STEADY-STATE ANALYSIS OF REGULAR HOLLOW PYRAMIDAL RADIATING FIN WITH TRIANGULAR CROSS-SECTION

by

Vijaikrishnan VENKATARAMANAN [a], Ramakrishnan MADHAVANESWARAN [a*] and N. Siva SHANMUGAM [b]

[a] Department of Mechanical Engineering, Shanmugha Arts, Science, Technology and Research Academy, Tirumalaisamudram, Thanjavur, Tamil Nadu, India
[b] Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India

Original scientific paper
DOI: 10.2298/TSCI120617029V

A new configuration for space radiator is proposed introducing a fin of regular hollow pyramidal shape with triangular cross-section, giving a higher improvement in heat loss per unit mass than that of other corresponding configurations previously proposed under same working conditions. The significance of the present configuration and its advantage over other regular hollow configurations are discussed and effect of various design parameters on heat transfer is analyzed in presence of radiation interaction with an isothermal base attached to it. Optimum parameters are identified for which improvement in heat loss per unit mass is the maximum. It is found that the fin efficiency decreases with increase in the emissivity and height of the fin and increases with increase in thickness and top radius of the fin. Correlations are presented for optimum design parameters, optimum improvement in heat loss per unit mass and fin efficiency.

Key words: *heat transfer, extended surfaces, radiating fin, 1-D analysis*

Introduction

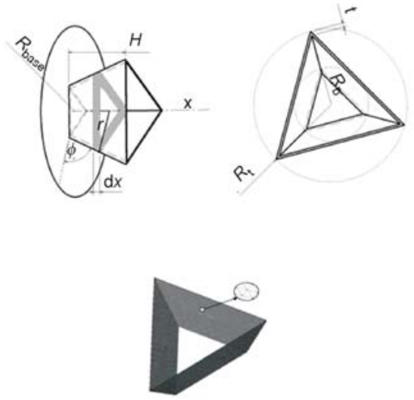
The removal of waste heat from spacecrafts can only be accomplished by the usage of radiating fins. A radiating fin rejects internally dissipated heat from various electronic components onboard to free space. Since the mass is one of the paramount criteria for a spacecraft, the radiating fins of different profiles are optimized with respect to mass. Because of this reason, various researchers have attempted to improve the design and provided the mass optimized radiating fins. An optimization procedure for achieving maximum dissipation of heat from a longitudinal fin system of trapezoidal profile with mutual irradiation is presented by Karlekar and Chao [1]. A suitable expression for comparing the performance of fins with different material properties is presented. Schnurr *et al.* [2] carried out the weight optimization of radiating fin arrays and presented suitable curves which are useful in finding fin arrays of minimum weight for the specified values of heat transfer rate, base cylinder surface temperature and thermal properties of fin material. Karam and Eby [3] optimized the linearization parameter to obtain an approximate solution to conduction – radiation problems. Chung and Zhang [4] developed a new

* Corresponding authror; e-mail: heattransfer2012@gmail.com

weight optimization approach for straight fins and obtained the optimum number of fins in an array. Kumar and Venkateshan [5] carried out the optimization of a tubular radiator with annular fins attached to a non-isothermal base. A design methodology assuming an infinite fluid side heat transfer coefficient has been presented. Krishnaprakas [6, 7] determined a design which minimizes the mass of a straight rectangular fin array extending from a plane wall and a cylindrical surface including fin-to-fin and fin-to-base radiation interactions. Deiveegan and Katte [8] proposed a hollow conical radiating fin and showed the effect of angle, thickness and emissivity on improvement in heat loss per unit mass. It is found that the value of Q_{im} for a hollow conical fin is 4.8 times that of a pin fin having a same top outer radius. Kamrava and Bazdidi-Tehrani [9] performed computational calculation using finite volume method to simulate the temperature distribution and evaluated the thermal efficiency of a space radiating fin for two different materials, aluminum and beryllium. From a literature review it is found that only a few attempts are taken for modifying fin configuration and optimizing its parameters. In order to achieve optimum amount of heat dissipation per unit mass of the fin, a new hollow pyramidal fin configuration with an equilateral triangular cross-section is proposed in the present study. The effect of various parameters influencing the improvement in heat loss per unit mass and efficiency of the configuration in heat removal is discussed. The optimum parameters are identified and correlations are developed for the same.

Physical description of the problem

The physical domain being considered is a hollow pyramidal fin with a cross-section of equilateral triangle mounted on a circular base. In the schematic diagram of the fin model shown in fig.1 (left), the top and bottom radius of circumscribed circles of corresponding equilateral triangles are given by R_t and R_b, respectively. The height and thickness of the fin is given by H and t, respectively.



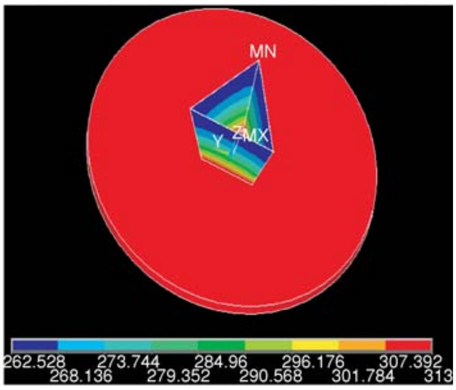


Figure 1. Schematic diagram showing hollow pyramidal fin with triangular cross-section attached to a circular base including a meshed domain (left) and contour showing temperature distribution along the axis of the fin (right)

According to the physics of problem, the inside and outside surfaces of the fin along with base dissipate heat to space as well as the surfaces of the fin and base mutually radiates to each other and at the same time the inside surfaces of fin radiate to each other. The conduction is assumed to be one dimensional along the axis of the fin. Space is considered to be a black body at temperature (T_s) and all the surfaces are considered to be diffuse and gray. The circular base is kept isothermal at the maximum temperature (T_{base}). The tip of the fin is given radiation boundary condition so as to have the best approximate solution irrespective of the limitations in the geometry of the fin. The material chosen for the model is aluminum (foil) which is the most abundant one and suitable for the space radiator modeling by virtue of its lesser weight and higher thermal conductivity. Moreover, as the working temperature is moderate, it has a negligible effect on physical properties. So the properties such as thermal conductivity and emissivity are assumed to be temperature independent. A visual understanding of present problem statement can be obtained from fig.1 (right) showing the temperature distribution contour of the fin having $H = 0.2$ m, $t = 0.001$ m, $\varepsilon = 0.85$, $R_t = 0.1778$ m, $R_b = 0.1078$ m, and $R_{base} = 0.5$m.

Mathematical formulation

The energy balance equation and boundary conditions for the differential element are given as:

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(r\frac{\mathrm{d}T}{\mathrm{d}x} \right) + \frac{r\varepsilon(\sigma T^4 - J_o)}{kt\sin\varphi(1-\varepsilon)} + \frac{(r-t)\varepsilon(\sigma T^4 - J_i)}{kt\sin\varphi(1-\varepsilon)} = 0 \tag{1}$$

$$T(x)_{x=0} = T_{\mathrm{base}}$$

$$\left(\frac{\mathrm{d}T}{\mathrm{d}x} \right)_{(x=H)} = \frac{-\sigma\varepsilon}{k}(T^4 - T_s^4)_{(x=H)} \tag{2}$$

Grid independence test

Out of three different 3-D- thermal solid elements, Solid 70, Solid 87, and Solid 90 available in ANSYS element library [10], Solid 87 is found to be having the element topology suitable to adapt the volume of the fin and identified for error free meshing. The element is tetrahedron in shape containing 4 nodes at corners and 6 nodes at middle of the edges. The details of the above elements are discussed in ANSYS program documentation [10]. In order to check the influence of the number of elements on the solution obtained, the grid sensitivity study is done for a fin with relatively larger dimensions by varying the number of element divisions along the region boundary lines. The range of number of elements varied and the respective results obtained are listed in tab. 1. It is found that the change in values of Q_{system}, Q_{base}, and Q_{fin} decreases and tends to zero due to increase in number of elements. Table 1 shows the results of grid independence test and how it affects the heat loss by the system, base and fin separately. From the results obtained from grid independent test, the number of elements for the parametric study is considered to be 23822.

Table 1. Results of grid sensitivity study for a larger fin of H = 0.5 m, t = 0.004 m, R_t = 0.2778 m, R_b = 0.1078 m, ε = 0.5, and R_{base} = 0.5 m

Number of divisions	Number of elements	Q_{system} [W]	Q_{base} [W]	Q_{fin} [W]
5	321	266.4	197.43	68.97
10	1483	265.95	197.83	68.12
20	5993	265.87	198.02	67.85
30	13373	265.85	198.12	67.73
40	23822	265.84	198.14	67.7
50	37039	265.84	198.14	67.7

Computational details

Commercial finite element-based software ANSYS-Multiphysics [10] is employed to perform the numerical study. The solid model of computational domain is created and discretized in to finite elements using Solid 87, a 10-noded tetrahedral element. Meshing is done in such a way that the elements are equally distributed throughout the domain with a decided number of elements as discussed in previous section. For accounting radiative interaction between fin and base and interaction between the walls of the fin, radiosity solution method is followed. Before solving the governing equation, the view factors are calculated for each element patches using hemi-cube method which is based on Nusselt's hemisphere analogy [11]. In this method, intermediate hemi-cubes are assumed over the center of each receiving element patch. The hemi-cube is divided to number of pixels which defines the direction and angle from the receiving element patch. First the delta view factors are calculated between the receiving patch center and each intervening pixels. Then the resulting delta view factors are summed up to obtain the overall view factor between every two element patches. Since the temperature and radiosities are interdependent in nature, a coupled solution procedure is used. The radiosities [Wm^{-2}] are calculated by Gauss Seidel iterative method using assumed temperatures and the calculated element view factors. The nodal temperatures are calculated by solving the finite element form of the energy equation using Gauss direct elimination approach involving triangular decomposition of matrix with the radiosity value obtained in previous step. The method of formulation of finite element equation and the shape function used for the considered element is explained in Ansys program documentation [10].

Validation

In order to ensure the capability of the software and to ascertain the accuracy of the solution, the code validation is carried. A similar work on hollow conical fin modeled by Deiveegan and Katte [8] is used to validate the commercial code of the present problem. The software chosen for the present problem is used to model and solve a hollow conical fin domain using solution procedure as mentioned in the section *Computational details*. Finally, using the same input parameters, the results of computation are compared with the results obtained by Deiveegan and Katte [8]. The results for different emissivities are shown in fig. 2 with a superimposed look.

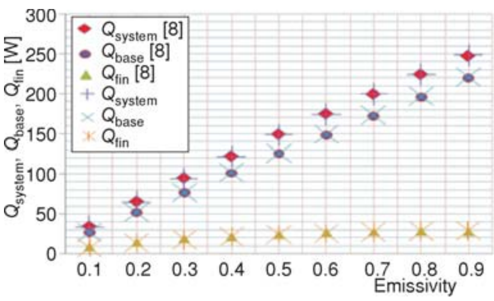


Figure 2. The plot validating the results with a hollow conical fin having T_{base} = 313 K, T_s = 4 K, R_b = 0.0625 m, φ = 55°, R_{base} = 0.398 m, k = 177 W/mK, ρ = 2770 kg/m^3, H = 0.1 m, thickness = 0.001 m for different emissivities as defined in [8]

It is evident from fig. 2 that the results obtained from the present method using APDL codes are in good agreement with results obtained by Deiveegan and Katte [8]. From the above comparative study of results, the suitability of the chosen software for solving the present problem is ensured.

Significance of the problem

To study the effect of the fin cross-section in heat loss, separate models are built for different cross-sections and comparison of Q_{im} and Q_{sytem} values is made between hollow fins of regular cross-sections such as circle, square, and triangle with sectional area 0.00094 m^2, emissivity $\varepsilon = 0.4$ and height $H = 0.15$ m. It is found that Q_{im} of a hollow fin having equilateral triangular cross-section is 11.23% greater than that of a fin having hollow circular cross-section.

Table 2. Comparison of regular hollow fins of different cross-sections with same conducting area, height, and emissivity

Cross-section	Mass [kg]	Radius [m]	Q_{system} [W]	Q_{im} [Wkg^{-1}]
Circle	0.39	0.15	196.05	64.6153
Square	0.39	0.18794	197.06	67.282
Triangle	0.39	0.2332	199.21	72.79

From the results listed in tab. 2, it is understood that for the same mass, height, and emissivity the increase in the number of sides of regular polygons, decreases the heat transfer and also the improvement in heat loss per unit mass of the fin. As a result of comparison, we can come to know that the hollow fin with equilateral triangular cross-section gives the maximum heat transfer rate as well as maximum improvement in heat loss per unit mass.

Results and discussion

The effect of various input parameters such as emissivity, thickness, height, and top radius on heat transfer and improvement in heat loss per unit mass is analyzed for the proposed fin configuration. The parametric study is done considering the most commonly used material, aluminum foil having $k = 177$ W/mK and $\rho = 2770$ kg/m^3. The space temperature (T_s) and base temperature (T_{base}) is considered as 4 K and 313 K, respectively. The sensitivity of the output parameters such as improvement in heat loss per unit mass ($Q_{\mathrm{system}} - Q_{\mathrm{ufb}}$)/m [Wkg^{-1}], heat loss by the fin (Q_{fin} [W]), heat loss by the base (Q_{base} [W]), heat loss by the system (Q_{system} [W]), fin efficiency(($Q_{\mathrm{fin}}/Q_{\mathrm{fin(max)}}$)·100)%, and overall efficiency(($Q_{\mathrm{system}}/Q_{\mathrm{system(max)}}$)·100)% is analyzed and discussed with respect to change in input parameters.

Effect of emissivity

The effect of emissivity is studied by taking height of the fin 0.1 m, thickness equal to 0.001 m, top and bottom outer radius equal to 0.17782 m and 0.10782 m, respectively. Figure 3

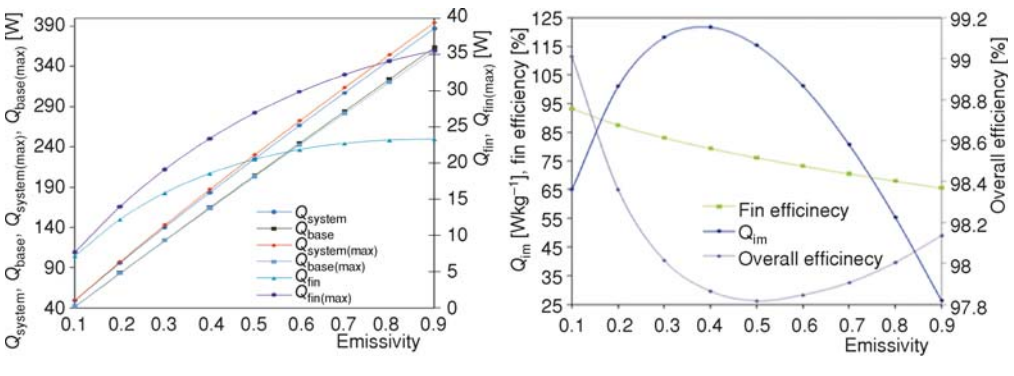


Figure 3. Effect of emissivity on heat loss by the fin, base, and system (left), and effect of emissivity on improvement in heat loss per unit mass, fin efficiency, and overall efficiency(right)

(left) shows the changes in values of heat loss by the system, base and the fin separately for the variation of emissivity from 0.1 to 0.9. The Q_{fin} increases with increase in emissivity due to more heat loss to the space. It is inferred from the gradual and non-linear increase in Q_{fin} that the emission of heat from the fin becomes more predominant and the fin-base interaction has an adverse effect on it.

Usually the area of direct exposure of the base to the space is more compared to that of fin. As the emissivity increases, the radiation from the base increases resulting in more heat loss to the space. Due the adverse effect of fin-base interaction on Q_{base} there is a slight non-linearity in the increase of Q_{base}. Similarly, the heat loss by the fin-base system increases gradually with lesser non-linearity. At lower emissivities, the difference between Q_{system} and Q_{ufb} is more due to increase in Q_{system} and after a particular point of emissivity, the decrease in their difference is realized due to increase in the value of Q_{ufb} resulting a non-monotonic variation of Q_{im} with mass being constant. The maximum heat loss $Q_{\text{(max)}}$ for fin, base and the system is calculated by keeping both fin and base at base temperature (T_{base}). As the fin is at maximum temperature, the heat loss by the system is greater than the fin-base system in actual temperature. When the emissivity is almost zero the heat loss by radiation is negligible and hence only conduction heat transfer takes place. So the heat loss by the fin at actual temperature is almost equal to the heat loss by fin at maximum temperature. Thus the ratio of Q_{fin} to $Q_{\text{fin(max)}}$ is almost equal to 1. When the emissivity increases and tends to 1, the $Q_{\text{fin(max)}}$ increases in higher rate and Q_{fin} increases in lower rate due to decrease in temperature along the length of the fin. Thus the fin efficiency decreases monotonically as the emissivity varies from 0 to1. At lower emissivities up to 0.5 the fin temperature is higher and hence the effect of fin to base interaction inhibiting the heat loss from base is more resulting in decrease of overall efficiency. With increase in emissivity beyond 0.5, the effect of fin to base interaction is less predominant and hence the system in actual temperature emits more heat resulting in increase of overall efficiency. The same can be noticed from fig. 3 (right).

Effect of thickness

Effect of fin thickness for the fin having top radius 0.1778 m, bottom radius 0.1708 m, height 0.1m, and emissivity equal to 0.85 is studied.

From fig. 4 (left), it is notable that the rate of increase of Q_{fin} is higher for lower values of thickness and *vice versa*. As the fin thickness increases, the conducting area of the fin in-

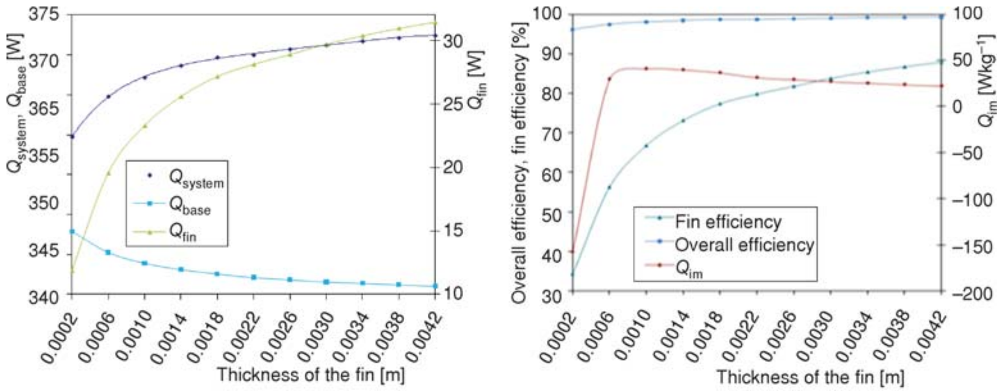


Figure 4. Effect of thickness on heat loss by the fin, base and system (left) and effect of thickness on improvement in heat loss per unit mass, fin efficiency, and overall efficiency (right)

creases resulting in the increase of fin temperature. Thus the enhancement in heat loss by the fin with increase in thickness is realized. Since the temperature of the fin goes on increases with increase in thickness, as discussed in the previous section the fin-base interaction affects the heat transfer from base resulting in decrease of Q_{base}. As a consolidated effect, the heat loss by the system increases with increase in thickness. Since Q_{system} increases at a higher rate for lower values of thickness and the mass being increased linearly, the value of Q_{im} increases non--monotonically in such a way that there is a very high rate of increase at the beginning followed by a lesser rate of decrease as shown in fig. 4 (right). At very low values of thickness, the conduction through fin is very less resulting in lesser radiation to space. Below a critical value of thickness, the screening of base radiation is more predominant than the heat radiated by the fin to space. In such cases the heat lost by the system is less than heat lost by the un-finned base. This leads to negative value of Q_{im}. When the fin is maintained at the maximum temperature, the $Q_{fin(max)}$, $Q_{base(max)}$, and $Q_{system(max)}$ are almost constant for all the values of thickness because of lesser increase of radiating area with increase in thickness. The variation in fin efficiency and overall efficiency relies mainly on the variation of Q_{fin} and Q_{system}, respectively, and also have a same trend.

Effect of top radius

The effect of top radius is studied by taking height of the fin 0.1 m, thickness equal to 0.001 m and emissivity 0.5. Figure 5 (left) shows the changes in values of heat loss by the system, base and the fin separately for the variation in top radius. With increase in R_t the surface area of the fin increases resulting in increase of view factor of the inner surface of the fin to space leading to higher heat transfer to the space. Although the effect of fin-base interaction on the outer surface of the fin reduces Q_{fin}, this effect is considered less dominant and as a net result there is an increase in Q_{fin} with increase in R_t.

At the same time with increase in R_t the covering of the base is significant. As R_t increases, the screening of radiation emanating from the base is more resulting in decrease of Q_{base}. From the graph it can be predicted that with further increase in R_t beyond 0.2578 m, there will be further decrease in the value of Q_{base} and increase in Q_{fin}. As the surface area of the fin increases with increase in R_t, the Q_{system} increases up to a certain point and after that, as the fin-base interaction is predominant, further decrease in Q_{system} is realized. From fig. 5 (right) it is seen that there is an initial increase in value of Q_{im} followed by a continuous decrease with in-

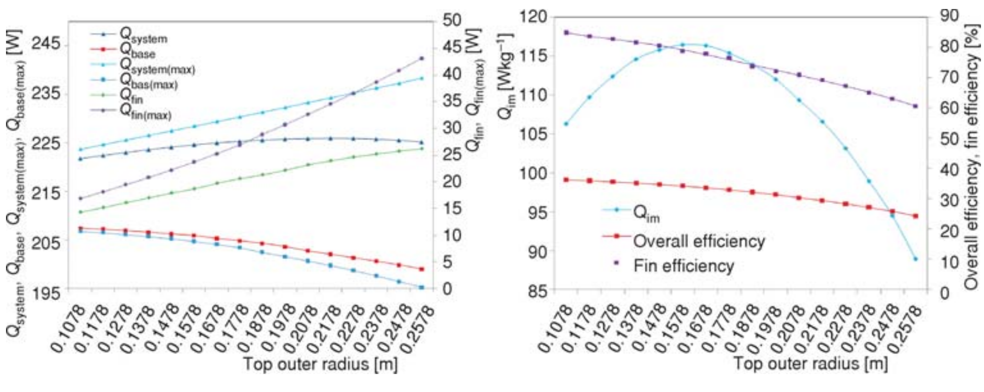


Figure 5. Effect of top radius on heat loss by the fin, base and system (left) and effect of top radius on improvement in heat loss per unit mass, fin efficiency, and overall efficiency (right)

crease in R_t. When R_t increases to a certain value, both Q_{system} and fin mass increases. The increase in Q_{im} for initial values of R_t is only due to increase in Q_{system}. But the decrease in Q_{im} is due to the higher value of mass and also due to decrease in the value of Q_{system}. With increase in R_t, $Q_{fin(max)}$ increases uniformly due to increase in radiation surface area of the fin. Though there is fin-base interaction, its effect is pronounced very less. Due to this reason $Q_{fin(max)}$ is always in increasing trend resulting in continuous decrease of fin efficiency. For the fin of maximum temperature, effect of fin-base interaction on the base is more. This will be much greater for higher R_t values leading to the decrease of $Q_{base(max)}$. But for the system at actual temperature, the fin-base interaction effect on base is comparatively less. Due to this reason the rate of decrease of Q_{base} with increase in R_t is always lesser than that of $Q_{base(max)}$. On considering the system in maximum temperature, with increase in R_t, its heat loss depends on two factors. One is increase in $Q_{fin(max)}$ and the other is decrease in $Q_{base(max)}$. Since the first factor is far more dominant than the second, the $Q_{system(max)}$ increases with increase in R_t. Hence the overall efficiency decreases similar to fin efficiency.

Effect of height and base radius

The increase in height always reduces the Q_{im}, fin efficiency and the overall efficiency. The $Q_{fin(max)}$ always increases with height which results in the decrease of fin efficiency. In case of system at maximum temperature, due to more fin-base interaction effect on the base, $Q_{base(max)}$ is lesser than Q_{base} resulting in the lesser rate of decrease of overall efficiency when compared to fin efficiency as shown in fig. 6 (left). Moreover as the mass keeps on increasing with height, Q_{im} always decreases. There is no optimum height with respect to Q_{im}.

From fig. 6 (right) it can be noted that the rate of increase of overall efficiency is more in the beginning and follows a gradual decrease. Finally the curve behaves asymptotic for an in-

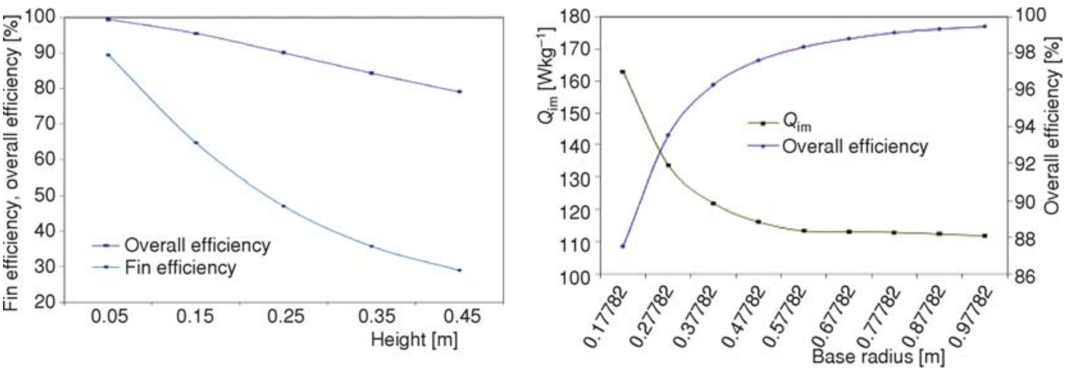


Figure 6. Effect of height on fin efficiency, overall efficiency (left) and effect of base radius on fin efficiency and overall efficiency (right)

finitely larger base. This is because of the reason that for lower values of R_{base} the contribution of Q_{fin} to Q_{system} is more. With increase in R_{base}, the radiation emanating from the base increases and hence the percentage of contribution of Q_{base} to Q_{system} increases very much. Due to the same reason, the difference between Q_{system} and Q_{ufb} decreases in higher rate at the beginning and in lower rate at the end. As the contribution of Q_{fin} exists for ever and the mass of the fin remains constant, the Q_{im} decreases asymptotically.

Correlations

A wide range of values of input parameters are considered and a list of Q_{im} is found out for each parameter by varying its values within its range keeping the rest of input parameters fixed. The value of the considered parameter for which Q_{im} is the maximum is identified as an optimum value. This method is repeated for number of times by keeping different possible fixed sets of other input parameters. Following this procedure, a number of optimum values of radius, thickness and emissivity are found out. Correlations are developed for these optimum parameters establishing their relationship with the other parameters:

$$R_{t(opt)} = 6.6928465(H^{-0.03642368})(\varepsilon^{-0.12548961})(t^{0.00269082})(R_b^{1.66078946}) \tag{3}$$

$$\varepsilon_{opt} = 1.99917616(R_b^{0.63278143})(H^{-0.29026859})(t^{0.21583522})(R_t^{-0.3376565}) \tag{4}$$

$$t_{opt} = 0.00143938(R_t^{0.35159927})(H^{0.08172889})(\varepsilon^{1.12124882})(R_b^{0.0170296}) \tag{5}$$

Correlations are also developed for maximum improvement in heat loss per unit mass and for fin efficiency:

$$Q_{im(max)} = 0.04296273(\varepsilon^{-0.79251254})(t^{-1.33517617})(R_b^{1.77246688})(R_t^{-0.68746})(H^{-0.28596316}) \tag{6}$$

$$\eta = 102.443812519944(\varepsilon^{-0.15731062})(t^{0.18750309})(R_b^{0.46097652})(R_t^{-0.35875911})(H^{-0.55121509}) \tag{7}$$

The range of parameters for the correlations are $0.015 \le R_t \le 0.42$ m, $0.015 \le R_b \le 0.15$ m, $0.05 \le H \le 0.5$ m, $0.0002 \le t \le 0.0042$ m, $0.05 \le \varepsilon \le 0.98$, $T_{base} = 313$ K, $T_s = 4$ K, $k = 177$ W/mK, and density, $\rho = 2770$ kg/m^3.

Conclusions

A new hollow triangular pyramidal configuration is proposed for space radiator applications. From a comparison of hollow fins having regular cross-sections with same conducting area, it is found that Q_{im} of a hollow fin having equilateral triangular cross-section is the maximum and 11.23% greater than that of a fin with hollow circular cross-section. From the results and discussion it is identified that both fin efficiency and the overall efficiency increases with increase in thickness and decreases with increase in top radius and fin efficiency always decreases with increase in the emissivity. The overall efficiency is the minimum when the emissivity is exactly 0.5.The improvement in heat loss per unit mass, decreases asymptotically with increase in base radius and height and varies non-monotonically with increase in emissivity, thickness and top radius. Optimum values of top radius, thickness and emissivity are identified for which improvement in heat loss per unit mass is the maximum. Correlations are presented for optimum top radius, optimum thickness, and optimum emissivity explaining their relationship with other variables. Correlations for maximum improvement in heat loss per unit mass and fin efficiency are also presented.

Acknowledgement

We thank National Institute of Technology, Tiruchirappalli, for providing the infrastructure.

Nomenclature

H – height of the fin, [m]
J – radiosity, [Wm^{-2}]
k – thermal conductivity, [WmK^{-1}]
m – mass of the fin, [kg]

Q – rate of heat loss, [W]
R – radius, [m]
T – temperature, [K]
t – thickness of the fin, [m]
x – co-ordinate

Greek symbols

ε – emissivity, [–]
η – fin efficiency, [%]
η_o – overall efficiency, [%]
ρ – density of the fin, [kgm^{-3}]
σ – Stefan-Boltzman constant, ($= 5.67 \cdot 10^{-8}$), [$Wm^{-2}K^{-4}$]
φ – fin angle, [deg.]

Subscripts

b – bottom of the fin
base – corresponds to base properties/dimensions
fin – corresponds to fin property
i, o – corresponds to inside and outside fin surfaces, respective
im – improvement per unit mass
max – corresponds to properties with maximum temperature/parameters
opt – corresponds to optimum parameter
s – corresponds to space
system – corresponds to properties of entire system
t – top of the fin
ufb – corresponds to unfinned isothermal base

References

[1] Karlekar, B. V., Chao, B. T., Mass Minimization of Radiating Trapezoidal Fins with Negligible Base Cylinder Interaction, *International Journal of Heat and Mass Transfer, 6* (1963), 1, pp. 33-48
[2] Schnurr, N. M., *et al*., Optimization of Radiating Fin Arrays with Respect to Weight, ASME, Transactions, Series C – *Journal of Heat Transfer, 98* (1976), 4, pp. 643-648
[3] Karam, R. D., Eby, R. J., Linearized Solution of Conducting-Radiating Fins, *AIAA Journal (Fluid Mechanics and Heat Transfer), 16* (1978), 5, pp. 536-538
[4] Chung, B. T. F., Zhang, B. X., Optimization of Radiating Fin Array Including Mutual Irradiations between Radiator Elements, *Journal of Heat Transfer, 113* (1991), 4, pp. 814-822
[5] Kumar, S., Venkateshan, S. P., Optimized Tubular Radiator with Annular Fins on a Non-Isothermal Base, *International Journal of Heat and Fluid Flow, 15* (1994), 5, pp. 399-409
[6] Krishnaprakas, C. K., Optimum Design of Radiating Rectangular Plate Fin Array Extending from a Plane Wall, *Journal of Heat Transfer, 118* (1996), 2, pp. 490-493
[7] Krishnaprakas, C. K., Optimum Design of Radiating Longitudinal Fin Array Extending from a Cylindrical Surface, *Journal Heat Transfer, 119* (1997), 4, pp. 857-861
[8] Deiveegan, M., Katte, S. S., One Dimensional Analysis of Hollow Conical Radiating Fin, *Journal of Thermo Physics and Heat Transfer, 18* (2004), 2, pp. 277-279
[9] Kamrava, M. H., Bazdidi-Tehrani, F., Computational Calculation of Thermal Efficiency in a Space Radiating Fin for Two Different Materials, *Trans Tech., Applied Mechanics and Materials, 110* (2011) pp. 23-28. DOI 10.4028/www.scientific.net/AMM.110-116.23
[10] ***, ANSYS Software and Program Documentation, http://www.ansys.com.
[11] Cohen, M. E., Greenberg, D. P., The Hemi-Cube: A Radiosity Solution for Complex Environments, *Computer Graphics, 19* (1985), 3, pp. 31-40

Paper submitted: June 17, 2012
Paper revised: June 17, 2013
Paper accepted: March 12, 2014