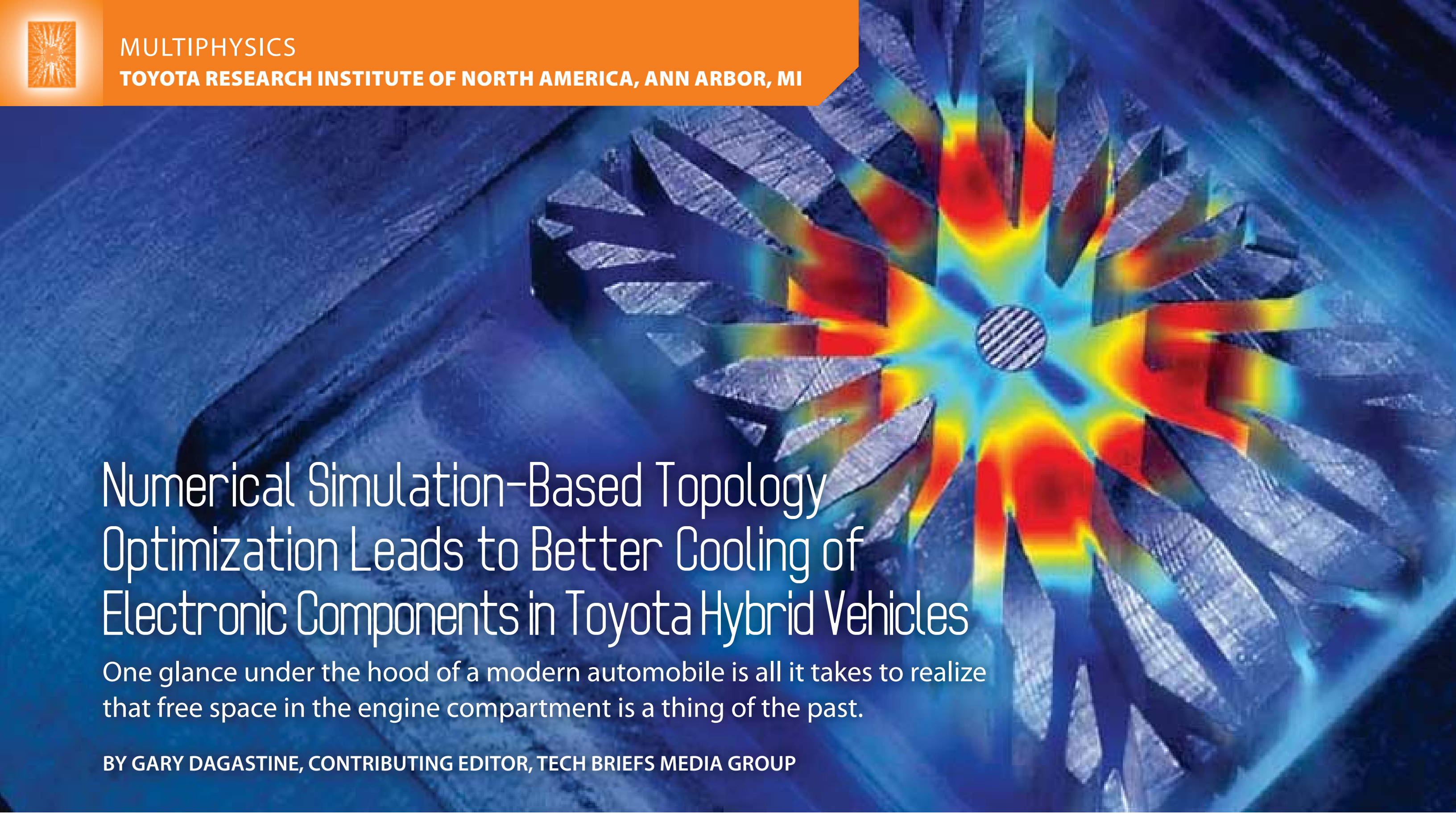

Numerical Simulation-Based Topology Optimization Leads to Better Cooling of Electronic Components in Toyota Hybrid Vehicles

One glance under the hood of a modern automobile is all it takes to realize that free space in the engine compartment is a thing of the past.

BY GARY DAGASTINE, CONTRIBUTING EDITOR, TECH BRIEFS MEDIA GROUP

If carmakers could reduce the number, size, and weight of the components in there, better fuel economy would result. A case in point is the design and development of optimized cooling structures, or advanced heat sinks, for thermally regulating the growing number of power electronics components used in the electrical system of Toyota hybrid vehicles.

To save the time and expense associated with analytical design methods and trial-and-error physical prototyping, researchers at the Toyota Research Institute of North America (TRI-NA) in Ann Arbor, MI instead used numerical simulation and multiphysics topology optimization techniques to design, fabricate, and test possible prototypes of a novel heat sink for future hybrid vehicle generations.

The Toyota Research Institute of North America's topology optimization team includes (from left) Ercan Dede Ph.D., Principal Scientist; Jaewook Lee Ph.D., Researcher; and Tsuyoshi Nomura Ph.D., Sr. Principal Engineer.

One example prototype combines single-phase jet impingement cooling in the plate's center region with integral hierarchical branching cooling channels to cool the periphery. The channels radiate from the device's center where a single jet impinges, and carry liquid coolant across the plate to dissipate heat evenly throughout and with minimal pressure loss.

Numerical simulations enabled Dr. Ercan (Eric) Dede, Principal Scientist in TRI-NA's Electronics Research Department, and colleagues to produce the optimized branching cooling channel patterns in an automated fashion using advanced simulation tools as opposed to a traditional trial-and-error design approach.

He carried out this work as part of TRI-NA's mission to conduct accelerated advanced research in the areas of energy and environment, safety, and mobility infrastructure. TRI-NA is a division of the Toyota Technical Center, which in turn is part of Toyota Motor Engineering & Manufacturing North America, overseeing R&D, engineering design and development, and manufacturing activities for Toyota's North American plants.

TRI-NA's Electronics Research Department focuses on two main areas: sensors and actuators, and power electronics. Among its resources are powerful modeling and simulation capabilities and prototype design tools, which enable its staff to develop effective solutions in the compressed timeframes demanded by the highly competitive automotive markets.

Hot Under the Hood

Toyota hybrid vehicles have sophisticated electrical systems in which many power diodes and power semiconductors such as insulated gate bipolar transistors (IGBTs) are used for power conversion and other applications. These components are standard planar silicon devices measuring a few centimeters per side, with high power dissipation.

In these hybrid vehicles, they are mounted on aluminum heat sinks, or cold plates, through which a water/glycol coolant mixture is pumped. In earlier model years, the cold plate design featured a fluid inlet on one side of the plate, outlet on the other side, and in between were arrangements of mostly straight cooling channels through which the coolant flowed. The long channels provided adequate heat transfer but it came at the cost of a significant pressure drop across the plate.

However, the technology roadmap for these power components calls for them to shrink to about half their current size while dissipating the same amount of power, meaning that heat fluxes will have to increase. In addition, although they have a 150 °C maximum operating temperature, typical silicon devices are kept at lower temperatures for greater component reliability. Moreover, the role of such devices is becoming more important as the electrification of vehicle systems increases.

All of these factors mean that thermal management of these devices will become more difficult than it has been to date.

It might seem reasonable to simply redesign the cold plates so that more coolant can be pumped through them. But that would require more pumping power, and with space already at a premium in the engine compartment where the pump is located, moving to a larger, more powerful pump or adding an additional pump is unacceptable.

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Instead, Toyota decided to look at re-engineering the cold plate with an eye toward achieving optimum heat transfer and negligible additional pressure drop simultaneously. If both could be achieved, thermal objectives could be met at no significant increase in system pumping capacity.

Jet Impingement an Incomplete Solution

“Many researchers working on diverse applications have identified jet impingement as an attractive way to cool surfaces,” said Dede. “But while jet impingement performs well with respect heat dissipation close to the jet, it’s less than optimum as you move away from the orifice.”

The reason is that the highest heat transfer occurs close to the jet entrance where the fluid is the coolest and velocity is the highest. As a result, much heat-transfer capability is lost by the time the coolant reaches the exit of the cold plate.

One solution to this problem is to combine jet impingement with a peripheral channel structure to increase the area-average heat transfer. “It’s in your interest to make those channels short to keep pressure drop to a minimum, but short, straight channels aren’t efficient enough for our use,” Dede explained. “Our goal was to come up with a combination jet-impingement/channel-flow-based cold plate with optimally designed branching

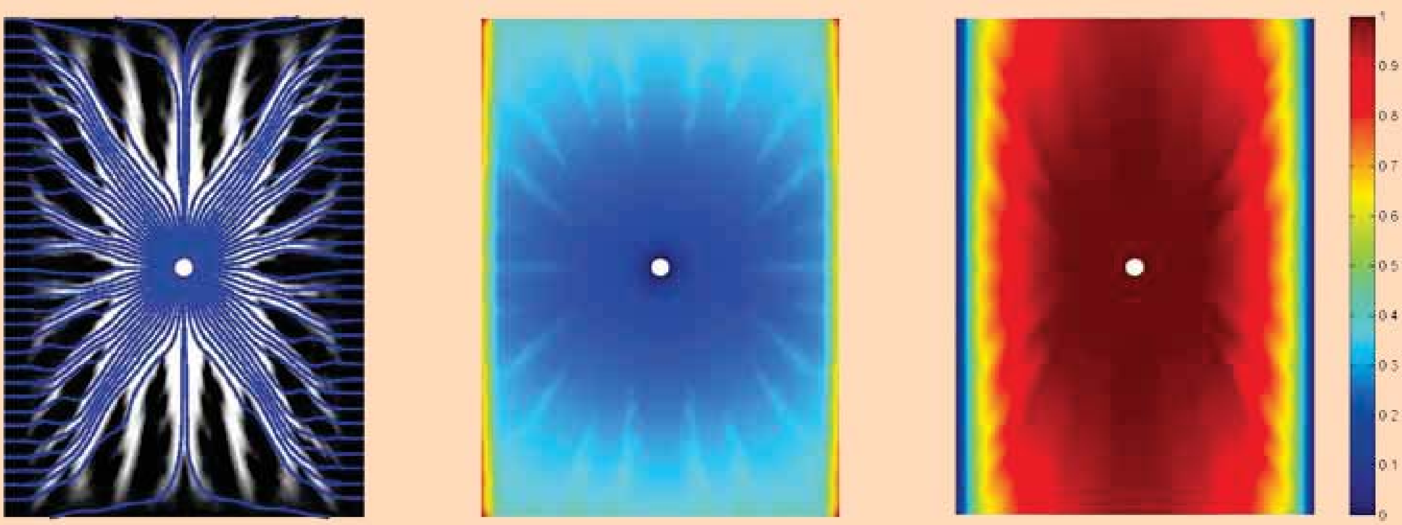

Figure 1. Optimal cooling channel topology with fluid streamlines colored blue (left); normalized temperature contours (center); and normalized pressure contours (right).

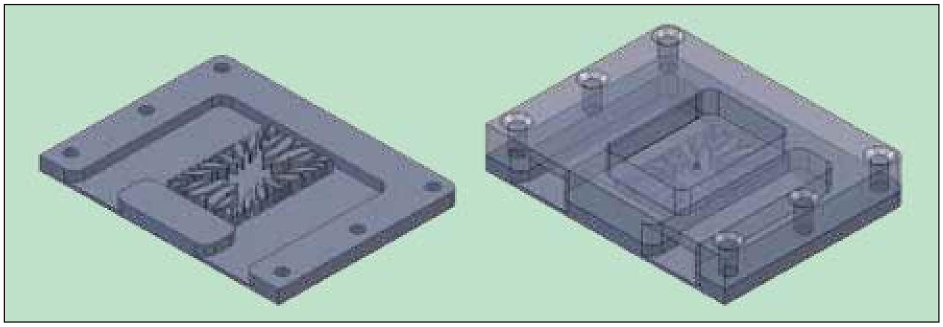

Figure 2. Isometric views of the derived hierarchical microchannel cold plate without a jet plate (left) and with a jet plate shown transparent for clarity (right).

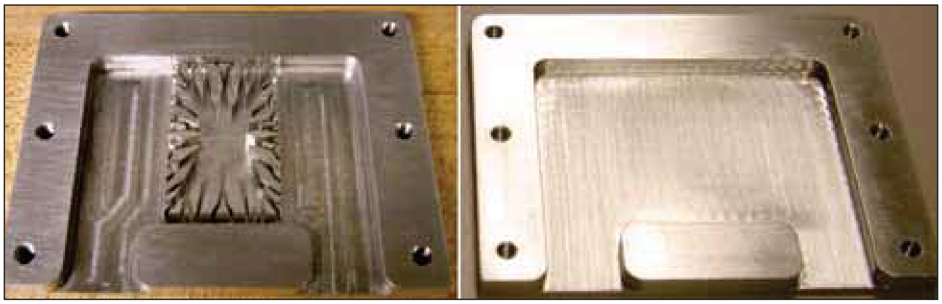

Figure 3. Prototype aluminum cold plates with (left) and without (right) the hierarchical microchannel topology.

channels to uniformly remove the most heat with the least pressure drop."

The CFD and Heat Transfer Modules of COMSOL Multiphysics software were essential to the numerical simulations at the heart of this work. COMSOL's LiveLink™ for MATLAB® also enabled Dede to work with the multiphysics simulations in a high-level scripting language as he went about the task of optimizing the cold plate's topology.

He examined how topology influenced such variables as steady-state convection-diffusion heat transfer and fluid flow. He did this using well-established material interpolation techniques and a Method of Moving Asymptotes (MMA) optimizer, moving back and forth between COMSOL and MATLAB in an iterative fashion to investigate cooling channel layouts. (MMA is a convex-approximation strategy to aid in optimizing physical structures.)

Although the aspect ratio of the channels (i.e. ratio of height to width) is quite important, to simplify the numerical simulations Dede assumed a thin 3D structure and then further "flattened" it. Once an initial channel topology was derived, the height of the fins that separate the cooling channels could be investigated and incorporated with a separate parametric sizing study. Dede's group had separately performed such studies so his assumptions were well-informed.

Ultimately, these numeric simulations produced an optimal cooling channel topology with fluid streamlines in branching channels (Figure 1).

Because these channels efficiently distribute coolant throughout the plate and create relatively uniform temperature and pressure distributions that are a function of branching complexity, this fractal-like topology was in turn used to guide the design of a cold plate prototype (Figure 2). The size of the plate was set to approximately 60 mm × 45 mm with a middle cooling zone covering a 25 mm × 15 mm-sized area to match a specific heat source. The plate's base substrate thickness was assumed to be 1 mm.

Real-World Performance

"Once we used COMSOL and MATLAB for the topology optimization routine, we then used the final channel concept from it to design and evaluate a prototype using COMSOL's LiveLink™ for SolidWorks®," Dede said. "COMSOL has a nice feature that allows you to actively link to computer-aided design tools, and it was easy to import various structures from SolidWorks back into COMSOL to verify pressure drop and heat transfer.

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"I think this is really the future of simulation, to be able to link your CAD tool to your simulation tool so that you can streamline the development of fast, accurate design iterations," Dede added. "It's not necessarily going to solve all of your problems, but it helps you to quick-

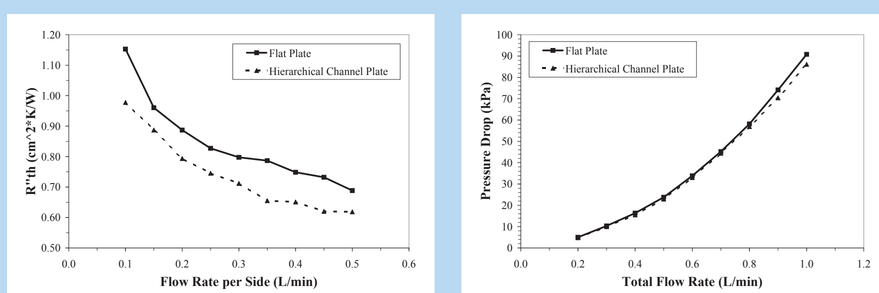

Figure 4. Comparison of cold plate unit thermal resistance (left) and pressure drop (right).

ly establish a reasonable starting point and to progress from there quickly."

Using the SolidWorks designs, two prototypes were fabricated from aluminum using standard micromachining techniques. Two such prototypes were produced that compared unit thermal resistance and pressure drop in a combined jet/hierarchical microchannel version against a version that utilized jet impingement of a simple flat plate (Figure 3).

The prototypes were then incorporated into a double-sided cooling test setup to see whether a dual configuration might provide higher-performance cooling in an ultra-compact package size.

On average, the dual-hierarchical microchannel version dissipated 12.8 percent more power than the flat plate version (Figure 4 — left). Indeed, using water as the coolant, it demonstrated very high heat transfer when cooling on both sides of the heat source was accounted for. With regard to pressure drop, both cold plates demonstrated similar results, although the dual-hierarchical version performed slightly better at higher flow rates (Figure 4 — right).

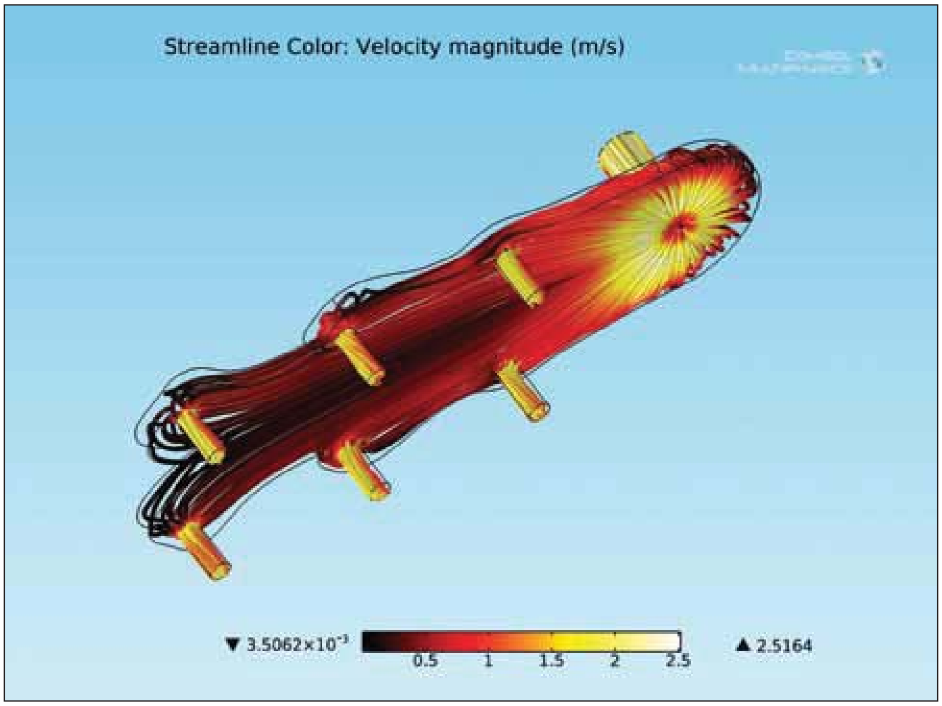

Figure 6. Manifold to feed fluid to multiple multi-pass cooling cells.

Future Directions

Dede noted that the cold plate concept could be applied to multi-chip packages or even could be used in a multi-pass configuration for a single-chip package for higher-performance cooling (Figure 5).

Along these lines, Dede performed other numerical topology optimization simulations to study the fluid flow of a cold plate inlet manifold comprising a single fluid inlet and six outlets. This manifold could feed fluid to multiple multi-pass cooling cells. In Figure 6, the fluid streamlines are colored with velocity magnitude. The curvy sidewall manifold shape was generated through COMSOL fluid-flow topology optimization studies, where the goal was to minimize the pressure drop across the manifold while balancing the flow rate to each outlet nozzle.

The flow rates across all nozzles are within 7 percent of each other and the pressure drop is about 2 kPa, meaning that the different local sections of the cold plate would receive the same coolant flow. This results in the device temperature distribution across the cold plate being evenly balanced.

"The work we've done here is really just the first iteration of this solution," Dede said. "In the future, we will also look at such things as manifold design to decrease the pumping penalty further. Also, we may be able to optimize the topology of each individual cooling cell so that it works optimally in a 3D configuration."

And what about even farther down the road? "We can apply these methods to other things, like electromagnetics and thermal stresses, as well. We believe this project is just the beginning for numerical-simulation-based topology optimization," he said. ■

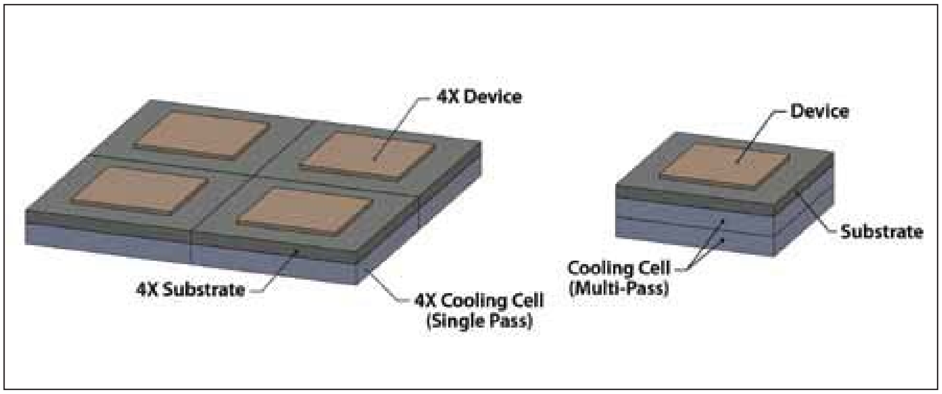

Figure 5. Multi-chip application (left) and multi-pass configuration for single-chip.

Learn More

For more information, see the paper "Experimental Investigation of the Thermal Performance of a Manifold Hierarchical Microchannel Cold Plate," by Toyota's Ercan M. Dede in the InterPack 2011 Conference Proceedings (the ASME 2011 Pacific Rim Technical Conference & Exposition on Packaging and Integration of Electronic and Photonic Systems).

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