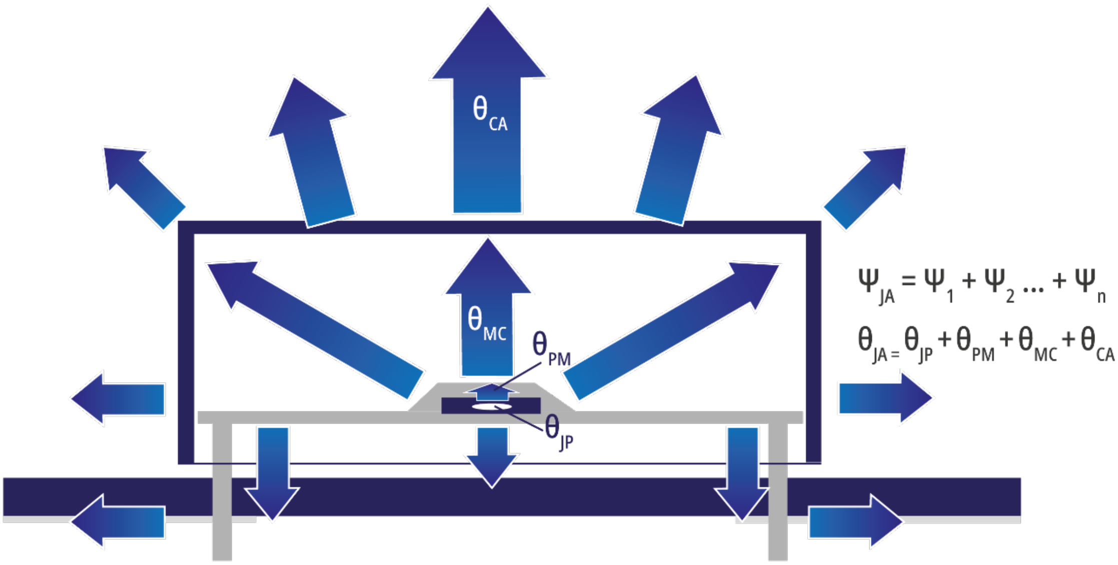
Whitepaper

Psi vs Theta



May 2021

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Introduction

A question often asked of RECOM technical support is, “What is the maximum operating temperature?” for a particular converter. Although there are several ways to determine this, it is still not an easy question to answer precisely. This is not because we don’t know how to characterise our products, but because the final answer depends on many different factors, many of which have nothing to do with the converter itself.

All operating power converters generate heat (caused by the internal power dissipation), which needs to escape the package to the ambient surroundings if the converter should not be overheating. Typical “hot spot” sources of heat are the power semiconductors such as transistors and diodes, which have switching junction losses, inductive components such as transformers and inductors that have both DC and AC losses and power resistors used in snubbers and filters with I^2R losses. The design engineer has to minimise these losses to maximise the efficiency of the converter, but they are unavoidable.

How the internal heat escapes from a hot junction inside a semiconductor package is also dependent on many factors. The shortest ‘path-of-least-resistance’ is typically from the junction to the top surface of the case or housing, but from there, the heat energy can escape to the surroundings by either convection, conduction or radiation. Furthermore, there could also be thermal conduction paths to the surroundings via a baseplate using heatsinks or gap-pads to the housing, through the mounting pins to the PCB itself or the sides or bottom surfaces of the converter case.

Depending on the setup, even the results from thermal measurements may differ significantly. For example, what is ‘free air convection’ cooling? Is the cooling flow of air completed unrestricted? Or could there be a local build-up of heat caused by closely positioned components, adjacent boards blocking the airflow or poorly ventilated cases? Additionally, are the thermal measurements done with ‘still air’ with zero LFM or with free-air movement (20 LFM) or with forced-air cooling (100 LFM)?

For board-mount converters, there may be other issues such as whether the board is mounted horizontally or vertically if the board is made from glass fibre (FR4) or uses a different substrate or what copper thickness is used for the tracks. All of these factors can affect the thermal performance of the parts mounted on the board.

Thermal Impedance, Θ

The classic way to calculate the maximum operating temperature is to use the thermal impedance figure (Theta or the symbol Θ). This essentially defines the path-of-least-resistance route, which the heat generates from a hot spot; for example, the junction of a switching transistor, travels out through the converter via thermal conduction and then convects away from the top surface to the ambient surroundings.

Diagrammatically, it can be shown as a series of thermal impedances: Θ_{JP} between the junction and the transistor packaging; Θ_{PM} packaging and the moulding material; Θ_{MC} the moulding material and the plastic or metal case and finally Θ_{CA} the case and ambient.

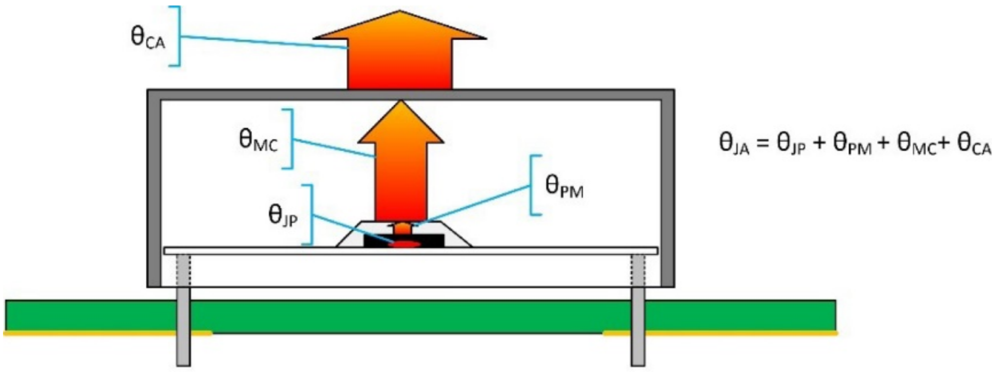

Figure 1: Theta junction-ambient thermal impedance model

Theoretically, it would be possible to find out or estimate all these different Theta values by studying the specifications of all of the different materials used in the part; but in practice, it is simpler to use the overall thermal impedance figure given in the manufacturer's datasheet to calculate the maximum operating ambient temperature.

Step 1: calculate the internal power dissipation, P_{diss}:

Eq.1 $P_{diss} = P_{in} - P_{out} = \frac{P_{out}}{\eta} - P_{out}$

Where η is the efficiency of the converter (use the figure given in the datasheet or, better still, use the efficiency/load graph to find out the operating efficiency at the load being used)

Step 2: calculate the case over-temperature, T_{over}

Eq.2 $T_{over} = R_{th}.P_{diss}$

Where R_{th} is the overall thermal impedance figure given in the datasheet (in Kelvin per Watt)

Step 3: calculate the maximum operating ambient temperature:

Eq.3 $T_{amb} = T_{case,max} - T_{over}$

Where $T_{case,max}$ is the maximum case (or baseplate) temperature given in the datasheet.

For example, from the RBBA3000-50 datasheet:

Take the RBBA3000-50 with 48V input voltage, 24V output voltage, 50A output current:

What is the maximum ambient operating temperature?

$T_{base,max} = 100°C, \ P_{out} = 1200W, \ \eta = 96\%, \ R_{th} = 1.2K/W$

From Eq.1: $P_{diss} = \frac{1200}{0.96} - 1200 = 50W$

From Eq.2: $T_{over} = 1.2 \ x \ 50 = 60K$

From Eq.3: $T_{amb} = 100 - 60 = +\mathbf{50°C}$.

Thermal Characterisation figure, ψ

The thermal characterisation figure (Psi or the symbol ψ) recognises that the path-of-least-resistance thermal impedance is not truly representative of the actual performance of many components. This is because there are usually multiple paths in which heat can be extracted from a hot spot – not least through the pins – in some converter designs, up to 30% of the internal heat can be extracted through the pins and thereafter dissipated via the PCB tracks and copper planes to ambient. As such, converters that use 3DPP® construction are designed so that the majority of the heat will be conducted away via the copper pads on the underside of the converter

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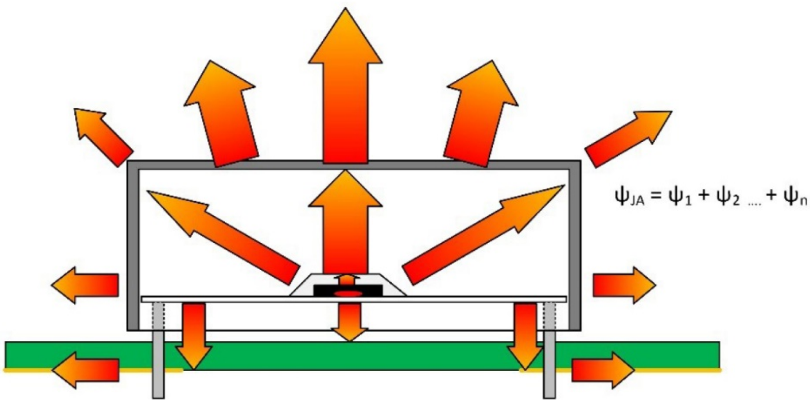

Figure 2: Psi Thermal characterisation multiple thermal path model

In general, ψ_{JA} is lower than Θ_{JA}, but depending on the thermal design of the converter and PCB layout, it can be much lower.

RECOM does not give ψ_{JA} values in our datasheets because the figure would be meaningless without including the factors arising from the customer's PCB and how the application is mounted and used.

However, where we know from experience or from the design of the converter that multiple thermal paths occur, we can test in a thermal chamber to determine a thermal impedance value that is closer to the thermal characteristic parameter. In this way, the same calculation as described above can be used, even when multiple thermal paths exist.

Experimental Measurement of Θ/ψ (example for a 2"x1" metal-cased converter)

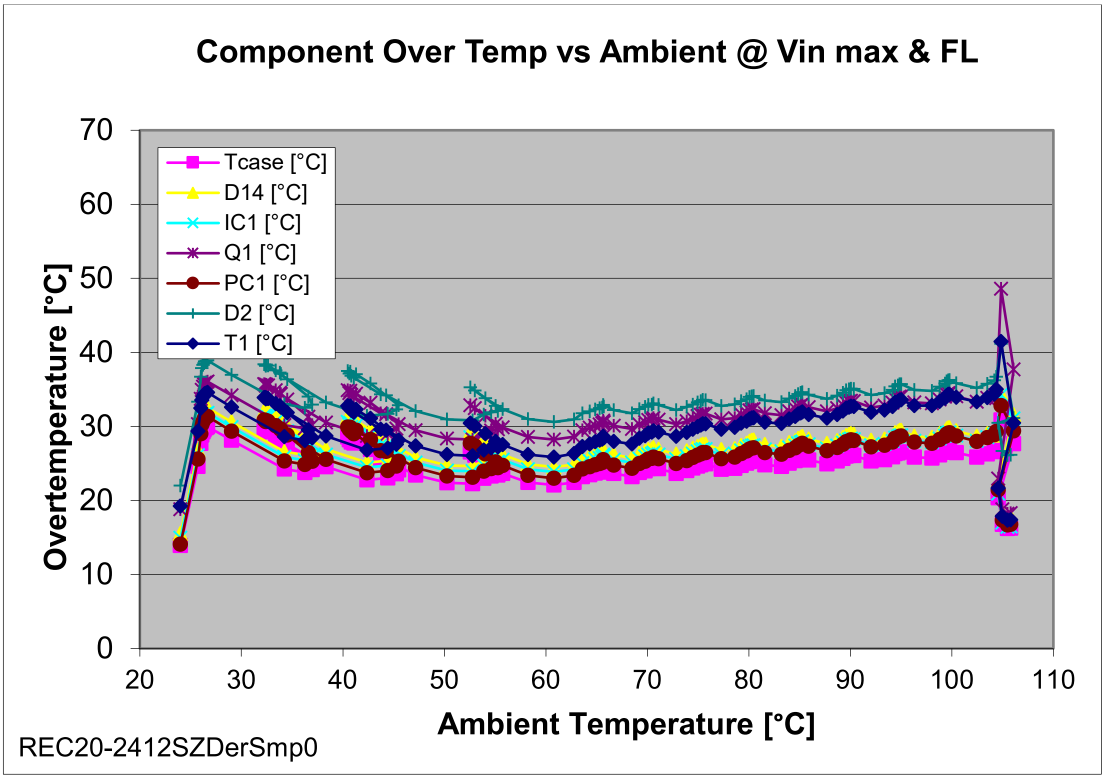

Figure 3: Over-temperature graph for a 2"x1" converter

In this test procedure, design limits were defined for the maximum component operating temperature – for example, the rule-of-thumb for semiconductors as that their packaging surface temperature should not exceed 120–125°C, that the PCB can typically withstand 120°C, while the core temperature of the transformer may not exceed 130–150°C, depending on the type. An open frame version of the converter was contactlessly tested at room temperature with an IR camera to record the case temperature as a reference point. Fine thermocouples were attached to all of the internal components known to run warm during operation (ICs, diodes, transistors, transformer core, etc.). Here, it is important to use the thinnest possible thermocouple wires so that the wires themselves do not act as a heatsink. To confirm, the case temperature measurement was repeated with the thermocouples attached so that any difference could be calibrated out. The converter was then potted to give a representative sample of the production part.

The over-temperature between the hot spots and the ambient was measured as the ambient temperature was slowly raised in 5°C steps up to the limit (defined as the maximum ambient temperature where any one of the key components exceeds its maximum permissible temperature), allowing sufficient time after each step for the internal temperatures to stabilise. The operating conditions were the worst case (max Vin and full load) and the D.U.T. was placed in a draught-free enclosure to ensure convection cooling only.

During this test procedure, the measured efficiency of the converter was also monitored and recorded. Using Equation 1 from above, the internal power dissipation could be calculated and plotted:

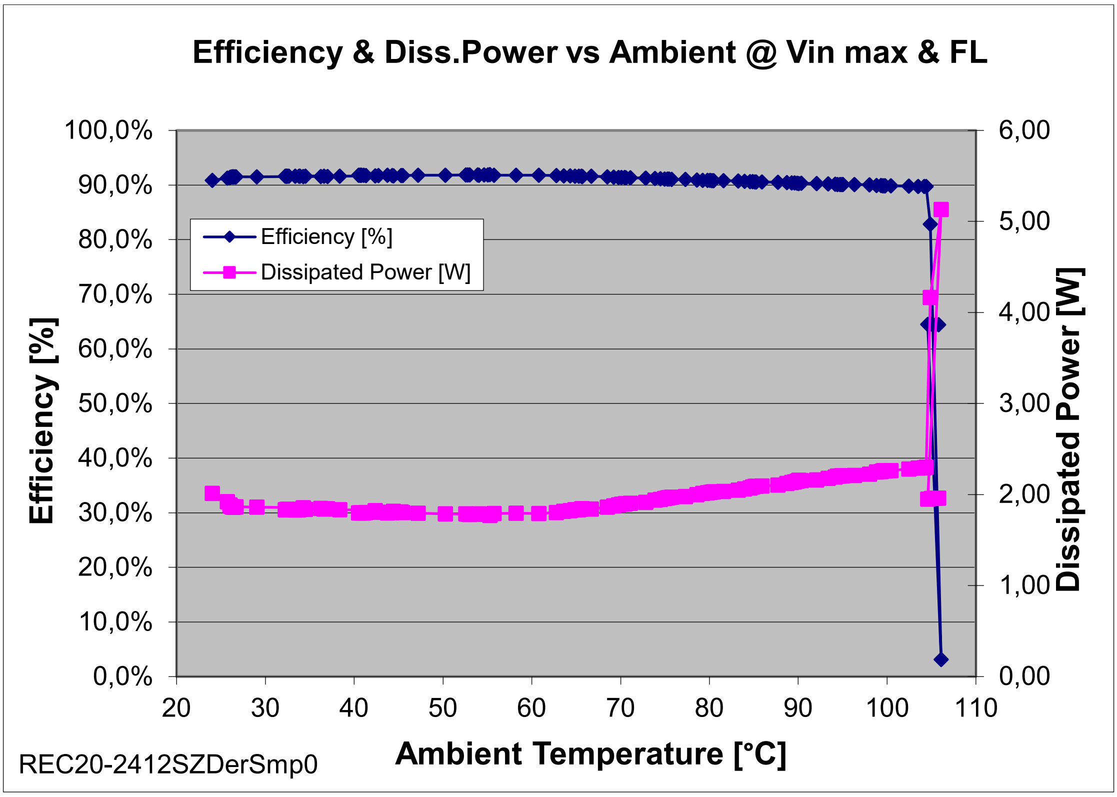

Figure 4: Dissipated Power vs ambient temperature

Now equation 2 can be rewritten to show the measured thermal impedance R_{th}, which is close to the thermal characterisation figure ψ_{JA}:

Eq.4 $R_{th} = \frac{P_{diss}}{T_{over}}$

Plotting this result gives a measured R_{th} vs ambient temperature (the jagged effect is due to the step changes in temperature):

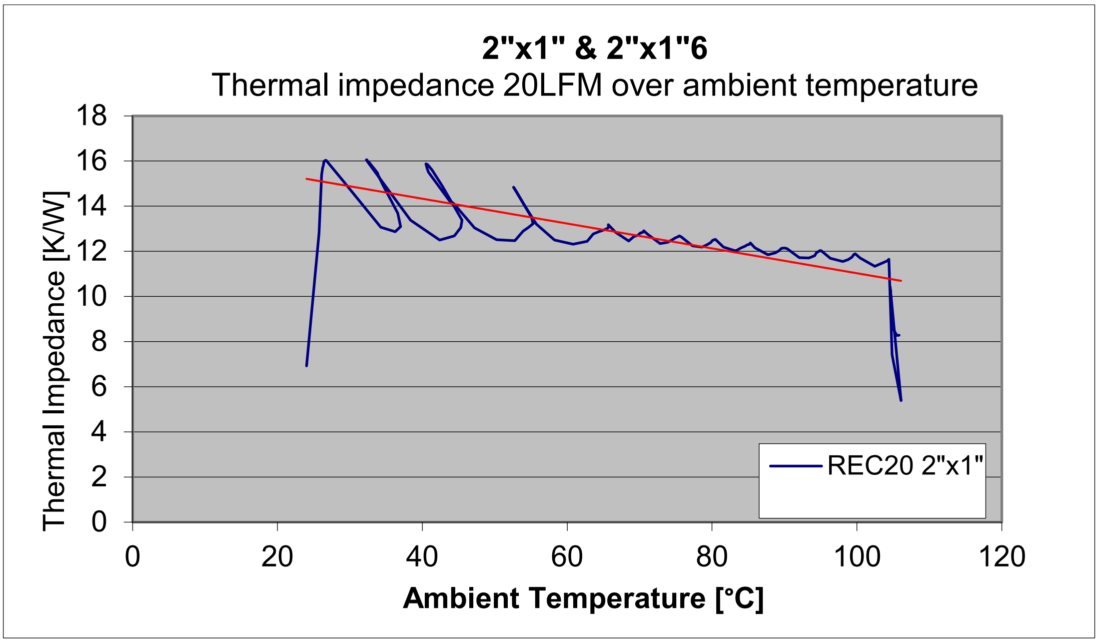

Figure 5: Plot of measure thermal impedance vs ambient temperature

The R_{th} value given in the REC20-SZ datasheet is the averaged value (shown by the red line) at the maximum ambient operating temperature of +85°C = 12°K/W. As can be seen from these results, the converter stopped working at an ambient temperature of 105°C, so the datasheet maximum of +85°C has a healthy margin of safety.

Conclusion

Predicting the actual thermal behaviour of a part in an application is difficult to calculate in advance; there are different thermal path models available and the data available can be based on different test regimes. Using datasheet R_{th} values to determine the maximum operating temperature based on internal power dissipation is a way of simplifying the calculation, but it cannot be a guarantee of success – there are simply too many variables involved to answer the simple question, 'What is the maximum operating temperature?' with a simple answer.

In practice, however, most power converters do not need to continuously operate at worst case input voltage at maximum load at maximum operating temperature, so using the R_{th} figure to calculate the case or baseplate over-temperature value is a useful guide to being reasonably sure that the converter will not overheat in normal use.

Further Reading: '*Some Like It Hot: What to look out for when optimising the thermal design of switched-mode power supplies*.' RECOM

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