Estimating the Inside Air Temperature

of a Natural Convection Sealed Enclosure

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1. Introduction

Sealed enclosures are normally used to protect the electronic equipments from corrosive or horse environment. The typical applications are RF communication sub systems, used in marine applications and Engine management control systems, used in automobiles. The accumulation of heat in an enclosure is potentially damaging to electrical and electronic devices. Overheating can shorten the life expectancy of components or lead to catastrophic failure. It is therefore important that system designers are aware of the temperature implications of their designs prior to implementation. At present, the inside air temperature is taken as one of the reference temperatures for the components and printed circuit board (PCB). The inside air temperature is affected by power dissipation of components and ambient temperature. It is important to know the internal air temperature of enclosure to design the components and PCB. This paper explains the three heat transfer modes and illustrates how to estimate the inside air temperature of the enclosure.

2. Heat transfer modes

Most readers will be familiar with the terms used to denote the three modes of heat transfer namely, conduction, convection and radiation. Any energy exchange between bodies occurs through one of these modes or a combination of them.

2.1 Conduction

The conduction mode of heat transfer occurs when there is a temperature difference in a stationary medium. On a molecular level, the high temperature area has a higher vibrational energy, and this energy is transferred molecule to molecule to the cooler region. There is no movement in the bulk media. The governing equation of conduction heat transfer is Fourier law, which states that the heat transfer rate per unit area is directly proportional to the temperature gradient.

$$\frac{q}{A} \propto \frac{\partial T}{\partial x} \tag{1}$$

$$q = -k\,A\,\frac{\partial T}{\partial x} \tag{2}$$

where q is the heat transfer rate and $\partial T / \partial x$ is the temperature gradient in the direction of heat flow. The positive constant k is called the thermal conductivity of the material and the minus sign is inserted so that the 2nd law of thermodynamics is satisfied: i.e., heat will flow from high temperature to low temperature. The thermal conductivity values of common materials are listed below:

Table 1. Thermal conductivity of materials at 300 K.

Material	k (W/mK)
Silver (pure)	427
Copper (pure)	399
Gold	316
Stainless steel (316)	14.4
Glass	0.81
Air	0.0262
Water	0.540

2.2 Convection

Convection occurs when heat is transferred due to diffusion and bulk motion, most commonly between a fixed surface and a moving fluid, liquid or gas. Convection can be further subdivided into free convection and forced convection. For free convection, the flow of the fluid is induced by buoyancy forces, whereas in forced convection the fluid flow is due to some outside means such as a fan, blower or pump. An example of free convection is the draft felt by an oven door. At the oven door surface, heat is diffused into the air. The increased temperature of the air causes it to expand. As it expands, it has a lower density than the cooler surrounding air causing it to rise. As the air moves up, heat is transported away from the oven door. An example of forced convection can be found under the hood with the car radiator. Air is forced by a fan over the fins of the radiator which has been heated by the engine coolant. Heat is diffused into the air as it comes into contact with the surface of the radiator, and is then transported away by the bulk motion of the air flow. The governing law for convection is Newton's law of cooling which states that the heat transfer rate per unit area is directly proportional to the temperature difference between wall and fluid.

$$\frac{q}{A} \propto \left(T_w - T_\infty\right) \tag{3}$$

$$q = h\,A\left(T_w - T_\infty\right) \tag{4}$$

The quantity h is called convective heat transfer co-efficient. An analytical calculation of h may be made for some system. For complex situation, it must be determined experimentally. The typical values of heat transfer coefficient is listed in the below table.

Table 2. Typical values of heat transfer coefficients.

Process	h (W/m^2K)
Free convection	
Gases	2 - 25
Liquids	50 - 1000
Forced convection	
Gases	25 - 250
Liquids	50 - 20,000
Convection with phase change	
Boiling or condensation	2500 -100,000

2.3. Radiation:

Thermal radiation occurs when thermal energy is exchanged via electromagnetic waves. A bulk media is not required in between the hot and cool regions for heat transfer to occur with radiation. For example, the earth receives thermal energy from the sun via radiation even though the void of space is in between. Radiation becomes the dominant mode of transfer at higher temperatures. For example, when standing in front of a camp fire you are warmed primarily by radiation. Heat is not diffused to you by conduction because the air surrounding you is still cool. Heat is transferred to the air by convection, but just in the draft above the fire which rises upwards. The warmth you feel when standing beside the fire is from infrared radiation intercepted by your clothing. The governing law for thermal radiation is Stefan-Boltzmann law which states that the heat transfer rate per unit area is directly proportional to the fourth power of absolute temperature for black body.

$$\frac{q}{A} \propto T^4 \tag{5}$$

$$q = \sigma\,A\,T^4 \tag{6}$$

where σ is the proportionality constant with a value of 5.669 x 10^{-8} W/m^2 K^4. The heat transfer form a non black body with emissivity of ε is given by

$$q = \varepsilon\,\sigma\,A\,T^4 \tag{7}$$

The emissivity of a material is the ratio of energy radiated by a particular material to energy radiated by a black body at the same temperature. The emissivity values of common materials are listed below.

Table 3. Typical values of emissivity

Material	Emissivity
Aluminium, polished	0.05
Aluminum, rough surface	0.07
Aluminum, strongly oxidized	0.25
Brass, polished	0.22
Bronze, porous, rough	0.55
Bronze, polished	0.1
Cast iron, rough casting	0.81
Cast iron, polished	0.21
Copper, polished	0.01
Copper, oxidized	0.65
Gold, polished	0.02

3. Mathematical Formulation

The dominant mode of heat transfer in sealed enclosure is convection and radiation. Figure 1 represents the energy transfer in a sealed enclosure.

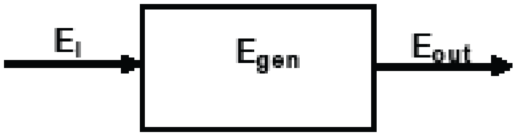

Figure 1. Energy transfer in enclosure

By energy balance,

$$E_{in} - E_{out} + E_{gen} = E_{st} \tag{8}$$

Where,

E_{in} is the energy entering the enclosure (if = to 0, no energy is entering to the enclosure)

E_{gen} is the energy generated inside the enclosure (=Power dissipation by components, P_v)

E_{out} is the energy leaving the enclosure (By convection and radiation)

E_{st} is the energy stored in the (=0 for steady state)

Therefore, based on equation 8, the equation is reduced to

$$0 - E_{out} + P_v = 0 \tag{10}$$

where,

$$E_{out} = Q_{conduction} + Q_{convection} + Q_{radiation} = 0 \tag{11}$$

The heat transfer due to conduction is negligible, since there is no heat sink attached to it.

Therefore,

$$E_{out} = Q_{convection} + Q_{radiation} \tag{12}$$

The heat transfer due to convection is given by,

$$Q_{convection} = hA\left(T_i - T_o\right) \tag{13}$$

Where,

h = convective heat transfer coefficient (5 to 10 W/m^{2}K) for natural convection

A = surface area of the enclosure

= 2 * (length * Width + length * Height + Width * Height)

T_i = Inside temperature

T_o = Outside temperature

The heat transfer due to radiation is given by,

$$Q_{radiation} = \varepsilon \sigma A\left(T_i^4 - T_o^4\right) \tag{14}$$

Where,

ε = emissivity of the enclosure material

σ = Stefan constant 5.669x10^{-8} W/m^2 K^4

a = surface area of the enclosure

T_i = Inside temperature

T_o = Outside temperature

Substituting the equations 13 & 14 in to equation 10,

$$hA(T_i - T_o) + \varepsilon \sigma A(T_i^4 - T_o^4) - P_v = 0 \tag{15}$$

The inside air temperature T_i can be found from the above equation.

Note: The temperature should be used in absolute Kelvin unit.

$$T\ (°C) + 273 = T\ (K)$$

3.1 Method of Solution

Since the temperature in equation 10 is non-linear, the solution can be obtained by the Newton-Raphson method. The Newton-Raphson method uses an iterative process to approach one root of a function. The specific root that the process locates depends on the initial, arbitrarily chosen x-value.

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{16}$$

Here, x_n is the current known x-value, $f(x_n)$ represents the value of the function at x_n, and $f'(x_n)$ is the derivative (slope) at x_n. x_{n+1} represent the next x-value that you are trying to find. Essentially, f'(x), the derivative represents f(x)/dx (dx = delta-x). Therefore, the term f(x)/f'(x) represents a value of dx.

$$\frac{f(x)}{f'(x)} = \frac{f(x)}{f(x)/\Delta x} = \Delta x \tag{17}$$

The equation 8 can be re written as

$$C_1\left(T_i T_0\right) + C_2\left(T_i^4 - T_o^4\right) - P_v = 0 \tag{18}$$

where

$$C_1 = hA \tag{19}$$

$$C_2 = \varepsilon \sigma A \tag{20}$$

Let,

$$f(T_i) = C_1(T_i - T_o) + C_2(T_i^4 - T_o^4) - P_v \tag{21}$$

$$f'(T_i) = C_1 + 4C_2 T_i^3 f' \tag{22}$$

For the first iteration, make a guess for T_i which should be $>= T_o$

3.2 Sample Calculations

Input data:

Inputs	
Ambient temperature	85°C
Length of enclosure	100 mm
Width of enclosure	100 mm
Height of enclosure	50 mm
Emissivity of enclosure	0.1
Convective heat transfer co-efficient	5 W/m²K
Power dissipation	10 W

Calculations:

a = 2x (100x100) + (100x50) + (100x50)/10^{-6}
= 0.04 m^2

C_1 = 0.2 W/K

C_2 = 2.268 x 10^{-10} W/K^4

Let $T_{i,0}$ = 90°C

Applying the Newton-Raphson method,

$T_{i,0}$ = 90°C

$T_{i,1}$ = 126.104°C

$T_{i,2}$ = 125.1353°C

$T_{i,3}$ = 125.1345°C

$T_{i,4}$ = 125.1345°C

Since there is no variation between $T_{i,3}$ & $T_{i,4,}$ we can stop the iteration at this point.

4. Results and Discussions

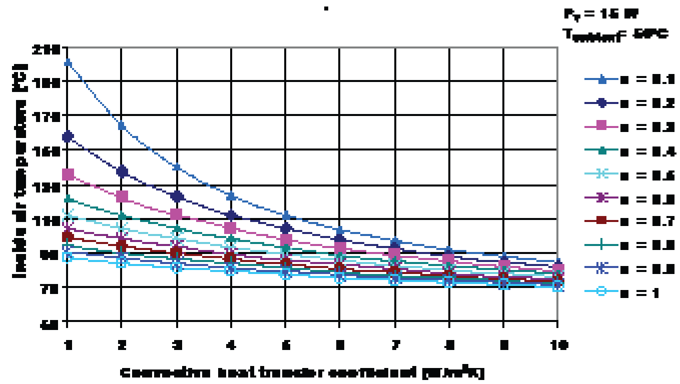

Figure 2. Effect of Emissivity and Convective Heat Transfer Co-Efficient On Inside Air Temperature for Ambient Temperature of 50 °C.

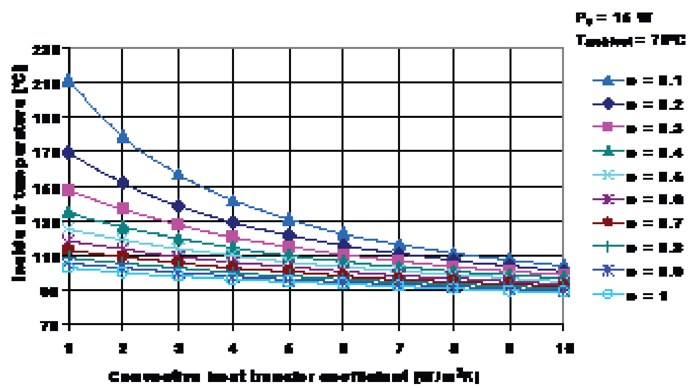

Figure 3. Effect of Emissivity and Convective Heat Transfer Co-Efficient On Inside Air Temperature for Ambient Temperature of 70 °C.

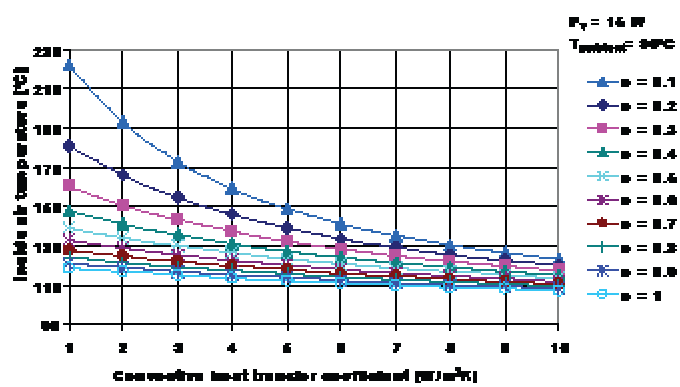

Figure 4. Effect of emissivity and convective heat transfer co-efficient on inside air temperature for ambient temperature of 90 °C.

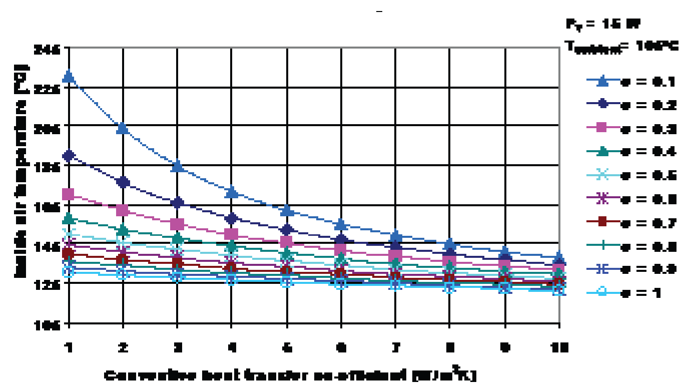

Figure 5. Effect of emissivity and convective heat transfer co-efficient on inside air temperature for ambient temperature of 105 °C.

Figures 2 to 5 show the effect of convective heat transfer coefficient and emissivity on inside air temperature for constant power dissipation and different ambient temperatures. For a constant power dissipation and ambient temperature, the inside air temperature decreases as the convective heat transfer coefficient and emissivity increases. For a natural convection cooled enclosures, the inside air temperature can be reduced by choosing a material with high emissivity. If the convective heat transfer coefficient is increased, the effect of increasing emissivity is minimal. Also if lower the ambient temperature, lower the inside air temperature.

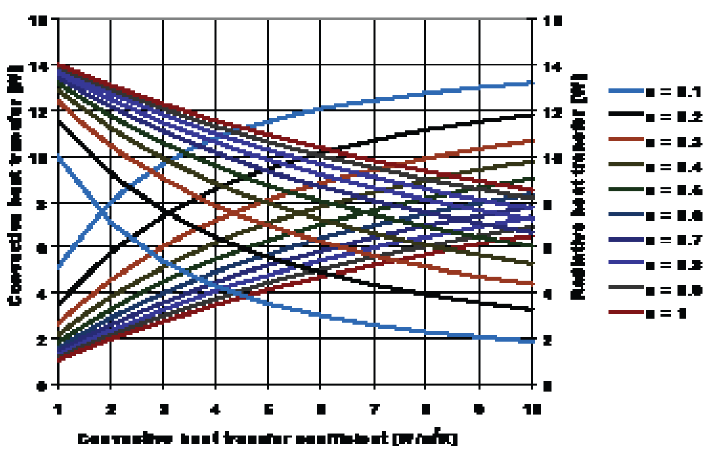

Figure 6. Effect of Emissivity and Convective Heat Transfer Co-efficient on Heat Transfer for Ambient Temperature of 105 °C, Power Dissipation of 15 W

Figure 6 shows the convective and radiative heat transfer for different convective heat transfer coefficient and emissivity. It is seen that the convective and radiative heat transfer increases as convective heat transfer coefficient and emissivity increases and vice versa.

5. Conclusions

This paper explains a method to calculate the inside air temperature of a sealed enclosure. The effect of emissivity and convective heat transfer coefficient on the inside air temperature was studied. The emissivity was varied from 0 to 1 and the convective heat transfer coefficient was changed from 1 W/m^{2}K to 10 W/m^{2}K. It is observed that variation of emissivity and convective heat transfer coefficient has significant effect on the inside air temperature.

References:

1. Incropere, F.R., and Dewitt, D.P., Fundamentals of Heat and Mass transfer, 5th ed., John Wiley & Sons, New York.
2. Holman, J.P., Heat Transfer, 8th SI Metric edition, McGraw-Hill Higher Education, New York.

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