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AN-9071

Smart Power Module, Motion SPM® 45 Series Thermal Performance Information

Thermal Impedance

Overview

Semiconductor devices are very sensitive to junction temperature. As the junction temperature increases, the operating characteristics of a device are altered from normal and the failure rate increases exponentially. This makes the thermal design of the package a very important factor in the device development stage and in an application field.

To gain insight into the device's thermal performance, it is normal to introduce thermal resistance, which is defined as the difference in temperature between two adjacent isothermal surfaces divided by the total heat flow between them. For semiconductor devices, the two temperatures are junction temperature, T_J, and reference temperature, T_x. The amount of heat flow is equal to the power dissipation of a device during operation. The selection of reference point is arbitrary, but usually the hottest spot on the back of a device on which a heat sink is attached is chosen. This is called junction-to-case thermal resistance, $R_{\theta JC}$. When the reference point is an ambient temperature, this is called junction-to-ambient thermal resistance, $R_{\theta JA}$. Both the thermal resistances are used for the characterization of a device's thermal performance. $R_{\theta JC}$ is usually used for heat sink carrying devices, while $R_{\theta JA}$ is used in other cases. Figure 1 shows a thermal network of heat flow from junction-to-ambient for the SPM, including a heat sink. The dotted component of $R_{\theta CA}$ can be ignored due to its large value.

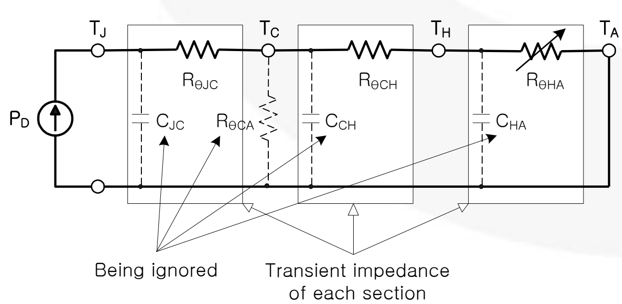

Figure 1. Transient Thermal Equivalent Circuit with a Heat Sink

The thermal resistance of the SPM is defined in the following equation:

$$R_{\theta JC} = \frac{T_J - T_C}{P_D} \quad (1)$$

where $R_{\theta JC}$ (°C/W) is the junction-to-case thermal resistance and P_D (W), T_J (°C), and T_C (°C) are power dissipation per device, junction temperature, and case reference temperature, respectively. By replacing T_C with T_A (ambient temperature), the junction-to-ambient thermal resistance $R_{\theta JA}$ can be obtained as:

$$R_{\theta JA} = \frac{T_J - T_A}{P_D} \quad (2)$$

where $R_{\theta JA}$ indicates the total thermal performance of the SPM including the heat sink. $R_{\theta JA}$ is a serial summation of various thermal resistances, $R_{\theta JC}$, $R_{\theta CH}$, and $R_{\theta HA}$:

$$R_{\theta JA} = R_{\theta JC} + R_{\theta CH} + R_{\theta HA} \quad (3)$$

where $R_{\theta CH}$ is contact thermal resistance due to the thermal grease between the package and the heat sink and $R_{\theta HA}$ is heat sink thermal resistance. From Equation 3, it is clear that minimizing $R_{\theta CH}$ and $R_{\theta HA}$ is an essential application factor to maximize the power carrying ability of the SPM, as well as the minimizing of $R_{\theta JC}$ itself. An infinite heat sink results if $R_{\theta CH}$ and $R_{\theta HA}$ are reduced to zero and the case temperature T_C is locked at the fixed ambient temperature T_A. Usually, the value of $R_{\theta CH}$ is proportional to the thermal grease thickness and governed by the skill at the assembly site; while $R_{\theta HA}$ can be handled, to some extent, by selecting an appropriate heat sink.

In practical application, the power loss P_D is cyclic and, therfore, the transient RC equivalent circuit shown in Figure 1 should be considered. For pulsed power loss, the thermal capacitance effect delays the rise in junction temperature and thus permits a heavier loading of the Motion SPM® 45 Series. Figure 2 through Figure 6 show the thermal impedance curves of FNA40560, FNA40860, FNA41060, FNA41560 and FNB43060Tx. The thermal resistance goes into saturation within about 1 second. Other kinds of Motion-SPM also show similar characteristics.

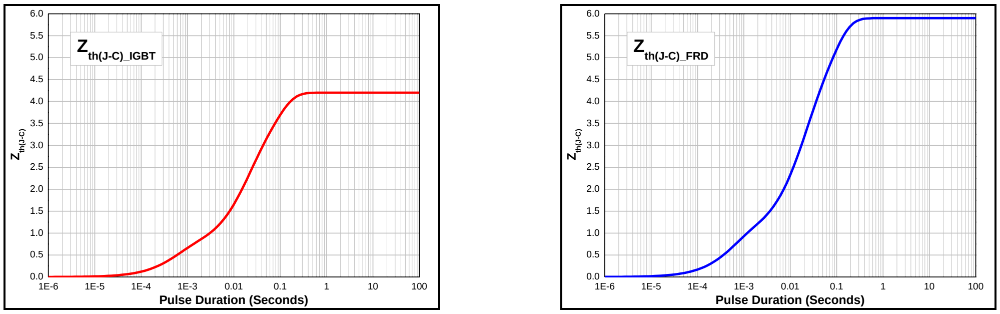

Figure 2. Thermal Impedance Curve of FNA40560

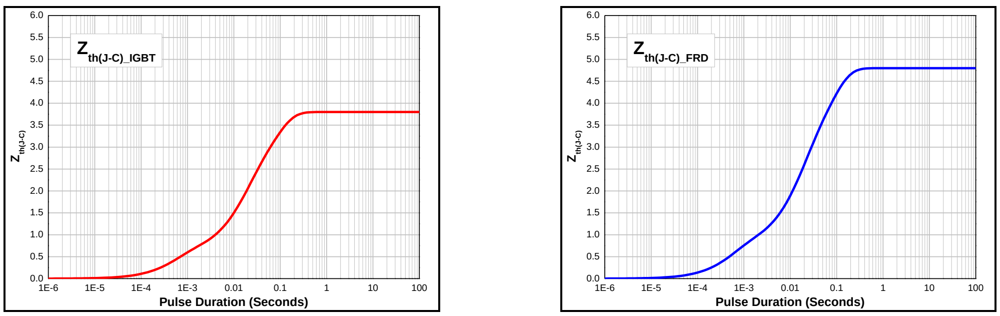

Figure 3. Thermal Impedance Curve of FNA40860

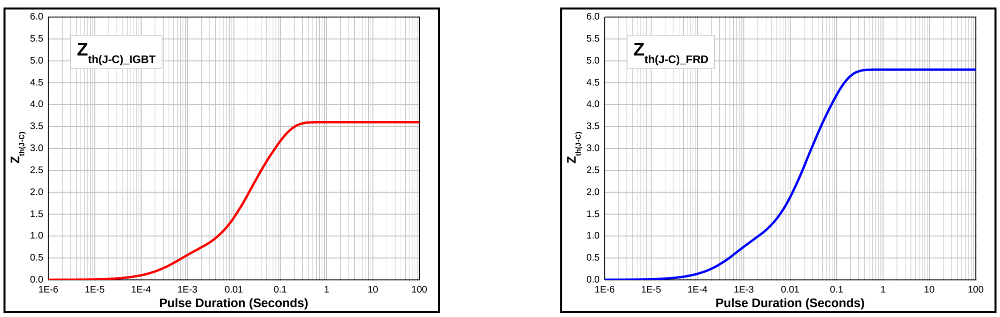

Figure 4. Thermal Impedance Curve of FNA41060

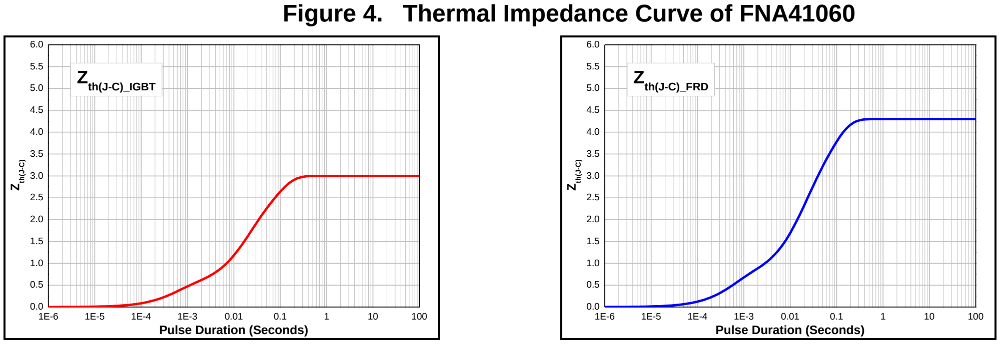

Figure 5. Thermal Impedance Curve of FNA41560

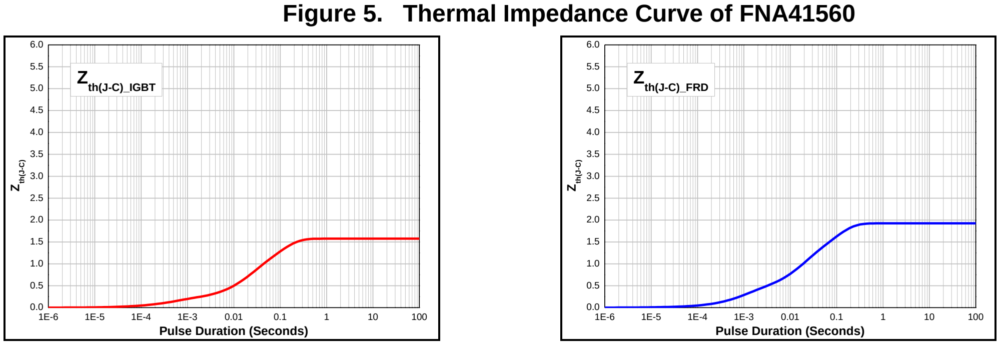

Figure 6. Thermal Impedance Curve of FNB43060Tx

Measurement Method

During the thermal resistance test, T_J, T_C (or T_A), and P_D should be measured. Since T_C, T_A, and P_D can be measured directly, the only unknown constant is the junction temperature, T_J. The Electrical Test Method (ETM) is widely used to measure the junction temperature. The ETM uses the relationship between forward drop voltage and junction temperature. This relationship is an intrinsic electro-thermal property of semiconductor junctions and is characterized by a nearly linear relationship between the forward-biased drop voltage and the junction temperature when a constant forward-biased current (sense current) is applied. This voltage drop of the junction is called Temperature Sensitive Parameter (TSP). Figure 7 illustrates the concept of measuring the voltage drop vs. junction temperature relationship for a diode junction. The device under test (DUT) is embedded in hot fluid to heat the DUT up to desired temperatures.

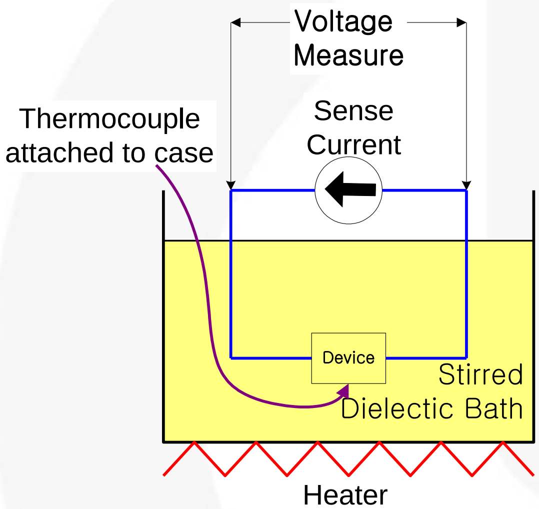

Figure 7. Illustration of the Bath Method for TSP Measurement

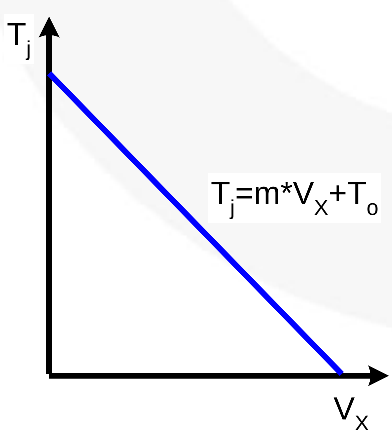

Figure 8. Typical Example of a TSP Plot with Constant-Sense Current

When the DUT attains thermal equilibrium with the hot fluid, a sense current is applied to the junction. Then the voltage drop across the junction is measured as a function of the junction temperatures. The amount of sense current should be small enough not to heat the DUT; for instance, 1mA, 10mA depending on the device type. The measurements are repeated over a specific temperature range with some specified temperature steps. Figure 8 shows a typical result.

The relationship between the junction temperature and voltage drop at a given temperature can be expressed as shown in the following equation:

$$T_J = m * V_X + T_O \tag{4}$$

The slope, *m (°C/V)*, and the temperature ordinate-intercept, T_o *(V)*, are used to quantify this straight line relationship. The reciprocal of the slope is often referred to as the "K factor *(V/°C)*". In this case, V_F *(V)* is the TSP. For semiconductor junctions, the slope *m* of the calibrating straight line in Figure 8 is always negative; i.e., the forward conduction voltage decreases with increasing junction temperature. This process of obtaining Equation 4 is called the calibration procedure for a given device.

During the thermal resistance measurement test, the junction temperature can be estimated by measuring the voltage drop at a given sense current during the calibration procedure and by using Equation 4. The TSP varies from device to device, since a specific device does not have the diode voltage TSP. However, the transistor saturation voltage can be used in that case. For instance, the gate turn-on voltage can be used as the TSP for an IGBT or a MOSFET.

Measurement Procedure

The thermal resistance test begins by applying a continuous power of known current and voltage to the DUT. The continuous power heats up the DUT to a thermally equilibrated state. While the device is heating, a continuous train of sampling pulses monitors the TSP; i.e., the voltage drop or the same as the junction temperature. The TSP sampling pulse must provide a sense current equal to that used during the calibration procedure for obtaining Equation 4. While monitoring the TSP, the applied power is adjusted to ensure a sufficient rise in T_J. Adjusting the applied power to achieve a T_J increase of about 100°C above the reference temperature generates enough temperature difference to ensure a good measurement resolution. A typical example is shown in Figure 9.

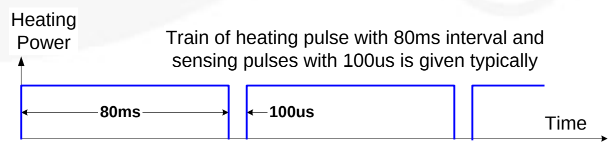

Figure 9. Example of a power and sample pulses train during the R_{JC} measurement of a SPM-IGBT

The TSP sampling time must be very short so as not to allow for any appreciable cooling of the junction prior to re-applying power. The power and sensing pulse train shown in Figure 9 has a duty cycle of 99.9%, which, for all practical purposes, is considered to be continuous power. Figure 10 illustrates that most of the total power is applied to the DUT.

Once T_J reaches thermal equilibrium; its value, along with the reference temperature T_C and applied power P, is recorded. Using the measured values and Equation 1, the junction-to-case thermal resistance $R_{\theta JC}$ can be estimated. $R_{\theta JC}$ here indicates the ability of a device to dissipate power in an ideal environment; that is, mounted with an infinite or temperature-controlled heat sink.

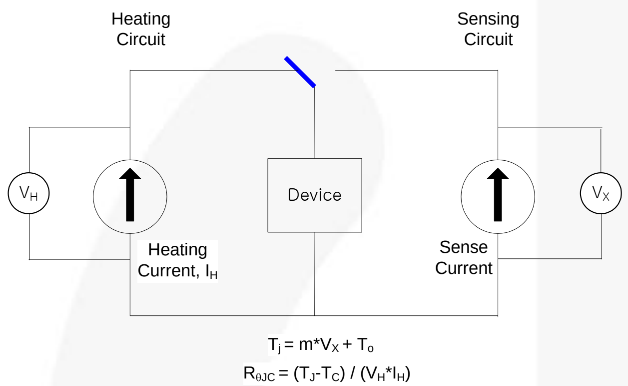

Figure 10. Illustration of the Thermal Resistance Test Method Concept

Figure 11 shows the thermal resistance measurement environment for SPMs. The SPM is placed on a heat sink with large heat carrying capacity. Thermal grease is applied between the SPM and heat sink to prevent an air gap.

A thermocouple is inserted through the heat sink and pressed against the underside of the SPM to record the SPM surface temperature. Although there is no stipulation on the thermocouple location on which the reference temperature (T_C here) needs to be measured, it is recommended that the ideal location is the hottest point. In this case, the SPM center or the heat sink center was chosen.

The thermocouple needs to make a good thermal contact with its reference location. Thermal grease and appropriate clamping pressure are needed as shown in Figure 11.

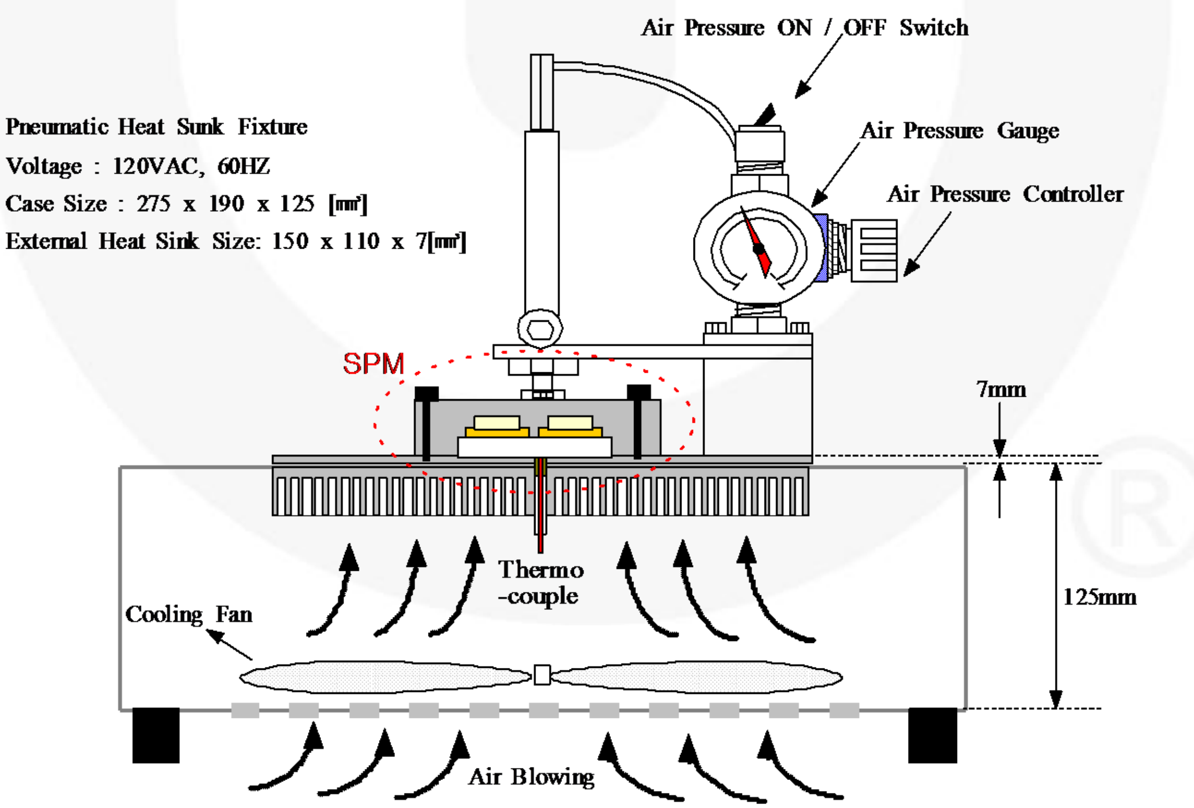

Figure 11. Thermal Measurement Environment of the SPM

Effective Load Current

The result of power loss simulation using the typical characteristics is shown in Figure 12 as "Effective Current vs. Carrier Frequency Characteristics." The conditions are:

Simulation Conditions

V_{PN}=300V, V_{CC}=V_{BS}=15V, $V_{CE(SAT)}$, $E_{SW(ON,OFF)}$=typical, T_J=150°C, T_C=125°C, $R_{\theta(J-C)}$=Max., M.I.=0.9, P.F=0.8, PWM=3-phase continuous PWM modulation, 60Hz sinusoidal waveform output.

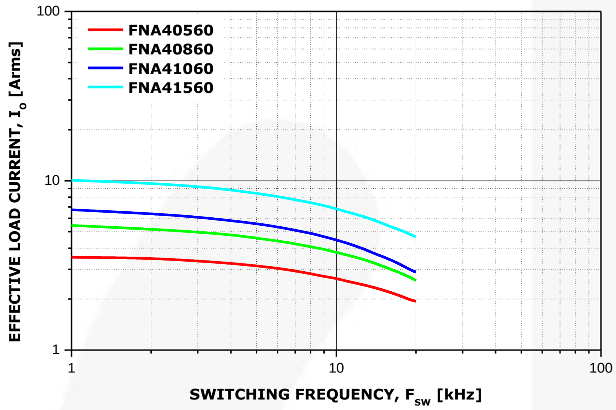

Figure 12. Effective Current－Carrier Frequency Characteristics

Note:

1. The above characteristics may vary in the different control schemes and motor drive types.

Figure 12 is an example of an inverter operated under the condition of T_C=125°C. It indicates the effective current, I_O, which can be outputted when the junction temperature T_J rises to the average junction temperature of 150°C (up to which, the Motion SPM® 45 Series operates safely).

Heat Sink Design Guide

The selection of heat sink is constrained by many factors; including set space, actual operating power dissipation, heat sink cost, flow condition around a heat sink, assembly location, etc. In this note, only some of the constraints are analyzed to give insights in heat sink selection from a practical application point of view.

Heat Sink for Use in Washing Machines

The type of heat sink is shown in Figure 13 can be applied under natural convection conditions in washing machine applications that have drive characteristics in which the power dissipated is alternatively high and low over periods of hundreds of milliseconds in the SPM.

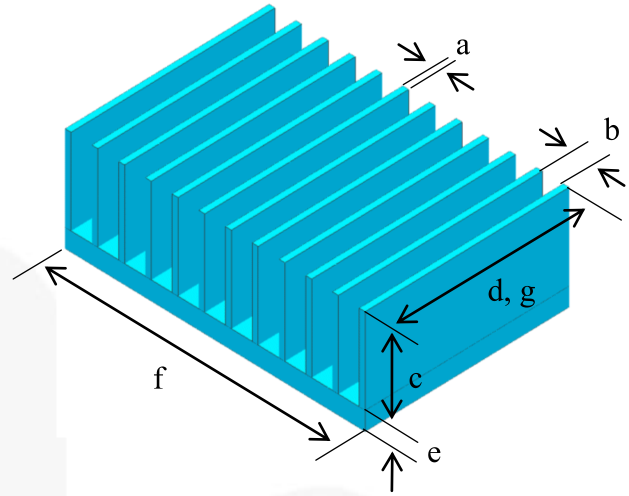

Figure 13. Heat Sink Example for Washing Machines

Notes:

2. a = Fin thickness, b = Fin spacing, c = Fin height, d = Fin length, e = Base-plate thickness, f = Base-plate width, g = Base-plate length.

Figure 10 through Figure 17 show the analysis results for the heat sink-to-ambient thermal resistance, $R_{\theta HA}$, in designing the heat sink. This varies widely with the changes in fin spacing, fin/base-plate length, and fin/base-plate width. It should be noted that the optimum fin spacing is approximately 4 or 5mm with a base-plate area of 73×53mm^2, as shown in Figure 14. Increasing the fin spacing results in a reduction of the total number of fins, i.e., the total convection area. Reducing the fin spacing interferes with the airflow field between the adjacent fins. This causes an increase in the thermal resistance when the fins are spaced below and above 4mm and 5mm, respectively. An increase in fin thickness decreases the total number of fins and the size of the heat sink, resulting in an increase in thermal resistance.

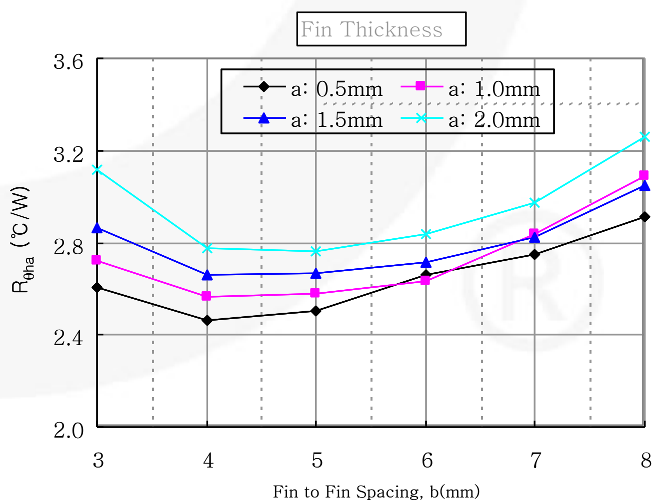

Figure 14. $R_{\theta HA}$ Variation by Change of the Fin Spacing (Constant: c=21mm, d=53mm, e=4mm, f=78mm, g=53mm)

Results in Figure 15 and Figure 16 show the effect of the base-plate length and width on thermal resistance. Note the increase in the length to 150% in Figure 15, that is 79.5mm (53mm×1.5), reduces the resistance to 85% (≅2.3 °C/W) and an increase of 200% (53mm×2=106mm) reduces the resistance to 78% (≅2.09 °C/W). Figure 16 is the result of the variation in the base-plate width and shows that the increase in the width to 150% (78mm×1.5=117mm) and 200% (78mm×2=156mm) reduces the resistance to 79% (≅2.144 °C/W) and 70% (≅1.88 °C/W), respectively. Therefore, increasing the width is more effective than increasing length for reducing the thermal resistance.

Figure 16 shows the thermal resistance variation with a change in the fin height.

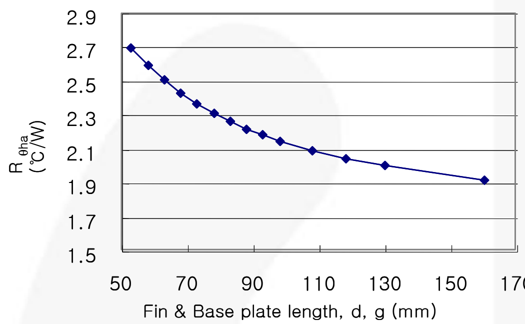

Figure 15. $R_{\theta HA}$ Variation by Change of the Base-plate Length (Content: a=1.5mm, b=5.45mm, c=21mm, e=4mm, f=78mm)

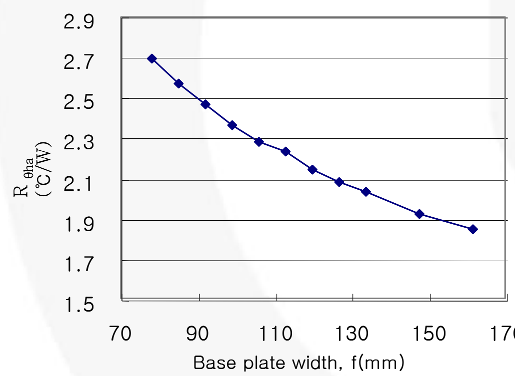

Figure 16. $R_{\theta HA}$ Variation by Change of the Base-plate Width (Constant: a=1.5mm, b=5.45mm, c=21mm, d=53mm, e=4mm, g=53mm)

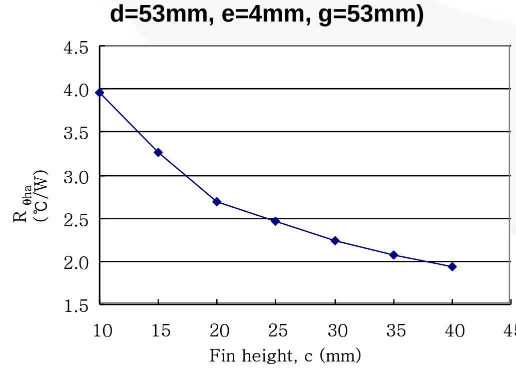

Figure 17. $R_{\theta HA}$ Variation by Change of the Fin Height (Constant: a=1.5mm, b=5.45mm, d=53mm, e=4mm, f=78mm, g=53mm)

Heat Sink for Use in Air-Conditioners

Inverters for air-conditioner applications need continuous power dissipation in the SPM, which are different from those used in washing machines. They generally use a heat sink with forced-convection using a fan for the SPM. Figure 18 shows the shape of a heat sink generally used in air conditioning systems. In this section, the airflow velocity effect on the thermal resistance is described based on using the heat sink shown in Figure 18.

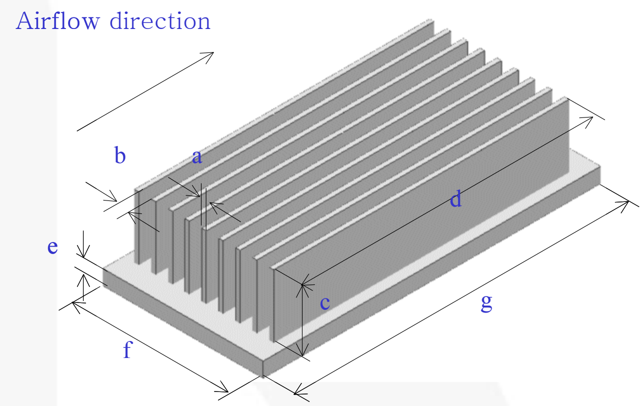

Figure 18. [Fig.3-6] Heat Sink Example for Air-Conditioner Applications (Constant: a= 2mm, b= 6mm, c= 30mm, d=140mm, e=7mm, f=76/100mm, g=160mm)

Figure 19 shows the airflow velocity effect on the resistance, $R_{\theta HA}$. Two kinds of heat sink base-plates are used and the reference values of the thermal resistance are around 1.4°C/W and 1.6°C/W, respectively, depending on the natural convection condition. The forced convection reduces the resistance approximately three times. In this case, the air velocity is about 2m/s. It is an optimal and cost-effective heat sink size. A fan having a velocity of 5m/s, reduces the resistance to 85% (≅0.25 °C/W).

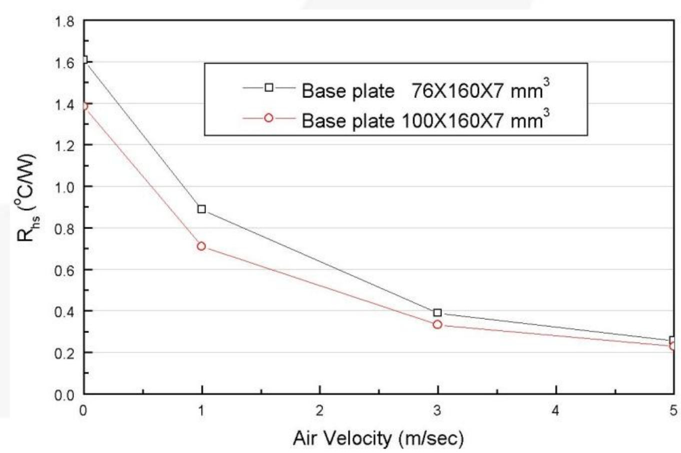

Figure 19. $R_{\theta HA}$ Variation by Change of Airflow Velocity

Related Resources

FNA40560 – Smart Power Module Motion SPM® 45

FNA40860 – Smart Power Module Motion SPM® 45

FNA41060 – Smart Power Module Motion SPM® 45

FNA41560 – Smart Power Module Motion SPM® 45

FNB40560 – Smart Power Module Motion SPM® 45

FNB41060 – Smart Power Module Motion SPM® 45

FNB41560 – Smart Power Module Motion SPM® 45

FNB43060Tx – Smart Power Module Motion SPM® 45

AN-9070 - Smart Power Module Motion SPM® 45 User Guide

AN-9072 - Smart Power Module Motion SPM® 45 Mounting Guide

Motion Control Design Tool

NOTE:
In this and other Fairchild documentation and collateral, the following terms are interchangeable:
DIP = Motion SPM® 2, Mini-DIP = Motion SPM® 3, Tiny-DIP = Motion SPM® 5, and µMini-DIP = Motion SPM® 45

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