3. Cooling efficiency

3.1 Scope

The intention of this chapter is to explore the possibilities of the cooling efficiency concept. It can be used for several purposes: as a meter of the quality of a PCB design, as a tool for measuring the heat transfer coefficient and as a front end design method.

As often is the case with simple ideas, the cooling efficiency concept has been proven to be extremely useful. Problems that take hours to solve with other methods can often be figured out in a few minutes. The cooling efficiency can also be used to create intuitively understandable overviews, which is very helpful in the early phases of the design process. In short, methods based on the cooling efficiency concept can save weeks of work.

3.2 Definition

The cooling efficiency is defined as the ratio of the heat dissipated by a PCB and the heat dissipated by an isothermal reference case, figure 3.1:

$$\eta_c = \frac{\dot{Q}}{\dot{Q}_{ref}} \qquad \textit{(Equ 3.1)}$$

The reference case and the PCB case are identical in all aspects except for the following 3 deviations:

1. The reference case is a smooth plate, (no components).
2. The reference case is isothermal and the surface temperature equals the maximum inner layer temperature of the PCB.
3. The airflow is front-to-end and there are no inlet disturbances.

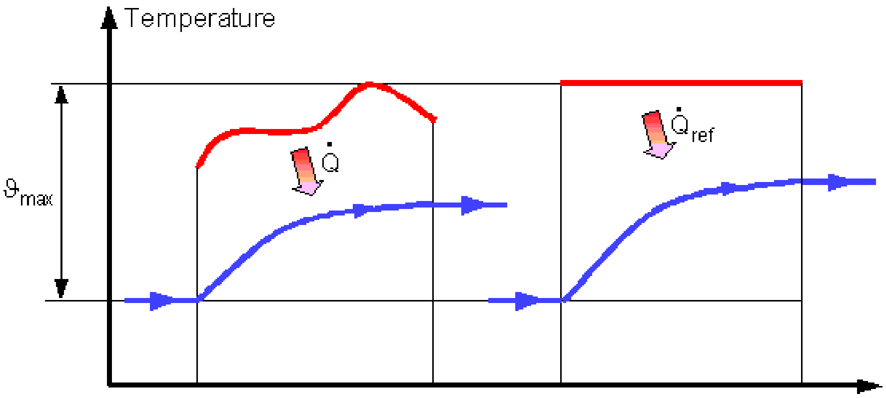

Figure 3.1
The PCB and the reference case used to define the cooling efficiency.

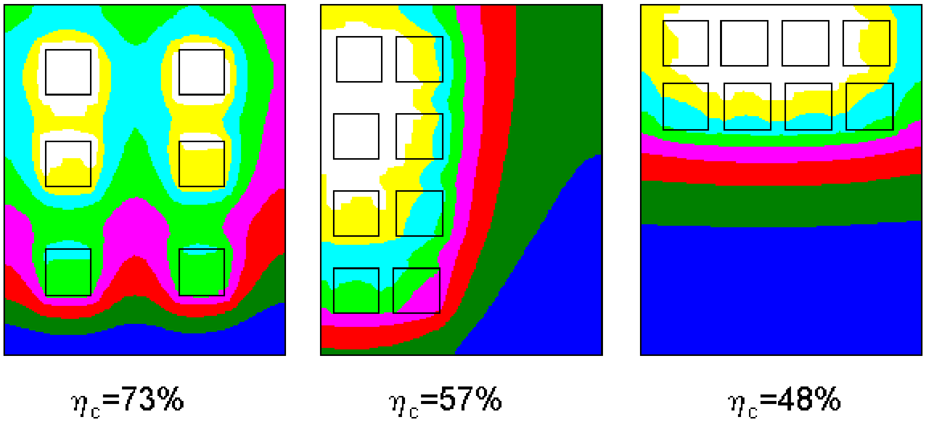

Figure 3.2
Lay out impact on cooling efficiency. Sub rack factor 1.0

The reference case is therefore a clean "text book" case for which adequate equations can be found in most heat transfer literature. The heat dissipated is given by Newton's cooling equation:

$$\dot{Q} = h_0 \cdot A_b \cdot \vartheta_{max} \qquad \text{(Equ 3.2)}$$

Following the definition, the heat dissipated by a PCB must be:

$$\dot{Q} = \eta_c \cdot h_0 \cdot A_b \cdot \vartheta_{max} \qquad \text{(Equ 3.3)}$$

It can be noted that equation 3.2 should be regarded as a definition of the heat transfer coefficient. Equation 3.3 is therefore a combination of two definitions. *It must consequently be absolutely correct*. All application errors must therefore originate from errors in the input parameters and not from the equation itself.

3.3 Lay out application

The cooling efficiency can be increased in three different ways:

1. By distributing the heat sources as uniform as possible, figure 3.2.
2. By increasing the thermal conductivity, (copper content), of the PCB.
3. By introducing flow disturbances or cold side PCBs that increase the effective heat transfer coefficient.

The cooling efficiency can be interpreted as a measure of the lay out quality. It is for example apparent that the improvement potential is much larger for a layout with 40% cooling efficiency than for one with 70%.

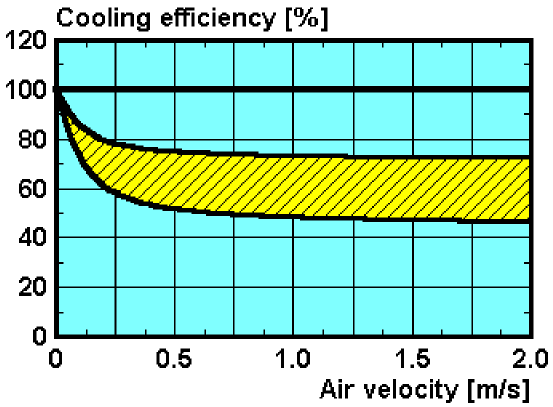

Figure 3.3
Experience values for multi layer signal processing PCBs without heat sinks.

The maximum PCB plate temperature is easy to identify with access to the temperature distribution. Thermal calculation tools that use this information to calculate the cooling efficiency are unfortunately rare. The work around this problem is to calculate the cooling efficiency separately, which includes an evaluation of the heat transfer coefficient for the reference case, h_0. A reformulation of equation 3.3 results in:

$$\eta_c = \frac{\dot{Q}}{h_0 \cdot A_b \cdot \vartheta_{max}} \qquad \text{(Equ 3.4)}$$

With access to a calculation tool that can handle isothermal plates it is alternatively possible to directly apply the basic definition, equation 3.1.

The cooling efficiency is typically below 100%. Figure 3.3 shows experience values for multi-layer PCBs without heat sinks. There are nevertheless cases that exceed the 100% limit. For example if there are large surface extensions, (heat sinks or daughter boards).

The cooling efficiency converges towards 100% for small air velocities. This is explained by the fact the temperature variation on a PCB only changes slightly when the heat transfer coefficients decline, whereas the mean PCB-air temperature difference changes substantially. The PCB level temperature differences therefore appears small in comparison with the mean PCB-air temperature difference.

3.4 Enclosure application

A common thermal design problem is to estimate temperatures for natural convection cooled PCBs inside enclosures. There are several ways to approach this problem. One of the safest is of course direct measurement. In most situations however, the PCBs does not yet exist physically, which disqualifies this method.

An alternative approach is to make the measurements on a PCB with a known cooling efficiency and apply equation 3.3:

$$\vartheta_{max2} = \vartheta_{max1} \cdot \frac{\eta_{c1} \cdot \dot{Q}_2}{\eta_{c2} \cdot \dot{Q}_1} \qquad \textit{(Equ 3.5)}$$

The test PCB can theoretically be any PCB that has a known cooling efficiency. A radical but effective approach is to use an aluminum plate with a foil heater. Such arrangements have cooling efficiencies in the range 90% -100%, (if the sub rack factor is 1.0).

Another common problem is to determine the natural convection heat transfer coefficient for PCBs mounted inside enclosures. The cooling capacity is in those cases typically 30% - 70% of that for truly free convection. Literature correlations representing that case can therefore not be used. The problem can however be solved with measurements on a test PCB with a known cooling efficiency. The heat transfer coefficient is given by equation 3.3:

$$h_0 = \frac{\dot{Q}}{\eta_c \cdot A_b \cdot \vartheta_{max}} \qquad \textit{(Equ 3.6)}$$

It should be noted that the heat transfer coefficient for natural convection is heat flux dependent. The measurement procedure should therefore span over a range of heat dissipation levels.

3.5 Front-end application

The cooling efficiency concept can be said to be a factor that, when introduced into Newton’s cooling formula, makes it possible to treat PCBs as smooth flat surfaces.

If the cooling efficiency is unknown, it is always possible to use an experience value. This will of coarse introduce an uncertainty. In the early phases of the design process this uncertainty is however mostly on the same level as other uncertainties, for example heat dissipation.

Figure 3.4 shows the result of a typical front-end estimation. It covers cooling efficiencies in the range 40% - 80%. The target

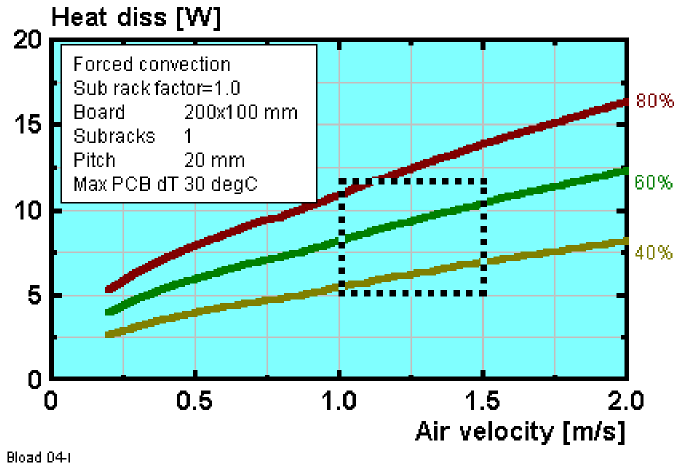

Figure 3.4
A front-end heat dissipation prediction example.

window is defined by the best and the worst cases. It only takes a few minutes to generate such diagrams. They are extremely useful in the early phases of the design process because they indicate if problems can be expected and if this is the case, the measures needed to avoid them.

3.6 Stacked sub racks

A common practice in telecommunications equipment is to stack sub racks. This is usually refereed to as serial cooling, figure 3.5. The inlet temperature to the top rack in a stack of N sub racks is given by the energy equation:

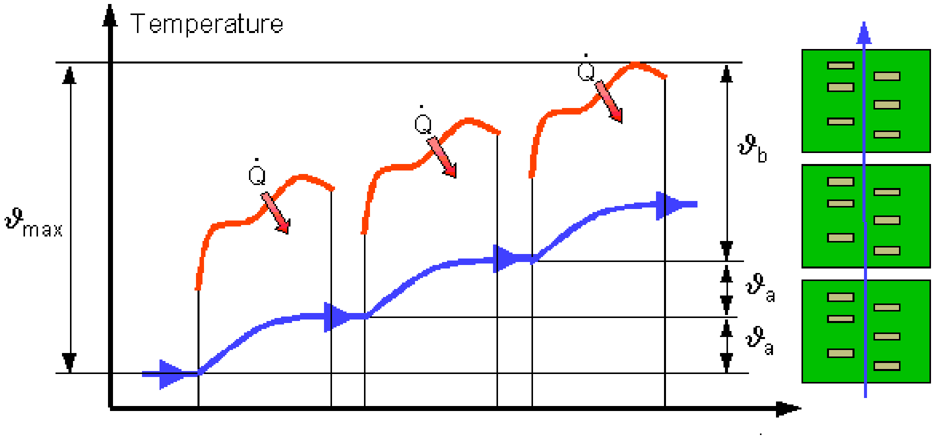

Figure 3.5
Stacked sub racks.

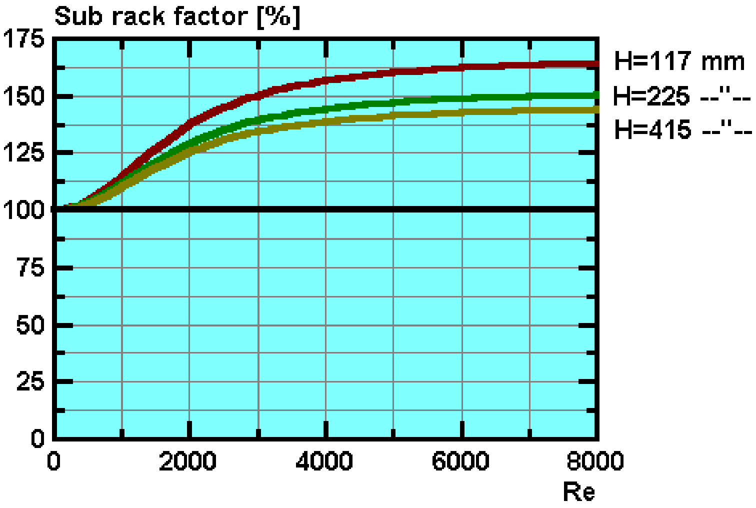

Figure 3.6
Example of measured sub rack factors.

$$\vartheta_a = (N-1)\cdot\frac{\dot{Q}}{\dot{m}\cdot c_p} \qquad \text{(Equ 3.7)}$$

The maximum PCB - inlet air temperature difference is therefore:

$$\vartheta_{max} = \dot{Q}\cdot\left(\frac{1}{\eta_c\cdot h\cdot A_b}+\frac{(N-1)}{\dot{m}\cdot c_p}\right) \qquad \text{(Equ 3.8)}$$

3.7 The sub rack factor

The sub rack factor represents the impact of mechanical inlet structures that enhance the heat transfer coefficient by causing disturbances in the airflow. Enhancement impacts as high as 60% has been observed. Figure 3.6 shows an example.

PCB guides and EMC grills cause this phenomenon. An explication on the intuitive level is that they make the air enter the sub rack as a shower of jets rather than as a smooth flow.

The impact can be considerable. It is therefore reasonable to treat it as a parameter. It is defined as the heat transfer coefficient measured in a sub rack and the heat transfer coefficient measured in a wind tunnel:

$$\eta_s = \frac{h_{0s}}{h_{ow}} \qquad \text{(Equ 3.9)}$$

The sub rack factor is 1.0 for low air velocities and natural convection. It can take considerable higher values for higher velocities.

3.8 The PCB efficiency

The reference case for the cooling efficiency is a clean "text book" case. The sub rack factor therefore always tends to increase the cooling efficiency. It is therefore convenient to look at the cooling efficiency as a parameter composed of two impacts. The sub rack part and the PCB part:

$$\eta_c = \eta_s \cdot \eta_b \qquad \textit{(Equ 3.10)}$$

The PCB efficiency is consequently defined by:

$$\eta_b = \frac{\eta_c}{\eta_s}. \qquad \textit{(Equ 3.11)}$$

The advantage with this definition is that the PCB efficiency, at least approximately, is the same for all types of sub racks whereas the cooling efficiency is not.