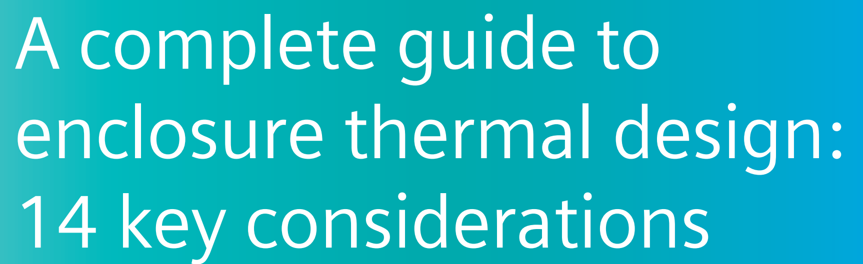

A complete guide to enclosure thermal design: 14 key considerations

Dr John Parry, CENG

Why is enclosure thermal design important?

Before we look at 14 key considerations in enclosure thermal design let's first consider why thermal issues need to be considered at the system, or enclosure level.

A natural focus when designing an electronic product is inevitably on the electronics. The electronics needs to work within some kind of enclosure, be it a standardized rack system[1], or a custom-built enclosure like the housing of a Smartphone or tablet computer, or part of another product like an automotive dashboard or aircraft flight deck.

In all cases, including standardized rack systems, the electronics has to be designed with the enclosure in mind, as the enclosure can act as either a barrier or a conduit for carrying the heat away to the ambient, or possibly both. Cooling is a system issue, which is why we advocate a top-down approach, starting at the enclosure level [ref. 1].

Figure 1: Airflow distribution in a 1U server modelled in Simcenter Flotherm

Often the air flow inside the enclosure is complex, making CFD the only viable approach to developing a successful design. The flow is affected by the electronics and the enclosure design, hence the electronics and enclosure interact to provide the application thermal environment. In the vast majority of cases, the primary cooling medium is ambient air. Even in something as small as a notebook computer where there is very limited space, designers look to circulate the air in order to improve cooling performance, although heat spreading and conduction to the casing will also be important.

Whenever enclosure-level air flow prediction is needed, Simcenter Flotherm™, shown in figure 1, has been the industry's primary tool of choice[2] for almost 30 years.

Simcenter Flotherm uses what is in CAD terms referred to as a "direct modeling" approach, in that objects are created, resized, repositioned, etc. graphically, in preference to defining them parametrically by typing in dimensions (although this is possible). As such it is extremely fast for use in early design. Models can be built in just a few minutes, and solved in seconds. In addition, Simcenter Flotherm objects are represented in the exact same hierarchy order as is common in many product developments: there is a main assembly with sub-assemblies and parts, and all part attributes are directly linked to and accessible through the part object. There is no step to map different hierarchies onto each other which translates in time savings and lower error rates. Miniaturization has increased importance of mechanical CAD in many electronics products, necessitating the need to work with native CAD geometry which is defined parametrically.

[1] *Chassis design to house third party circuit card assemblies is a more specialized topic.*

[2] *See references to the ThermaNator in 'Hot Air Rises and Heat Sinks' [Ref. 2]*

Optimizing the air flow

Enclosure thermal design is then all about optimizing the system air flow when the electronics are installed. That doesn't mean that it needs to be done as an afterthought, when the design of the electronics is completed. On the contrary, to ensure the shortest design time, lowest design cost and arrive at a product that has a low-cost high reliability cooling solution it's essential that a co-design approach is taken. The golden rule is to "start early and start simple" [ref. 1].

This co-design can start at the concept design phase. Indeed, it can be a prerequisite for getting the architectural design for the electronics correct. Where there is flexibility over the enclosure design, Simcenter Flotherm and Simcenter Flotherm™ XT provide an Enclosure SmartPart offering a fast, parametrically-defined representation of the enclosure.

In other cases the enclosure design may be largely predefined, but there may still be a need to optimize the enclosure for cooling the electronics. For Simcenter Flotherm, Simcenter FLOMCAD Bridge provides the ability to simplify and import native CAD and standard CAD neutral file formats. For Simcenter Flotherm XT, both native CAD geometry and standard CAD neutral file formats can be imported, manipulated and modified directly within the software using Simcenter Flotherm XT's inbuilt CAD kernel.

The main design flows, both MCAD and EDA (or ECAD) focus on the physical geometry, and in doing so miss the most important part of most electronics designs from a cooling perspective – the air gaps. Hence we have our first key consideration.

> *"Your thermal design is made or broken in a few vital early architecture choices — it is absolutely essential to figure out what they are — and then guard these choices through the entire design flow."*
>
> *Ir. G. A. (Wendy) Luiten, Thermal Specialist & DfSS Master Black Belt*

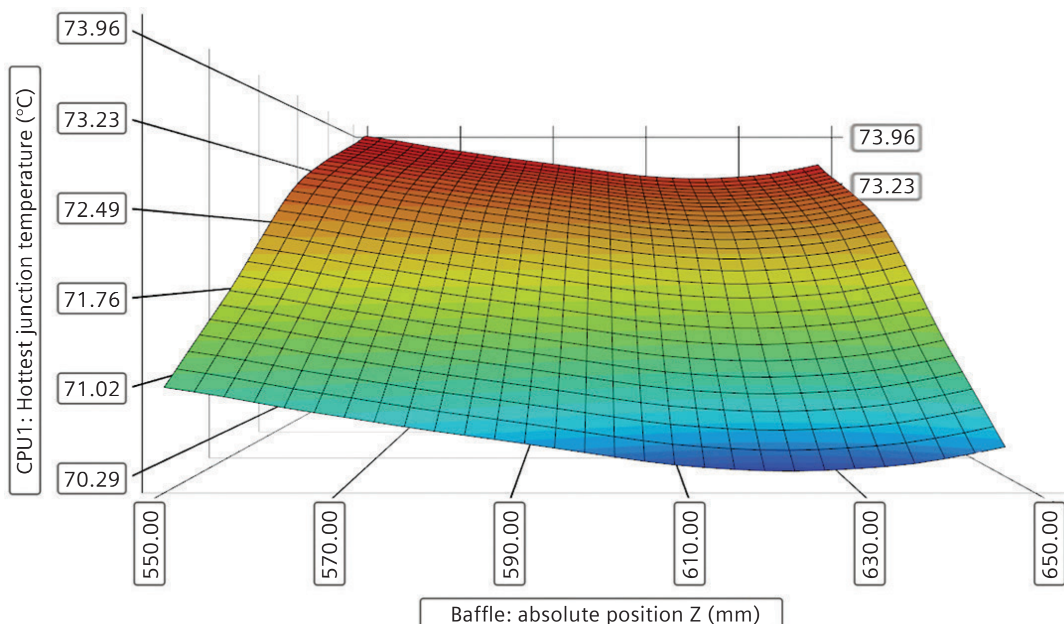

Figure 2: Response surface showing junction temperature variation with baffle position

1. Protect the critical "white space" in your design

The "white space" is all the gaps between the geometry in the design. Not all of this will play an important role in cooling the electronics, but in many cases, providing an adequate space for the cooling air to pass through is an important part of the design. One problem that thermal designers face is that the air is not part of the bill of materials associated with the product. As such, gaps can be adjusted, and even closed, without any change request being raised. Even if that doesn't happen, other people involved in the design activity are free to fill these spaces, for example with cables to connect the boards and other components together. As Wendy Luiten puts it, "Beware of the cable guy!"

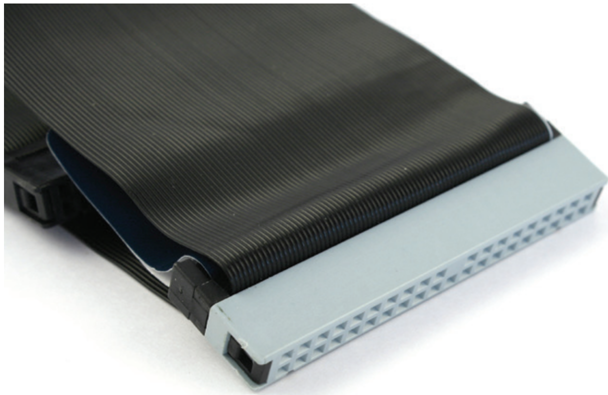

Figure 3: Strip cable for a computer hard disk drive

The cables may not fill the space, but they reduce the area available for flow, and increase the surface area, reducing the effective hydraulic diameter of the channel, and hence the flowrate through it and for systems with a fan, increasing the pressure drop. For fanless systems, a cable in an air duct can block flow in this duct totally. Strip cables in particular, placed across the air flow, can have a major disrupting influence on the system-level air flow, so when considering the design of a board from a thermal perspective, pay attention to the connectors not just the high power dissipating components.

One approach to gaining control over this is to have the MCAD designers include dummy parts for the important air gaps, which then can't be changed without a change request, with the thermal engineer involved in the approval process for changes to that part.

Open, forced convection systems

Due to their prevalence, we talk first about the key considerations when designing open systems, and then discuss closed, or sealed systems.

2. Select the right fan type and size

Different types of fan are available – axial, centrifugal, radial, and even mixed flow fans. These have different flow rate vs. pressure characteristics.

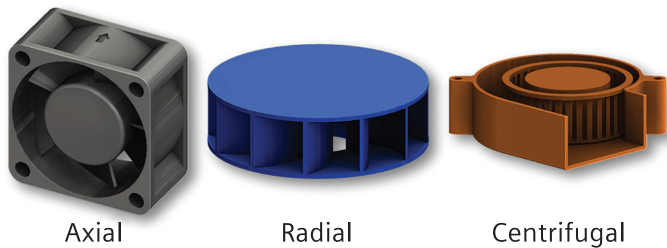

Figure 4: Common types of fan used for electronics cooling

Radial fans generally produce the highest maximum pressure rise, but at the cost of delivering a lower maximum flowrate.

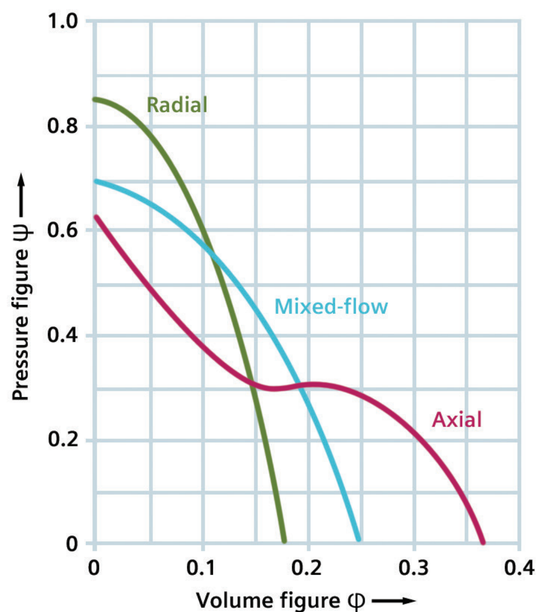

Figure 5: Normalized pressure vs. volume flowrate for different fan types [ref. 3]

To achieve the same airflow, albeit with different flow rate and pressure rise characteristics, and if space permits, there may be a choice to be made between using larger fans, operated at a lower speed or smaller fans operated at higher speed.

There are benefits of using a larger fan operating at lower speed as it will generate less aeroacoustic noise and will have a longer field life. Using a larger fan in early design work is conservative, as there is a risk that the initial power estimates may turn out to be on the low side. A smaller fan could then be used, whereas the reverse may not be the case. This is not only a question of finding the space to mount the larger fan itself, but also because a fan needs about 1 fan diameter of free space at the inlet and the outlet, and this typically is not available. If the powers being designed for are lower than expected, the fan size may be reduced later on, or the fan may be replaced with another of the same size that delivers less flow for a lower cost and lower power consumption. It also allows scope for intelligence to be built into the cooling solution as discussed below. There is clearly a cost implication as the larger fan is likely to be more expensive, and electromagnetic emissions (EMC) may be harder to contain, depending on how the equipment is shielded. Finger guards fitted to fans can be grounded to the casing to help reduce EMC issues.

3. Select the best fan flow arrangement

Another common system-level design consideration is whether to opt for a 'push' or a 'pull' type arrangement, i.e. whether fans are to be used to push air through the system or draw air out of the system. In general pull type arrangements are the most common, being found in most deskside, desktop and laptop computers. Here the air is pulled into the enclosure through vents by a fan or fans that exhaust out of the enclosure.

In pull type arrangements, the electronics (e.g. a rack of boards) acts as a flow resistance which tends to even out the flow through the card slots. For a bespoke system, in which the designs of PCB the system will house will not change, the board spacing can be optimized to get the best cooling for each board. For modular systems designed to house a range of PCBs, often from different vendors, and with potential upgrades over the life of the system, this is not recommended.

Some systems may require a dual push and pull arrangement in order to achieve higher volume flowrates.

If a pull type arrangement is used, the static pressure inside the system will be lower than the ambient. Consequently any leaks in the system will allow air to bleed into the system and may bypass the electronics and therefore not contribute to cooling the system. This air will also bypass any inlet filters designed to prevent dust and dirt entering the system. Conversely, if a push type system is used, air can bleed out and again not contribute to the system cooling.

During the detailed design phase, or earlier if a pre-existing enclosure is being repurposed, the mechanical design of the enclosure available as a CAD model should be used and particular attention paid to joins in the casing.

4. Use a plenum

In push-type arrangements the incoming air naturally forms a jet, with recirculation regions forming at the sides of the jet. However, we want the incoming air to flow uniformly over the downstream electronics, especially when forced air cooling a rack of PCBs where equally apportioned airflow through the gaps between the cards is desired. A pressure plates can be introduced downstream of the fan to make flow more uniform. The downside is that this adds to the overall system pressure drop that the fan has to overcome. The higher the flow resistance, the more uniform the flow rate through it. Hence the flow uniformity needs to be balance with the cost, in terms of increased pressure drop, required to achieve it. Both Simcenter Flotherm and Simcenter Flotherm XT have a general flow resistance and perforated plate SmartParts to assist with this task.

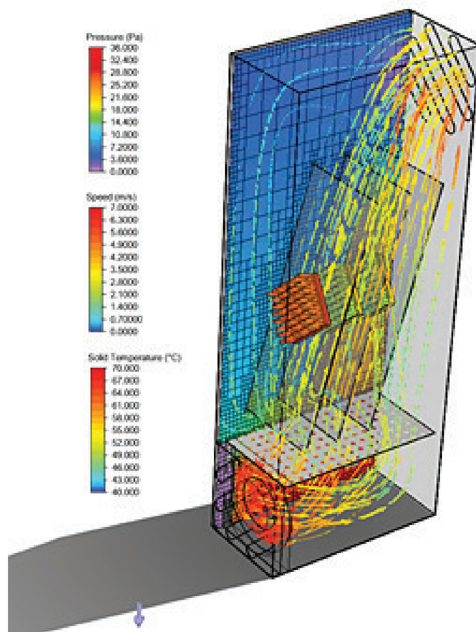

Figure 6: Flow resistance SmartPart in Simcenter Flotherm XT model of a rack system

Another factor to consider is that even axial fans generate non-axial flow. At high volume flowrate and low pressure rise, axial fans predominantly exhaust air axially. At lower flowrates the radial and tangential components of the air leaving the fan increase. Unless a plenum arrangement is used, this can change the near field flow pattern downstream of the fan and hence the local cooling.

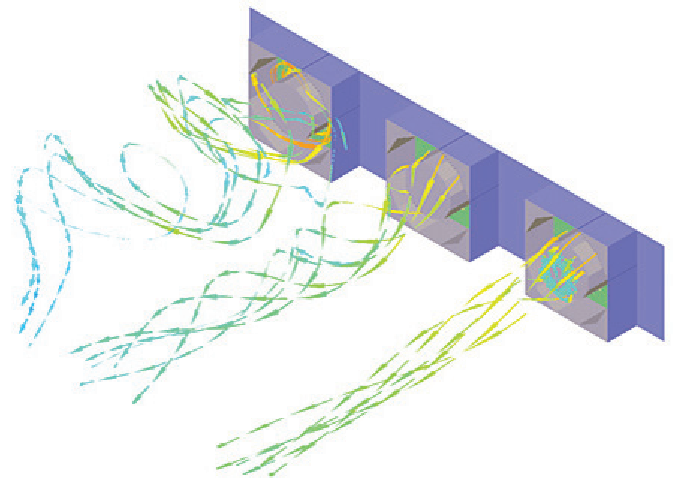

Figure 7: Simcenter Flotherm model of an identical fan operating at three different operating points and showing different spreads

5. Size vents correctly

Regardless of whether a push or pull type fan arrangement is used, arrangements need to be made for air to enter or exit the system. The size of the vent or vents affects the volume of air flowing through the system. What is perhaps less apparent is that it will also affect the flow pattern within the system.

Similar considerations to fan sizing also apply to vent sizing. Larger vents will reduce the overall system pressure drop which will increase the volume flow through the system. How much will depend on the flow resistance of all the other geometry. It will also affect the speed with which air enters or exits the system via the vent. In pull-type systems the jet effect caused by the air entering at high speed can set up flow recirculation regions within the system, potentially leading to hot spots.

Vents in the system may also give rise to EMC issues, which in turn restrict the maximum hole size of the screen used for the vent. The flow resistance of this screen has to be taken into account. Honeycomb EMC screens offer excellent shielding, and have a very low blockage factor as the aluminium sheet used is very thin, giving an open area greater than 95 percent. However, the small diameter combined with the length of these honeycomb cells results in a surprisingly high pressure loss, comparable to that of a conventional drilled plate.

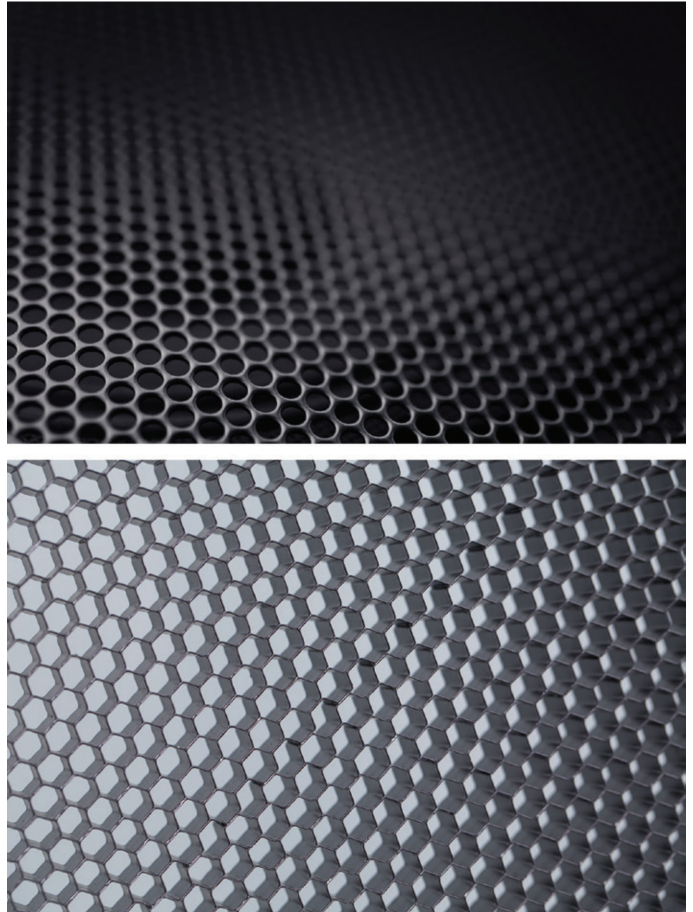

Figure 8: EMC screens conventional drilled plate (top) and Honeycomb (below)

6. Optimize the fan and vent placements

Where a fan is placed on one wall of the enclosure, typical of desk side computers, rack mounted servers, etc. the position of the fan will influence the flow pattern within the system, as will the location of the vent(s) that supply the fan, so the fan and vent placements should be optimized together.

In the case of pull type systems, having the exhaust fan near to the top of the enclosure helps ensure that it exhausts the hottest air from the system, as buoyancy effects are always present, otherwise a blanket of hot air will develop at the top of the enclosure. Conversely, in push type systems, the inlet fan should be positioned near to the bottom of the enclosure to ensure that cold air is brought into the bottom of the enclosure to ensure that it passes up over the electronics, assisted by buoyancy effects.

We advocate activating buoyancy in all simulations as this adds to the realism of the results obtained at no cost in terms of the simulation time taken when using Simcenter's software. It is obviously essential for naturally ventilated systems, as it is only buoyancy that drives the airflow in such an arrangement, but it is also essential in case the mechanical layout does not allow for optimal fan placement. Cases exist where a slowly rotating fan in the wrong location inadvertently balanced and counteracted natural convection – resulting in a pocket of still air and corresponding too high temperatures.

Care with vent placement is also needed to prevent hot exhaust air being drawn back into the system. If in doubt, the model can be extended to include the air flow in the local environment. This is also recommended for high vertical structures as this allows for calculation of the vertical temperature gradient in the outside air adjacent to the enclosure wall.

7. Optimize board placement

Something that's often overlooked is the potential to adjust the location of the PCB or PCBs within the enclosure. In a rack system it is obvious that the card spacings can be altered, but in other systems this is perhaps less apparent. Altering the position of the PCB can adjust the amount of air that flows both over and under the PCB. Minor changes can provide a cost-free improvement in the cooling performance, for example by increasing the cooling off the back side of the board. This may arise from the interaction of the leading edge of a PCB with the near field flow around a fan or vent for example.

Open, free convection systems

Free convection systems range from digital TV set top boxes to rack systems and historically telecoms racks. In naturally vented systems, all the convective cooling arises from buoyancy induced by air inside the system becoming hotter, and therefore lighter, than the surrounding air.

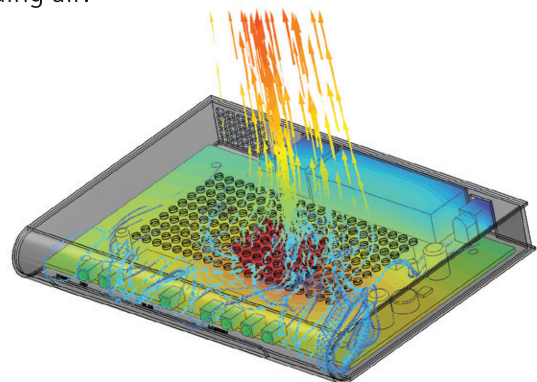

Figure 9: Buoyancy induced airflow in a Simcenter Flotherm XT model of a router

8. Design vents carefully

Smooth uniform air flow is key to good design, and consideration needs to be given to the detailed design of the vent grilles to minimize pressure loss while maintaining electromagnetic compatibility and immunity (EMC/EMI).

To design the inlet vent grille it is often necessary to consider how the air approaches the vent, requiring the solution domain to be extended beyond the enclosure, to include the mounting surface for the unit.

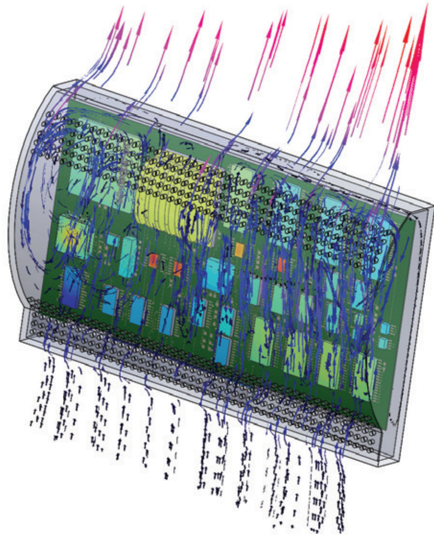

Figure 10: Flow distribution in Simcenter Flotherm XT showing the optimised vent arrangement for a naturally ventilated, wall mounted electronics system

In addition, location and open area are especially important for free convection cooled systems. Air inlets should be placed low, air outlets should be placed high, and open area should be roughly the same size both in the vents and along the flow path through the system.

Enclosed/sealed systems

In small sealed systems the size of the enclosure is a major parameter affecting the cooling performance. In larger enclosed systems, fans can be used to recirculate the air, e.g. through an internal heat exchanger. When considering using a fan within an enclosed system it's important to bear in mind that the fan itself, and the additional power draw on the power supply will also add heat into the system, so the improvement in cooling performance needs to outweigh the additional cooling required.

9. Don’t ignore conduction to the enclosure

Conduction to the enclosure can be the primary cooling mechanism for some fully-enclosed systems, e.g. avionics boxes, and even Smartphones.

Thought needs to be given to how heat is to be removed from the casing. Often only natural convection to the ambient or conduction to a human hand are the only ways in which heat can ultimately leave the system. In both cases it is highly desirable to spread the heat as much as possible to make the best possible use of the surface area of the casing. As such, the casing should be as thermally conductive as possible, so that it extends the hot area in the same way that a heatsink does. If not heat loss from the casing will be reduced, and at the same time a hot spot will arise which may lead to problems due to the safe limit for touch temperature [ref. 4]. In addition to conductive casings also miniature heat pipes are available for this purpose as well as graphite foil heat spreaders. The graphite foils have the added benefit of providing EMC screening.

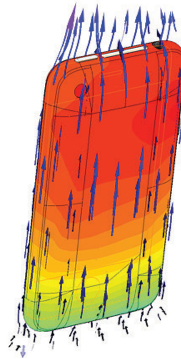

Figure 11: Case temperatures and buoyancy-driven airflow shown on a Simcenter Flotherm XT model of a Smartphone

As a system-level cooling solution, we should also mention that conducting rails can be used to carry heat to wedgelocks that clamp a PCB to an externally cooled cold wall e.g. as part of a ruggedized enclosure also providing mechanical stability for the board mounting. This approach only applies to a certain type of system, e.g. a sealed avionics box, but it is sometimes possible to apply the same principal in other systems where the casing itself can be used as part of the cooling solution. Gap pads can for example be inserted between the top of board-mounted components and a metal enclosure to provide additional heatsinking.

10. Design-in internal heat spreaders as necessary

A final point about conduction concerns the use of heat internal spreaders. Depending on the type of system, internal heat spreaders can be used to augment the cooling. These can be either tightly mechanically integrated as part of the PCB construction, as in the case of a metal core PCB (MCPCB), or a mechanically-separate system-level cooling solution that provides heat spreading on either the top or back of the PCB or memory module. Such solutions usually need to be designed in from the outset.

Many material options are available – graphite foils, highly oriented pyrolitic graphite (HOPG), various ceramics, silicon carbide (SiC) and flat heat pipe constructions. Material and processing costs vary considerably, and the use of an internal heat spreader also adds to the assembly cost as heat must be efficiently conducted into the heat spreader for it to be effective. Although internal heat spreaders can offer a simple means of improving thermal performance, the benefit should be weighed against other options.

11. Understand whether a phase change material can help

Phase change materials are a relatively new addition to a thermal designer's toolset. Phase change materials absorb heat by turning from a solid to a liquid over a relatively narrow temperature range, limiting the temperature rise until all the solid has become liquid. Phase change materials have been used as thermal interface materials for heatsink attachment for a number of years, dating back to the first Intel Pentium processor, but have more recently found use in applications where a high bursts of power have to be designed for, for example watching a video on a mobile phone. Using a phase change material can delay the need to throttle back the performance to manage the heat dissipation. When the power is reduced, the temperature drops and once the range of the phase transition is reached, the phase change material starts to re-solidify, rejecting the stored heat. The phase change material is typically contained in a bag which can conform to the shape of the cavity into which it is inserted, providing good contact with the electronics, and in some cases the enclosure, to assist with heat rejection. Reference 5 is a study into the effects of incorporating a phase change material into an existing design of a laptop computer.

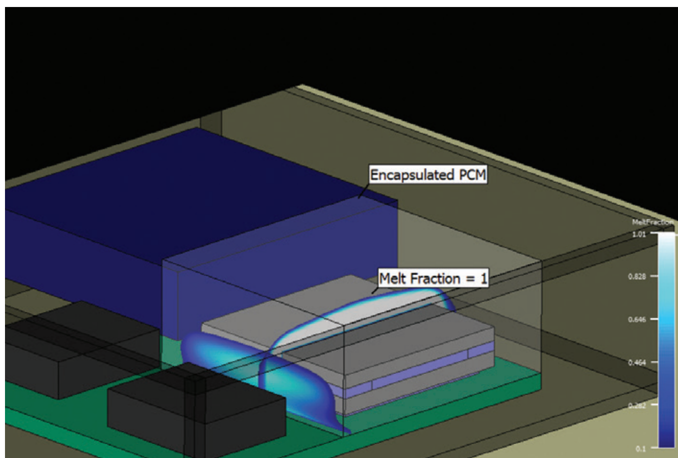

Figure 12: Melt fraction shown in an encapsulated phase change material heated by a package.

It is relatively easy to model a phase change material in a transient simulation with electronics cooling CFD, helping thermal designers decide whether this should be part of the cooling solution during the architectural design phase, and optimizing the design later. The phase change material will require a heat spreader, due to the relatively low thermal conductivity of the material itself. Introducing a phase change limits the temperature rise within the enclosure, and can also alter the heat flow paths, so that the temperature rise after the phase change material may be different to that when there is no phase change material included.

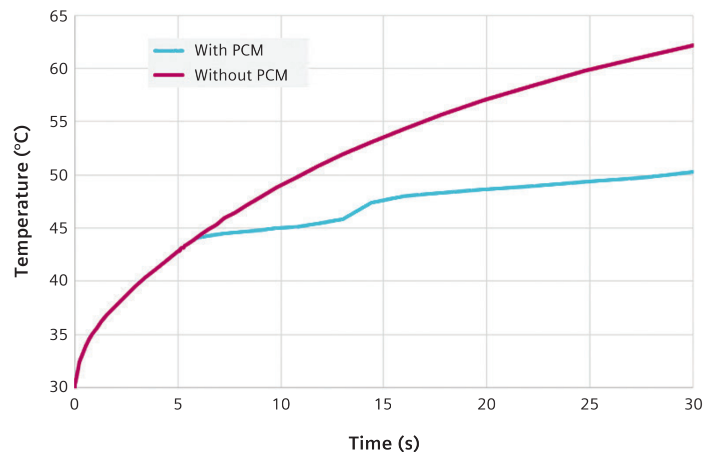

Figure 13: Component temperature rise for system with and without phase change material.

12. Include thermal radiation effects

Thermal radiation effects are often ignored in early design as this is generally a conservative assumption, and often the model fidelity does not provide sufficiently accurate surface temperatures to warrant the addition computational overhead. If radiative heat loss is considered important its effects can be represented as an augmentation to convective heat transfer coefficients, increasing them by about 5 W/m2K on materials having a high emissivity (e.g. greater than 0.8). This is in the same order of magnitude as the heat transfer coefficient for natural convection, hence it is advised to incorporate thermal radiation in early design of natural convection cooled products.

Radiation effects should be considered during detailed design both to avoid general overdesign but also to avoid problems. For example a temperature-sensitive component on one board may be heated by radiation from a high power dissipating component on an adjacent PCB. Radiation is particularly important when natural convection makes a significant contribution to the cooling. In rack systems cooled by natural convection for example, boardboard radiation and radiation to the side panels of the sub-rack can significantly reduce the temperature variation across the rack preventing overdesign of the cooling for centrally-located boards. Surface emissivity influences the heat loss and for metal enclosures it is worth testing the sensitivity of the simulation results to see if coating or painting the inside of the enclosure is worthwhile. In one case painting the inside of the aluminium housing of an automotive electronic control unit was found to reduce component temperature by up to 7°C, easily warranting the additional cost.

Solar radiation deserves a special mention at this point. For outdoor equipment that’s exposed to sunlight, solar heating of the system can present a major challenge. Shielding the electronics from the heating effects of sunlight may require a dual skin design with ventilation that is controlled and with additional heating to prevent frost protection. Specialized cabinets are available for this purpose. It should be noted that the colour of the enclosure is important as this affects the solar absorptivity.

13. Co-design the enclosure and the electronics

In this white paper we've talked about the design tasks associated with enclosure design. We have not yet talked about these tasks in the context of the overall product design process.

In conceptual design a very simple representation of the enclosure may be all that is possible, but the flip side is that there is very little is constraint from other aspects of the design, so there is great scope for designing a highly thermally-efficient enclosure that has low design, manufacturing and operating costs.

Simcenter Flotherm's Command Center provides an easy way to explore the design space in early design. Developing a complete understanding of the design space and allows the thermal engineer to make informed design decisions. Automatic design optimization tools can be deployed in Command Center to systematically improve aspects of the product.

"I find the Command Center indispensable for running the many scenarios that I need to make sure that I do not just have a working design, but the best working design possible for my circumstances."

Ir. G. A. (Wendy) Luiten,
Thermal Specialist & DfSS
Master Black Belt

The enclosure design itself should be updated in the thermal model as soon as design details are committed to the CAD system, and updated thereafter in step with updates to the CAD geometry to ensure that these changes do not negatively impact the overall thermal design. The system-level model should be re-run whenever there is a change to the PCB layout and heatsinking arrangements for any components, and if information about the component powers changes. The aim should be to keep the thermal model of the system in sync with the design information held in main MCAD and EDA design flows.

14. Design-in cooling intelligence

Increasingly it is both impractical and not cost effective to design cooling solutions for systems based on the maximum thermal load. For example, multicore computers and servers often spend periods of time running with relatively low workloads. Today's equipment is designed to draw little power when idle, so the cooling can be throttled back for much of the time. This is a thermal opportunity, but also a challenge – as it directly links the cooling performance to the system performance.

Incorporating cooling intelligence makes good electronic cooling solutions more important, not less as an inadequate cooling solution will cause earlier throttling and hence directly impact functional performance. This loss of performance will negatively impact the user experience of a proportion of the users of the product. It is difficult to relate that working point to use cases to determine how often this will occur, and when it does how the use of the product will be affected.

In early design a representative Thermal Design Power [ref. 6] can be used, allowing steady-state calculations to be used to investigate different aspects of the cooling solution discussed above. In the detailed design phase however, it may be necessary to consider different use cases, each having different power levels for the critical components and in some cases even different power distributions on the surface of some of the packaged die, e.g. in high power density mobile applications.

The task is to optimize the cooling solution for a range of use cases and design the cooling solution to adapt to the different power levels it has to cool, thereby allowing the power required by the cooling solution to be minimized. In the simplest case this can be having the fan normally run at slow speed and increasing the fan speed when a component temperature exceeds a predefined value.

Simcenter Flotherm has the ability to run design variants, and supports the simulation of systems with dynamic cooling solutions such as temperature controlled variable speed fans. The Command Center is the go-to tool to run the various scenarios necessary to determine the transfer function between temperatures, cooling intelligence and system performance, enabling the design to work for operating points that fulfil end customers expectations.

Conclusion

This white paper provides a complete guide to enclosure thermal design, covering all the main points that need to be considered. If you are responsible for enclosure-level thermal design, Simcenter provides a range of thermal design software, allowing you to select a product that is an ideal fit with your company's thermal design workflow and supply chain needs.

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