Cooling Technologies Research Center (CTRC)

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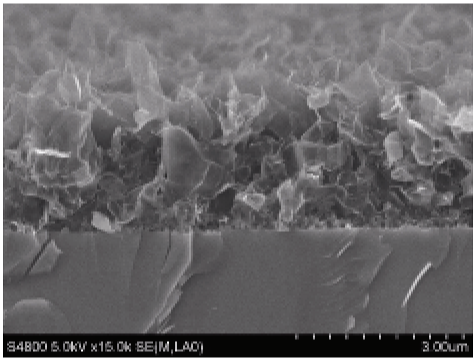
Center website: https://engineering.purdue.edu/CTRC/

Graphene-Based Thermal Interface Materials (TIM)

Efficient heat dissipation is critical in many applications in integrated electronic circuits and other similar applications. Thermal interface materials (TIMs) are necessary for heat dissipation because microscale gaps/voids between thermal transfer surfaces (e.g., between a CPU and heat sink) are unavoidable. The heat transfer efficiency across these interfaces can be dramatically enhanced by filling these gaps/voids with appropriate TIMs.

Graphene, a single atomic layer of graphite with honeycomb lattice structure, exhibits very high thermal conductivity (3000-5000 W/m-K). this makes it an outstanding candidate for TIM applications. Graphene flakes can be vertically grown on multiple substrates by either plasma enhanced chemical vapor deposition (PECVD) or chemical reduction from graphite oxide. A mixture of commercial thermal paste or polymer with graphene flakes is another candidate graphene-based TIM option.



Scanning electron micrograph of vertically aligned graphene petals grown by microwave plasma enhanced chemical vapor deposition and bonded to a substrate for use as low thermal resistance interfaces.

CTRC researchers are synthesizing and characterizing both graphene composites and vertically grown graphene. Researchers have synthesized vertical graphene sheets on silicon and copper substrates and measured their thermal interface resistance. The measured resistance is among the lowest resistance values reported in literature, indicating their excellent promise for high-performance interface applications. Also, simulations of the vertical graphene properties have demonstrated that the synthesized graphene density on the substrate is a key factor determining composite thermal interface resistance. By isolating this trend, researchers are able to match simulation results with experimental data for the first time.

Currently, the TIMs industry primarily uses thermal greases and pastes. One of the common problems is that it may leave unwanted residues on the surface after removing the TIMs. Vertically grown graphene can be easily applied to a surface by growing graphene on thin supporting layers or directly on the surface of the products that need increased thermal contact. Even though excellent preliminary thermal performance has been measured, facilitating its use in industry applications requires further attention.

Economic Impact: Companies who improve their high-performance thermal interface materials will improve their chip and device packaging strategies. Graphene-based TIMs can possibly reduce costs. The economic impact has been the reduced headcount and overhead related to doing this research and development because the faculty and students of CTRC perform this preliminary and foundational research. CTRC provides industry with the methods, modeling and data needed to implement graphene TIMs in their devices. It is difficult to precisely measure the impact of this work but it has been estimated to be between one and 10 million USD for at least one of our member companies.

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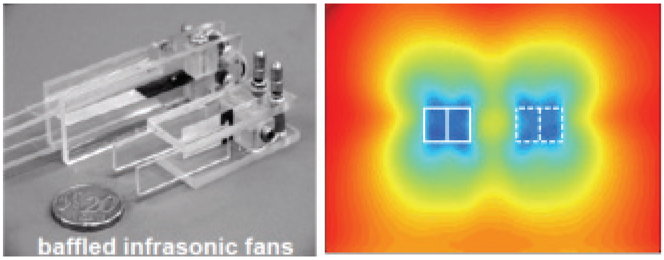
Miniature Piezofan Arrays for Cooling Electronics

Innovative, miniature piezoelectric fans have been developed in this CTRC project into a viable technology for meeting a variety of cooling needs in portable and small-scale electronic devices. Analytical tools have been developed for modeling the flow field, heat transfer, and fan structure; flow-structure interaction is currently being investigated, to allow the design of optimal cooling systems. Studies have been done to test and characterize the thermal, electromechanical, fluid dynamic and acoustic performance of piezoelectric fans. Interactions between multiple fans are being studied; coupling effects between the fans can cause the amplitude to increase by up to 40% over that of a single fan.



The images show the fan and the heat transfer distributions brought about by two fans vibrating in front of a heated surface.

In smaller devices, where rotary fans are not practical and electronics are pushed to the limits of their heat dissipation capacities, piezoelectric fans offer the only realistic cooling solution while meeting the noise and power constraints of portable devices. Piezofans have no bearings or wearing parts that cause cyclic breakdown or noise-producing concerns. These fans are small, silent and very low-power devices. They present no electromagnetic interference, nor will they affect magnetic fields. They produce negligible heat and are reliable over a high temperature range. The piezofans are cost-effective, use simple circuitry, highly efficient, and lightweight. In order to realize the potential of piezoelectric fans in industry, CTRC optimized the design of fan blades based on robust electromechanical and flow-structure modeling. They are well suited to providing supplemental cooling in hot spots and other stagnant areas in devices where rotary fan action is ineffective. Applications are in wireless devices, video game systems, automotive applications and multimedia systems where compact, low noise and low power consumption is essential.

Economic Impact: Center research has advanced the science to a stage that it is now possible to use them in applications where cooling requirements need to be met for low profile products such as laptops and cell phones. The impact of piezofans to many industries and markets is on the cusp of increased commercial use. Piezofans are the solution to many problems in various industries where the traditional rotary fan failed. They result in lower cost, lower noise, lower power consumption, better size capability and better reliability. Center members have new products aligned to use this technology in ways that will give them a marketing edge.

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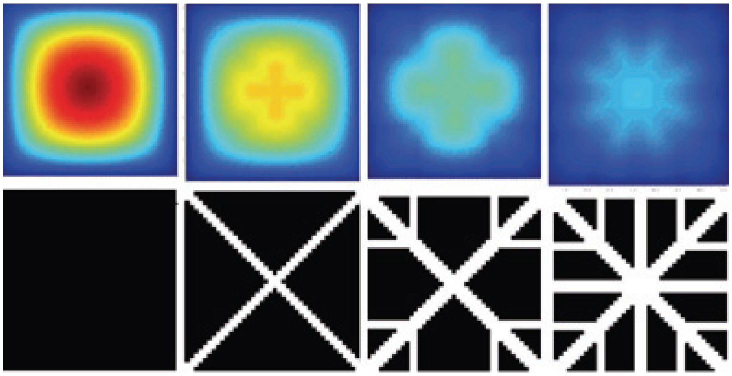
Validated Models for Particulate Thermal Interface Materials

Thermal Interface Materials (TIMs) continue to be a bottleneck for developing the next generation of micro-processors with smaller chip sizes and increased power. Development of better TIMs is imperative to ensure efficient heat removal from the microelectronic systems, which in turn improves the system reliability and performance. Accurate modeling of thermal interface materials requires either complex 3-D computational simulations or improved analytical models. Most existing models do not consider particle-particle interactions. Many fail when volume loading exceeds 30%. Numerical modeling of realistic three-dimensional microstructures (at high filler volume loadings) considering inter-particle interactions was performed using full-field meshless simulations and random particle network simulations. The developed models are validated with experiments on representative systems.



Bingham fluid model prediction of polymeric thermal interface material squeezing force (top row) for multiple hierarchically nested channel designs (bottom row).

The models can be efficiently used to accurately predict the effect of varying:

1) the filler particle conductivity;
2) the base polymer matrix conductivity, and;
3) size distribution and arrangement of the filler particles, on the composite thermal conductivity of TIMs.

These models are expected to provide critical help in the design of high performance TIMs.

Economic Impact: Precise contact resistance values, studying different materials, and analyzing degradation of TIMs are necessary for heat transfer models in the electronic cooling industry. Improved models will allow for the design of more efficient heat sinks for electronic applications and lead to lower energy use and higher performance. The thermal interface materials research that comes out of CTRC is immediately used by the member companies and has an impact in power electronics, telecommunications, cellular base stations and mobile phones, automotive electronics, portable/wearable electronics, pervasive computing devices, electric vehicle batteries, power distribution systems in computers, large-scale servers, military electronics and avionics.

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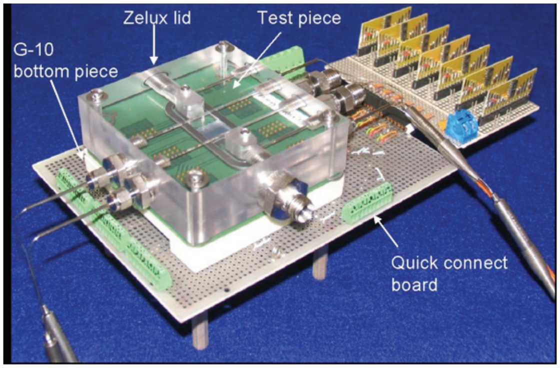
Two-Phase Transport in Microchannels

Researchers at the Cooling Technologies Research Center are exploring boiling and two-phase (liquid and vapor) flow in microchannels. Transport through microchannels that range in width from 100 to 400 micrometers in copper and silicon substrates has been characterized. A predictive model has also been formulated that aids in the design and optimization of microchannel heat sinks.



State-of-the-art silicon thermal test chip used for investigation of two-phase flow in microchannels cut directly into the chip surface. The test chip is capable of producing uniform heat dissipation and local measurements of temperature.

This CTRC work has resulted in better understands of transport in microchannels, and hence in rendering microchannel heat sinks implementable in electronics cooling applications. Several novel experimental and modeling tools have been developed. Laser-induced fluorescence thermography is used to measure the liquid temperature during flow boiling heat transfer within microchannels. Infrared Particle Image Velocimetry (IR-PIV) is being developed as a tool to make measurements inside silicon microstructures (with no optical access), capitalizing on the transparency of silicon to infrared light. System-level analysis of microchannel cooling systems, with an emphasis on design for energy efficiency and manufacturability, is now possible through a software tool developed in the Center. CTRC research has developed models to use of this technology in cost sensitive, very high power electronic applications. Liquid cooling techniques using microchannels enables high power electronics in hybrid vehicles, avionics and spacecraft. This technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2011.

> **Economic Impact:** Microchannel heat sinks that employ two-phase liquid cooling are compact and requires less pumping power for cooling, hence making them an attractive option from economic perspective. The ease of integration of these devices into high power electronic systems is an added advantage. The net cost associated with thermal management devices can be reduced by 60 to 70 percent.

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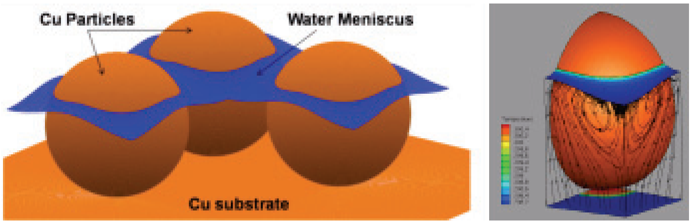
Enhancement of Heat Pipe Transport Properties and Thin Film Evaporation



Prediction of static meniscus shape formed by water in an arranged packed bed of copper particles (left) and complex toroidal vortex formed due to Marangoni convection obtained via three-dimensional simulation of evaporation from a wick pore (right).

One of the key limiting factors in electronics technology today is the ability to remove heat from the processor inside nearly every device. Heat pipes are commonly used in electronics cooling applications due to their ability to move large amounts of heat over reasonable distances with only small drops in temperature. This efficient heat transport is due to the phase change of an internal working fluid from liquid to vapor and porous structures imbedded inside which passively drive the working fluid. Efficiency increases would allow the device to operate with less temperature drop across the heat pipe, therefore keeping electronic components relatively cooler at the same heat load. While typical devices in industry today use randomly packed particles as a porous wick, this work has shown how device performance may be dramatically improved upon by designing the wick structure at a microscale level.

> **Economic Impact:** As devices in industry are packaged into ever decreasing sizes, microscale design techniques promise substantial impacts. By operating heat pipes at a lower temperature, the overall power consumption of the cooling solution is decreased because auxiliary cooling components, such as axial fans which dump heat to the ambient atmosphere, do not have to work as hard. Improvement of heat pipe devices may dramatically aid the semiconductor industry. Thermal management technology, such as heat pipes, which has the ability to dissipate higher heat loads, has the potential to spur technological and economic growth in these industries.

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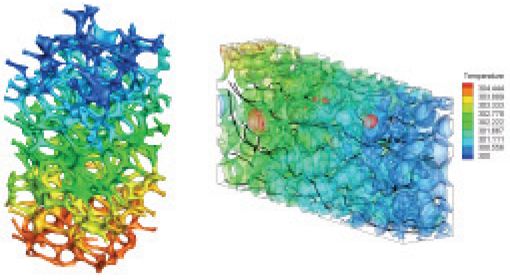
Transport in Porous Structures and Metal Foams



Advanced microtomography based prediction of temperatures within (left) a metal foam, and (right) a sintered copper porous bed.

Metal foams are novel heat transfer surfaces with potential use as heat sinks and heat exchangers. They have been successfully employed in the heat exchanger industry by companies such as Honeywell. Power electronics is another potential industry where this technology is increasingly finding use. Porous structures are also found as sintered particle beds in heat pipes – a device found today in technologies as diverse as laptops and satellites alike. Advanced military electronics often use heat pipes for their high effectiveness and reliability in harsh environments, apart from being self-powered.

A novel computational methodology for detailed modeling of open-cell foams and heat pipe wick structures using advanced imaging techniques such as microtomography (commonly known as CT scanning) has been developed at the CTRC. Applications include heat exchangers, energy absorbers, breather plugs, CO_2 scrubbers, micrometeorite shields, heat shields, optics and mirrors, wind screens and baffles, cryogenic tanks, lam discs, missile baffles, anti-slosh baffles, air oil separators, and high temperature filters.

Economic Impact: Devices such as solar inverters and uninterruptable power supplies, where the technology will be implemented, will benefit from advantages such as cooler electronic components and smaller heat sinks; thereby increasing the life of the equipment as well as shrinking the overall dimensions. With reliable property information, expensive experiments are avoided. The designer can just choose samples based on the values of the properties we measure, thereby cutting down the design time significantly. The greater impact would be once the technology is fully optimized and realized. It can be employed to cut down the equipment size by half or more, thereby cutting down significant material costs. The other savings are in terms of pumping power. These novel structures, use a far lower pumping power (cost) compared to their conventional alternatives.

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