Advanced Heat Sinks Enabled by Three-Dimensional Printing

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Reviewed, accepted September 15, 2009

Abstract:

With the rapid rise in power dissipated by integrated circuits, improved heat sinks designs are needed to decrease the thermal resistance between them and forced air streams. Manufacturing methods such as extrusion, machining and die-casting have been used to fabricate conventional longitudinal fin designs. Although these technologies add relatively little cost, they preclude the fabrication of more complex heat sink designs. We discuss novel heat sink designs which increase surface area and/or modulate air flow streams. Fabrication of these unconventional designs is enabled by using 3D printing technologies with the subsequent conversion of the printed parts into monolithic copper structures by investment casting.

Introduction:

The use of longitudinally finned heat sinks in electronics cooling is ubiquitous. With ever increasing thermal loads and densities such conventional heat sink designs, with 2-dimensional flat fins, have reached the limit of their usefulness for some applications and will not be capable of providing adequate cooling for future high density and functionality products. For example, some circuit packs dissipate more than 300 Watts of power and thermal designers are struggling to accommodate such high heat dissipation rates using conventional, longitudinally finned heat sinks while maintaining junction temperatures below those required to assure the long term reliability requirements of telecommunications products. Often, the only viable means of insuring adequate heat dissipation is by attaching the heat sink bases to a vapor chamber to enhance heat spreading over larger areas. This solution adds considerable complexity and cost to the circuit packs.

One approach to increasing the heat dissipating capacity of 2D heat sinks is to increase the velocity of the forced air flow through them. Higher air flows will increase the heat transfer coefficient by decreasing the static boundary layer thickness between fin and air and, moreover, decrease the caloric temperature rise of the air. Higher levels of acoustic noise and pressure drop, however, accompany increased air flow rates. For many applications these acoustic limits (e.g., 85 dBa for data center products) have already been reached and consumer electronics are striving

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to reduce noise levels. In addition, faster air flow rates require greater electrical power to achieve, thus increasing the overall power consumption and carbon footprint of the product. In short, increasing the air flow rate can increases the capacity of 2D heat sinks, but, beyond a certain limit, this approach is unfeasible due to both acoustic noise and power consumption limits.

A second approach that can be used to increase heat sink performance is the use of high surface area fins. For example, non-planar fin arrays have been commercially available for many years (e.g., elliptical pin-fin arrays, bent folded fins, etc.). However both the magnitude of the deviation from a flat fin, as well as the performance enhancement achieved by such designs, is limited. One reason for this small impact is that the overall surface area of such designs is not significantly different than for flat fin heat sinks. Metal foams exhibit a significantly increased surface area as compared to these designs. Sandwiching stochastic metal foams between flat fin heat sinks has been reported [1] where an adhesive was used to bond the foam to the fin. These heat sinks have not found practical applications, however, as their performance is limited by two effects: (1) a low thermal conductivity interface between fin and foam resulting from the use of an adhesive to assemble the components and (2) a significant pressure drop across the heat sink resulting from the tortuous air flow path created by the random size and alignment of pores in the foam.

Other approaches to increase heat transfer have been demonstrated by incorporating structures that introduce beneficial flow characteristics including flow unsteadiness or flow instabilities (such as Tollmien-Schlichting waves or Kelvin-Helmholtz instabilities). Patera and Mikic [2] introduced the concept of resonant heat transfer enhancement based on excitation of shear-layer instabilities in internal separated flows. They reported three to four fold increase in heat transfer augmentation under given viscous dissipation penalties over conventional channel geometries [3]. It was shown by the Reynold's analogy that the problem of designing optimal heat-transfer enhancement systems is best considered as a problem in hydrodynamic stability theory: a more unstable flow will generate larger Reynolds fluxes at lower Reynolds numbers, and thus achieve commensurate heat transfer at a fractional dissipative penalty [2]. In order to exploit the natural instabilities Patera and Mikic proposed the following system requirements [2]: creation of a system with separated flow; determination of the system's resonant frequency; and excitation of that frequency with appropriate modulation.

Conventional heat sink manufacturing processes, however, are limited in their ability to create structures that can increase surface area, induce flow unsteadiness, or modify air flow patterns in some other, useful way. Extrusion is the most widely used technique to manufacture heat sinks as it is especially well suited to create a monolithic component composed of parallel fins on a heat-spreading base plate. This process has many advantages including low cost, simple tooling, limited post-extrusion processing and fins monolithic with the base of the heat sink. With a simple 2D die, thin fins of aluminum can be formed; typically less than 1.0mm thick. By partially cutting the extrusion perpendicular to the fins, a square pin-grid array of fins can be formed which may increase surface area slightly. Inherent to extrusion, however, is the formation of parallel flat fins as only a 2D die is possible.

To achieve more complex fin designs other manufacturing processes must be employed. Stamping and assembly processes are used to fabricate closed channel heat sinks for today's high power microprocessor chips. This approach enables the use of thinner fins (<0.5mm) as well as the formation of closed (i.e., ducted) channels which increase surface area for a given heat sink volume. Fins are formed from stamped metal into a "C" shape, mechanically interlocked into parallel channels and soldered onto a heat-spreading base. However, these assembled heat sinks remain essentially parallel finned structures.

Lost wax casting is a process which enables metal heat sinks to be manufactured with significantly more detail and a greater variety of shapes. The original part (fabricated by any technique including machining metal) is used to create a rubber mold from which multiple wax patterns are formed. The wax patterns are connected by sprues and surrounded by a plaster-like investment. By heating the investment, the wax melts away leaving a replica in the investment which is subsequently filled with molten metal. After removing the investment, faithful duplicates of the original part are obtained. The only requirement to replicate a heat sink by investment casting is that the shape can be removed from the mold. For example, pin fin arrays where each pin has an elliptical cross-section can be fabricated by such lost wax casting techniques. Many other shapes (e.g., re-entrant features), however, cannot be molded as they incorporate features which cannot be separated from the mold and thus currently find no suitable path for manufacture.

In this paper, we describe a sacrificial pattern casting technique which enables the manufacture of essentially any 3D shape as a monolithic heat sink. A commercially available Multi-Jet Modeling (MJM) system is used to fabricate the original heat sink models. These models are then used as sacrificial patterns in an investment casting process. By combining these two techniques, any arbitrarily shaped fin, duct or channel can be created. Complex, 3D designs can be cast as a monolithic structure, eliminating the thermal contact resistance created when solid surfaces are attached by conventional means (e.g., adhesively bonded or soldered). With fabrication constraints removed, the challenge becomes the design of a heat sink which exploits this new fabrication freedom to improve thermal performance. We present three novel heat sink design approaches, enabled by the sacrificial pattern casting process, which increase the heat that can be transferred to a forced convection air stream.

Experimental:

Computer aided design (CAD) files of the heat sink designs were created using ProEngineer or 3dsMax software and exported as .stl files. These files were sent to an InVision® HR 3-D Modeler, manufactured by 3D Systems, which is a commercially available MJM system. In the InVision HR, heat is used to reduce the viscosity and facilitate jet dispensing of the wax based support material (VisiJet® S100) and the pre-polymer model material (VisiJet® HR 200). The latter is cured upon exposure to UV light after completion of one or more build layers. After completion of the build, support material was removed by heating the part in a forced air convection oven at 70^{o}C. Casting was performed by Best-Cast (River Edge, NJ) where sprues were attached to the pattern before being encased with investment. The pattern was burnt-out from the investment at high temperature leaving a cavity mold within the hardened investment. The investment was inserting into a vacuum casting machine and evacuated to remove trapped air. Then, molten metal was forced into the mold using pressurized inert gas. A copper alloy was used to reduce the casting temperature and improve flow of the molten metal. After casting, the investment material was removed with a water jet and sprues were cut and sanded.

To facilitate testing and minimize thermal interfaces, the heat sinks were incorporated into a test platform to hold them in proper position within a wind tunnel and provide a mounting location for a thin-film heater. The test platform and heat sink were cast together as a unified, monolithic structure as shown in Figure 1. The heat sink volume (see Figure 1) measures 32 mm x 15 mm x 32 mm (L x H x W). The heat sink is integrated with a flanged base. The base (32 mm x 15mm x 32mm) is hollow to accommodate a thin-film heater (Minco). The flange facilitates mounting within the wind tunnel.

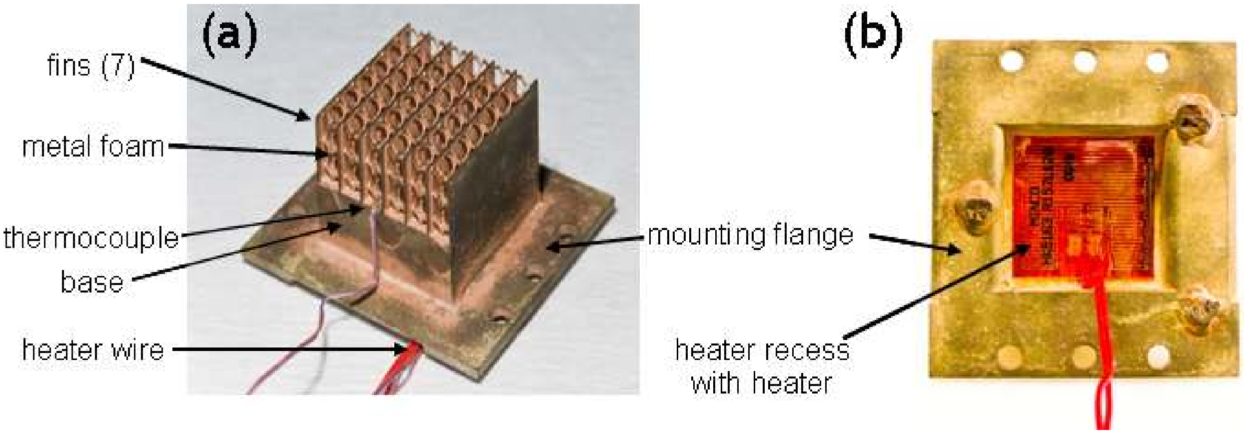

Figure 1 Fin-foam heat sink (7 fins) cast with base and mounting flange in a copper alloy as seen in perspective and instrumented for wind tunnel measurements (a) and from the back side (b).

The governing flow and heat transfer equations for incompressible, steady flow of a Newtonian fluid are solved using the commercial software FLUENT^{TM}. The computational geometry was created using the software GAMBIT^{TM}. The geometry was meshed using hybrid (tetrahedral and hexagonal) elements in GAMBIT by specifying the minimum edge length. The mesh so created was exported to FLUENT for fluid and heat flow simulations. A second-order upwind scheme was used for the flow and heat transfer calculations. A co-located pressure-velocity formulation in conjunction with the SIMPLE algorithm was used for obtaining the velocity fields, and the linearized systems of equations are solved using an algebraic multigrid algorithm. For the calculations reported here, a total of approximately 1 million finite volumes was found to be sufficient and were used for numerical calculations.

The wind tunnel used to characterize the heat sinks is an ATS CWT-100 and consists of honeycomb, screen, contraction and screen sections, respectively, upstream of the test section inlet to reduce the background turbulence intensity of the flow and to produce a uniform velocity profile in the test section. The test section is made from Plexiglas and the prototype heat sinks were placed in a fully ducted arrangement within the wind tunnel. The wind tunnel is powered by two 12W fans that are placed downstream of the diffuser section. Wall mounted static pressure taps, located upstream and downstream of the heat sink, were used for pressure drop measurements. Type-T thermocouples were used to measure the inlet air and maximum heat sink temperatures. A Minco heater with pressure sensitive adhesive was affixed to the base of the heat sink to simulate microprocessor power input. To mitigate heat losses to the environment a Aspen aerogel foam insert was placed directly on the back-side of the heater. Inlet velocity to the heat sink was measured (approximately 30 mm) upstream of the heat sink in the test section of the wind tunnel using a Pitot-static probe (United Sensors). The heat sinks were characterized in the wind tunnel by measuring the thermal resistance (i.e., ratio of difference between maximum temperature of the heat sink and inlet air temperature to heater power) of the heat sink against pressure drop, pumping power and velocity.

Results and Discussion:

Heat Sink Design Approaches. The objective of any air-cooled heat sink design is to optimize the distribution of highly thermally conductive material in the allowable volume to minimize thermal and flow resistances. In general, any increase in surface area increases the heat dissipated from the surface. Concomitantly, however, fluid frictional loss increases thereby increasing the pressure drop across and caloric resistance of the heat sink. The challenge is to optimize the heat sink design to increase the heat transfer with minimal fluid frictional losses. From a conceptual framework, enhancement of heat transfer can be achieved under minimal fluid frictional losses by exploiting various heat and fluid flow phenomena such as boundary-layer restarting, tripping of boundary layers and self-sustained flow unsteadiness [4].

Our goal was to demonstrate the usefulness of the sacrificial pattern casting approach to fabricate heat sinks with enhanced performance by incorporating such air flow manipulation features into the structure. A three-pronged approach was undertaken to enhance heat transfer from a wall by streaming the flow through a two-dimensional array of polygonal ducts (Hexagonal Perforated Duct Arrays), by introducing flow-obstacle-induced local mixing (Ordered Metal Foams), and by exploiting hydrodynamic instabilities to sustain flow unsteadiness (Schwartz Structures).

Hexagonal Perforated Duct Arrays. Ducted heat sinks are one of the simplest ways to increase surface area compared to flat, 2D fin heat sink designs. By enclosing the channel, more metal surface is present over which heat may be transferred to the flowing air stream. However, the challenge becomes how to design the duct array to increase surface area without introducing a significant pressure drop into the system. Honeycomb structures have been discussed for heat exchanger applications [5] where the honeycomb structure was brazed or attached via thermal adhesive to the upper and lower heat transfer surfaces. As stated previously, this will cause extra thermal barriers that will reduce the effectiveness of the design. Also, these honeycomb structures were limited to straight channels and did not contain any perforations that manipulate the flow to increase the heat transfer.

To optimize the cooling capacity of a two-dimensional duct arrays, the performance of a model system was analyzed for various cell shapes and arrangements. The model reported by Gu et al [6] was modified here for heat sinks applications. Details of the model can be obtained from [6]. The heat sink volume considered was 32 x 15 x 32 mm (L x H x W). A constant pressure drop value of 1 Pa was fixed across the heat sinks. Fin equations were written in generalized local coordinates for heat transfer from the wall to the air flow through an array of polygonal ducts. Fully developed flow conditions were assumed and local Nusselt number and friction factors were specified for the duct shapes being analyzed. After a series of algebraic manipulations, an analytical expression for thermal resistance as function of geometry and flow parameters was obtained[7]. Figure 2 plots the thermal resistance as a function of cell pitch, ℓ, for a fixed fin/wall thickness of 0.5 mm. As seen clearly from the figure, optimized hexagonal ducts significantly out-performed the other shapes for a fixed pressure drop value across the heat sinks of 1 Pa.

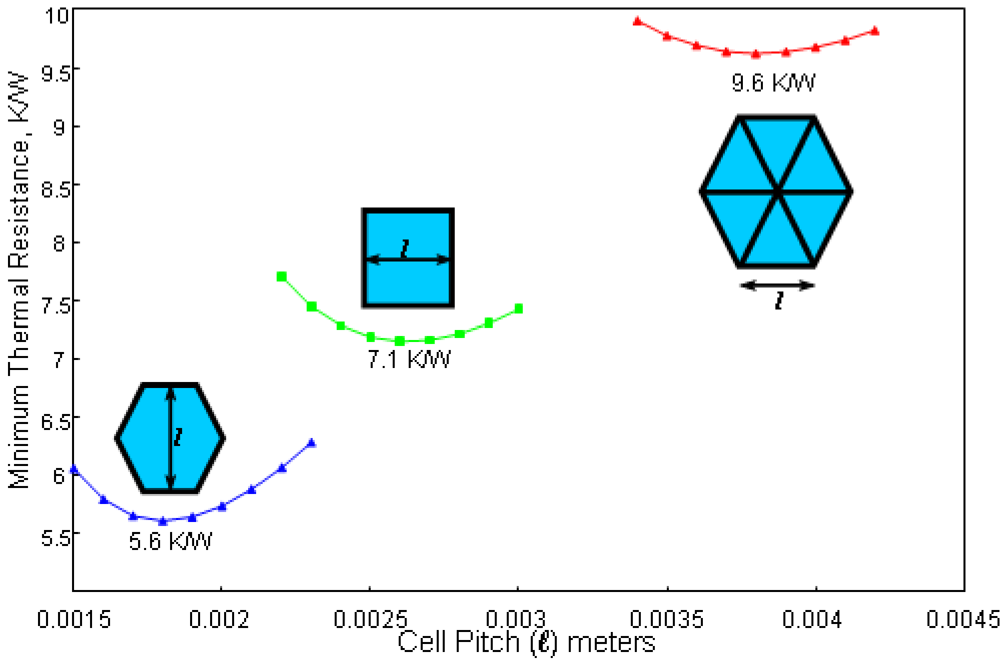

Figure 2: Predicted thermal resistance as a function of cell pitch for triangular, square and hexagonal ducts.

Having assessed the effect of the shape of the duct, numerical simulations were performed on hexagonal ducts to precisely predict their optimal size [7]. A periodic unit-cell was used and the cell-pitch and cell-thickness was varied systematically based on the initial guesses derived from the analytical solutions. A 10% improvement in thermal resistance for hexagonal ducts was observed over a conventional parallel plate heat sink.

It can be shown by a simple analytical treatment for fully-developed thermal and fluid flow conditions that there exists a critical flow length above which having multiple ducts instead of a straight channel would not be optimal. In order to further improve the performance of cellular structures, periodic slots or perforations were introduced to restart the boundary layers and to mitigate the problem of non-optimal number of ducts. The boundary layer is a region adjacent to the duct wall of relatively static air and containing strong gradients in the flow thereby acting as a thermal insulator from the cooling effect of the free stream air flow. By disrupting the boundary layer growth and subsequently restarting the boundary layer development, heat transfer will be increased owing to the development of thinner boundary layers. Further, the introduction of slots promotes local mixing of hot air near the heat source with cold air near the top of the heat sinks.

One example of an enhanced 3D heat sink that incorporates hexagonal ducts is shown in Figure 3. This is a type of cellular structure in which fluid flows through ducts which are periodically perforated by slits. Although it would be possible to manufacture continuous hexagonal ducts by extrusion, such extrusion die would be complex and expensive to fabricate, necessitating a large volume application to recover the development and tooling costs. Perforation of the hexagonal ducts with slits would not be possible by extrusion or conventional casting techniques alone. Three-dimensional printing allows for the introduction of slots anywhere along some or all of the ducts. The hexagonal perforated duct heat sink fabricated by the sacrificial pattern casting process has several advantages over both hexagonal duct and parallel fin heat sinks. First, as the heat sink is monolithic, no thermal barriers exist between hexagonal ducts or between the base and the ducts. The heat transfer surface area has increased substantially over a parallel fin heat sink with the same volume. In addition, the honeycomb channels can be continuous or they can incorporate openings of any design in either the horizontal and/or the vertical directions.

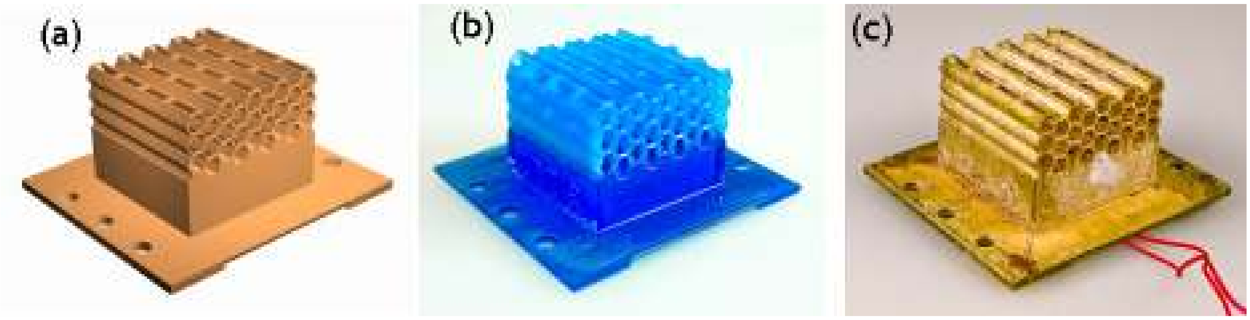

Figure 3: CAD model of a honeycomb heat sink with slits (a), polymer pattern created with the InVision MJM printer (b) and copper alloy heat sink created by the sacrificial pattern casting process.

Ordered Metal Foams. Metal foam structures can be generated with any arbitrary geometry, either random or ordered, including body-centered cubic (BCC), face-centered cubic (FCC) or A15 lattice arrangements. The foam can be located between fins, as shown in Figures 1a and 4, or the heat sink could be made of just the foam structure and have no fins. One of the key advantages is that a monolithic foam structure can be manufactured, eliminating the need for low thermal conductivity interfaces. Another advantage of this design is the increase in the surface area that is available for heat transfer compared to a standard heat sink design. For example, the surface area available for heat transfer on a fin/foam structure with 4 fins is more than 15% greater than the surface area of a parallel fin heat sink with identical length, height and width dimensions.

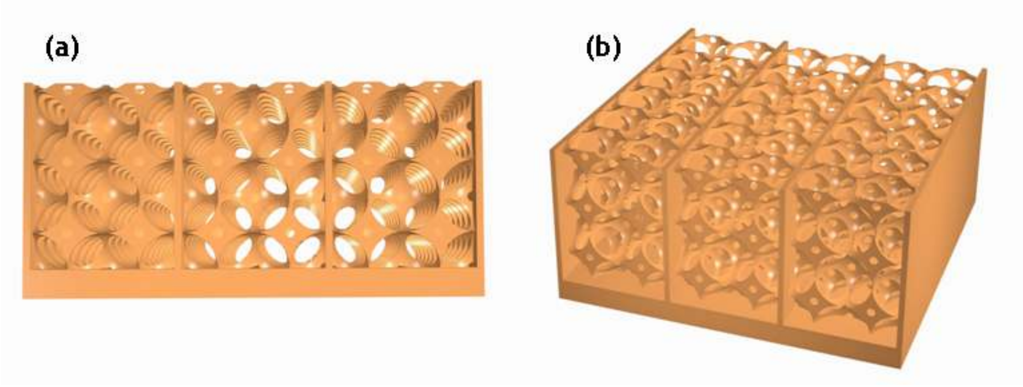

Figure 4: CAD model of a monolithic four-fin foam heat sink seen from the front (a) and in perspective (b). The metal foam located between parallel fins was fabricated with an ordered BCC structure.

A third key feature of the fin-foam structures is the beneficial flow characteristics that are induced downstream of the foam ligaments within the fin passages. Flow through metal foam gives rises to local disturbances in velocity due to eddies that are shed in the wake of the flow past the solid fibers [8]. The presence of pore-level temperature and velocity gradients results in the enhancement of diffusion (or dispersion) sometimes referred to as anomalous diffusion. This enhanced diffusion is often characterized by the total thermal diffusivity. In addition to these thermal dispersion effects, flow instabilities, unsteady, laminar, transitional and turbulent flows can also be set up which increase the heat transfer.

Figure 5 shows a typical computational simulation result for modeling fin-foam heat sinks and exemplifies the complexity of the air flow patterns in such structures. This figure illustrates the predicted temperature distribution in a 4-finned foam heat sink geometry. In order to reduce prohibitive computational cost, only a unit-cell is modeled by exploiting the periodicity in the geometry.

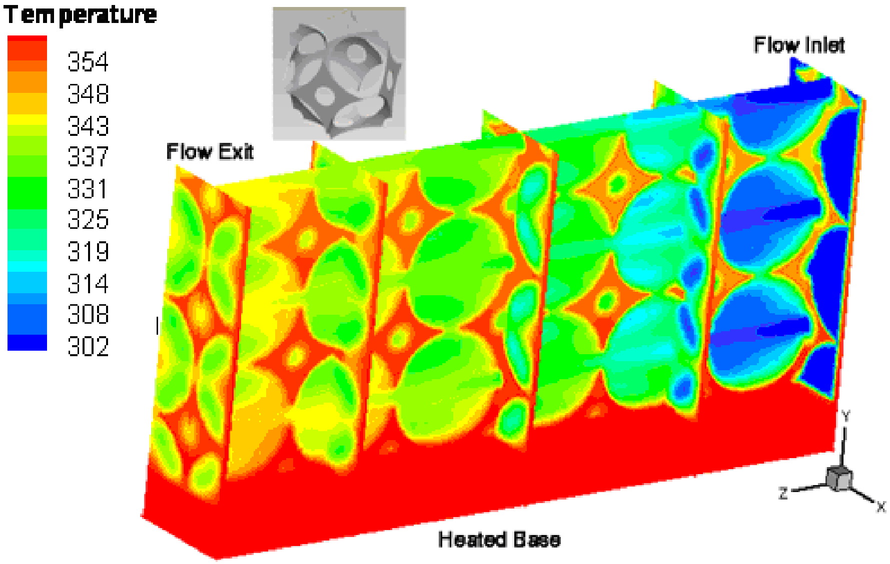

Figure 5: Predicted temperature distribution in a 4Finned-Foam Heat Sinks. Inset shows a BCC type periodic unit cell.

Figure 6 compares numerically predicted fin-foam heat sink results with the experimentally measured thermal performance of cast heat sinks. Considering the complexity of the geometry of the heat sinks, predicted results are in excellent agreement with experimental values. One exception to this agreement occurs for the metal foam heat sink without fins. In this case, the numerical model imposes a geometrical constraint which restricts transverse dispersion. For fin-foam heat sinks, this constraint is valid as the solid fins physically restrict air flow to the direction along the axial flow axis and prevent transversal flow disturbances. The physical validity of the numerical model results in excellent correlations to experimental measurements. Without fins, air can flow both along and transverse to the axial flow axis, making the numerical model invalid for this case.

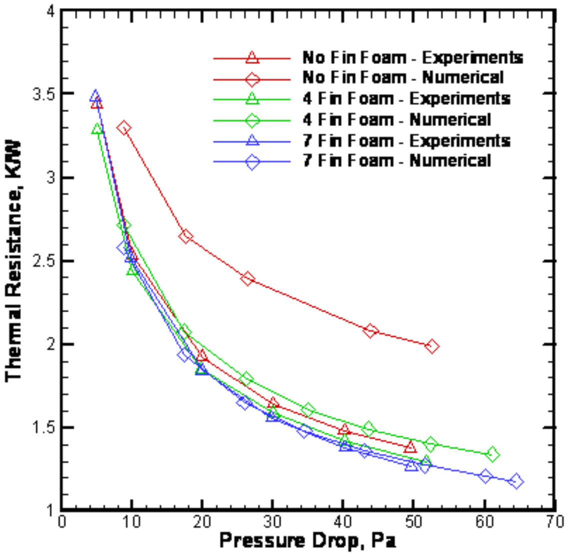

Figure 6. Comparison of numerically predicted fin-foam heat sink performance with experimentally measured thermal resistance as a function of pressure drop.

Schwartz Structures. The concept of excitation of shear-layer (laminar) instabilities for heat transfer augmentation was investigated by fabricating heat sinks based on Schwartz P type minimal surfaces. A minimal surface is a surface with a mean curvature of zero and is locally area minimizing. In order to exploit the flow instabilities, the geometry of the heat sink needs to have a separated flow regime; then, at the system's resonant frequency heat transfer augmentation will be achieved. The Schwartz structure, owing to its undulating path, naturally establishes a separated flow and, at appropriate flow velocities, heat transfer augmentation could be achieved. Schwartz surface unit cells were formed into various arrays, as shown in Figure 7.

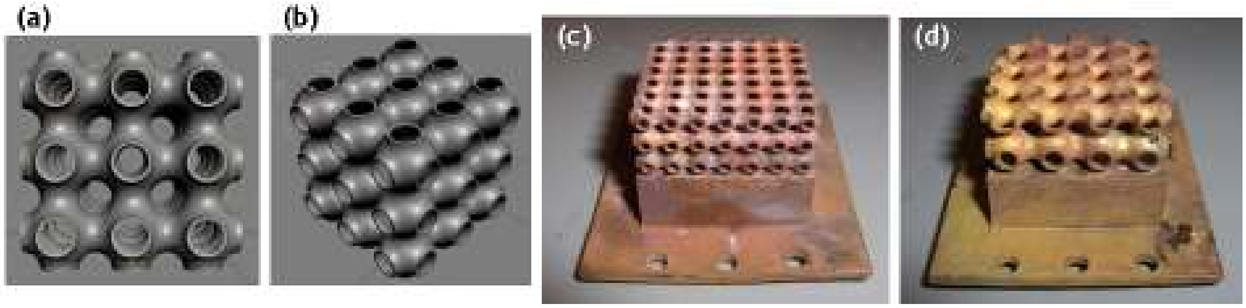

Figure 7: Arrays of Schwartz P-surface unit cells: CAD model of a 3 x 3 x 3 array (a), same model as (a) viewed in perspective (b), copper casting of a 7 x 3 x 7 array (c), copper casting of a 4 x 1.5 x 4 array (d).

Thermal and Fluidic Performance of Heat Sink Designs. Figure 8 shows plots of the thermal resistance (Figure 8a) and pressure drop (Figure 8b) of the three heat sink concepts discussed in this work as a function of air flow velocity. Results from a conventional parallel fin heat sink, fabricated by the same sacrificial casting process, are included in these plots for comparison. It is readily evident that all three novel heat sinks show superior thermal performance compared to a parallel plate heat sink. However these novel heat sink designs incur higher pressure drops, as compared to the parallel plate designs.

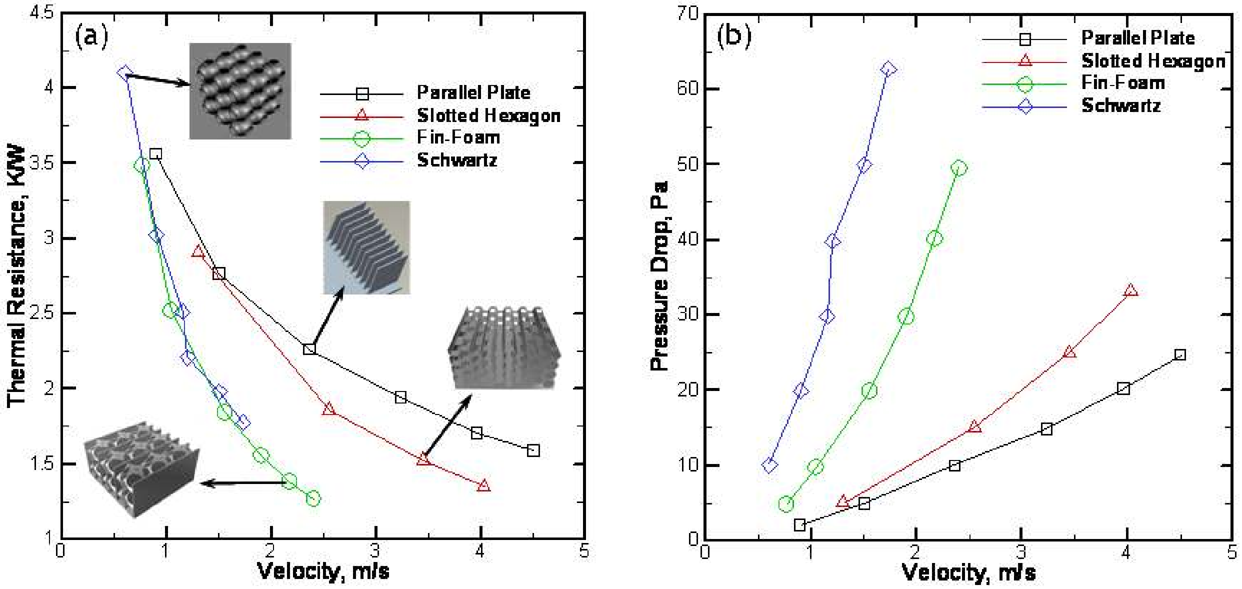

Figure 8 (a): Experimentally measured thermal resistance of different heat sink concepts compared against a conventional parallel plate heat sink, (b) Measured pressure drop as function of velocity.

Conclusion:

The new heat sink designs presented in this paper can offer advantages over conventional, longitudinally finned heat sinks, depending upon the application requirements. For applications where pressure drop is a concern, honeycomb or parallel plate heat sinks will be suitable. For applications where pumping power (which is a more realistic metric because it is a measure of energy expended) is prescribed, any of the three new concepts can be adopted for increased thermal performance. For applications where pressure drop is not a concern, a finned-foam or Schwartz type structure would be most suitable. Casting these designs from sacrificial polymeric patterns (prepared by three-dimensional printing) is a feasible approach for manufacturing small quantities for specialty products or where conventional heat sink designs are inadequate. The design space accessible to heat sink designers has been significantly increased by this fabrication approach and we anticipate that further thermal performance enhancements will be forthcoming.

Acknowledgements:
This work was supported by IDA Ireland.

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