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Active heat transfer enhancement in air cooled heat sinks using integrated centrifugal fans

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ABSTRACT

The enhancement of convective heat transfer in an air-cooled heat sink using integrated, interdigitated impellers was investigated. The experimentally investigated heat sink is representative of a subcomponent of an unconventional heat exchanger with a loop heat pipe, multiple parallel flat-plate condensers, and integrated, interdigitated centrifugal fans, designed to meet the challenges of thermal management in compact electronic systems. The close integration of impeller blades with heat transfer surfaces results in a decreased thermal resistance per unit pumping power compared to conventional forced convection heat sinks.

The fan performance (i.e. fan curve and power consumption) and heat transfer of a single integrated fan heat sink were experimentally characterized for 12 impeller designs and modeled in terms of dimensionless correlations. Correlations were developed to give estimates of the dimensionless fan curve and the dimensionless power curve based on the fan geometry. Additionally, a two-parameter correlation was developed to estimate the dimensionless heat flux based on the fan's operating point. The heat transfer in the integrated fans was observed to be a function of the operating point (i.e. the rotational speed of the impeller and the flow rate of air), with only a weak direct dependence on the fan geometry. The insensitivity of the heat transfer performance to the impeller geometry greatly simplifies the design process of integrated fan heat sinks because the fan design can be optimized independently of the heat transfer performance. Finally, the heat transfer enhancement (compared to pressure-driven flow at the same flow rate) appears to be due to turbulent flow structures induced by the impeller.

1. Introduction

1.1. Motivation

Modern electronics and computing power depend on effective thermal management to achieve high levels of performance. Considering the economic impact, it is not surprising that computer users and manufacturers are interested in state-of-the-art thermal management technologies. The International Electronics Manufacturing Initiative (iNEMI) roadmap [1] states that new processor technology will demand improved cooling and high density packaging technologies. In addition, the International Technology Roadmap for Semiconductors (ITRS) [2] predicts that the required thermal resistance for high performance ICs will decrease from its 2009 level of 0.27 K/W to 0.08 K/W in 2024, a more than threefold reduction. This forecast predicts that current air cooling technology will be incapable of meeting the increasingly stringent demands of the ICs: "The high junction-to-ambient thermal resistance resulting from an air-cooled heat sink provides inadequate heat removal capability at the necessary junction temperatures for ITRS projections at the end of this roadmap".

Clearly, there is a broadly recognized need for more effective cooling — in particular, air cooling. The iNEMI roadmap also points out another important issue in thermal management solutions: heat sinks are subject to volume constraints. Minimum volume traditionally comes at the expense of thermal performance. These volume constraints are particularly evident in high end applications (e.g. telecommunications, radar, sensing and imaging), which can have a larger ($\sim 10\times$) thermal duty than consumer CPUs, but still be constrained to a similar volume envelope. Many such applications have resorted to "exotic liquid-cooled manifolds, spray-cooled enclosures, and vapor-compression refrigeration" due to the insufficient performance of the current state-of-the-art air cooling solutions [3]. With improvements in air cooling, simpler heat sinks could replace these bulky and complex solutions.

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Cooling of electronics also has a surprisingly high energy cost, which translates to monetary cost and environmental impact. Meijer reported that data centers accounted for about 2% of worldwide energy consumption in 2009, and half of this was devoted to cooling [4]. Koomey estimates that the power use for data centers in 2010 accounted for 1.1–1.5% of worldwide electricity use, about half of which was used for cooling [5]. Any improvements in the efficiency of thermal management solutions would help to reduce some of this energy use.

Finally, compact and efficient air cooling solutions are critical for enabling proliferation of new technologies such as solid-state lighting. With increased adoption of these technologies and the continued pervasiveness of computing technology, any improvements in air cooling have the potential to effect appreciable energy savings with associated financial and energy security benefits.

1.2. Background literature

Conventional finned heat sinks have been studied by many investigators. Tuckerman and Pease [6] studied a microchannel heat sink etched on silicon and minimized thermal resistance by choosing the appropriate channel width, fin width and aspect ratio subject to constraints on the geometry and pressure drop. Knight et al. [7] developed an analytical method to minimize thermal resistance of a heat sink with pressure driven flow in a closed finned channel by varying the geometry. Teertstra et al. [8] developed an analytical model to calculate the Nusselt number for a plate fin heat sink as a function of geometry and flow properties. Bejan [9] illustrated a heat sink optimization using entropy generation minimization (EGM), a method whereby the entropy production is quantified and ascribed to the various loss producing mechanisms, and the free parameters are altered to minimize the overall entropy generation rate (for an overview of the method, see [10]). Culham and Muzychka [11] presented a method similar to that of Bejan, where the geometry of plate fin heat sinks is optimized by minimizing the entropy generation rate. Their method also allowed for the incorporation of real fan performance data in the model. Similarly, Khan et al. [12] applied EGM techniques to optimize a pin fin heat sink. Bar-Cohen and Iyengar [13,14] presented methods of optimizing a parallel plate heat sink. Their methods accounted for the energy used in the manufacture of the heat sink and the cooling energy used over the expected life of the computer in which it resides; their optima sometimes differed from the EGM optima, since the latter did not account for manufacturing energy. Furukawa and Yang [15] performed a numerical analysis of a plate fin heat sink in natural convection, and found their optimum design predictions to be very close to those of Bejan, Culham and Muzychka, and others.

Several recent studies have shown that finless designs can provide improved performance in small heat sinks. Egan et al. [16] looked at a miniature, low profile heat sink with and without fins and used particle image velocimetry to detail flow structures and heat transfer. Stafford et al. [17] studied forced convection cooling on low profile heat sinks with and without fins and showed that heat transfer rates of the finless designs were better than their finned counterparts.

A fundamentally different approach to air cooling was developed by Koplow [18]. The "Sandia Cooler", or "air bearing heat exchanger" (ABHE), consists of a rotating disc atop a circular stator plate. The top of the disc has fins that extend upward and act as impeller blades to draw air in axially and discharge it radially. The air bearing between the disc and the stator has a low thermal resistance due to its thinness and large area. The ABHE exploits the slow boundary layer development that occurs in an accelerating reference frame (a phenomenon studied experimentally by Cobb in 1956 [19]). The performance of the Sandia Cooler is significantly better than traditional air cooled heat sinks on a per-unit-volume basis.

This work focuses on the air flow in a heat sink developed at MIT to address the needs of high performance electronics. This heat sink, referred to as "PHUMP", consists of a loop heat pipe with multiple parallel condensers and integrated, interdigitated centrifugal fans [20–23]. The fan impellers drive air radially outwards across a multitude of parallel-plate condensers (Fig. 1). Heat transfer into the bottom of the device causes the working fluid, water, to evaporate and travel up the vertical pipes into the parallel condensers (the condensers are described in detail by Peters [24] and Hanks [21]). Heat is removed from the condensers by convective heat transfer to the air flow. Fresh, cool air is drawn in through the inlet at the top. This configuration exploits the tremendous heat transfer coefficient associated with evaporation to achieve a high heat flux at the evaporator base (the evaporator and system operation are described in detail by Kariya [20]). Although the heat transfer coefficient from the condensers to the air is much lower than in the evaporator, the large thermal power input from the evaporator is distributed among the parallel condensers. By parallelizing the condensers, their overall thermal resistance is greatly reduced, analogous to the lower equivalent resistance of electrical resistors in parallel. Finally, a practical advantage is that the device is self-contained, using the surrounding air as the heat exchange fluid and therefore requiring no external fluid connections.

The air flow design of the PHUMP also has advantages. First, a low profile motor can be used to drive the fans, which share a common shaft; this allows for a compact architecture that does not occupy much vertical space. Second, the fans actually enhance the convective heat transfer between the condenser surfaces and the air flowing through the device. Depending on the regime the fan is operating in, this heat transfer enhancement has been observed to be as high as $3\times$ the equivalent flow rate of pressure-driven air flow. Finally, the integrated fan approach results in a device whose thermal resistance is very low compared to conventional heat sinks with a comparable volume. To illustrate this, the expected performance of an integrated fan heat sink that fits in a 102 mm cube (similar to the heat sink in Fig. 1) was compared to twenty commercially available air-cooled heat sinks (tested by Page [25]). The thermal resistance and volume of these commercial heat sinks are shown in Fig. 2. The commercial air-cooled heat sinks form a Pareto performance frontier, with the Sandia Cooler and PHUMP exceeding the frontier.

1.3. Objectives of present study

In the present study, we sought to accomplish the following:

- Experimentally measure the fan curves and power consumption of planar, fully unshrouded centrifugal fans that are well-suited to integration into a stack of planar heat pipe condensers.
- Experimentally measure the heat transfer in this integrated-fan system.
- Develop dimensionless correlations for these fan curves, power curves, and heat transfer coefficients.
- Develop an understanding of the trade-off between thermal performance and mechanical power consumption in these integrated-fan systems.

In Section 2, we discuss the prototype impeller/gap systems that were used and the experimental apparatus we used to map their performance. In Section 3, we describe the trends we observed in the system and try to reconcile them with several reasonable analyses. Dimensionless correlations are formulated based on the geometries characterized; the experimental data can be estimated with an accuracy of 20% or better relative root-mean-