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A parametric study of heat transfer in an air-cooled heat sink enhanced by actuated plates

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ABSTRACT

Heat transfer in air-cooled heat sinks must be improved to meet thermal management requirements of modern microelectronics devices. This need is addressed by putting agitator plates into channels of a heat sink so that heat transfer is enhanced by agitation. A proof-of-concept exercise was computationally conducted in a single channel consisting of uniform-temperature base and two side walls and an adiabatic fourth wall. The channel side walls are fins of the heat sink fin array. The agitator plate is within the channel. Air flows through the channel and the agitator plate generates periodic motion in a transverse direction to the air flow and to the channel surface. Turbulence is generated along the tip of the agitator plate due to its periodical motion, resulting in substantial heat transfer enhancement in the channel. Heat transfer is enhanced by 61% by agitation for a representative situation. Translational operation of the plate induces 33% more heat transfer than a corresponding flapping operation. Heat transfer on the base surface increases sharply as the tip gap size between it and the agitator plate tip is decreased, while heat transfer on the sidewalls is insensitive to the tip gap size. Heat transfer from the channel wall to the flow increases linearly with increases of amplitude or frequency of the agitator plate. The primary operational parameter to the problem is the product of amplitude and frequency, with amplitude being slightly more influential than frequency.

1. Introduction

Air-cooled heat sinks have been attracting continued investigation due to their high reliability, simplicity, and low cost. Various configurations of air-cooled heat sinks have been investigated. Teertstra et al. [1] developed an analytical model, based on developing flow and fully-developed flow, to predict average heat transfer rates for forced convection in channels of plate-fin heat sinks. Their model calculated average Nusselt numbers as functions of heat sink geometry and air flow velocity. The model was validated for heat sinks of high fin-height-to-fin-spacing ratios. Duan and Muzychka [2] experimentally studied developing laminar flow in rectangular channels of a plate-fin heat sink having various channel dimensions and air flow velocities. Air flow was downwardly impinged to the center of the heat sink and allowed to depart the channels at the two ends of the heat sink. They proposed a simple correlation, $Nu_{D_h} = 0.49L^{*-1/2}$ with $L^* = (L/2)/(D_h \mathrm{Re}_{D_h} \mathrm{Pr})$, for predicting mean heat transfer coefficients. By placing an adiabatic shroud above the fin tips of a plate-fin heat sink, Sparrow and Kadle [3] experimentally investigated effects of gap size between the fin tips and the shroud on turbulent heat transfer in the heat sink. They reported that heat transfer coefficients decreased to 85, 74, and 64 percent of that of a zero gap size case as the gap size was increased to 10%, 20%, and 30% of the fin height, respectively. El-Sayed et al. [4] extended a similar study to surface-roughened shrouds and even larger gap sizes. They found that surface-roughened shrouds induced higher Nusselt numbers than did plain shrouds and the effects of the shrouds on heat transfer diminished when the gap size was greater than the fin height. With a fixed total space for the combination of fan and heat sink and a fixed fan power for cooling the CPUs of desktop computers, Saini and Webb [5] discussed the effects of air flow configuration. Air flow introduced centrally to downwardly impinge on the heat sink removed 19% more heat than air flow passing laterally. Moffat [6] compared common approaches for describing thermal resistances of heat sinks and advocated heat exchanger theory as the most appropriate methodology for heat sink analysis. Ortega et al. [7] showed that an effectiveness-NTU approach more accurately characterized heat transfer performance of heat sinks than commonly-used overall thermal resistance approaches. Bar-Cohen and Iyengar [8] emphasized sustainability, in that not only thermal design and pumping power but also material costs and operating life must be considered in design so that least-energy-consumed heat sinks are achieved. Heat transfer capacity of air-cooled heat sinks is known to be much less than capacities of liquid or boiling cooling

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Nomenclature

A	peak operational amplitude, mm
a_0	operational amplitude, mm
D	agitator plate thickness, mm
D_h	channel hydraulic diameter, mm
f	operational frequency, Hz
G	tip gap size, mm
H	fin height, *mm*
h	convective heat transfer coefficient, W/m^2 K
Nu	Nusselt number, hD_h/k
p	amplitude–frequency product, m/s
q''	heat flux, W/m^2
Re	Reynolds number, Re = VD_h/v
s	heat transfer area of fin surface
T	temperature of fin surface or air flow, K
t	time, sec
V	channel flow or agitation velocity, m/s
W	fin channel width, mm

Subscripts

air	air flow
base	fin base
fin	fin
wall	fin wall

devices. But there is a reluctance to move to the more complex liquid or boiling systems. Therefore heat transfer of air-cooled heat sinks must be continually improved to meet the thermal management requirements of modern microelectronics devices, as noted by Rodgers et al. [9].

Piezoelectrically-driven agitators or fans have recently been considered for heat transfer enhancement. This is attributed to the large deflections that piezoelectric materials may generate and their small power consumption at resonant frequencies. A common piezo-fan is a thin plate with piezoelectric material bonded to it, as studied by Toda and Osaka [10]. When excited by an alternating voltage, the piezo-material contracts and expands, causing the plate to deflect accordingly. Another type of piezo-fan is a piezo-bow configuration proposed by Joshi and Priya [11]. A piezo-stack contracts and expands along its axial direction and the bow structure transforms this motion into deflections perpendicular to the stack's axial direction. Deflections generated by either type of agitator can stir the air surrounding it, resulting in enhanced mass or heat transfer.

Kim et al. [12] measured the air flow generated by an agitator plate using phase-resolved particle image velocimetry and smoke visualization techniques. They observed that within each oscillation cycle, a pair of counter-rotating vortices was generated and a high-velocity region was formed between the counter-rotating vortices. They concluded that the flow features near the plate tip were quite complicated. Eastman and Kimber [13] measured the flow field as induced by a single piezo-fan using 2-D particle image velocimetry. They found that larger amplitudes generated more repeatable and predictable vortex patterns.

Shmidt [14] measured local and average mass transfer on a surface located perpendicular to a dual piezo-plate arrangement using the naphthalene sublimation technique. The two plates were operated 180° out of phase and three plate-to-surface separation distances were discussed. The maximum local Sherwood numbers occurred at two locations, the projection locations of the tips of the plates when they were in their mean position. The average Sherwood number was relatively insensitive to the plate-to-surface distance.

Kimber et al. [15] and Kimber and Garimella [16] measured local heat transfer coefficients on a surface that was perpendicular to a piezo-fan. The fan-tip-to-surface distance, fan frequency, and amplitude were shown to affect the heat transfer coefficients significantly. Kimber and Garimella [17] extended this to similar investigations with arrays of piezo-fans. Liu et al. [18] measured heat transfer on a flat surface under different fan-to-surface arrangements. They concluded that heat transfer augmentation was due to air flow entrained during each oscillation cycle and by jet-like air streams at the fan tip; with the two modes of heat transfer enhancement, entrainment and jetting nearly equal.

Açıkalın et al. [19] developed a simplified, 2-D CFD model to study the flow field and heat transfer as induced by a piezo-fan. They documented changes in local circulation and vortices as the fan-tip-to-heat-transfer-surface distance was varied. The relationships between flow features and heat transfer enhancement were discussed. Abdullah et al. [20] conducted 2-D CFD computations of heat transfer enhancement on a surface by flow induced by a piezo-fan. The fan was parallel to the surface when at its zero-deflection position. The fluid vorticity and temperature contours were generated near the fan tip, then moved downstream along the fan axis and away from the fan. Lin [21] analyzed heat transfer and fluid flow induced by a piezo-fan near a flat heated surface. His 3-D CFD simulations showed that interaction between the normal force exerted on the air surrounding the moving blade and the impingement jet flow produced at the blade tip prompts formation of two counter-rotating screw-type flow circulations, one at each edge of the blade.

Because of the 3-D feature of the induced fluid flow, piezo-fans are integrated with heat sinks to enhance heat transfer. Petroski et al. [22] optimized the configuration of an air-cooled heat sink coupled with piezo-fans so that the latter improved heat transfer on not only the base surface but also the fin surfaces. Ma et al. [23] investigated a cooling system composed of a single-channel heat sink and a piezo-fan within the heat sink channel. Large velocity and temperature gradients next to the mid section of the fin base and side wall were predicted by 3-D simulations and confirmed by experiments. Effects of operating frequency, fan amplitude, fan arrangement, and power consumption were analyzed to optimize the design of the cooling system. Abdulla et al. [24,25] integrated multiple piezo-fans with a fined heat sink for microelectronics cooling. With the given operating frequency, they reported that the tip gap, operating amplitude, and orientation of the piezo-fans affect heat transfer significantly. Smaller tip gap, larger amplitude, and an orientation perpendicular to both heat-sink base and fins induce higher heat transfer enhancement. Ma et al. [26] also developed multiple piezo-fans operating at 20–50 Hz frequency to cool heat sinks with air.

In order to augment heat transfer of high-heat-flux electronic systems, Yeom et al. [27] and Yu et al. [28] integrated piezo-agitators and a blower into a heat sink so that more thermal energy may be dissipated from the heat sink. The blower generates bulk channel flow between fins of the heat sink; the piezo-agitators, vibrating in a transverse direction between the fins, agitate the channel flow. Such integration of channel flow and agitation improves heat transfer on not only the fin bases (channel bases) but also the fin walls (channel side walls). Significant heat transfer enhancement from the integrated system, compared to pure channel flow, was reported. To effectively agitate the channel flow, the vibration of the agitator velocity must be high, comparable to the channel flow