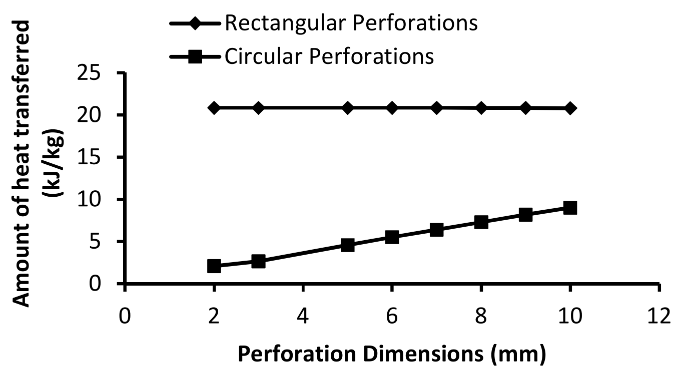

Figure 7: Effect of perforation on heat transfer through fins

3.5. Effect of Change in Diameter with a Constant Fin Length on a Cylindrical Fin

The result of varying the diameter of the cylindrical fin with constant length was presented in the Figure 8 using aluminum and copper materials. As the diameter of the fin increases, the fin effectiveness decreases, while both heat transfer and efficiency of the fin increases in the two cases considered, the reason could be the fact that as the fin diameter increases there was an increase in the surface area.

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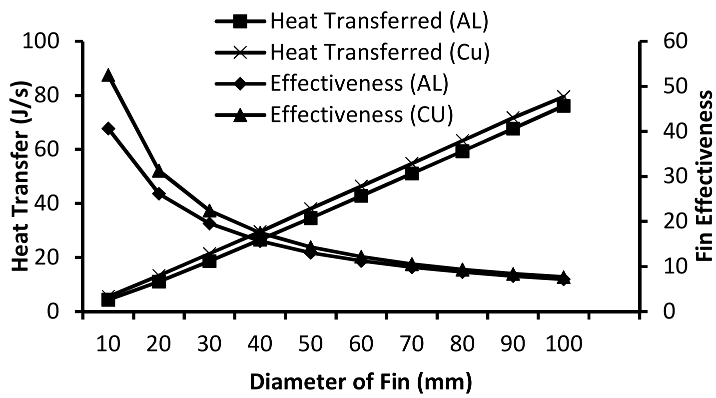

Figure 8: Variation fin properties with increase in diameter of cylindrical fin

4. CONCLUSION

The study has shown that fin width, fin length, fin thickness and thermal conductivity play an important role in heat transfer through fins. The fin length should be high, as an increase in fin length increases heat transfer while the fin width should be kept as small as possible because the smaller the fin width the more effective the fin. The optimum thickness of the fin should be 3.3 mm for efficient performance. From the investigation of the three materials namely iron, copper and aluminum, copper was selected as the best material for fin production because of its high thermal conductivity which results in smaller fin dimensions to achieve the same amount of heat transfer with cost saving.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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