CHAPTER 2

THEORY

2.1 Electronic System Structure

The electronic system structure consists of 3 main parts, for example, a computer system as shown in Figure 2.1 The first part is the electronic chips in the central processing unit, CPU, and acts as the heat source which is the main aspect in thermal management. The second part is the main board that contains the electronic chips and the third part is the system that covers the whole boards including the electrical supply systems and the cooling systems.

Figure 2.1 An electronic system structure (www.electronics-cooling.com).

Figure 2.2 shows a structural integration of an electronic enclosure. There are a set of electronic modules which are the heat source inside. Figure 2.3 also shows the structure of an electronic module and directions of heat release.

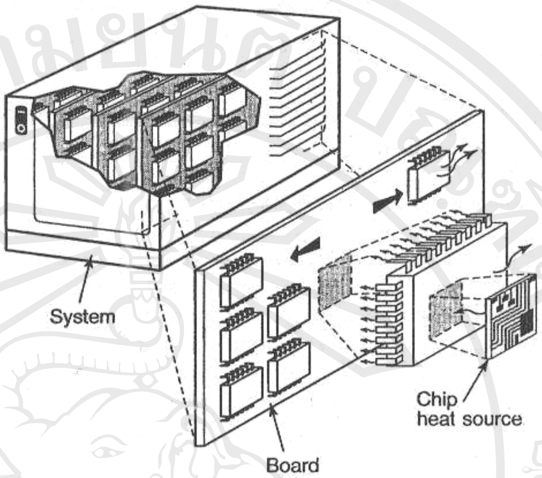


Figure 2.2 A structural integration of an electronic enclosure (Azar, 1997).

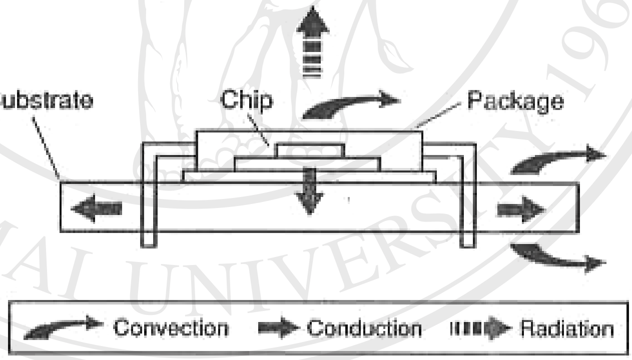


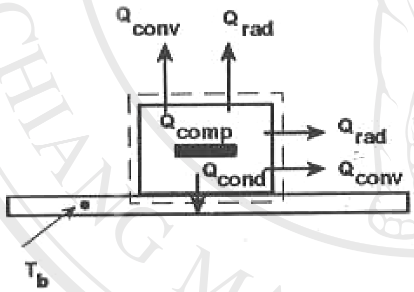
Figure 2.3 Heat transfer at an electronic module on a print circuit board, PCB (Jerry et Al .,1998).

There are 3 modes of heat transfer which are conduction, convection and radiation. Heat release from the chip is mainly transported to the environment by convection and radiation. Some parts of the heat are conducted to the substrate directly at the back and to the legs and then to the substrate again. After that there is heat convection from the substrate to the environment.

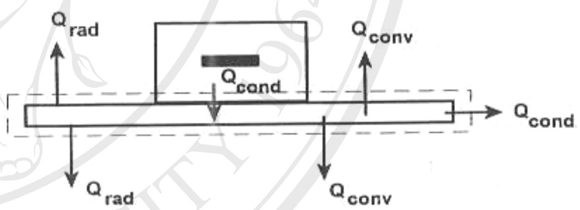
2.2 Module Temperature, T_{module}

In practice, it is necessary to control the chip or the module temperature not to exceed the value that is recommended by the manufacturers. Consider an electronic module on a board as shown in Figure 2.4. The energy flows at the chip, the board and the air that is exchanging heat could be carried out with the assumptions as follows:

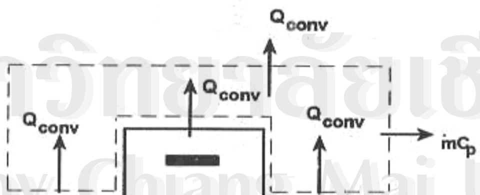
- The problem is done at steady state condition.
- The air properties are similar to those of the ideal gas.
- The board has uniform temperature is uniform throughout.
- The convective heat transfer coefficient is uniform throughout the control volume.



(a) Chip



(b) Board



(c) Fluid

Figure 2.4 The heat flows at the chip, the board and the fluid of an electronic module (Azar, 1997).

The energy balance at the module could be

$$Q_{\mathrm{mod}ule} = Q_{cond} + (Q_{conv} + Q_{rad})_{top} + (Q_{conv} + Q_{rad})_{side} \tag{2.1}$$

where

Q_{module}	=	heat release from the module (W)
Q_{cond}	=	heat conduction from the module to the board (W)
Q_{conv}	=	heat rate by convection (W)
Q_{rad}	=	heat rate by radiation (W).

The heat rate can be rewritten in terms of temperatures as

$$Q_{\mathrm{mod}ule} = \frac{kA(T_1 - \mathrm{Tb})}{L} + hA_{top}(T_1 - \mathrm{T_f}) + 4\sigma\varepsilon F_{1,top} A_{top} T_m^3 (T_1 - \mathrm{T_{top,board}})$$

$$+ hA_{side}(T_1 - \mathrm{T_f}) + 4\sigma\varepsilon F_{1,side} A_{side} T_m^3 (T_1 - \mathrm{T_{side,board}}) \quad , \quad \mathrm{T_f} = \frac{(\mathrm{T_{fluid,in}} + \mathrm{T_{fluid,out}})}{2} \tag{2.2}$$

where T_{module}, T_b, T_f are the temperatures of the module, the board and the fluid, respectively(K); h is heat transfer coefficient(W/m^{2}K); A is heat transfer area(m^2), σ is Stefan-Boltzmann constant which is 5.67×10^{-8} W/m^{2}K^{4}and ε is surface emissivity.

For the board, the energy balance could be

$$Q_{board} = Q_{cond} + (Q_{rad} + Q_{conv})_{top} + (Q_{rad} + Q_{conv})_{bottom} . \tag{2.3}$$

The equation could be set in terms of the temperatures as

$$\frac{kA}{L(T_1 - T_b)} = k_b\left(t\frac{W}{L}\right)_b(T_b - T_{amb}) + 4\sigma\varepsilon A_{f,p}T_m^3(T_b - T_{top,board})$$
$$+ hA_{f,p}(T_b - T_f) + 4\sigma\sigma\varepsilon_B T_m^3(T_b - T_{bottom,board}) \qquad (2.4)$$
$$+ hA_b(T_b hA_{side}(T_1 - T_f) + 4\sigma\varepsilon F_{1,bottom}T_m^3(T_1 - T_{bottom,board}) + hA_b(T_b - T_{f,bottom})$$

where W, L and t are the board width, length and thickness, respectively.

The energy balance at the fluid could also be

$$\dot{m}C_p(T_{f,o} - T_{f,i}) = h(A_{top} + A_{side})(T_1 - T_f) + h(A_{f,p} - A_{top})(T_b - T_f) \qquad (2.5)$$

Since
$$V_1A_1 = V_2A_2 \qquad (2.6)$$

With the values of the airflow rate, the inlet air temperature, the heat release from the module, the radiation properties of the module and board and the heat transfer coefficient, the module temperature can be estimated from these energy balance equations.

In practice, over 80 % of the heat generated is released by heat convection, therefore, it is necessary to find the technique to enhance the convective heat transfer thus the module temperature could be controlled and the electronic system will be high reliable.

2.3 Convection Heat Transfer in Electronic Equipment

The heat release from the electronic module is mainly absorbed by the cooling air. In heat convection, the heat transfer coefficient, h, comes from empirical formulas which are mostly based on actual experiments and observations.

2.3.1 Forced Convection Flow a Single Module

Circuit board components are available in a variety of shapes and sizes. If the object protrudes into a gaseous free stream, for a simple shape as shown in Table 2.1, a correlation for the average Nusselt number is based on the following empirical formula as

$$\overline{Nu_D} = \frac{\bar{h}D}{k} = I\,\mathrm{Re}_D^J \tag{2.7}$$

where the value for I and n are found in the Table 2.1 (Jacobi and Shah, 1995).

Table 2.1 Constants, I and J for a fluid flow across an object with different Shapes.

Shape	Reynolds Number	I	J
Square	$5\times10^3 < \mathrm{Re} < 1\times10^5$	0.160	0.699
Diamond	$5\times10^3 < \mathrm{Re} < 1\times10^5$	0.222	0.624
Hexagon	$5\times10^3 < \mathrm{Re} < 1\times10^5$	0.144	0.638
Hexagon	$5\times10^3 < \mathrm{Re} < 1\times10^5$	0.138	0.638
Ellipse	$2.5\times10^3 < \mathrm{Re} < 1.5\times10^4$	0.224	0.224

2.3.2 Adiabatic Heat Transfer Coefficient and Thermal Wake Function

Generally, a printed circuit board contains a number of electronic chips or modules as shown in Figure 2.5 and Figure 2.6 gaves an example of in-line chip arrangement. x is the direction of air flow, y is the horizontal direction normal to the air flow and z is the vertical direction normal to the air flow. Each module has a height of B, a length of L_X and a width of L_Y. C_X and C_Y are the spacings between the chips in x and y directions. The chip density could be defined as

$$D = \frac{L_X L_Y}{S_X S_Y}, S_X = L_X + c_Y, S_Y = L_Y + c_Y\,. \tag{2.8}$$

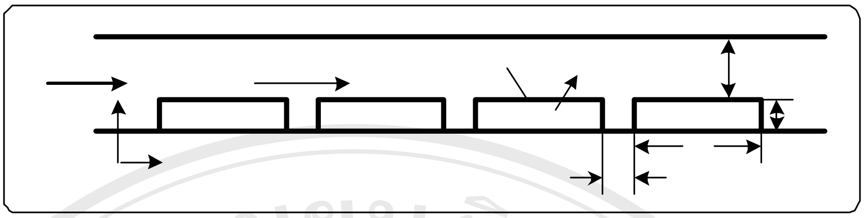


Figure 2.5 Chip array in a printed circuit board (Lee and Kim, 1996).

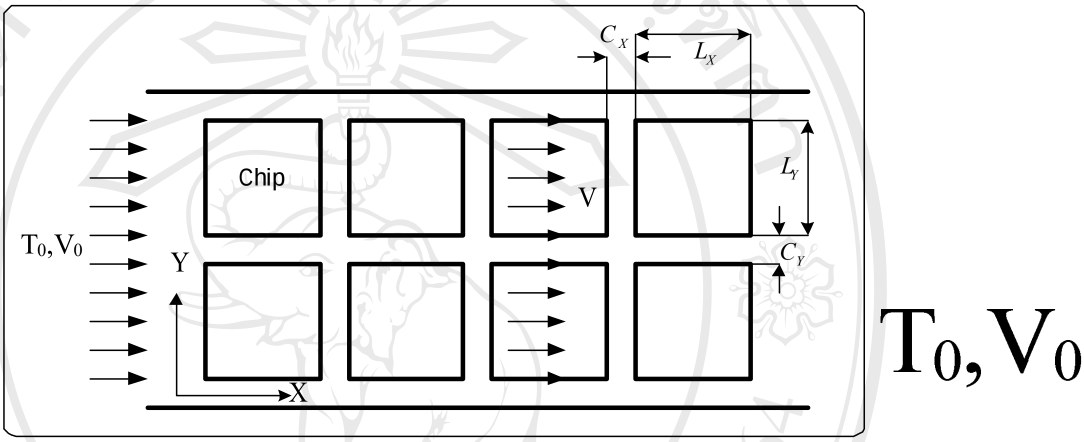


Figure 2.6 An example of in-line chip array (Lee and Kim, 1996).

Two convective effects contribute to the temperature rise of an electronic module. The first part, called self-heating effect, is due to heat generated within the module while the second part is the effect of heat releases from the other components those are upstream from the considered module. These upstream heat releases raise the mean temperature of the coolant which then washes over the module and raises the module temperature. This second heating effect is often called thermal wake effect.

For forced convection cooling (no buoyancy effects or radiation heat transfer), these two effects may be combined by simple addition (superposition) and a convenient expression (Arvizu and Moffat, 1982) is

$$T_k - T_0 = \left(\frac{q_k}{h_k A_k}\right) + \sum_{i=1}^{k-1} \theta_{k-i}\left(T_i - T_0\right), i < k \,. \tag{2.9}$$

The first term on the right of the equation expresses the self-heating temperature rise of element k above the entrance temperature, T_o, in terms of its convective heat release rate, q_k, heat transfer surface area, A_k, and the adiabatic heat transfer coefficient, h_k. The term adiabatic is used in describing h_k since it is the heat transfer coefficient observed in the absence of other (upstream) heat releases, and this serves as

$$h_k = \left. \frac{q_k}{A_k (T_k - T_0)} \right| only q_k \neq 0 \qquad (2.10)$$

h_k is a function of flow rate, channel and array geometry, fluid properties, and perhaps position in the array.

The second term on the right of the equation expresses the temperature rise of element k due to thermal wakes from all elements in array rows upstream from k. It contains the thermal wake function, θ_{k-i}, which is the fractional temperature rise of element k due to heat release from element i with q_k = o, therefore

$$\theta_{k-i} = \left. \frac{T_k - T_0}{T_i - T_0} \right| q_i \neq 0, q_k = 0 \qquad (2.11)$$

Like h_k, θ_{k-i} is a function of flow rate, channel and array geometry, fluid properties, and position in the array. Its experimental determination is relatively straightforward. Experiments are conducted with one array element heated, and the temperature increases of elements downstream from it are recorded.

From the methods described above, it could be seen that there are two methods for evaluating the convective heat transfer coefficient. For the first one, the heat transfer coefficient is based on the difference of the module and the bulk air temperatures whereas the other method the value is based on the difference of the module and the inlet air temperatures and the superposition technique is added to evaluate the module temperature.

2.3.3 Vortex Generator

Usually the vertical motions may be classified as transverse and longitudinal. The axis of a transverse vortex lies perpendicular to the flow direction while longitudinal vortices have their axes parallel to the main swirl around the primary flow. In general, longitudinal vortices are more effective than transverse vortices from the heat transfer perspective (Fiebig, 1997) . The vortex generators often take forms of small protrusions which may be incorporated into the main surface by embossing, stamping, punching, or attaching. Figure 2.7 shows the commonly employed vortex generators. Swirl flow is generated as the mainstream flow across the small protrusions.

Fiebig(1998) point out that there are three major heat transfer enhancement mechanisms of enhanced surfaces, namely: (1) developing boundary layers, (2) swirl or vortices, and (3) flow destabilization or turbulence intensification. A recent technology review article in common enhanced surfaces are the interrupted surfaces in the form such as slit, offset strip, and louver.

Though interrupted surface can significantly improve the heat transfer performance, the associated penalty of pressure drop is also tremendous. In contrast to the common interrupted surfaces, the vortex generator not only improves the heat transfer performance via all three heat transfer mechanisms but also reveals comparatively small pressure drops. This is because wall friction is related to the derivative of streamwise velocity but spanwise and normal velocities. The vortex generator characterized the secondary flow pattern from the vertical motion that is caused by the spanwise and normal velocities. Heat transfer enhancement is associated with the secondary flow but with small penalty of wall friction (Jacobi, 1995). Therefore, longitudinal vortices are recognized especially suitable for heat transfer applications.

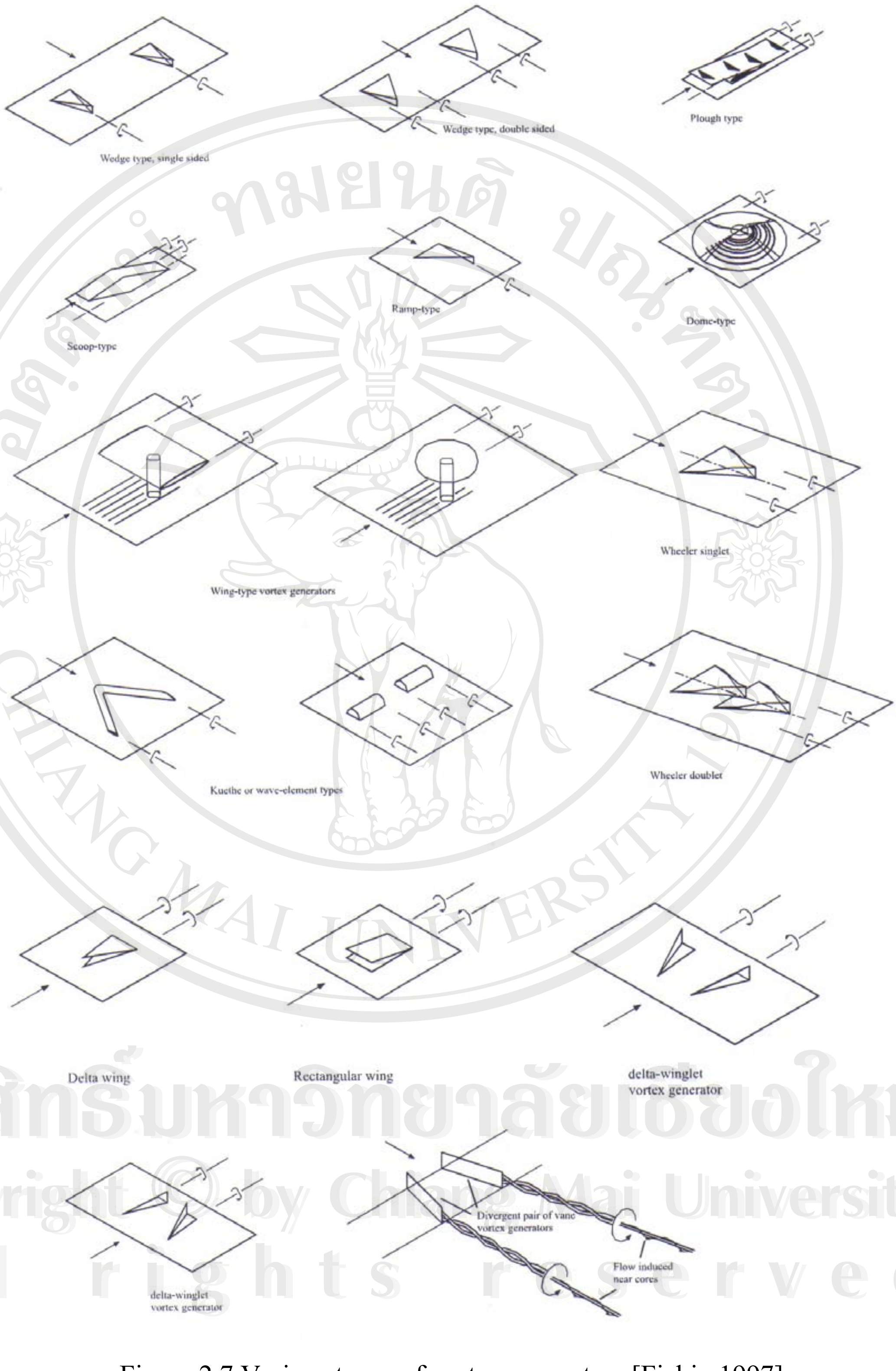


Figure 2.7 Various types of vortex generators.[Fiebig,1997]