Cooling Technologies Research Center (CTRC)

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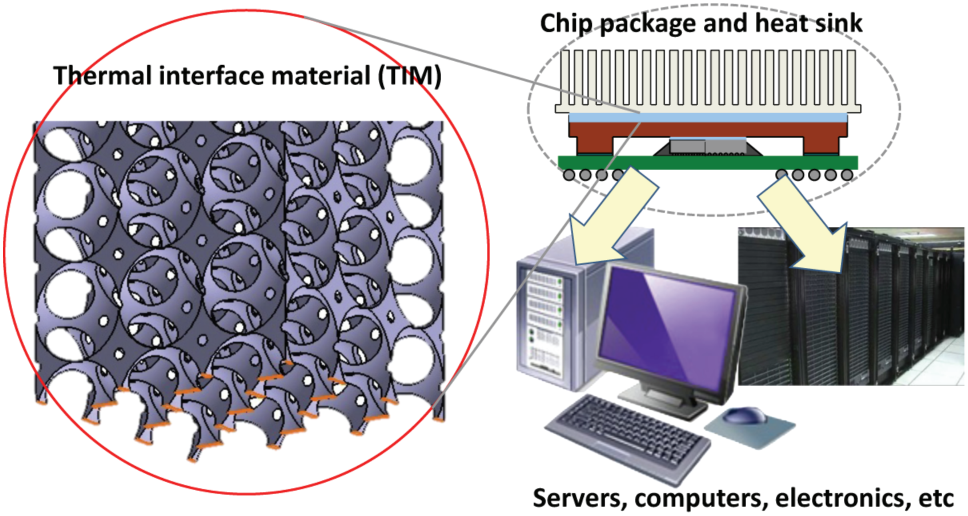
Center website: https://engineering.purdue.edu/CTRC/

Engineered Metal Network Thermal Interface Material

Thermal interface materials (TIM) facilitate heat transfer between two mating surfaces, such as an electronic device to a heat sink that keeps the device cool. This is particularly important for cooling today's increasingly powerful electronics (e.g., graphic processors, power electronics, and highly integrated circuit chips in cell phones, etc.). This is because performance is often limited by the ability to remove heat. The contribution of interface between materials in the heat removal path sometimes accounts for more than 30% of overall resistance to heat flow. If the interface contact fails, the electronic system easily fails catastrophically due to thermal runaway - the electronics literally melt themselves.



Engineered metal network is designed as a thermal interface material (TIM) to directly conduct heat from a chip to heat sink in electronic equipment.

This breakthrough focuses on the performance of a novel approach to thermally coupling the interfaces via theoretical analysis and experimental validation. It is leading to improvements in the ability to dissipate heat from today's advanced electronics.

TIMs must demonstrate three major aspects. They should: 1) be made of material that has good thermal conductivity; 2) be capable of making good thermal contacts between the two surfaces; and 3) be mechanically compliant to the target surface. This work deals with a trade-off between these three physical aspects by engineering the porous and mesh structure for making the heat transfer better across the interface.

Researchers at Purdue University's Cooling Technologies Research Center (CTRC) have introduced the use of a metal mesh accompanied by a novel design that directly connects the two interface surfaces. A metal mesh allows heat to pass through the interface easily from one side to the other - the ligament acts like open highways for the heat to travel across. The surface of the metal mesh is envisioned as a naturally flexible array of small protrusions to make a good contact to the target device, which has a small roughness and some curvature.

Conventional technologies have been based on indirect contacts of many disparate metal pieces embedded in a polymer, hence, the heat must stop and go many times as it travels across the material. The most innovative part of this work is that it provides a theoretical model to determine the best design, prior to any experimental research and development (R&D) work. In contrast, conventional approaches, even state-of-the-art technologies, require experimental repetition of many R&D cycles to find a good recipe.

Based on the three-dimensional geometry of the porous metal mesh, this research will give a theoretical prediction of performance to be validated by strategically organized experiments. The work is based on aluminum porous media available in market, but the theoretical model is not limited to this particular geometry or this particular raw material, nor is it limited to any manufacturing process. Any hypothesized geometry or raw materials can be engineered analytically. The result of this research should extend the possibilities for new material developments exponentially, and the performance improvements resulting from engineering metal networks in TIMs will help to dissipate heat more effectively.

> **Economic Impact**: Networked TIMs enable the design of heat sinks that are both simpler and smaller for compact electronics design, as well as more cost effective. The economic impact resulting from the improvement of a single ingredient component for electronics is difficult to isolate due to the highly integrated nature of the systems. Making better thermal interface material should avoid costs associated with heat sinks and cooling fans. We speculate that a 30% performance improvement of the TIM over the state-of-the-art materials could relax performance requirements by as much as 17%. This would translate to a 24% cooling cost reduction (linear to 1.5 exponent of the performance). Considering that the heat sink market is in scale of a couple of billion dollars per year, the potential cost reductions for electronics could exceed tens of millions of dollars per year. More importantly, considering a higher penetration rate of electronics in the United States, the work should provide higher value electronic products to end-users. The reduction of aluminum usage for the heat sinks could also help saving the energy consumption during the manufacturing.

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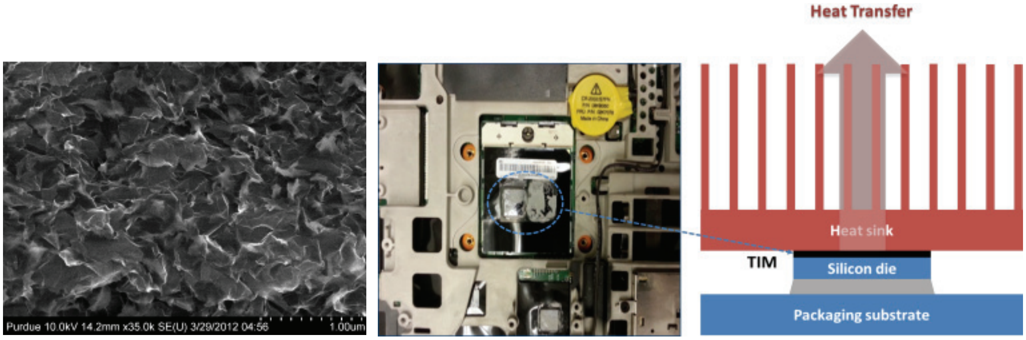
Graphene-Based Thermal Interface Materials (TIM)

Because the density of electronic components in integrated circuits (ICs) has increased tremendously during the past few decades with a trend of miniaturization of individual electronic components, the density of dissipated power has also increased significantly. This has led to degradation of device performance. Therefore, thermal management in ICs or high-power electronics becomes a crucial issue to maintain device performance.



Scanning electron microscopy (SEM) image of graphene/polymer composites (left) and thermal interface materials (TIMs) applied to the interface between silicon die/metal heat sink in the laptop to enhance the efficiency of heat transfer (right).

Thermal interface materials (TIMs) between dissimilar thermal junctions (e.g., between CPU/heat sink) are necessary for efficient heat dissipation because microscale gaps or voids are unavoidable. These prevent efficient heat transfer. By filling out those thermal junctions with appropriate TIMs, the heat transfer efficiency across interfaces can be dramatically enhanced.

Graphene is a single planar sheet carbon atom with a honeycomb lattice structure. It has the highest thermal conductivity (~5000W/mK), and it is a thermally and mechanically stable material. By using these excellent properties, CTRC researchers have developed graphene/polymer composites for TIM applications based on "few-layer" graphene, which is prepared by a new and simple exfoliation technique. Unlike most previous conventional preparation methods, the new technique can be readily applied to mass production. Moreover, the measured thermal interface resistance between copper heat sinks and composites is comparable to current state-of-the-art TIMs. This indicates that graphene-based TIMs are good candidates for future thermal management applications.

Currently, the TIMs industry mainly focuses on ceramic/metallic particle-based TIMs (e.g., silver particles). One of the common problems is that these require high production costs compared with graphene-based TIMs. One of the most significant virtues of the graphene-based TIMs developed by CTRC researchers is their low-cost of production and their high performance characteristics (high thermal conductivity and low thermal interface resistance of graphene-based TIMs).

> **Economic Impact:** The global market for TIMs is expected to increase to ~ $760 million by 2017. Polymer-based and metal-based TIMs still occupy the largest portion of the market. With increasing demands of thermal management applications, it is likely that the market will expand even more significantly than the current prediction. The TIMs market will be extended from conventional applications such as PCs or laptops to many types of consumer electronics applications including high-power light-emitting diodes (LEDs), display applications, and flexible and wearable electronics. By replacing conventional filler materials with graphene, we can develop high-performance TIMs with much lower production costs. Therefore, this work can open a new chapter in thermal management industries.

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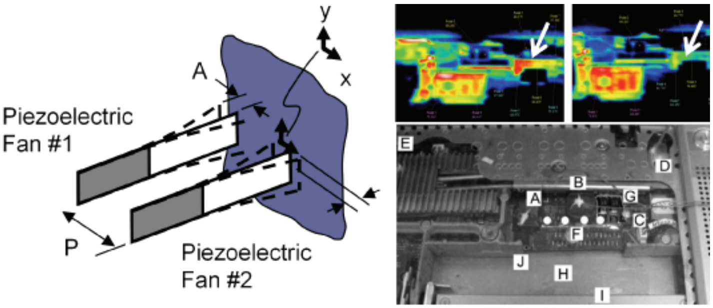
Miniature Piezofan Arrays for Cooling Electronics



Laptop Cooling Demonstration

A piezofan cools a surface by oscillating a single fan blade, similar to a hand-held folding fan, but is instead driven by a highly efficient piezoelectric element that wafts the blade in response to an electric signal. The cooling capability is demonstrated by placing the fans into a laptop device, and observing a drop in the temperature with an infrared camera.

Innovative, miniature piezoelectric fans have been developed by the CTRC project into a viable technology for meeting a variety of cooling needs in portable and small-scale electronic devices, as well as in larger scale thermal systems that reject heat to ambient air. A piezofan cools a surface by oscillating a single fan blade, similar to a hand-held folding fan, but is instead driven by a highly efficient piezoelectric element that wafts the blade in response to an electric signal. Analytical tools have been developed for modeling the flow field, heat transfer, and fan structure to allow the design of optimal cooling systems. Studies have been completed to test and characterize the thermal, electromechanical, fluid dynamic, and acoustic performance of piezoelectric fans. Interactions between multiple fans have been studied; coupling effects between the fans can cause the amplitude to increase by up to 40% over that of a single fan.

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. They 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, and are 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 now better suited to providing supplemental cooling in hot spots and in other stagnant areas in devices where rotary fan action is ineffective. Applications are in wireless devices, video game systems, automotive systems, data centers, telecommunication base stations, and multimedia systems where heat is typically rejected to air, and efficiency and durability are paramount.

> **Economic Impact:** 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 higher reliability. Since the original development of piezofans within CTRC, numerous piezofan-based thermal management products have been introduced to the market, most notably CTRC member company GE's highly publicized Dual Piezoelectric Cooling Jets (DCJ). The wealth of piezoelectric thermal management devices is a result of the burgeoning light-emitting diode (LED) light bulb market. Consumption of LED lamps in the United States totaled $891M in 2012 and is expect to grow to $2.77B by 2017 (ElectroniCast Consultants). While LED lights may have a significantly longer lifespan and lower energy consumption than incandescent alternatives, the devices produce significant amount of heat. Unlike conventional light bulbs, the solid-state devices at the heart of LEDs must be kept cool to retain efficiency. Energy consumption of a traditional rotary fan would offset any potential energy efficiency gains, making piezoelectric fans a viable alternative. Multiple piezoelectric-based LED thermal management devices have reached the market, such as the Nuventex SynJet.
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> The combined worldwide electricity consumption of data centers has increased from 71 billion kWh per year (in 2000) to 152 billion kWh per year (in 2005) to approximately 238 billion kWh per year (in 2010), representing a growth of roughly 11% per year over the last decade. As a fraction of the worldwide total electricity usage for all sectors, the contribution of data centers has increased from 0.53% in 2000 and 0.97% in 2005 to 1.31% in 2010. The growing IT demand is outpacing technological developments in sustainable energy management for these systems. Between 2003 and 2008, the total energy consumption of servers has doubled. Such growth levels are unsustainable and are especially worrying because IT equipment already contributes significantly to global energy use and carbon emissions. The main advantages of piezofans are low cost, low power consumption, low noise, good reliability, and good thermal performance in the low to moderate heat flux range. Piezofans can be used to replace or augment traditional air flow movers like axial fans. These devices can be combined with existing speed-controlled axial fans to achieve significant gains in heat transfer performance when the fans are operated at lower speeds. Even with marginal improvements to air cooling technologies, there is potential to save greatly on electricity consumption cost in current IT equipment for CTRC companies such as Huawei, IBM, and Intel.

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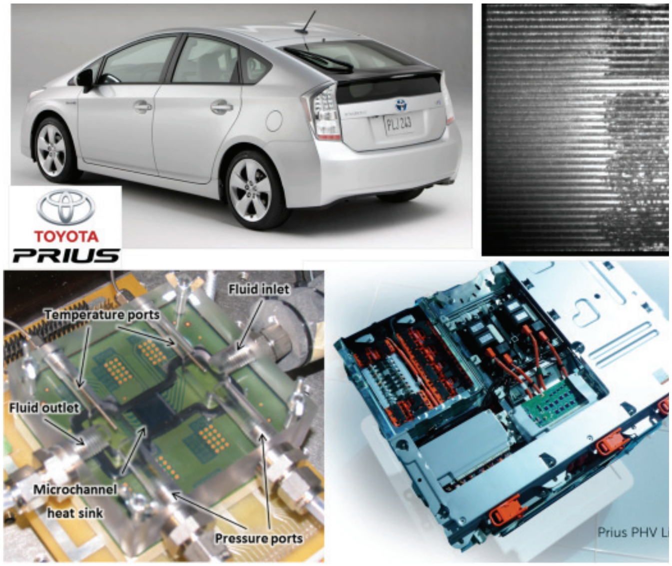
Two-Phase Transport in Microchannels

Researchers at the Cooling Technologies Research Center (CTRC) are exploring boiling and two-phase (liquid and vapor) flow in microchannels. Researchers have completed numerous studies on the direct cooling of silicon chips using microchannel heat sinks with dielectric (non-conducting) fluids. This CTRC work has resulted in better understandings of transport in microchannels and hence in rendering microchannel heat sinks more implementable in electronics cooling applications. Several novel experimental and modeling tools have been developed.



Heat is removed from high-power electronics by boiling liquid that flows through a microchannel heat sink.

This breakthrough technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2011.

Microchannels are very small channels that increase the total area of contact between the cooling fluid and the test chip. The large surface area allows for effective dissipation of heat from high power electronics commonly found in electric and hybrid vehicles. Transport through microchannels that range in width from 100 to 1,000 micrometers in copper, silicon, and acrylic substrates has been characterized.

Total heat dissipation and the local chip temperatures have been measured under a variety of flow conditions. Several heating configurations that range from a uniform distribution of heat input over the entire chip to a local hotspot have been tested. Additionally, the flow structure, including the shape and amount of gas flowing through the channels, has been experimentally measured. A predictive model has also been formulated that aids in the design and optimization of microchannel heat sinks.

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 CTRC.

The effects of hotspot heating on the overall performance of microchannel heat sinks have been studied. CTRC research has developed models to use 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.

Economic Impact: Delphi Corp. (Kokomo, Ind.) helped commercialize this technology for electronic components in hybrid and electric cars. The new system will be used to prevent devices called insulated gate bipolar transistors that are used in hybrid and electric vehicles from overheating. The chips are required to drive electric motors, switching large amounts of power from the battery pack to electrical coils needed to accelerate a vehicle, perform regenerative braking, generating power to recharge the battery pack, and to convert alternating current to direct current to charge the battery from a plug-in line. The high-power devices produce about four times as much heat as a conventional computer chip and require novel cooling technologies. Delphi has created working prototypes and is commercializing this cooling technology. Other CTRC member companies are using this research, including Honeywell and Raytheon (aircraft avionics), HTRI (heat exchangers for the petroleum industry), Intel and Oracle (high-performance computing), and Eaton (power electronic systems - uninterruptible power supplies and motor soft starters). A patent titled "Microchannel heat sink" (#7,277,284) has been issued to Purdue University as a result of the work and 14 additional US and European patents, and patent applications were filed by Delphi as a result of the collaboration with CTRC. Additionally, correlations developed from this research have been implemented in Honeywell's in-house evaporator design code.

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Enhancement of Heat Pipe Transport Properties and Thin Film Evaporation

One of the key limiting factors in electronics technology today is the need to remove heat from the processor inside nearly every device. Because of their ability to move large amounts of heat over reasonable distances with limited electronics chip temperature rise, heat pipes are commonly used in electronics cooling applications. This efficient heat transport is due to the phase change of an internal working fluid from liquid to vapor and porous structures imbedded inside that passively drive the working fluid. Efficiency increases would allow devices to operate with less temperature drop across heat pipes, therefore keeping electronic components relatively cooler at the same heat load. While typical devices in industry use randomly packed particles as porous wicks, designing the wick structure at microscale levels has shown how device performance may be dramatically improved. These advances affect a wide range of applications, from increasing the range and resolution of military air and missile defense radar systems, to operation of laptops and mobile phones at cooler temperatures, all with extended battery life.

As a follow-on collaboration to pre-competitive heat pipe research performed in CTRC, Raytheon acquired external funding totaling $2.5M in partnership with Purdue University to develop a "Radio Frequency Thermal Ground Plane" (RFTGP). This provides significantly improved performance relative to state-of-the-art commercial heat spreaders. As part of this work, Raytheon was provided an experimentally validated model for transport in vapor chambers. This resulted in a direct increase in the technology readiness, which, in turn, led to additional funding of work at Raytheon for further technical demonstration.

Heat pipes may be used to keep electronic processors cool in next-generation radar defense systems and mobile phones alike.

Economic Impact: The heat spreading efficiency of heat pipes reduces the overall power consumption of the cooling solution because auxiliary cooling components, such as axial fans, which dump heat to the ambient atmosphere, do not have to work as hard. While these are conventionally employed in larger-scale laptop and desktop computers, recent efforts within the CTRC have focused on heat pipes that may be used in mobile platforms such as cell phones and tablets (worldwide smartphone shipments are expected to surpass 2.3 billion units per year in 2017). A CTRC member has recently launched a $1.5M "platform thermals" research program through their University Research Office, targeted at thermal management in this market. Faculty in the CTRC have been awarded funding through this program to investigate transformational advancement of heat pipe technologies for ultra-thin mobile platforms.

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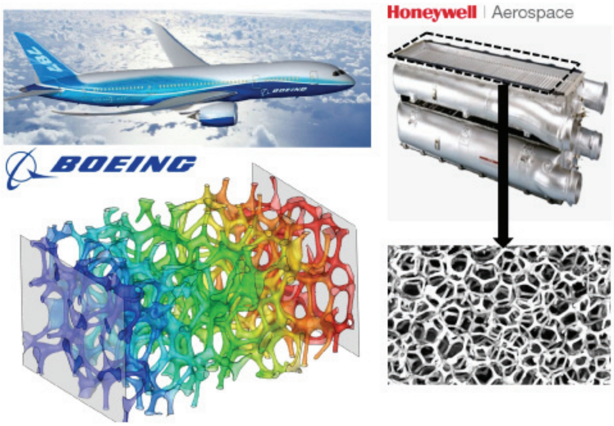
Transport in Porous Structures and Metal Foams



Heat transfer is simulated using a high-resolution x-ray microtomography scan of porous metal foams that are used in aerospace heat exchanger components and as heat sinks for other electronic devices.

Metal foams are novel heat transfer surfaces with potential use as heat sinks and heat exchangers. Their inherently high surface area allows extremely effective dissipation of heat to passing air stream. As a result, they have been recently come to be used in the heat exchanger industry, particularly by aerospace and power electronics companies. Naturally occurring and engineered porous materials are used in a wide range of other mechanical, biological scaffolding, energy storage, and thermal management applications. They have central functions in desalination, filtration, and in battery technologies.

The characterization and design of porous structures is critical for many industries, but generalized prediction of their properties is extremely difficult due to their random nature and geometric complexity. A novel computational methodology for detailed modeling of open-cell foams and other porous structures using microtomography imaging techniques (commonly known as CT scanning) has been developed at the CTRC. X-ray microtomography can visualize the intricate details of porous materials at extremely high resolutions, higher than would otherwise be possible with traditional destructive methods that rely on physical sectioning of the material. This approach has been used to generate geometrically faithful models to simulate heat transfer in porous metal foams.

Economic Impact: The heat exchanger market in the chemical, petrochemical, oil and gas, HVAC, and refrigeration industries is expected to have a compound annual growth rate (CAGR) of 11.5% that is expected to reach $19.5 million by 2018 (*Markets and Markets*, July 2013). Heat exchange applications 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. The technology can be used to cut down heat exchanger equipment size by half or more, thereby cutting down significantly on material costs. Other savings will be in terms of decreased power consumption. The novel porous foam structures are able to transfer more heat at a far lower pumping power (energy cost) compared to their conventional alternatives. Researchers in CTRC have collaborated on internally-funded, proprietary research projects with Eaton Corporation and Honeywell Aerospace to commercialize heat exchangers that leverage these advanced structures and design methodologies.

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