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Undergraduate engineering design experience in the thermal science area

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ABSTRACT: One important educational outcome required of any engineering programme, as per ABET 2000 Criteria 3, is the ability of engineering graduates to design a component or a system. Engineering design is an integral part of several mechanical engineering courses throughout the curriculum. The author of this article presents an example of engineering design experience in the thermal science area. One of the requirements in the undergraduate junior level heat transfer course is design projects. In these design projects, students employ the theory, fundamentals and heat transfer concepts learned in the heat transfer course. In this article, the author presents a brief description of a heat transfer design project. In this design project, the students are asked to design a *heat sink* (finned attachment) to maintain a square silicon chip temperature at a certain value, with the lowest cost possible.

INTRODUCTION

The success and continual growth of many industries are strongly dependent on the design of relevant components and systems. Therefore, one important and essential task confronted by engineers is that of design. Engineers not only must know and understand the scientific fundamentals of their discipline, they also must be able to analyse and design components and systems typically encountered in their field of specialty. For an engineering curriculum to be successful, it must provide students with the opportunity to be exposed to engineering design.

ABET 2000 Criteria 3 requires that, for an engineering program to be accredited, it must demonstrate that appropriate educational programme outcomes are met. In 2000, ABET changed from a *bean counting* approach to an outcome-orientated approach - EC2000. Engineering programmes must now demonstrate that their graduates have 11 specific outcomes (a) through (k). According to these criteria, all undergraduate engineering programmes need to provide design experience. This fact is stated in outcome (c): *an ability to design a system, component, or process to meet desired needs* [1]. To meet the requirements of the ABET accreditation criteria, the mechanical engineering faculty at Indiana University-Purdue University Fort Wayne have integrated engineering design throughout the curriculum, spanning freshman, sophomore, junior and senior level courses.

Heat transfer is a highly important subject and has long been an essential part of mechanical engineering curricula all over the world. Heat transfer is encountered in a wide variety of engineering applications where heating and cooling is required. Heat transfer plays an important role in the design of many devices, such as spacecraft, radiators, heating and air conditioning systems, refrigerators, power plants and many others. One of the important fundamental topics covered in the undergraduate heat transfer course is extended surfaces (i.e. fins). Extended surfaces are used to enhance the rate of heat transfer from surfaces, especially in thermal engineering applications where increasing the convective heat transfer coefficient is not an option. Thus, in thermal engineering applications where cooling is required, it is essential to understand the basic mechanism of heat transfer in such surfaces. The extended surface (i.e. fin) is a good application that involves combined conduction, convection and radiation effects.

In this article, the author presents a design project that deals directly with extended surfaces. In the proposed design project, students are asked to design a heat sink (finned attachment) to dissipate a certain amount of heat generated by a silicon chip mounted on a board in order to maintain the chip under a certain (desired) temperature.

THEORY

The analytical analysis for fins of uniform cross-sectional area can be found in any standard heat transfer textbook (see for example, Incropera and DeWitt [2] and Özisik [3]). The analysis is simplified by the following assumptions: onedimensional conduction in the x direction, steady-state conditions, constant thermal conductivity, no heat generation, constant and uniform convection heat transfer coefficient over the entire surface, and negligible radiation from the surface. Under these assumptions, the system of energy equation and boundary conditions assumes the form (refer to Figure 1):

$$\frac{d^2T}{dx^2} - m^2(T - T_\infty) \quad (1)$$

$$T = T_o \quad at\ x = 0 \quad (2)$$

$$k\frac{dT}{dx} + h(T - T_\infty) = 0 \quad at\ x = L \quad (3)$$

where: $m = \sqrt{\frac{hP}{kA_c}}$

The resulting total heat transfer by the fin is given by:

$$Q_f = (T_o - T_\infty)\sqrt{PhkA_c}\left[\frac{\sinh mL + \left(\frac{h}{mk}\right)\cosh mL}{\cosh mL + \left(\frac{h}{mk}\right)\sinh mL}\right] \quad (4)$$

Where A_c is the cross-sectional area, h is the convection heat transfer coefficient, k is the thermal conductivity, L is the length of fin, P is the perimeter of fin, Q_f is the rate of heat loss from fin, T is the temperature, T_o is the base temperature, T_∞ is the ambient temperature, x is the axial location.

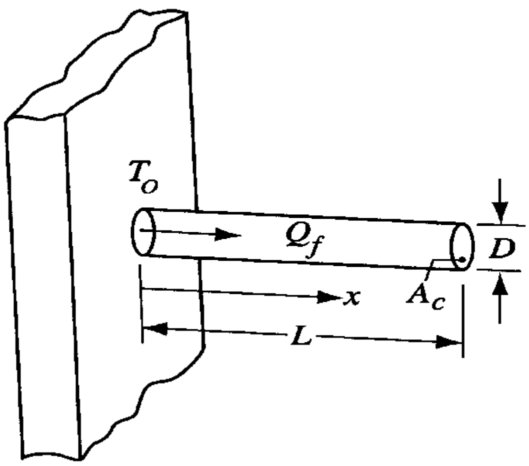

Figure 1: Schematic of the fin.

DESIGN PROJECT STATEMENT

Square silicon chip (10 mm square, 2.0 mm thick), is dissipating 1.5 Watts at steady state. The 2.5 mm thick glass/epoxy boards (have thermal conductivity of 5 W/m.K and contact resistance of 6.5x10^{-4} m^2 K/W) on which the chip is mounted is situated horizontally in a card cage with a nominal board spacing of 20 mm. The boards are cooled by air at 25^{o}C flowing parallel to the boards. Chips are located on one side only of the boards.

- Design a *heat sink* (finned attachment) to maintain the chip temperature at a maximum of 65^{o}C, assuming the convective heat transfer coefficient is a uniform 30 W/m^2.K on all surfaces subjected to the convective boundary condition.
- Use reasonable assumptions as needed and document them.
- Your goal is to meet the requirements at minimum cost.
- You are constrained to choose one of the following materials and the fin profile should be rectangular.

Material A:

ρ = 2700 kg/m^3; C_p = 0.95 kJ/kg.K; k = 230 W/m.K; α = 97x10^{-6} m^2/s
material cost = \$6/kg
Manufacturing cost = \$[0.15 + 0.0016a$^{2.2}$] (straight or annular fins).

Material B:

ρ = 8800 kg/m^3; C_p = 0.387 kJ/kg.K; k = 400 W/m.K; α = 120x10^{-6} m^2/s

material cost = $10/kg
Manufacturing cost = $[0.18 + 0.0014a^{1.6}]   (straight or annular fins).

The manufacturing cost equations were obtained from a curve fit of the company's empirical data and *a* is the aspect ratio of the fin, defined as L/t (See Figures 3.18 and 3.19 in the textbook by Incropera and DeWitt [2]). For structural reasons, $t \geq 0.5$ mm.

In your report you need to address the following:

1. Is your design conservative? Why or why not?
2. What is/are the source(s) of uncertainty and how great is/are it/they?
3. If your goal is to reduce the cost, would you look for better material manufacturing methods? Explain.
4. The reliability of electronic components increases as temperature decreases; suggest at least one way to further lower the temperature of the chip beyond your baseline design and discuss practical problems with implementation of this modification.

DESIGN/SOLUTION

Procedure

The procedure for determining the best configuration is rather straightforward. The first step is to determine the amount of heat dissipated by convection from all surfaces without any fins (employing Newton's law of cooling: $Q = hA\,(T_o - T_\infty)$, including the heat conducted through the mounting board and then convected to the air (utilising the thermal resistance composite system).

In this proposed design, as a safety factor, the temperature of the chip is considered 60^{o}C instead of 65^{o}C as stated in the design project statement above. Based on this temperature value, the amount of heat lost from the chip without any fins is 0.29 W. This leaves 1.21 W that must be dissipated by the attached fin. The relative equations can be coded into a MATLAB M-File that allows the number of fins to be chosen, and then the amount of heat dissipated by the fin(s) as a function of the length of the fin is obtained as shown in Figure 2.

Moreover, the cost of the fin(s) versus the material and the length of the fin is also determined (Figure 3). The total heat dissipated by all surfaces including the fin(s) is presented in Figure 4.

Results

A single fin of 7.15 mm long, 0.5 mm thick, and 10 mm wide made of material *B* is capable of dissipating the desired amount of heat in conjunction with the heat loss from all surfaces of the chip. Figure 2 shows the amount of heat dissipated when one fin is attached. As can be seen from the figure, material *A* cannot be used for this design as it cannot dissipate the desired amount of heat.

Figure 3 compares the cost associated with one fin versus a certain length requirements. As the figure shows, material *B* will cost $US0.282 per chip. This is the cheapest amount of money needed to meet the design requirements. Figures 5 and 6 show that the cost increases for multiple fins.

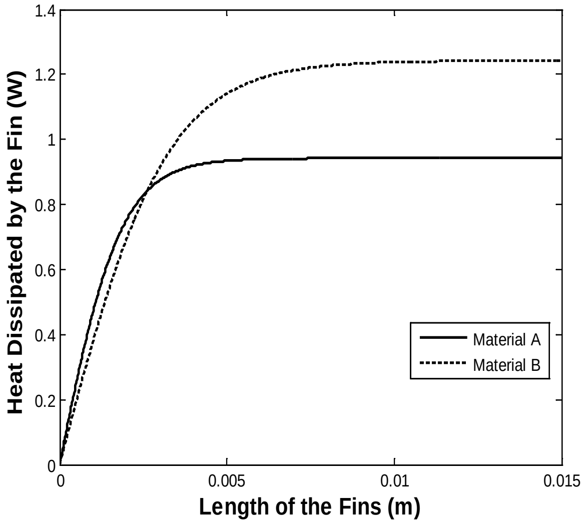

Figure 2: The amount of heat dissipated by one fin.

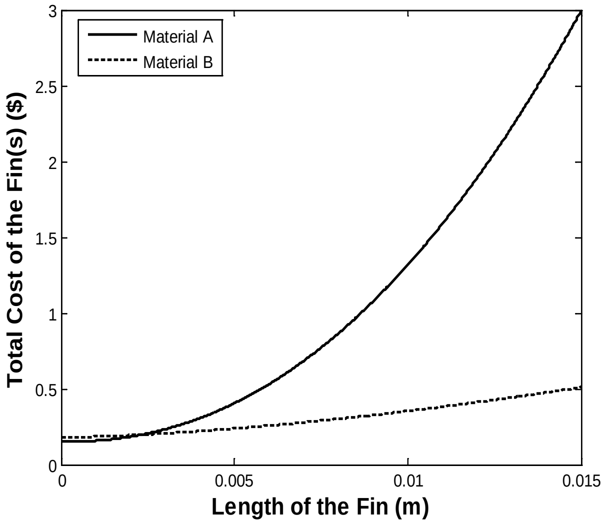

Figure 3: The cost associated using one fin.

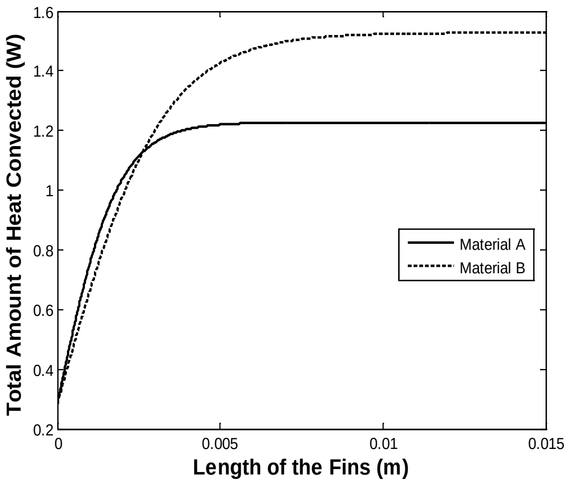

Figure 4: The total heat convected using one fin.

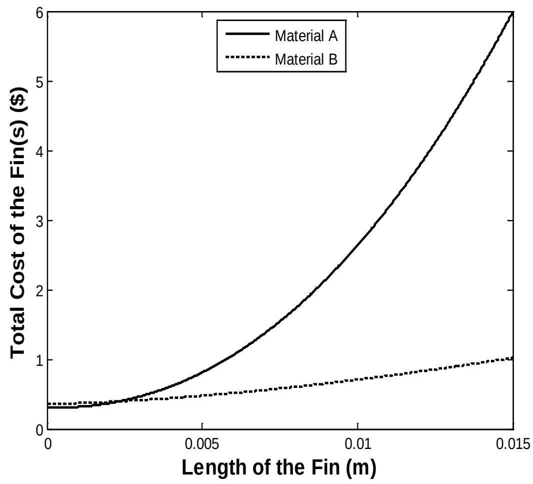

Figure 5: The cost associated using two fins.

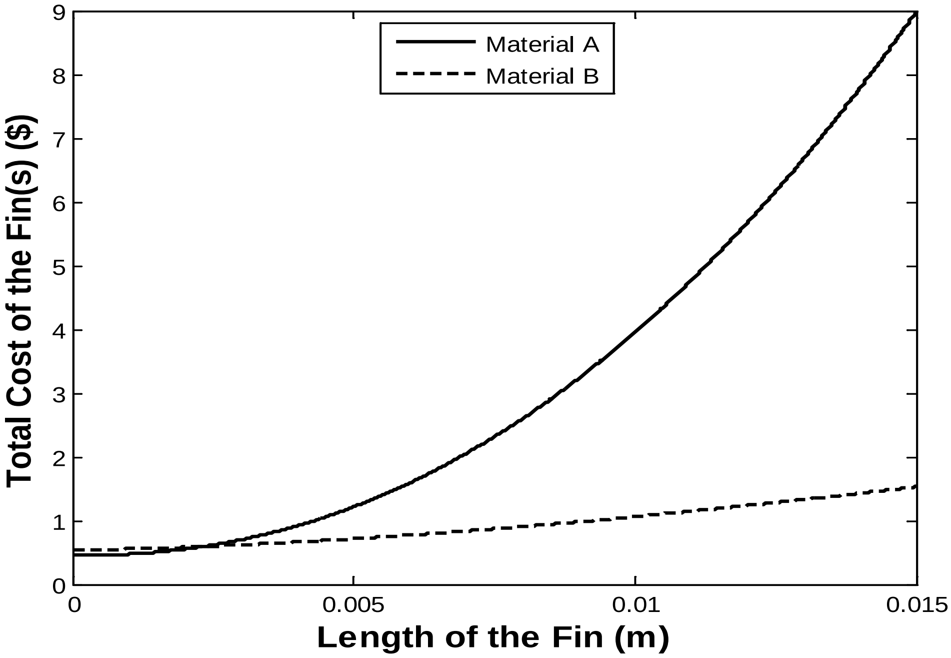

Figure 6: The cost associated using three fins.

CONCLUSION

A practical example of an engineering design project in the area of thermal sciences (heat transfer) is presented in detail. The project involves the design of a *heat sink* (finned attachment) to maintain a square silicon chip temperature at a certain value, with the lowest cost possible. This kind of design project can be used as a measure of students' understanding of the topic of extended surfaces normally covered in any undergraduate heat transfer course. Feedback from students has been very positive.

REFERENCES

1. ABET Engineering Accreditation Criteria, Criterion 3: Program Outcomes and Assessment, http://www.abet.org
2. Incropera, F.P. and DeWitt, D.P., *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons (2006).
3. Özisik, M.N., *Heat Transfer*. McGraw-Hill (1985).