WHITE PAPER

Methods for Evaluating Advanced Electronics Cooling Systems

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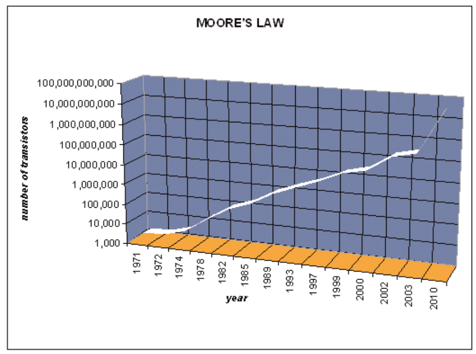
ABSTRACT

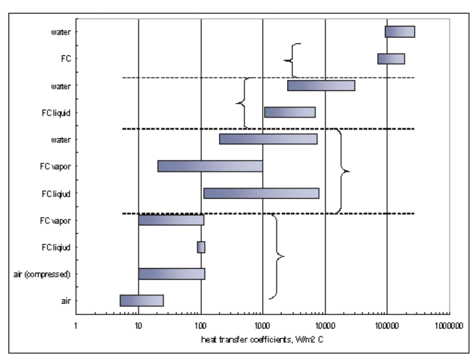
As predicted by Moore's law, microprocessor power dissipation is on a steady rise. In addition, the current technology is also enabling considerable feature size reduction resulting in an even sharper increase of local heat fluxes on dies. If the current pace continues, estimates indicate that power densities of 100 W/cm^2 will eventually be reached. In fact, hardware manufacturers have determined that dual core processor technology is the path to profitability. A processor with two 2.5- gigahertz processors can outperform a chip with a single 3.5-gigahertz processor in certain situations. The higher the temperature of a typical semiconductor, the lower its performance reliability and life expectancy. The inverse proportionality is not linear, but exponential, meaning that a mere reduction in chip temperature will have a considerable effect on both performance and durability. Since the final sink temperature, ambient air temperature, is constant, removing the ever-increasing heat fluxes while maintaining the same junction-to-ambient temperature will only be possible through the introduction of advanced cooling systems. Examples include active heat sinks, air jet impingement, micro channel cooling, heat pipes, immersion cooling, and spray cooling. Those systems, though far superior in heat removal rates, pose a more challenging problem to the designer and require novel tools for their design and analysis.



The graphical user interface showing the 'wizard' panel and pressure distribution on a cyclone.

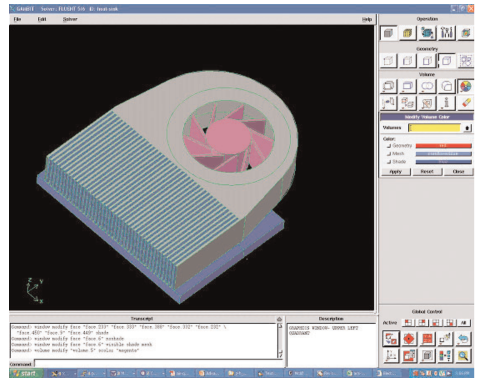
CURRENT CHALLENGES

Forced-air cooling using the traditional fan sink system will continue to be a work horse for electronics cooling because of its cost, reliability, and its familiarity to the design engineer. However, given the current and futuristic dissipation trends in chip design, it is evident that hybrid cooling systems, containing both traditional forced air cooling and an advanced cooling system that enables the local removal of high heat fluxes, will be the practical solution in thermal management. An overview of leading-edge advanced cooling systems follows.



The graphical user interface showing the 'wizard' panel and pressure distribution on a cyclone.

ACTIVE HEAT SINKS



Active heat sinks are the solution to minimize the ducting and leakage problems present in forced convection air cooling. By making the heat sink an integral part with the fan, leakage is non-existent. However, care must be taken in the design of active heat sinks since the performance of the fan(s) is now affected by the presence of the heat sink attached to it and how the active heat sink is located within the global system. It may not be appropriate to use a lumped analysis model based on the known fan curve to represent the fan within the active heat sink. Actual non-uniform flow into the fan and the nature of the flow dictated by the heat sink at the fan exit pose a different operating scenario than the fan curves obtained during typical fan tests. Additionally, the fins in the active heat sink may be designed based on a certain air speed that may differ from that provided by the fan after being installed within the active heat sink. Thus, the design of the active heat sink should involve the conjugate design of both the fan and the heat sink.

ACTIVE HEAT SINK IN PRACTICE

problem

According to fan manufacturer data, it was believed that it would deliver a sufficient amount of air. After being integrated within the heat sink and installed in the system, the amount of air delivered by the fan was found to be less than required by the design.

→

solution

- Due to the location of the active heat sink within the system, the flow was found to be non-uniform at the fan inlet. Also, the presence of the fins at the exit of the fan was changing the flow nature exiting the fan and thus the fan performance.
- Flow visualization has revealed the flow non-uniformity entering the active heat sink.
- Detailed flow analysis at the fan exit showed recirculation zones between the fan and the fins. This has lead to redesigning the fan blades with the intent to adjust the fan outflow to align with the fins.

→

result

- The new fan design inside the active heat sink has increased the flow rate by 15%.
- Analyzing the performance of the active heat sink within the system has proven important.

Another aspect of increasing importance is the amount of noise generated by the fan. The design should not only provide sufficient cooling, but also should have noise levels that are acceptable, and comfortable, to the end user. Additionally, similar to the flow performance of the fan, the acoustical performance of a stand-alone fan may be different for the same fan when installed in a system, e.g. within an active heat sink which is in turn installed in a bigger system. The resulting airflow in and out of the fan under installed conditions would affect the acoustical noise generated from the fan.

FAN NOISE PREDICTION IN PRACTICE

problem

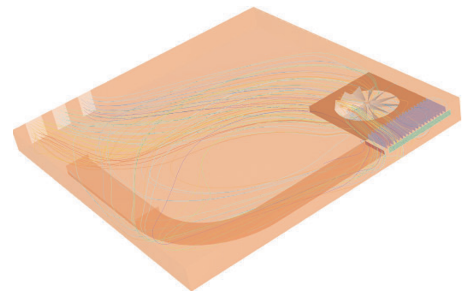
Two fans have proven to deliver a similar amount of air that is found acceptable. The designer would like to select the most acoustically friendly one.

solution

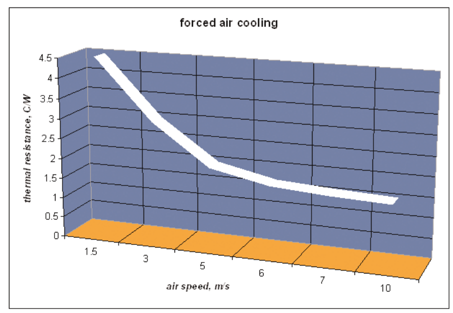
Air flow analysis of each design under consideration reveals the acoustical behavior of the two fans under installed conditions, including acoustical pressure, most dominant frequencies, and acoustical power densities.

results

By comparing the acoustical behavior of the two fans, the favorable fan acoustically (least power spectral density and Sound Exposure Level SEL) is selected.



System level analysis including detailed fan modeling within the active heat sink



Junction-to-ambient thermal resistance eventually reaches an asymptotic value with the continual increase of air speed for forced air-cooling systems

AIR JET IMPINGEMENT

The concept of using a concentrated jet for localized high heat flux cooling is similar to that used for metal quenching. Jet impingement offers not only the ability to remove high heat fluxes but also the ability to target hot spots or uneven heating. In addition, the jet placement is not a crucial factor with respect to the cooled part. A concentrated jet does not spread out in a conical fashion as a typical spray would and that makes its design simpler. The drawback is that a high pressure head is needed that would be converted to high kinetic energy of the jet. Also, there may be some noise concerns because of the high speeds. These cautions can be analyzed up front at the time of design to weigh out the benefits and risks.

MICRO CHANNELS

Micro channels are based on a very simple heat transfer concept: the heat transfer coefficient for laminar flow (very slow flow through a narrow channel) is inversely proportional to the hydraulic diameter. This means that the smaller your channel is, the higher your ability to draw heat from the source. Micro channels typically have sizes in the 5 to 100 µm range leading to a heat transfer coefficient of that may reach 80,000 W/m2K. They are typically etched on the die surface in the shape of rectangular grooves. There are commonly two main problems when designing a system of micro channels: pressure drop and flow uniformity across the channels. The smaller hydraulic diameter results in a higher heat transfer coefficient on the one hand but higher pressure-drop on the other hand. This would require higher pumping power. One solution for that is called "stacking" – instead of having a single layer of micro channels on top of the heat source, you

MICRO CHANNELS IN PRACTICE

problem

When testing the design, it was found that the die temperature at certain points was higher than allowed. Also, the pressure drop across the micro channels was too high.

↓

solution

Flow analysis through the micro channel stack has revealed that the manifold feeding the micro channels does not result in uniform flow through all the channels. Non-uniform flow results in nonuniform cooling and temperature distribution.

↓

results

By redesigning the manifold, uniform flow through the channels was ensured. Uniform flow also leads to lower pressure drop across the stack. Maximum temperature was reduced by 10%.

may have two, three, or more stacks. Studies have shown that most often two or three stacks are a good compromise between heat transfer behavior and pressure drop. Flow non-uniformity across the micro channels would result in non-uniform cooling, which may have implications on both the performance and reliability.

HEAT PIPES

Heat pipes are now the darlings of portable electronics cooling. They offer a high degree of flexibility in design and have proven to be extremely reliable since they are passive with no moving parts. Their heat transfer characteristics are superb, offering effective conductivities up to several thousands of that of copper, enabling the transfer of heat with minimal temperature gradient. Keep in mind when designing or selecting a heat pipe for a certain system, the known "limits" must be taken into consideration. These limits include the capillary limit, boiling limit, sonic limit, entrainment limit, and flooding limit. Depending on the design of the heat pipe, its orientation within the system (e.g. gravity-aided, acting against gravity or horizontal), and the heat flux applied to it, it may hit one of its limits and fail to perform its cooling duties. To ensure the proper function of the heat pipe within the system, the dynamic operation of the system with the heat pipe has to be analyzed under different conditions to ensure continuous performance.

SPRAY COOLING

Spray cooling has the promise of extracting heat fluxes in excess of 100 W/cm^2. Typically a liquid is sprayed directly on the die, which makes the use of a dielectric fluid essential, where it gains heat, converts to vapor and is cooled far away from the heat source, condenses and then re-pumped to be sprayed again. Sprays may be generated through different mechanisms, such as nozzles (pressure sprays or atomization sprays) or even through the use of inkjet-inspired technology[1]. The latter has the advantage of being able to target non-uniform heat sources and avoid "pooling" of liquid on cooler parts of the heat source. Design variables include nozzle design, spacing between nozzle exit and target, spray flow, liquid properties, and heat flux – all of which must be analyzed closely to avoid potential problems.

PROPERTY	FC-72	H_2O
Boiling Point @ 1atm (°C)	56	100
Density (kg/m^3)	1680	997
Specific Heat (W-s/kg-K)	1088	4179
Thermal Conductivity (w/m-K)	0.0545	0.613
Dynamic Viscosity x10^4 (kg/m-s)	4.50	8.55
Heat of Vaporization x10$_L^{-4}$ (W-s/kg)	8.79	243.8
Surface Tension x10^3 (N/m)	8.50	58.9
Thermal Coefficient of Expansion x10^3 (K^{-1})	1.60	0.20
Dielectric Constant (= 1 for vacuum)	1.72	78.0

Why use a dielectric liquid instead of water?

- Same weight of water will extract more than three times the heat for the same temperature rise (higher specific heat)
- Water is eleven times more conductive
- Same weight of water upon evaporating will extract 27 times more heat (higher heat of vaporization)
- However, FC-72 has a dielectric constant that is 2% that of water, i.e. much less unwanted current will flow!

SPRAY COOLING IN PRACTICE

problem

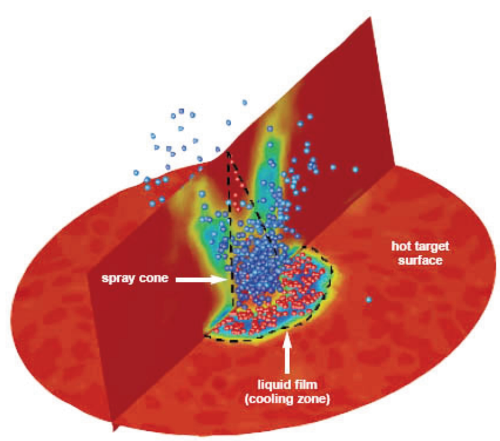
The heat source had non-uniform heat generation. The tested spray array was not able to extract the non-uniform heat and resulted in local hot spots. Spray analysis results showed that local liquid pools are formed at areas with lower heat fluxes. Amount of spray reaching high heat fluxes areas was inadequate.

solution

By adjusting the nozzle locations with respect to the target and changing the nozzle array, better targeting of hotter surfaces was achieved and pooling was avoided.

result

Results showed that the maximum liquid film thickness on the die is reduced by 100% and therefore pooling is avoided. Temperature uniformity on the die surface was also improved by 20%.



Spray cooling of a hot surface with liquid droplets; temperature contours are shown; liquid droplets are colored by diameter (red = initial large droplets, blue = smaller splashed droplets)

IMMERSION COOLING / DIRECT CONTACT COOLING

The terms "immersion" or "direct" are used to describe this approach because the working liquid comes into direct contact with the chip. The liquid may be moving passively due to natural convection or be driven by a pump. The liquid may also undergo partial phase change in which case much higher heat fluxes may be attained. Typically, excessive boiling should be avoided in order to reduce the creation of large bubbles that would lead to local hot spots. Instead, the preferred condition is that of sub-cooled boiling where the bubbles are small enough to re-condense into the main flow.

IMMERSION COOLING IN PRACTICE

problem		solution		result
Local hot spots were observed on the die.	→	Flow analysis showed that the design of the passages and the die geometries lead to the existence of recirculation zones near some dies. Liquid trapped in these zones eventually would heat up excessively.	→	By redesigning the flow passages to accommodate for the existing die geometries, flow uniformity was improved and recirculation zones were minimized. Maximum temperature was reduced by 8%.

CONCLUSIONS

Several advanced cooling systems have been discussed. The main objective behind all of these approaches is to be able to extract high heat fluxes from the chip while keeping the junction temperature acceptable. Having an advanced tool like computational fluid dynamics (CFD) software which enables the exact modeling of the physics involved (flow, heat transfer, phase change, condensation, boiling, spray) is essential for rapid and accurate design and comparison of these novel cooling systems. Also, the performance of individual components of the cooling solution, like fans and heat pipes, may be affected by the performance of the overall system surrounding them. It is important to test the performance of individual components under real system operating conditions to ensure their proper operation. CFD technology has proven to be effective in visualizing such conditions.

[1] Bash, C.E., Patel, C.D., Sharma, R.K., 'Inkjet Assisted Spray Cooling of Electronics,' International Electronic Packaging Technology Conference and Exhibition, July 6-11, 2003, Maui, Hawaii, USA.

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