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Active heat sink with piezoelectric translational agitators, piezoelectric synthetic jets, and micro pin fin arrays

Taiho Yeom[a,b], Terrence Simon[b], Min Zhang[b,c], Youmin Yu[b], Tianhong Cui[b,*]

[a] Department of Mechanical Engineering, University of Mississippi, University, MS 38677, USA
[b] Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, USA
[c] Graduate School at Shenzhen, Tsinghua University, Shenzhen 518055, China

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ABSTRACT

Air-cooled heat sinks are widely used for electronics cooling. Active and passive cooling components can be added to enhance the performance of the air-cooled heat sinks. In this paper, piezoelectric translational agitators and synthetic jets are integrated as active cooling components while micro pin fins are adopted as a passive cooling scheme. The heat transfer performance of the active heat sink system that combines these active and passive cooling components along with a suction fan is experimentally investigated. The piezoelectric translational agitators installed within cooling channels are operating at 222 Hz ~ 820 Hz with a peak-to-peak displacement of 1.0 mm ~ 1.4 mm, depending on the attached carbon fiber blade type. The piezoelectric synthetic jet array provides impingement flow into the cooling channels with an inclined configuration, that has been successfully integrated into the system without interference with other components by using a wedge platform. The jet operates at 720 Hz with the jet velocity of up to 39 m/s. Micro pin fins are fabricated onto both surfaces of each heat sink channel walls by a double-sided microfabrication technique. They have diameter, height, and spacing of 500 µm, 250 µm, and 1500 µm, respectively. The experimental results indicate that the micro pin fins are most efficient among the employed active and passive cooling components, reducing thermal resistance up to 38%, compared to plain heat sink performance. The piezoelectric translational agitator reduces system thermal resistance by 22%, compared to the non-agitated condition, at the same through-flow rate. The synthetic jet shows weaker cooling capability in the setting tested, compared to enhancement by the agitator plates or pin fins. The active heat sink with the micro pin fins, agitators, and jets provides a thermal resistance of 0.064 °C/W at 70 CFM (33 L/sec) through-flow of air, about a 48% reduction from that of the non-agitated, plain heat sink under the same operating conditions. The results demonstrate how more effective the active heat sink system is compared to traditional air-cooled heat sinks.

1. Introduction

Increasing heat dissipation of modern power electronics drives continuous development of a variety of passive and active cooling technologies using air, water, and other non-conductive liquids, as coolants. Liquid cooling, such as single-phase [1,2], direct spray [3–7], microchannel geometries [8–10], and boiling heat transfer [11–18], can provide substantial cooling capability. However, liquid cooling adds considerable cost, weight, volume, and complexity to complete an entire cooling loop, such as pumps, pipes, hoses, reservoirs, nozzles, and orifices. Reliability is another issue as leakage, condensation, and corrosion can cause critical failures to electronics. On the other hand, air possesses many advantages over liquid cooling due to its inherent characteristics. For instances, it is more reliable, cost effective, and environmentally favorable. Therefore, though cooling with air-using traditional methods is less effective than liquid cooling, there is still strong motivation for further advancing air cooling to maximize its capability. A traditional air cooling technique for electronics is the combination of fins and an external blower that can generate forced air flow through channels between fins. However, the blower-aided heat sink system is continuously challenged by rising system heat fluxes with each generation of electronics, and requires increasing cooling capability to meet elevating heat removal needs. To address, without moving to liquid cooling, one can consider incorporating active and passive cooling components into a blower-driven heat sink system. Effective active components disturb thermal boundary layers to enhance surface heat transfer beyond those in simple channel flows. Many active air cooling techniques have been developed, either as a stand-alone or

* Corresponding author.
E-mail address: cuixx006@me.umn.edu (T. Cui).

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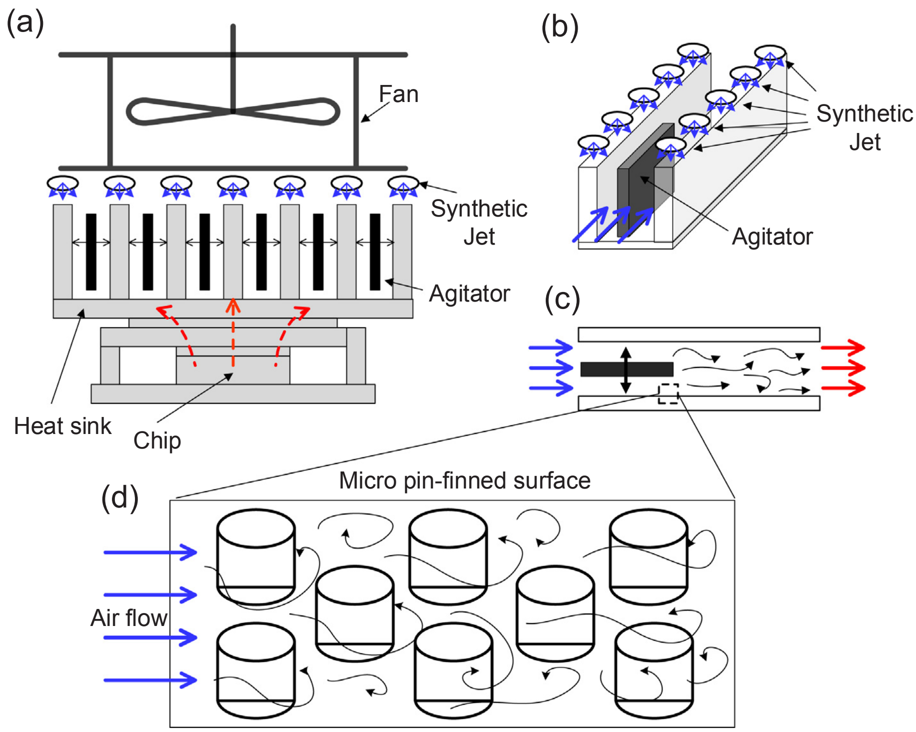

Fig. 1. Conceptual schematic of proposed active heat sink system with translational agitators, synthetic jets, and micro pin fin arrays; (a) Active heat sink; (b) Single channel configuration with synthetic jet arrays and agitator; (c) Flow behavior in the active heat sink channel with an oscillating short agitator blade; (d) Micro pin fin arrays on the heat sink channel surfaces.

as added devices, to air-cooled heat sink systems. A piezoelectric fan is one of them. Bi- or mono-morph piezoelectric ceramic layers resonate attached flexible blades, yielding flapping motion from the tips of the blades. Air currents from the flapping tips are used to cool heated surfaces. Since Toda and Osaka [19] proposed the concept of a piezoelectric fan, extensive studies have been conducted to understand and optimize their characteristics. Yoo et al. [20] investigated vibration characteristics of a piezoelectric fan operating at 60 Hz with a maximum peak-to-peak displacement of 35.5 mm. The applied voltage was 220 V. The size of the fans ranged from 28.6 mm to 69 mm. Açikalin et al. [21] studied thermal performance of piezoelectric fans in a small portable electronics environment with various overlapping displacements and mounting configurations relative to the heat sink. The length of one fan was 63.5 mm and its resonance frequency was 20 Hz. The fan generated a peak-to-peak displacement of 15 mm. The results show that the half-overlapped and horizontally-positioned fan provided the largest heat transfer coefficient of 102 W/m^2 K. Wait et al. [22] investigated via numerical and experimental methods piezoelectric fans operating under higher resonance modes. They concluded that the second resonance mode generated the best thermal performance, while exhibiting the largest power consumption. Recently, there have been attempts to incorporate piezoelectric fans in heat sink channels. Ma et al. [23] analyzed the effects of operating frequency, displacement, fan arrangement, and power consumption in a heat sink channel made of aluminum. The optimum system showed that the dimensionless PZT-convection number, the ratio between the PZT convection to heat sink natural convection, reached 2.3. Sufian and Abdullah [24] conducted experimental and numerical studies on a finned heat sink with vertically inserted piezoelectric fans used as a high-power LED cooling system. Quadruple piezoelectric fans improved thermal performance of the heat sink system by 3.8 times. Yeom et al. [25] proposed a piezoelectric agitator that can generate translational movement to blades embedded in heat sink channels. In a single channel experiment, the agitator, coupled with a channel flow, improved heat transfer by 55%, compared to a channel-flow only forced convection. Another type of active cooling technique is a piezoelectric synthetic jet. A diaphragm attached to one side of a cavity oscillates, driven by a piezoelectric patch, generating a train of vortex rings emerging from an orifice on the opposite side. Beratlis and Smith [26] performed a numerical optimization study of synthetic jets as cooling devices for laser arrays. Mahalingam et al. [27] developed a piezoelectric synthetic jet ejector that can generate secondary flow in the heat sink channel. The heat sink combined with the synthetic jet ejector achieved 350% enhancement in heat transfer, compared to natural convection values. Arik [28] investigated the localized heat transfer performance of a piezoelectric synthetic jet driven at a resonance frequency of between 2000 Hz and 6000 Hz. Over a heater of 6.25 mm length, the synthetic jet enhanced thermal performance by 10 times, compared to natural convection. Passive cooling, such as micro pin-finned surfaces, can bring significant contributions in enhanced heat transfer performance to a heat sink system. Marques and Kelly [29] achieved up to 450% heat transfer enhancement using a nickel micro pin fin heat exchanger with cross flow of air. Wang et al. [30] performed an experimental study to understand thermal and hydraulic mechanisms of a single micro pillar in a microchannel with different cross-sectional shapes. The microchannel with a micro pillar provided a heat transfer coefficient that was two times that of the plain microchannel. Among the different cross-sectional shapes; circular, triangular and diamond, the triangular pillar showed the best thermal performance. Much effort has been made to optimize on pin-fin geometry, size, spacing, array configuration, and materials [31–35]. Most of these studies were done in mini or microchannel conditions. Yeom et al. [36] conducted an experimental study on heat transfer and pressure drop characteristics of micro pin fin arrays in an air-flow channel under both laminar and turbulent flow regimes. The maximum heat transfer enhancement of 79% was achieved over plain surfaces due to the micro pin fin arrays that had a height of 250 μm and a diameter of 400 μm. The array configuration was staggered. Yeom et al. [37] introduced an active heat sink system combined with a piezoelectric translational agitator and micro pin fin arrays. The full-size heat sink with 26 channels aided by the agitator and micro pin fins decreased the system thermal resistance to 0.065 °C/W. This was a 45% reduction in thermal resistance, compared to that of a heat sink system with plain surfaces and no agitation. The current paper extends the previous study on active heat sink technology by Yeom et al. [37], combining the piezoelectric translational agitators, piezoelectric synthetic jets, and micro pin fins to maximize the heat transfer