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Transient Thermal Response of Chip and Selection of Fin Design for Efficient Heat Dissipation

Shreyas Kotian

Department of Mechanical and Aerospace Engineering, University of California- San Diego, San Diego, CA, 92093, USA

ABSTRACT

Electronic cooling is one of the leading engineering problems in today's world. As we all know the heat generated by electronic devices is huge up to 20 W/cm^2 – 100 W/cm^2 (Kadambi and Abuaf (1985), Byon *et al.*, 2011, and Krishnan and Jain (2023)) and it becomes essential to dissipate the heat as quickly as possible. In this current study, we analyze the transient thermal response of a chip and an optimal choice of a heat sink for the efficient removal of heat. In this case, we use fins as a source of heat dissipation. Although there are various fin designs such as straight fin, parabolic fin, helical fin, trapezoidal fin, circular fin, and many more, in this study we limit them to a rectangular fin and a circular fin for the sake of simplicity.

Key words: Transient Thermal, Chip, Fin Design, Efficient Heat Dissipation

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METHODOLOGY

We provide an analytical solution of the heat distribution for the chip as well as its transient response. Results such as temperature distribution as a function of length, heat transfer rates from the two fins, and the efficiencies of the fin are also calculated.

Key Assumptions

- Heat generation is constant and not a function of current through the chip.
- Neglecting the presence of Thermal Interface Material (TIM) between the interface of chip and heat sink.
- Heat conduction only in x-direction.
- Radiation effects neglected.
- Thermal conductivity is constant and not a function of temperature.

ANALYTICAL SOLUTION

The following represents the analytical solution for the transient heat response and the temperature distribution for the chip. We assume internal heat generation in the chip with a 1D heat flow. One end of the chip is considered to be adiabatic and the other end has a temperature of T$_c$.

GOVERNING EQUATIONS

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + {Q_v}'''$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\nabla^2 T + \frac{{Q_v}'''}{\rho C_p}$$

We use the superposition principle such that the steady state term takes care of the heat generation, and the other component is the transient response of the chip.

$$T(x,t) = T_a(x) + T_b(x,t)$$

Now, we first solve for $T_a(x)$

$$k\frac{d^2T_a}{dx^2} + Q_v''' = 0$$

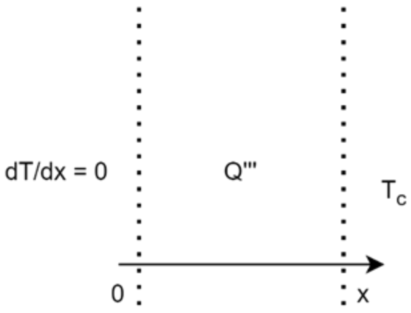
Now, moving the constants to one side and integrating twice, we arrive at the following equation,

$$T_a(x) = \frac{-Q_v'''x^2}{2k} + C_1x + C_2$$

Using the boundary conditions,

$At\ x = 0, \frac{\partial T}{\partial x} = 0$

$At\ x = L, T = T_c$



After applying both these boundary conditions we arrive at the final equation for $T_a(x)$

$$T_a(x) = \frac{-Q_v'''x^2}{2k} + \frac{Q_v'''L^2}{2k} + T_C$$

Now we solve for $T_b(x,t)$

Boundary conditions are as follows

Initial condition, $t = 0;\ T_2(x,0) = T(x,0) - T_a(x)$

Boundary condition, $t > 0, x = 0;\ \frac{\partial T}{\partial x} = 0$

$x = L;\ T = T_c$

$Let\ \xi = \frac{t}{t_c} = \frac{t}{L^2/\alpha}$

$\eta = \frac{x}{L}, \theta = \frac{T-T_C}{T_o-T_c}$

Initial condition, $\xi = 0, \theta = \frac{T_2-T_C}{T_o-T_c} = \frac{T_o - T_a(x) - T_c}{T_o-T_c}$

Boundary condition, $\xi = 1, \eta = 0, \frac{\partial\theta}{\partial\eta} = 0, and\ \eta = 1, \theta = 0$

Now, we also know that

$\theta = H(\eta)Z(\xi)$

General solution,

$$\theta = \sum_{n=0}^{\infty} A_n \exp\left(-\lambda_n{}^2\xi\right)\cos\left(\lambda_n\eta\right)$$

Using the initial condition and orthogonality of the Fourier series, we evaluate the constant A_n,

$$A_n = \frac{\int_0^1 (T_o - T_a(x))\cos(\lambda_n\eta)d\eta}{\int_0^1 cos^2(\lambda_n\eta)\,d\eta}$$

After plugging in the equation for T_a and solving the integral we arrive at a value for A_n given as follows

$$A_n = 2[\frac{T_o\sin(\lambda_n)}{\lambda_n} + \frac{Q_v'''L^2}{2k}\left(\frac{\left(\lambda_n{}^2 - 2\right)\sin(\lambda_n) + 2\lambda_n\cos(\lambda_n)}{\lambda_n{}^3}\right) - \frac{Q_v'''L^2}{2k}\frac{\sin(\lambda_n)}{\lambda_n} - T_c\frac{\sin(\lambda_n)}{\lambda_n}]$$

Now, the temperature distribution can be determined by plugging in the value of A_n.

We will only be taking the first eigen value since the other values starting from n = 2, would be small that it would not make a considerable difference.

$$T(x,t) = A_1 \exp\left(-\lambda_1{}^2 \xi\right) \cos\left(\lambda_1 \frac{x}{L}\right) + [\frac{-Q_v{}'''x^2}{2k} + \frac{Q_v{}'''L^2}{2k} + T_C]$$

Table 1: Chip parameters

Parameter	**Value**
Length of chip (cm)	0.50
K (silicon) (W/cm-K)	1.56
Initial Temp (T_o) (°C)	40.00
Heat generation (Q_v) (W/cm^3)	100.00
Case temperature (T_c) (cm)	20.00
Area of chip (cm^2)	0.25

Fig. 2 shows the transient temperature response of the chip along its length at different Fourier number. It can be noticed that the temperature of the chip keeps rising as time progresses.

Fig. 3 depicts the variation in the maximum temperature of the chip with the Fourier number. It can be observed at after Fo=0.1 the solution will eventually achieve steady state.

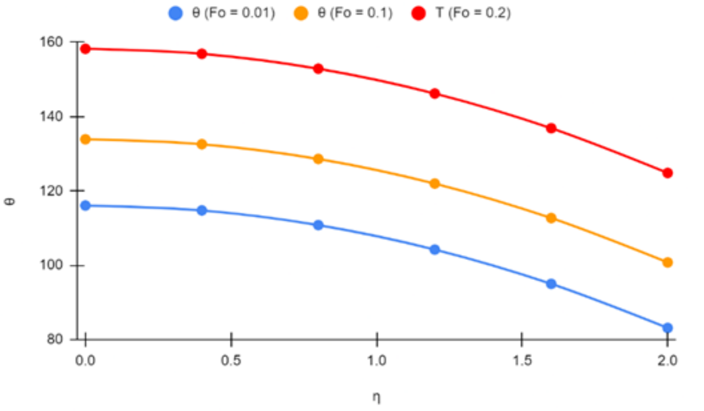


Figure 1: Variation of temperature distribution along the length.

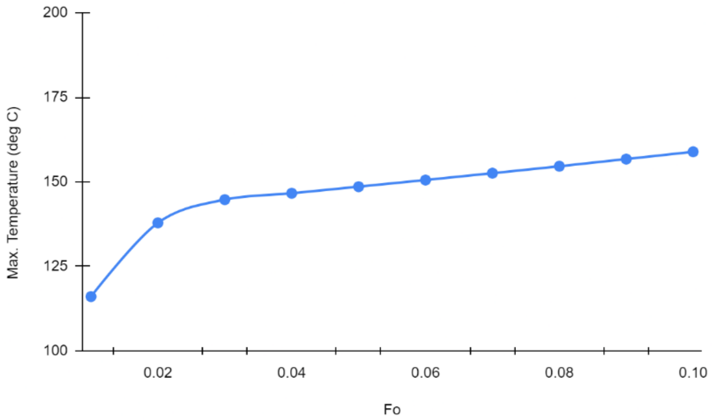


Figure 2: Variation of maximum temperature with Fourier number.

Now, the heat transferred from the chip at x = L, will be equal to the heat flux at the base of the fin. Keeping this in mind we make the calculations for fin efficiency for the rectangular fin and pin fin.

RECTANGULAR FIN:

Heat transfer rate by a rectangular fin is given by,

$$\dot{Q}_{fin} = k_{fin} A_{fin} \Delta T_b \beta \tanh(\beta L_{fin})$$

Heat transfer rate by the chip is given by,

$$\dot{Q}_{chip} = -k_{chip} A_{chip} \frac{dT}{dx}(x = L)$$

Solving for Q_{chip}, we get

$$\dot{Q}_{chip} = -k_{chip} A_{chip} \left[\frac{-A_1 e^{-\lambda_1{}^2 \xi} \lambda_1 \sin(\lambda_1)}{L_{chip}} - \frac{Q_v{}''' L_{chip}}{k_{chip}} \right]$$

Equating both the heat transfer rate, we get

$$\Delta T_b = \frac{\dfrac{k_{chip} A_{chip} A_1 e^{-\lambda_1{}^2 \xi} \lambda_1 \sin(\lambda_1)}{L_{chip}} - Q_v{}''' L_{chip} A_{chip}}{k_{fin} A_{fin} \beta \tanh(\beta L_{fin})}$$

$$\Delta T_x = \frac{\cosh(\beta(x - L_{fin}))}{\cosh(\beta L_{fin})} \Delta T_b$$

CIRCULAR FIN:

$$\dot{Q}_{fin} = -k_{fin} A_{fin} \beta \Delta T_b \frac{e^{-2\beta L_{fin}} - 1}{e^{-2\beta L_{fin}} + 1}$$

$$\dot{Q}_{chip} = -k_{chip} A_{chip} \left[\frac{-A_1 e^{-\lambda_1{}^2 \xi} \lambda_1 \sin(\lambda_1)}{L_{chip}} - \frac{Q_v{}''' L_{chip}}{k_{chip}} \right]$$

$$\Delta T_b = \frac{\left[\dfrac{k_{chip} A_{chip} A_1 e^{-\lambda_1{}^2 \xi} \lambda_1 \sin(\lambda_1)}{L_{chip}} - Q_v{}''' L_{chip} A_{chip}\right](e^{-2\beta L_{fin}} + 1)}{\beta k_{fin} A_{fin} (e^{-2\beta L_{fin}} - 1)}$$

$$\Delta T_x = \frac{e^{\beta(x - 2L_{fin})} + e^{-\beta x}}{(e^{-2\beta L_{fin}} + 1)} \Delta T_b$$

Table 2: Parameter considered for numerical solution for fin

Parameter	**Value**
Length of fin (cm)	5
K (Al) (W/cm-K)	2.37
Fin parameter (βL_{fin})	0.6
Heat Transfer Coefficient (W/cm^2-K)	0.02
Air Temperature (°C)	25

Fin efficiency can be calculated as follows –

$$\eta_{fin} = \frac{\dot{Q}}{h_c P L (T_b - T_e)}$$

RESULTS

From **Fig. 3** it can be showcased that the pin fin has a much higher gradient of temperature compared to the rectangular fin. This proves that the pin fin has a much higher heat dissipation rate than rectangular fin.

Fig. 4 shows the comparison of temperature of pin fin and rectangular fin along their length at different Fourier numbers. We can infer from this plot that, the temperature gradient of the rectangular fin at long time of Fo=0.3 is still lesser than the temperature gradient of the pin fin at short time Fo = 0.1. This helps us to conclude that a pin fin helps in dissipating the heat faster compared to that of the rectangular fin.

The final efficiencies of the both the rectangular fin and the pin fin for the same fin parameter ($\beta L_{fin} = 0.6$) are:

$$\eta_{fin(rectangular)} = 63.64\%$$
$$\eta_{fin(pin)} = 76.36\%$$

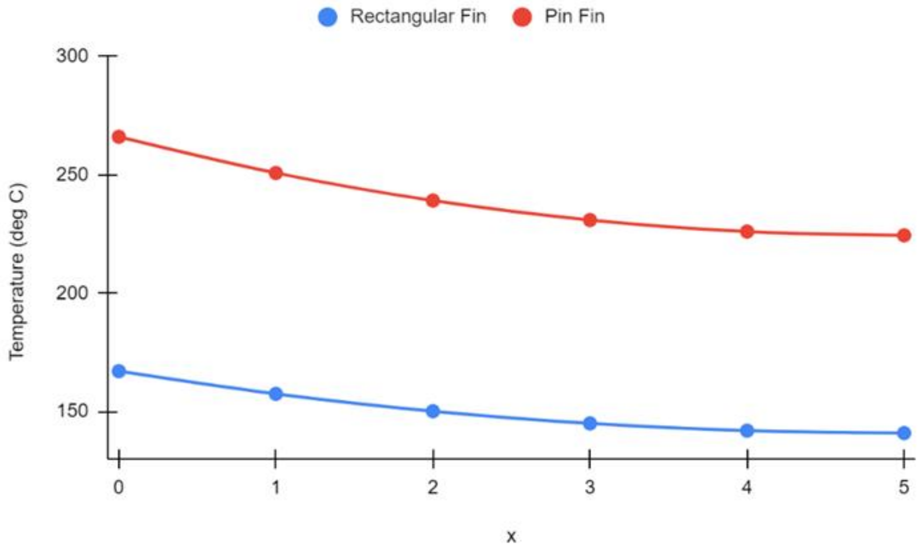


Figure 3: Temperature variation along the length of the fin.

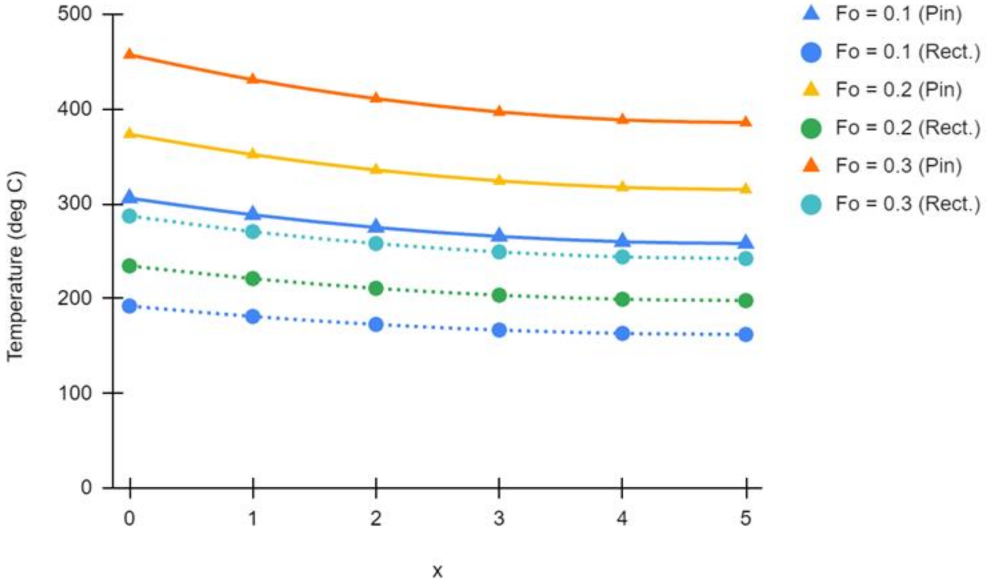


Figure.4: Comparison of temperature of pin fin and rectangular fin along their length for different Fourier numbers.

FUTURE WORK AND IMPROVEMENTS:

- Model the entire 3D domain using a Multiphysics software and check for potential hotspots.
- Model the Thermal Interface Material, which is going to lower the thermal resistance between the chip and the heat sink.
- Check temperature distribution and efficiency for other fin geometries.
- Go for a more staggered configuration for the pin fin heat sink to improve cross flow and break hotspots.

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