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Material Selection for an Optimized Fin Geometry Through Longitudinal Perforations by Using Analytical Hierarchy Process

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Abstract – Fins are basic structures which can be easily added to many engineering designs to improve heat transfer from hot surfaces. The addition of a fin to a particular heated surface can significantly increase the cooling at no extra cost. In some cases, standard fin structures are required to be optimized due to drawbacks of the application such as limited space and mass. Accordingly, the determination of appropriate fin material has crucial importance. In this study, selection of fin material for an optimized fin geometry through longitudinal perforations is evaluated systematically by using common decision tool called Analytical Hierarchy Process (AHP). The success of using AHP technique is revealed by using common heat engineering materials. It has been shown that, no single option is present for material selection. As a conclusion, a standard decision procedure to determine appropriate fin material can be implemented and alternatives schemes can be investigated.

Keywords – Extended surface, AHP, heat transfer, decision, passive cooling.

I. INTRODUCTION

The material selection at the manufacturing process is one of the most important parts in engineering applications [1]. Optimum design should be sought by a designer to accomplish an efficient system. At the material selection step, several parameters are getting really important such as operating temperature, cost, availability, manufacturability, weight and space. An optimization problem arises during the heat transfer applications when fins are used. Fins are extremely helpful structures in augmenting the heat transfer from hot surface to the surrounding flow by increasing the effectiveness of the surface [2]. For the cooling of many devices such as engines, electronic circuits, heat exchangers, solar collectors and turbine blades [3, 4]. Thus, fins are manufactured in different types and can be shaped in different forms for different applications. Fins can be optimized in such a way that mass or volume of the fin can be reduced in order to achieve lighter designs for a given amount of heat loss or fin can be reshaped to provide better heat dissipation for a given fin volume or mass [5-7]. The effect of the optimization is significant since the output performance of some electronic devices such as photovoltaic cells is a strong function of temperature [8, 9]. Efficiency of the fin, total heat dissipation from fin surface, weight and cost of the fin are important parameters in fin design. Manufacturers can determine appropriate materials in their designs in order to maximize performance and reduce the expenses.

Analytical Hierarchy Process is originally developed by Thomas L. Saaty in 1977 and the process is available to be adapted to common engineering problems [10, 11]. The application of AHP is relatively simple but still highly used for decision making process as a part of data storage, fuzzy logic, goal programming and business management applications [12-15]. It can be concluded that AHP is currently being used in many different applications to systematically decide between alternatives and also have great potential in engineering applications. Accordingly, Dweiri et al. was used this study to decide best material for the keys [10]. Herein, AHP will be used in material selection for optimized fin shapes. By this way, alternative materials can be revealed in systematic way for different fin cases.

II. MATERIALS AND METHOD

The AHP input can be based on actual measurements or subjective opinions. In this study AHP inputs are collected from actual calculations and actual cost data. The scaling of input values is systematically accomplished by assigning judgment values to corresponding intervals which are calculated based on input ranges. The scale for judgement values is initially proposed by Saaty [11].

Table 1. Judgement scale and definitions [11].

Value	Definition
1	Equal
3	Slightly Favors
5	Strongly Favors
7	Very Strongly Favors
9	Extreme Favors
2,4,6,8	Middle Values

Based on the rankings from Table 1, pair wise comparison matrices are formed. Herein, four 5x5 comparison matrices are constructed for each criterion, since five different kind of materials are considered. After that, priority vectors are calculated from the normalized Eigen vectors of the matrices. To evaluate the consistency of the judgement, consistency index and consistency ratio are calculated. Consistency ratio (CR) is a number derived from the division of consistency index (CI) by random consistency index (RI). The value of RI can be obtained from Table 2.

Table 2. Random consistency index [10].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The hierarchy between alternatives and factors can be seen from Fig. 1. Level 0 represent the goal of the analysis. Level 1 corresponds to multi criteria that consist of several factors. And alternatives are given in the lowest level.

The amount of total heat transfer from fin surface is an irrevocable parameter from engineering aspect, on the other hand cost and mass of the fin structure are under primary interest. The general form of heat transfer equation can be given in Eq. 1.

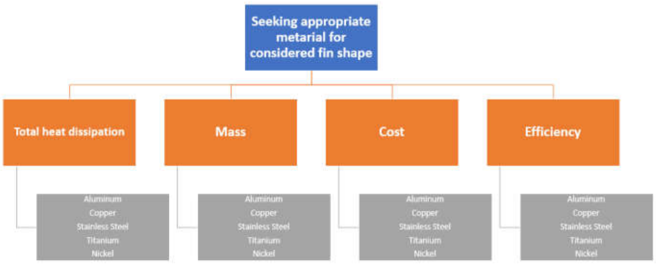

Fig. 1 Schematic view of the structure of hierarchy in this example.

$$\frac{d^2T}{dx^2}+\left(\frac{1}{A_c}\frac{dA_c}{dx}\right)\frac{dT}{dx}-\left(\frac{1}{A_c}\frac{h}{k}\frac{dA_s}{dx}\right)(T-T_\infty)-\left(\frac{1}{A_c}\frac{\varepsilon\sigma}{k}\frac{dA_s}{dx}\right)(T^4-T_\infty^4)=0 \qquad (1)$$

The parabolic function that shapes the fin surface can be written in terms of the radii as follows;

$$r(x)=r_1+(r_2-r_1)\left(1-\frac{x}{L}\right)^n \qquad (2)$$

where n is the concavity level which will change from case to case. After substation and calculations, the resulting equation can be given as follows;

$$\frac{d^2T}{dx^2}-\left(\frac{2n}{L}\right)\left(1-\frac{x}{L}\right)^{(n-1)}\frac{(r_2-r_1)}{r_1+(r_2-r_1)(1-x/L)^n}\frac{dT}{dx}-\left(\frac{2h}{k}\right)\frac{1}{r_1+(r_2-r_1)(1-x/L)^n}(T-T_\infty)-\left(\frac{2\varepsilon\sigma}{k}\right)\frac{1}{r_1+(r_2-r_1)(1-x/L)^n}(T^4-T_\infty^4)=0 \qquad (3)$$

Since it is too hard to seek a solution for this type of equations, the solutions are obtained numerically by using commercial software ANSYS/FLUENT. The schematic view of representational fin profile used in this study can be seen from Fig. 2.

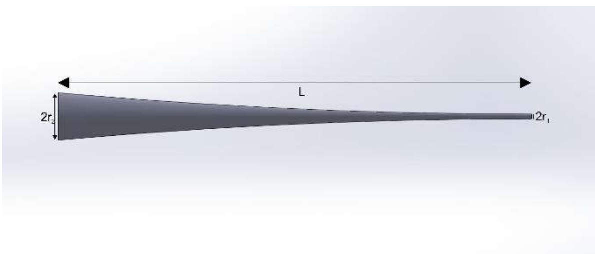

Fig. 2 Schematic view and dimensions of a fin used in this study.

Accordingly, the efficiency of the fin can be calculated as follows;

$$\eta=\frac{q_f}{q_{\max}} \qquad (4)$$

The total amount of heat dissipation from fin surface (Q_{total}), efficiency and mass are used to construct pair wise comparison matrices. Cost data is obtained from online sources to get recent values [16]. Pair wise comparison matrices (representative data for only n=0) are formed and presented in Table 3-6 based on Saaty's priority scale.

Table 3. Comparison matrix for total heat dissipation. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

Total Heat	A	C	S	T	N
A	1	1	9	9	3
C	1	1	9	9	3
S	0.1111	0.1111	1	1	0.1428
T	0.1111	0.1111	1	1	0.1428
N	0.3333	0.3333	7	7	1

Table 4. Comparison matrix for mass of the fin. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

Mass	A	C	S	T	N
A	1	9	7	3	9
C	0.1111	1	0.3333	0.1428	1
S	0.1428	3	1	0.2	3
T	0.3333	7	5	1	7
N	0.1111	1	0.3333	0.1428	1

Table 5. Comparison matrix for efficiency of the fin. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

Efficiency	A	C	S	T	N
A	1	1	9	9	3
C	1	1	9	9	3
S	0.1111	0.1111	1	1	0.1428
T	0.1111	0.1111	1	1	0.1428
N	0.3333	0.3333	7	7	1

Table 6. Comparison matrix for cost of the fin. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

Cost	A	C	S	T	N
A	1	5	1	9	9
C	0.2	1	0.2	5	5
S	1	5	1	9	9
T	0.1111	0.2	0.1111	1	1
N	0.1111	0.2	0.1111	1	1

Next step is to divide each element with the sum of its column, so we can obtain normalized relative weight. Normalized principal Eigen vector can be calculated by averaging values across the rows. This vector is called priority vector and it shows relative weights among the alternatives that will be compared. Matrix can be normalized by using Eq. 5 and Eq. 6 can be used to form priority vector.

$$w_{ij}=\frac{a_{ij}}{\sum_{i=1}^{n}a_{ij}} \qquad (5)$$

$$w_i=\frac{\sum_{j=1}^{n}w_{ij}}{n} \qquad (6)$$

In Eq. 6, n is the number of alternatives which is taken to be 5 for this study.

III. Results and Discussion

To evaluate the consistency of judgments for the alternatives based on each criterion, consistency index (CI) and consistency ratio (CR) are calculated. Table 7 shows the priority vectors and CR values.

Table 7. Priority of selected materials and CR values. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

n=0	Total heat	Mass	Efficiency	Cost
A	0.3722	0.5253	0.3722	0.3968
C	0.3722	0.0433	0.3722	0.1305
S	0.0361	0.0975	0.0361	0.3968
T	0.0361	0.2903	0.0361	0.0378
N	0.1833	0.0433	0.1833	0.0378
CR	0.0266	0.0429	0.0266	0.0395
CR (%)	2.6609	4.2980	2.6609	3.9554

As seen from Table 7, all consistency ratios are under 10% which indicates sufficient consistency for all matrices. Every material has its own priority in each criterion. However, appropriate material selection will be made based on final results. Before that, pair-wise comparison matrices will be constructed which consists of judgments for criteria. First matrix is formed for high-tech applications i.e. space missions where mass is slightly more important than cost (Case 1) and second one is formed for common applications i.e. electronics cooling where cost is slightly more important than mass (Case 2).

Table 8. Pair-wise comparison matrix for selected criteria for high-tech applications (Case 1).

Criteria	Total heat	Efficiency	Mass	Cost
Total Heat	1	7	3	5
Efficiency	0.1428	1	0.2	0.3333
Mass	0.3333	5	1	3
Cost	0.2	3	0.3333	1

Table 9. Pair-wise comparison matrix for selected criteria for electronics cooling applications (Case 2).

Criteria	Total heat	Efficiency	Mass	Cost
Total Heat	1	7	5	3
Efficiency	0.1428	1	0.3333	0.2
Mass	0.2	3	1	0.3333
Cost	0.3333	5	3	1

Similarly, the CR values are calculated for comparison matrices of criteria. CR value is found to be equal for two cases which is 4.4 percent for matrix presented in Table 8 and 9, respectively. It was concluded that all comparison matrices are satisfied consistency criterion. At the last step, decision will be made on final points according to analyses. The appropriate material can be determined by multiplying priority vector calculated based on comparison matrices for materials with priority vector calculated based on comparison matrices of criteria. The final grades are presented in Table 10 for all materials.

Table 10. Final results for selected materials. A: Aluminium, C: Copper, S: Stainless Steel, T: Titanium, N: Nickel

% points w.r.t. concavity level	n=0		n=0.5		n=4,8		n=2,10	
Case number	1	2	1	2	1	2	1	2
A	41.5	39.7	41.2	39.4	30.6	28.8	40.6	38.8
C	25.6	26.8	25.3	26.5	31.1	32.3	24.7	25.9
S	9.6	13.8	10.2	14.4	11.9	16.1	11.3	15.6
T	10.3	6.75	10.9	7.3	12.6	9	12	8.5
N	12.8	12.7	12.2	12.1	13.6	13.5	11.1	11

The priority points for aluminum are 41.5, 41.2, 40.6, 30.6, 30.6 and 40.6 percent for concavity levels of 0, 0.5, 2, 4, 8 and 10 for case 1, respectively. On the other hand, the priority points for copper are 25.6, 25.3, 24.7, 31.1, 31.1 and 24.7 percent for concavity levels of 0, 0.5, 2, 4, 8 and 10 for case 1, respectively. Similarly, the priority points for aluminum are 39.7, 39.4, 38.8, 28.8, 28.8 and 38.8 percent for concavity levels of 0, 0.5, 2, 4, 8 and 10 for case 2, respectively. The priority points for copper are 26.8, 26.5, 25.9, 32.4, 32.4 and 25.9 percent for concavity levels of 0, 0.5, 2, 4, 8 and 10 for case 2, respectively.

IV. CONCLUSION

The Analytical Hierarchy Process (AHP) is used to determine appropriate fin materials in each case. Fin is optimized by changing its shape due to longitudinal perforations with different concavity levels. Several material options are analyzed systematically.

1) It has been shown that AHP can be successfully used in heat transfer problems such as material selection for fins.

2)Aluminium is found to be appropriate fin material in many cases.

3) Copper is good alternative to aluminium, moreover the use of copper is slightly more advantageous for cases 4 and 8.

4) The change in fin mass and heat transfer due to optimization significantly effects material selection and aluminium is not a single solution for some cases.

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