Technical Note
August 1997

Thermal Management for High-Power Board-Mounted Power Modules

Introduction

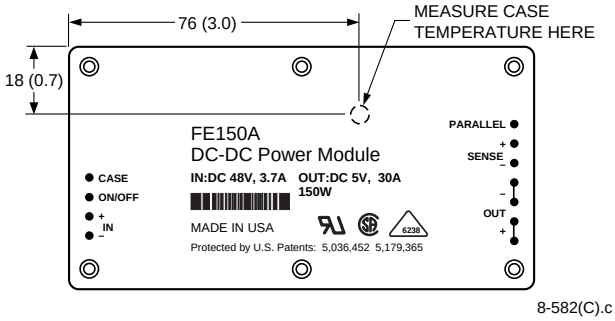
Board-mounted power modules (BMPMs) enhance the capabilities of advanced computer and communications systems by providing flexible power architectures; however, proper cooling of the power modules is required for reliable and consistent operation. Maintaining the operating case temperature (T_C) within the specified range keeps internal-component temperatures within their specifications, which, in turn, helps keep the expected mean time between failures (MTBF) from falling below the specified rating.

Tyco's FC-, FE-, and FW-Series 50 W to 200 W BMPMs are designed with high efficiency as a primary goal. The 5 V output units have typical full-load efficiencies greater than 80%, which result in less heat dissipation and lower module case temperatures. Furthermore, these modules use temperature-resistant components, such as ceramic capacitors, that do not degrade during prolonged exposure to high temperatures, as do aluminum electrolytic capacitors.

This application note provides the information to verify that adequate cooling is present in a given operating environment. A thermal model is included that can be used to design heat sinks and other means for meeting the cooling and reliability requirements for a given application. The information can be applied to all Tyco high-power BMPMs in the 121.9 mm x 63.5 mm x 12.7 mm (4.8 in. x 2.5 in. x 0.5 in.) package.

Basic Thermal Management

Proper cooling can be verified by measuring the T_C of the module at the location indicated in Figure 1. T_C must not exceed 95 °C (85 °C for 200 W modules) while operating in the final system configuration. After the module has reached thermal equilibrium, the measurement can be made with a thermocouple or surface probe. If a heat sink is mounted to the case, make the measurement on the base of the heat sink as close as possible to the indicated position, taking into account the contact resistance between the mounting surface and the heat sink (see Detailed Thermal Model section).



Note: Top view, pin locations are for reference.
Dimensions shown in millimeters and (inches).

Figure 1. Case Temperature Measurement

While this is a valid method to check for proper thermal management, it makes the assumption that the final system configuration exists and can be used for a test environment or can be modeled. The following graphs provide guidelines to predict the thermal performance of the module for typical configurations that include heat sinks in natural or forced-airflow environments.

The goal of thermal management is to transfer the heat dissipated by the module to the surrounding environment. The amount of power dissipated by the module as heat (P_D) is the difference between the input power (P_I) and output power (P_O) as shown by the equation below:

$$P_D = P_I - P_O$$

Also, module efficiency (η) is defined as the ratio of output power to input power, shown by the following equation:

$$\eta = \frac{P_O}{P_I}$$

The input power term can be eliminated by combining these two equations. They yield the equation below, which can be used to calculate module power dissipation:

$$P_D = \frac{P_O(1-\eta)}{\eta}$$

Basic Thermal Management (continued)

However, efficiency is a nonlinear function of the module input voltage (V_I) and output current (I_O). Typically, a plot of power dissipation versus output current over three different line voltages is given in each module-specific data sheet. This is because each power module output voltage has a different power dissipation curve. The typical curves of P_D vs. I_O for three input voltages for the FE150A Power Module are shown in Figure 2.

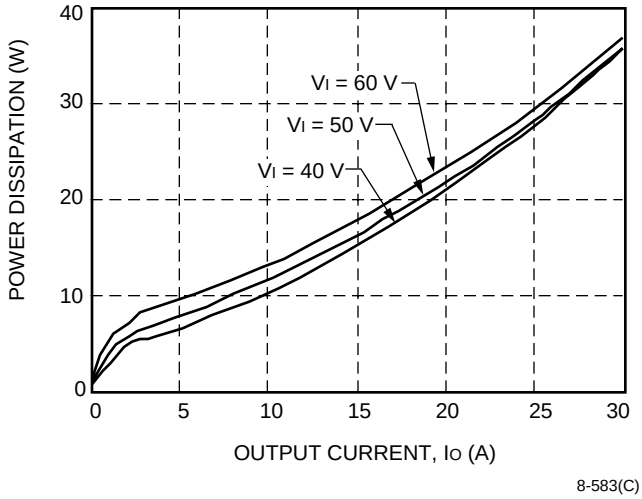


Figure 2. FE150A Power Dissipation as Heat vs. Output Load

Module Derating

200 Watt Power Modules

Please see module specific data sheets for the FE200 and FW200 Series BMPMs. These modules have an 85 °C maximum case temperature.

Forced Convection Without Heat Sinks

Increasing the airflow over the module improves cooling. Figure 3 shows power derating vs. local ambient temperature (T_A) at airflows from natural convection to 4.0 m/s (800 ft./min.)

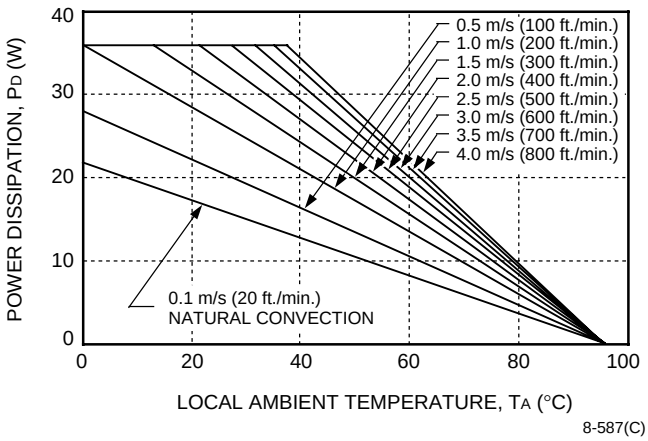


Figure 3. Forced Convection Derating Without Heat Sinks

The curves in Figure 3 were obtained from measurements made in a free stream of air approaching a vertically oriented module mounted on a printed-wiring board (PWB) in a rectangular passage, as shown in Figure 4.

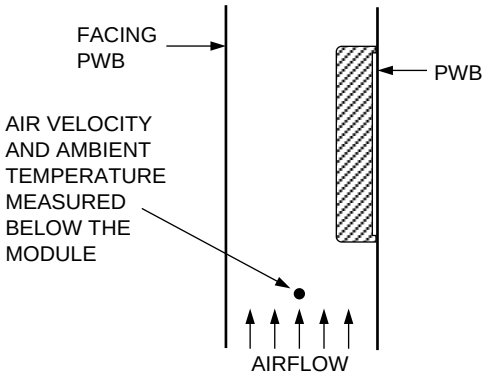


Figure 4. Location for Measurements

Figure 3 can be used to determine the appropriate airflow for a given set of operating conditions. For example, at P_D = 20 W and T_A = 40 °C, an airflow of 1.0 m/s (200 ft./min.) is sufficient to keep the module within its ratings.

Heat Sinks

Several standard heat sinks are available for high-power BMPMs, as shown in Figures 5 and 6 with their respective thermal resistances for natural convection. The heat sinks mount to the top surface of the module using #4-40 hardware torqued to 0.56 N-m (5 in.-lb.) Placing a thermally conductive dry pad or thermal grease between the case and the heat sink minimizes contact resistance and temperature drop.

Module Derating (continued)

Heat Sinks (continued)

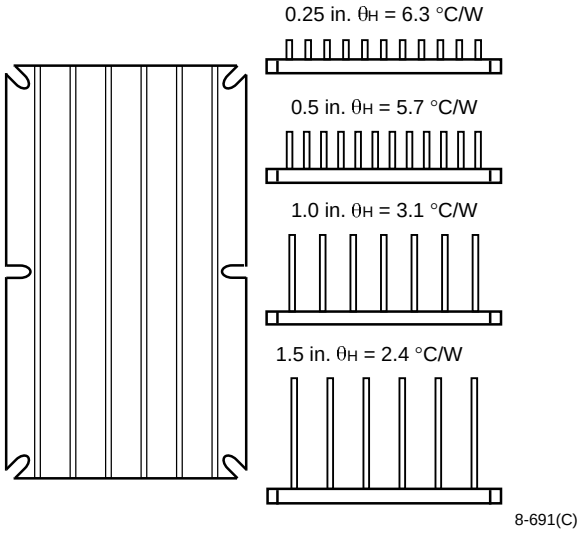


Figure 5. Heat Sink with Fins Oriented Along Length

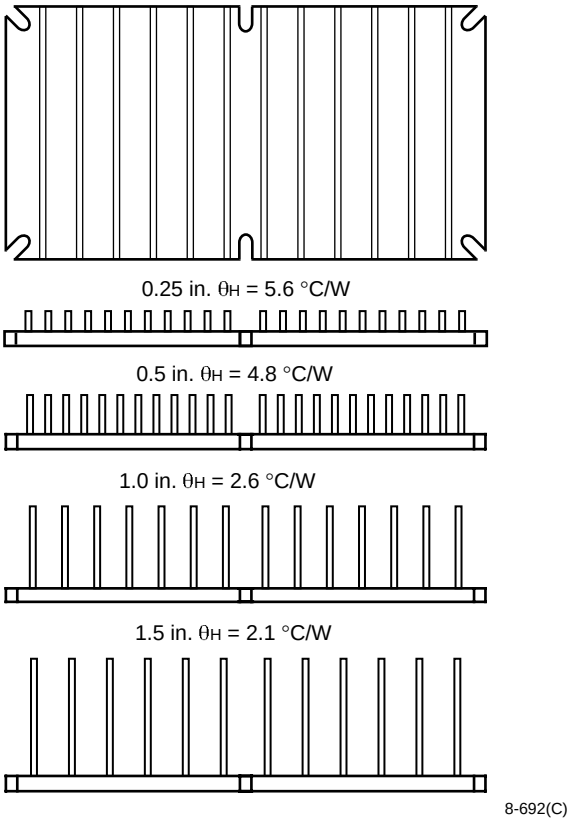


Figure 6. Heat Sink with Fins Oriented Along Width

Natural Convection with Heat Sink

Figures 7 and 8 represent power derating for a module in natural convection with the heat sinks shown in Figures 5 and 6. Natural convection is the airflow produced when air in contact with a hot surface is heated, causing it to rise. An open environment is required with no external forces moving the air. Figures 7 and 8 apply when the module is the only source of heat present in the system.

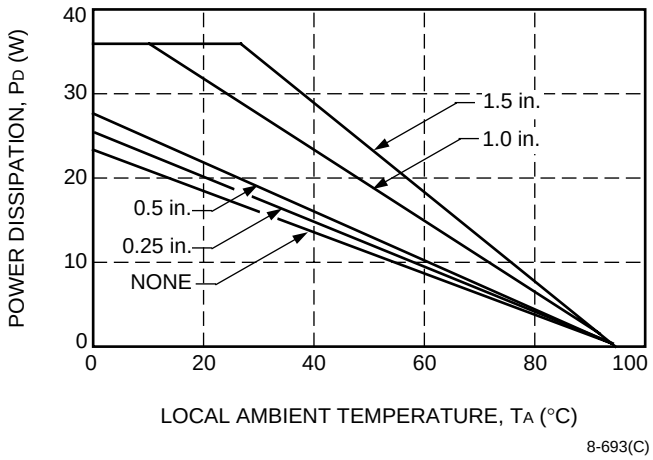


Figure 7. Heat-Sink Derating Curves; Natural Convection; Fins Oriented Along Length

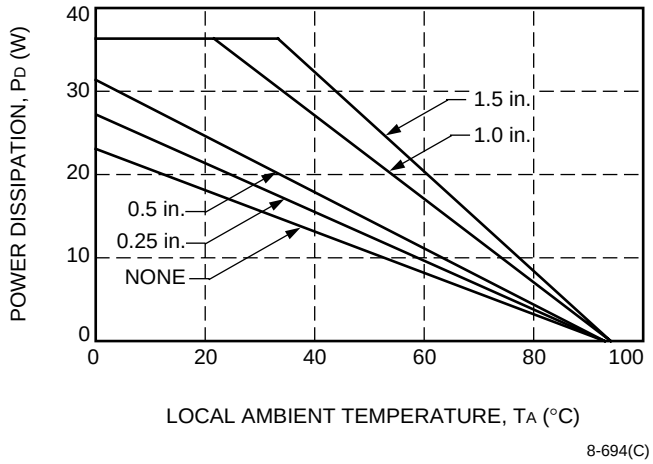


Figure 8. Heat-Sink Derating Curves; Natural Convection; Fins Oriented Along Width

With a known P_D and T_A, the appropriate heat sink can be chosen from the derating curves. For example, if P_D = 20 W and T_A = 30 °C with the heat sink oriented along the width, the 0.5 in. heat sink would keep the module within its temperature rating.

Basic Thermal Model

Another approach for analyzing thermal performance is to model the overall thermal resistance of the module. Total thermal resistance (θ) is defined as the maximum case temperature rise ($\Delta T_{C,\,max}$) divided by the P_D of the module:

$$\theta = \frac{\Delta T_{C,\,max}}{P_D}$$

where: θ = total thermal resistance
$\Delta T_{C,\,max}$ = maximum case temperature rise
P_D = power dissipated as heat

This can be represented by the simplified model shown in Figure 9. In this model, P_D, $\Delta T_{C,\,max}$, and θ are analogous to current flow, voltage drop, and electrical resistance, respectively, in Ohm's law.

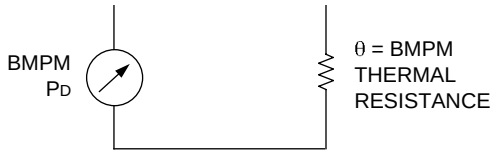


Figure 9. Basic Thermal-Resistance Model

For FE-, FC-, and FW-Series 50 W to 200 W BMPMs, the thermal-resistance value vs. air velocity has been determined experimentally and is plotted in Figures 10 and 11 for a unit without a heat sink and with six of the heat sinks mentioned in the previous section. Note that the highest values on the curves represent natural convection. In a system with free-flowing air and other heat sources, there may be additional airflow.

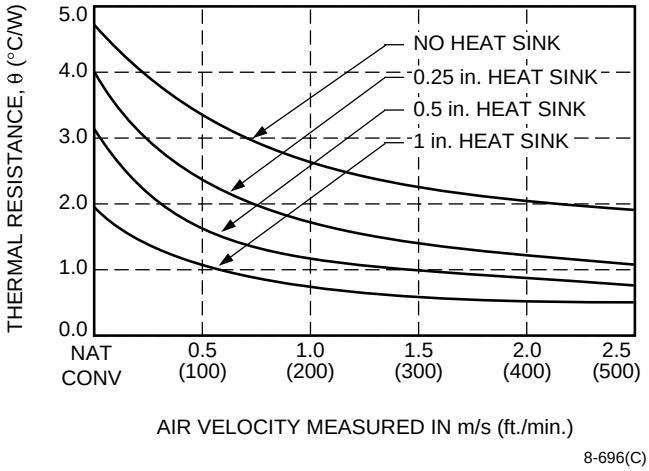


Figure 10. Heat-Sink Resistance Curves; Fins Oriented Along Width

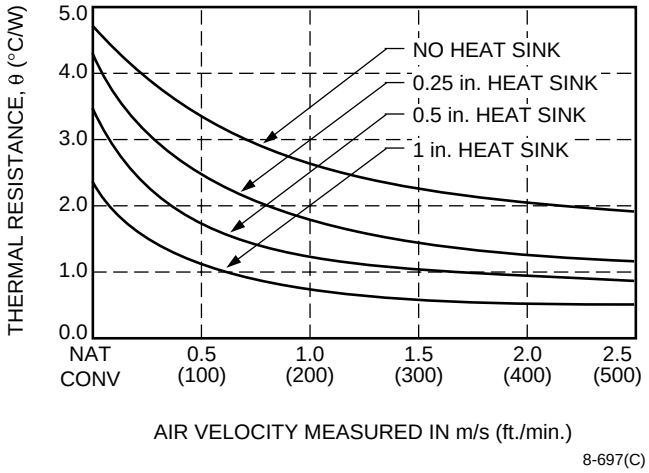


Figure 11. Heat-Sink Resistance Curves; Fins Oriented Along Length

Use an airflow measurement just upstream from the module when determining θ from these curves (see Figure 4).

The following examples illustrate how the curves can be used to determine thermal performance under various airflow and heat-sink configurations.

Example A. Airflow Required to Maintain T_C

An FC150A operates at I_O = 20 A and T_A = 50 °C with no heat sink. Determine the airflow required to maintain $T_{C,\,max}$ = 95 °C.

$P_D \approx 22.5$ W for the FC150A; therefore, the necessary thermal resistance (θ) is:

$$\theta = \left[\frac{(T_{C,\,max} - T_A)}{P_D}\right]$$

$$\theta = \left[\frac{(95 - 50)}{22.5}\right]$$

$$\theta = 2\ °C/W$$

From Figure 10, the required airflow is 2.2 m/s (440 ft./min.)

Basic Thermal Model (continued)

Example B. Determining T_C

If an airflow of only 0.75 m/s (150 ft./min.) is available for the same arrangement as in Example A, determine T_C when using the 0.5 in. heat sink oriented along the length.

From Figure 11, $\theta \approx 1.3$ °C/W; therefore, ΔT_C is:

$$\Delta T_C = P_D (\theta)$$
$$\Delta T_C = 22.5 (1.3)$$
$$\Delta T_C = 29.3 \text{ °C}$$

and T_C is:

$$T_C = T_A + \Delta T_C$$
$$T_C = 50 + 29.3$$
$$T_C = 79.3 \text{ °C}$$

Detailed Thermal Model

Thermal resistance in the previous section includes heat transfer by conduction, convection, and radiation from the entire module to the surrounding environment. Typically, the power module is soldered to a vertically oriented PWB as shown in Figure 4. Although most of the heat is transferred by convection and radiation from the top mounting surface of the module, significant amounts of heat are also removed by convection from the sides of the module, and by conduction to the PWB and then convection off of the opposite side of the PWB. Heat flow paths in this configuration are shown in Figure 12.

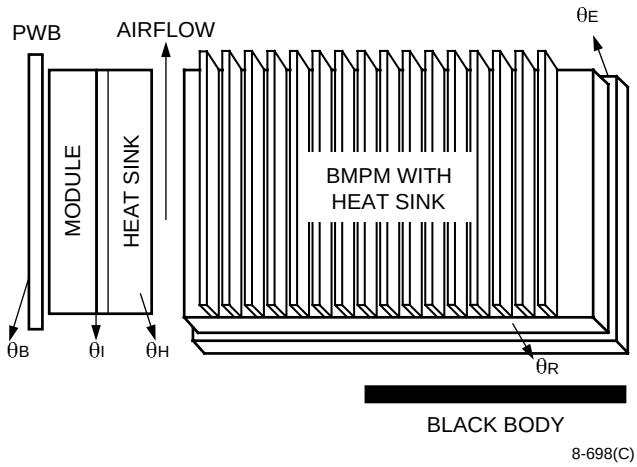


Figure 12. Boundaries Contributing to Thermal Resistance

θ_T = Convection resistance from module top to ambient

θ_B = Convection and conduction resistance from module bottom to ambient

θ_E = Convection resistance from edge to ambient

θ_H = Convection resistance from heat sink to ambient

θ_R = Radiation resistance for entire module

θ_I = Contact (interface) resistance

When a heat sink is mounted to the top surface of a module, θ_T is equivalent to the sum of θ_H and θ_I:

$$\theta_T = \theta_H + \theta_I$$

Several types of heat transfer cool the module. In a fan-cooled environment, convection is the predominant mode of heat transfer. Radiation is also important, especially in natural convection. Conduction is important when using unusual heat sinks or cold-plate methods of cooling.

Convection Heat Transfer

Convection heat transfer is a function of the surface area, ΔT_C, and the heat transfer coefficient. A simplified approach to convection cooling over a flat plate leads to the following relationship:

$$\theta \approx \frac{c}{V^{0.5}}$$

where: θ = thermal resistance
c = surface-dependent constant
v = airflow in m/s

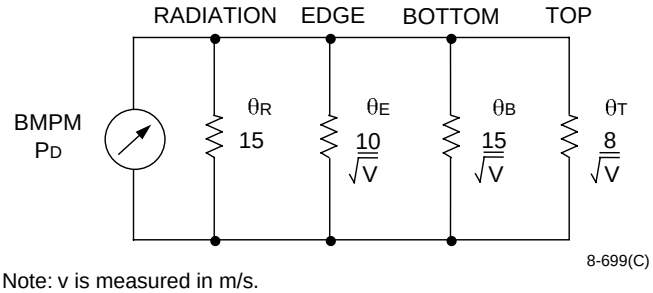
Radiation Heat Transfer

Radiation is not dependent upon the airflow over the module, but on the temperature difference between the module and the surrounding environment. For a particular module type, θ due to radiation can be determined experimentally. For example, Tyco's high-power modules operating at T_C = 95 °C and T_A = 25 °C, result in $\theta_R \approx 15$ °C/W.

Detailed Thermal Model (continued)

Detailed Thermal-Resistance Model

Thermal resistances can be represented in an electrical analogy as resistances in parallel (see Figure 13). This model is valid for forced convection. Natural convection can be estimated using v = 0.25 m/s (50 ft./min.) for open environments with no additional heat sources.



Note: v is measured in m/s.

Figure 13. Detailed Thermal-Resistance Model

The following examples illustrate how this detailed model can be used to solve specific thermal problems and to analyze unusual thermal applications.

Example C. Custom Heat-Sink Design

An FE150H is operated at P_O =150 W with natural convection and T_A = 50 °C. $\theta_R \approx$ 30 °C/W represents the radiation thermal resistance from the sides and back, and θ_I = 0.15 °C/W is a conservative value for the contact resistance between the heat sink and the mounting surface. Determine the thermal resistance of the smallest heat sink required for this application.

Using the data sheet for the FE150H, $P_D \approx$ 24 W is calculated. In order to maintain $T_{C,\,max}$ = 95 °C, the overall module resistance must be:

$$\theta = \left[\frac{(T_{C,\,max} - T_A)}{P_D}\right]$$

$$\theta = \left[\frac{(95 - 50)}{24}\right]$$

$$\theta = 1.9\ °C/W$$

From Figure 13, the equivalent resistance to heat flow from other than the top surface of the module is:

$\theta_{other} = \theta_R \,||\, \theta_E \,||\, \theta_B$
$\theta_{other} = 1/(1/\theta_R + 1/\theta_E + 1/\theta_B)$
$\theta_{other} = 1/(1/30 + 1/20 + 1/30)$
$\theta_{other} = 8.6$ °C/W

The thermal resistance for heat flow off of the top surface of the module should be:

$\theta_T = 1/(1/\theta_{total} - 1/\theta_{other})$
$\theta_T = 1/(1/1.9 - 1/8.6)$
$\theta_T = 2.4$ °C/W

And the heat sink requires a thermal resistance of:

$\theta_H = \theta_T - \theta_I$
$\theta_H = 2.4 - 0.15$
$\theta_H = 2.25$ °C/W

Example D. Contact Resistance

Using the module and heat sink selected in Example C, determine the temperature drop from the surface of the module to the heat sink.

First determine the heat flow through the top surface of the module. This is given by:

$P_{D,\,top} = (T_{C,\,max} - T_A)/\theta_T$
$P_{D,\,top} = (95 - 50)/2.4$
$P_{D,\,top} = 18.8$ W

The temperature drop is heat flow multiplied by the resistance:

$\Delta T = P_{D,\,top}(\theta_I)$
$\Delta T = 18.8(0.15)$
$\Delta T = 2.8$ °C

Therefore, to keep the module from overheating, do not allow the temperature on the top surface of the heat sink to exceed:

$T_H = T_{C,\,max} - \Delta T$
$T_H = 95 - 2.8$
$T_H = 92.2$ °C

The contact resistance between the top surface of the module and the heat sink should not be allowed to exceed 0.2 °C/W. Typically, with an appropriate dry pad, θ_I < 0.15 °C/W.

Detailed Thermal Model (continued)

Conduction Through a Cold Plate

In some instances, heat can be removed from the top surface of the module by conduction through a solid object. One-dimensional conduction heat transfer can be expressed as:

$$\theta = L/kA$$

where: θ = thermal resistance
L = heat travel distance hot to cold (m)
k = material conductivity (W/m • °C)
A = material cross-section area (m^2)

For example, an FE150A operating at I_O = 30 A and T_A = 40 °C in natural convection is mounted to a copper base plate that conducts heat to a cooling surface held at 40 °C (T_{CS}). The base plate cross-section is 0.000806 m^2, its length is 0.127 m and k = 380W/m • °C. From the efficiency curves, P_D = 33 W. Determine the case temperature (T_C).

The thermal resistance of the base plate is:

$$\theta_{BP} = L/kA$$
$$\theta_{BP} = 0.127/(380 \bullet 0.000806)$$
$$\theta_{BP} = 0.4\ °C/W$$

So the overall module resistance is:

$$\theta_{total} = \theta_{other} \parallel \theta_{BP}$$
$$\theta_{total} = 1/(1/\theta_{other} + 1/\theta_{BP})$$
$$\theta_{total} = 1/(1/8.6 + 1/0.4)$$
$$\theta_{total} = 0.4\ °C/W$$

And T_C is:

$$T_C = T_{CS} + P_D(\theta_{total})$$
$$T_C = 40 + 33(0.4)$$
$$T_C = 53.2\ °C$$

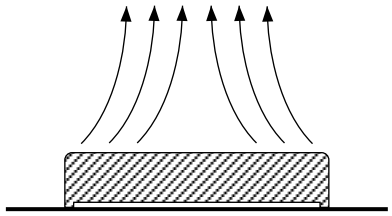
In this example, thermal resistance from the top surface is low enough that other resistances are negligible when computing overall resistance.

Operation in Narrow Spaces

Figure 4 shows the typical mounting configuration with the module oriented vertically in a rectangular passage. When clearance between the facing board and the top surface of the module is reduced, airflow between these two surfaces drops, thereby lowering the heat transfer. This increases the value of θ_T. Flow interference begins when the clearance approaches the boundary layer thickness on the top surface of the module. When operating the module in tight spacing, make a calculation of the boundary layer thickness and use a higher value of θ_T, if necessary, when calculating θ_{total}. For assistance, contact a Tyco Application Engineer.

Horizontal Orientation

In some applications, the module is operated in natural convection and oriented horizontally as shown in Figure 14. In this situation, use θ_{total} = 4.8 °C/W for overall module thermal resistance.



8-700(C)

Figure 14. Horizontal Orientation



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