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Thermal management

How thermal management affects your product and business

White paper

Fundamental – all electronics generate heat

All electronic devices and circuitry generate excess heat and thus require thermal management to improve reliability and prevent premature failure. The demand in these industries is on the rise at an ever increasing pace. Whether you are creating a breakthrough new high-tech product or are working in extreme high volume consumer products, it is important to use dependable thermal management products. Having cost effective and reliable solutions is crucial to your success.

We take it from the beginning. The first and most fundamental fact pertaining to electronics thermal management that needs to be known is this:

All electronics generate heat.

Electrons moving through materials encounter a resistance, and analogously to mechanical friction, overcoming this resistance generates heat. The greater the electrical power running through these materials, the greater also the heat generated.

The power input into any device, whether it be an entire application or a single component is simply:

$$Q_{tot} = U \cdot I$$

Where Q_{tot} is the total power [W], U is the voltage [V], and I is the current [A].

The power used for the desired output from the device is defined by its efficiency, η. The rest, $1\text{-}\eta$, is waste heat.

Thus, the thermal power generated by the device is defined as:

$$Q=U\cdot I\cdot(1-\eta)$$

In any thermal management solution, the solution must be able to dissipate this amount of heat, otherwise the heat will accumulate as increased temperature.

The Nature of Heat – temperature is the consequence of heat

The last six words in the previous paragraph are pivotal to understanding the nature of heat: "heat will accumulate as increased temperature".

It is common to think of heat as temperature, but the temperature is only the *consequence* of heat – built-up thermal potential, if you will.

Heat moves from high temperature to low temperature – hot to cold. It can only slide down a thermal gradient like this; if there is no thermal gradient – no temperature difference – heat does not move.

How steep the gradient needs to be for the heat to shift along it depends on the thermal resistance through the medium the heat is required to move in.

If there is no temperature difference, but there is a heat source – i.e. a source of thermal power – the power will accumulate as a raised temperature at the point where it is being generated, until the gradient is steep enough for the heat to slide along it at the same rate as it is being generated.

This correlation can be described as follows:

$$\Delta t=Q\cdot R_\theta$$

Where Δt is the temperature difference between the heat source and the ambient [K or °C], Q is the thermal power [W] – in most cases, the same thermal power as that being generated in the previous formula – and R_θ is the thermal resistance [K/W].

This energy balance – and its consequence – is vital to understand: heat in *will always* equate heat out. It is merely a question of how hot will the heat source need to get in order for the heat to dissipate at the same rate it is being generated. Hence we can rearrange and combine the last two formulae:

$$U \cdot I \cdot (1-\eta) = \frac{\Delta t}{R_\theta}$$

The Δt, being equal to heat source temperature minus ambient temperature, determines what temperature we end up with in our components. If we want to keep that low, we can either reduce the input – left – side of the equation by using less power and/or using more efficient components, or reduce the one variable we have left on the output side: the thermal resistance. More on this later.

Heat Transfer – Conduction, Convection and Radiation

At a quantum level, heat is vibration – molecules and atoms vibrating. Feed power in some form into such a particle, and it will store this power as an increased rate of vibration; thus, the higher the frequency of the vibration, the higher the thermal potential, i.e. temperature. No vibration equals no temperature – i.e. absolute zero (0K, or –273.15°C).

This vibration can be can be transmitted or transferred between particles through three physical mechanisms: conduction, convection, and radiation.

To look at each of these in a bit more detail:

Conduction

Conduction is heat transfer within solid bodies or still fluids (a “fluid” in physics is any gas or liquid). It’s quite simply the vibration of one particle catching off to its neighbouring particles, and then to the next, and the next, and so forth.

Conduction is mathematically described by Fourier’s Law, as follows:

$$Q = -k \cdot A \frac{\Delta t}{\Delta x}$$

Where Q is thermal power conducted over the body [W], A is the cross-sectional area of the conductor m^2], Δt is the temperature difference over the conducting body [K or °C], and Δx is the distance the heat is conducted [m].

This leaves k, which is the *thermal conductivity* [W/(m·K)].

Thermal conductivity is a material property which describes how easily heat propagates through the material in question. It is a bulk property, meaning that assuming an isotropic body, it will always be constant, irrespective of the geometry. Anisotropic bodies (e.g. a PCB) may have different conductivities in different directions.

The span of thermal conductivities ranges from 0.02W/(m·K) for still air, through 0.2 for most polymers, about 16 for stainless steel, 200 for typical extruded aluminium 398 for copper, up to about 2,000W/(m·K) for diamond, and then graphene, which may have an in-plane conductivity of up to 5,000W/(m·K), depending on who measures it and how.

Convection

Convection occurs when the next particle the vibration catches on to no longer is locked in place by its neighbours, but is free to fly off. In doing so, it carries the vibration – the thermal charge, as it were – with it. It may then hit upon another particle somewhere else, to which it transfers the heat through conduction.

The convective heat transfer from a surface into a surrounding fluid is described by Newton's Rule:

$$Q = h \cdot A \cdot \Delta t$$

Where Q is still the thermal power being transferred [W], A is the area of the surface [m^2], and Δt is the temperature difference between the surface and the surrounding fluid [K or °C].

The variable h is the *heat transfer coefficient* [W/(m^2·K)]. The heat transfer coefficient depends on a large number of factors, including (but in no way limited to) the convection mechanism (is this natural convection of forced convection), the geometry of the convection surface (is this a flat vertical plate, a horizontal cylinder, the inside of a cylindrical pipe, etc), the convection fluid (is it air, or water, or mineral oil, etc), and the flow characteristics of the fluid over the surface (rapid, slow, laminar, turbulent, etc).

The number may typically span from low single digits for natural convection in air to several thousand for forced convection in water – and very much higher still, if phase change (boiling) is brought into the equation.

It bears noting that in mathematical terms, a fan does not “blow away” the heat from a surface. Instead, it modifies the surface’s heat transfer coefficient.

Radiation

These vibrating particles also give off waves in sync with their vibration in the form of electromagnetic radiation. The higher the frequency of vibration – i.e. temperature – the higher the frequency – i.e. shorter the wavelength – of the radiation. When this radiation hits another particle, that particle will catch some of its energy, somewhat akin to objects resonating with sound waves that hit them.

The coldest temperature known in nature is the cosmic microwave background at 2.7K which peaks at about 1mm – the very top end of the EHF radio band. Typical ambient temperatures on the surface of the Earth are around 300K, which peaks at about 10µm i.e. infrared, while the surface of our sun at 6,000K peaks at around 500nm, which is right in the middle of the spectrum of visible light. Some supernovae heat their gasses up towards 55,000,000K, which peaks somewhere in the nanometre, i.e. x-ray, region.

Mathematically the heat emitted by a body is described by the deceptively simple-looking Stefan-Boltzmann’s Law:

$$Q=\sigma\varepsilon AT^4$$

But radiative heat dissipation is somewhat complex to calculate, first because it is a heat *exchange* – since all bodies radiate heat, while you emit heat you will also receive heat from your surroundings – and second, it depends on a vast number of geometry factors.

However, if we can assume that the area of the body is significantly smaller than the area of its ambient environment, and that this environment has a more or less uniform temperature, the net exchange can be simplified as follows:

$$Q=\sigma\cdot\varepsilon_1\cdot A_1\cdot(T_1^4 - T_2^4)$$

Where T_1 is the absolute surface temperature of the emitting body [K], T_2 is the absolute surface temperature of the ambient environment [K], A_1 is the total surface area of the emitting body [m²], and σ is Stefan-Boltzmann's constant [~5.7·10-8W/(m²·K⁴)].

The final variable ε_1 is the *emissivity* of the radiating surface.

Emissivity represents a surface's effectiveness in emitting its thermal energy as radiation. It is a value between 0 and 1, where 1 represents an ideal emitter; a *blackbody*. For most opaque solids, ε is also equal to α, the absorptivity, which is a surface's effectiveness in absorbing radiated thermal energy.

The value depends on the temperature region, i.e. on the radiation wavelength. Thus a surface may well have a structure that is highly radiative in infrared, while having a colour that reflects the visible thermal radiation from the sun.

Commonalities

While studying the formulae for conductive, convective, and radiative heat dissipation, it is well worth noting that certain factors recur in all of them.

One is the temperature difference. In all of them, it is clear that the larger the temperature difference, the more heat will flow.

Even more interesting however is the observation that *area* is a significant factor in all three formulae. The larger the area, the better the heat flow – in other words, if we can have larger areas, we can reduce the temperature difference for any given thermal power.

This is important for thermal management, since the heat source – i.e. component – temperature in the end will be equal to the temperature difference added on top of the ambient temperature.

We can thus begin to conclude that increasing the area – *heat spreading* – will be a key task in all thermal design.

Thermal Resistance

While Fourier's Law, Newton's Rule, and the simplified Stefan-Boltzmann's Law are useful tools, most zeroth and first order approximations tend instead to rely on *thermal resistance*.

The unit for thermal resistance is K/W, or °C/W. This means, how many degrees will the temperature increase over the resistance *per watt of thermal energy* transferred through it.

We have already touched upon one definition of thermal resistance:

$$R_\theta = \frac{\Delta t}{Q}$$

It is in a sense analogous to Ohm's law, where electrical resistance equals voltage over current. It's the same here: the resistance equals the potential over the flux.

If we plug in Fourier's Law into this formula, we can arrive at a definition of thermal resistance for conductive heat transfer:

$$R_\theta = \frac{\Delta x}{k \cdot A}$$

For convective heat transfer, we can instead plug in Newton's Rule, and arrive at the following:

$$R_\theta = \frac{1}{h \cdot A}$$

With an appropriate adjustment of the *h* value, this formula is actually useful also for the combined effects of convective and radiative transfer, as these usually occur simultaneously.

These formulae enable calculation of the thermal resistance of most components in a heat transfer chain, simply by plugging in known geometries and material data.

It bears noting that thermal resistance is an application specific value – it depends on geometries and other specific circumstances that may not necessarily translate into another application.

Thermal resistance is simple to use, as resistances in a heat transfer chain – whether empirically determined, calculated, or read off from data sheets – can simply be added the same way as electrical resistances.

A junction-to-case resistance from a component data sheet can thus be added to the calculated resistance for a thermal pad, to which a thermal resistance for a heat sink can be added from another data sheet, to give a rough inkling of where the junction temperature could be expected to land at a certain given power dissipation and ambient temperature.

While thermal resistance is in many ways analogous to Ohm's law, it bears pointing out that the analogy is limited. And while we do speak of thermal conductivity, there is really no meaningful definition of a reciprocal "thermal resistivity"; just as while we speak of thermal resistance, again, a reciprocal "thermal conductance" is not really meaningful term.

Once again, it is worth underscoring that – as can be seen in the formulae above – area is a key factor for low thermal resistance. Therefore, spreading heat as much and as early as possible in the heat transfer chain is vital in thermal design.

Why is this interesting for us in the electronics industry?

Electronics hardware today is developing in three very distinct directions – and this is true regardless of what type of electronics we consider:

Miniaturisation – components and devices become smaller, more compact.

Capability – devices are able to run larger and more demanding software applications, performing a greater number of operations in parallel.

Speed – digital communication speeds increase, as do bus speeds and read/write speeds in storage devices, etc.

All of these development trends have one very crucial thing in common: they drive heat dissipation.

Miniaturisation increases power density. When a device is made smaller, the heat sources in it – conductors, components, all the places where electrons encounter resistance – come closer together.

More capable devices inevitably consume more power, since the more they do, the more electrons they move, ergo the more power they need. Consequently, they also generate more waste heat.

Speed in electronics is a question of moving more data packets in any given amount of time. Each data packet is, simply put, a bust of electrons – and again, more packets equals more electrons, equals more heat.

The net effect is that not only are thermal issues on the increase in the industry; they are escalating at an exponential rate!

Certainly, the advent of new, more efficient semiconductor materials with less electrical resistance and better knowledge in how to design efficiently could be seen to counteract these trends, but the fact of the matter is that any design ceiling gained by improved efficiency is always and immediately claimed for boosted performance. The thermal bottom line thus remains unchanged.

So, thermal design is a crucially important factor for the electronics industry. Our ability to deliver the hardware and the performance levels that our respective markets demand hinges completely on our ability to design sufficiently efficient and effective thermal solutions.

Conclusion

All electronic devices and circuitry generate excess heat and thus require thermal management to improve reliability and prevent premature failure. For the electronics industry thermal design is a crucially important factor. The ability to deliver hardware and performance levels that our respective markets demand hinges completely on our ability to design sufficiently efficient and effective thermal solutions. The importance of reliable thermal management products is therefore essential to your success.

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