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Enhancing heat transfer in air-cooled heat sinks using piezoelectrically-driven agitators and synthetic jets

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ABSTRACT

Air-cooled heat sinks are widely used for microelectronics cooling. Piezoelectrically-driven agitators and synthetic jets (syn-jets) have been reported as good options in enhancing heat transfer on nearby surfaces. This study proposes that agitators and syn-jets be integrated within air-cooled heat sinks to significantly augment heat transfer performance. The proposed integration is investigated experimentally and computationally in a single-channel heat sink with one agitator and two syn-jet arrays. The study of a single channel between two fins is a precursor to the design of a full scale, multi-channel heat sink. The agitator and syn-jet arrays are separately driven by three piezoelectric stacks operating at their individual resonant frequencies to actively disrupt and mix the bulk air flow within the channel. The experiments show that the combination of the agitator and syn-jets raises the heat transfer coefficient of the channel by 82.4%, compared with a same channel having channel flow only. The computations show similar rises that agree well with the experiments. The numerical simulations attribute the active heat transfer enhancement to the turbulence introduced in the channel flow near the tips of the fins which constitute the channel walls by the syn-jets and the vortices introduced in the channel flow near the side and base of the channel walls by the agitator plate. Heat transfer enhancement by the agitator and syn-jets increases as their amplitude or frequency increases, but the increase percentage by these active components decreases as the channel flow velocity increases. A correlation between the average Nusselt number for the channel walls and the Reynolds numbers for the channel flow, agitator, and syn-jet is established.

1. Introduction

Fluid flow in air-cooled plate-fin heat sinks is laminar or weakly turbulent in many applications due to limited space or pumping power. Consequently, convective heat transfer performance in such heat sinks may be limited and needs to be enhanced. Teertstra et al. [1] investigated heat transfer caused by air flow varying from laminar regime to turbulence regime in channels of a plate-fin heat sink. They presented an analytical model for predicting average heat transfer rate in such heat sinks. Duan and Muzychka [2] experimentally studied laminar flow in channels of plate-fin heat sinks having different channel dimensions and air flow velocities. They proposed a correlation for predicting mean heat transfer. Placing a cover above the fins of a finned heat sink forces more air flow to pass along the fin surfaces so that heat transfer within the heat sink is improved. Sparrow and Kadle [3] experimentally investigated effects of the gap size between the fin tips and the cover on heat transfer in heat sinks. El-Sayed et al. [4] extended a similar study to surface-roughened shrouds and expanded gap sizes. Their general conclusions were that heat transfer coefficients of heat sinks decrease as the gap size increases and the effect of cover on heat transfer enhancement diminishes when the gap size is greater than the fin height.

Piezoelectrically-driven fans or agitators have recently been reported as effective techniques for heat transfer enhancement. This is due to the large deflections they generate and small power they consume when operating at their resonant frequencies. One type of piezo-agitator is a thin plate with piezoelectric material bonded to it, as proposed by Toda [5]. When excited by an alternating voltage, the piezo material contracts and expands, causing the plate to bend one direction then the other. Another type of piezo-agitator is a piezo-bow configuration proposed by Joshi and Priya [6]. As a piezo-stack contracts and expands along its axis within the bow structure, the bow structure transforms this motion into deflections perpendicular to the piezo-stack axis. This motion can be used to drive an agitator plate. Deflections generated by either type of agitator mix the surrounding air, resulting in enhanced heat or mass transfer.

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Nomenclature

A	heat transfer area of fin surface, or cross-sectional area, m^2
c_p	specific heat of the air, J/kg K
D	hydraulic diameter of the channel, syn-jet nozzle, or the agitator plate, mm
f	agitator or syn-jet frequency, Hz
h	heat transfer coefficient, W/m^2 K
I	DC current, A
k	thermal conductivity, W/m K
P	cross-sectional perimeter, mm
q	heat transfer rate, W
$\dot{Q}$	volumetric air flow rate, LPM
ρ	density of the air, kg/m^3
Nu	Nusselt number, $Nu = hD/k$
Re	Reynolds number, $Re = VD/\nu$
S	agitator displacement, mm
T	temperature of fin surface or air flow, K
ΔT	temperature difference, K
t	time, s
U	DC voltage, V
V	channel flow, syn-jet flow, or agitator operational velocity, m/s
ν	kinematic viscosity of the air, m^2/s

Subscripts

0	agitator amplitude or syn-jet peak velocity
ai	air flow at channel inlet
ag	channel flow and agitator
ao	air flow at channel outlet
ch	channel flow
fi	fin channel inlet
fo	fin channel outlet
sj	channel flow and syn-jets
sys	channel flow and combined system

Fluid flow, heat and mass transfer generated by piezo-fans were investigated by many researchers. Kim et al. [7] investigated the air flow generated by a piezo-cantilever using phase-resolved particle image velocimetry and smoke visualization techniques. The piezo-cantilever was immersed in air which is initially quiescent. They observed that within each oscillation cycle, a pair of counter-rotating vortices was generated; a high velocity region was formed between two counter-rotating vortices; and the maximum velocity within the region was nearly four times the maximum speed of the free end of the cantilever. Schmidt [8] studied mass transfer on a surface located perpendicularly to dual piezo-agitators. The naphthalene sublimation technique was used for transport measurements. The two plates were operated 180° out of phase and three plate-tip-to-surface separation distances were discussed. The maximum local Sherwood number occurred at two locations, the two projections of the plates to the test surface. The overall average Sherwood number was relatively insensitive to the plate-tip-to-surface distance. Kimber et al. [9], Kimber and Garimella [10] experimentally investigated the local heat transfer rate on a surface cooled by a piezo-fan. The surface was perpendicular to the fan tip when the fan was at rest and the air near the fan and surface was initially quiescent. Effects of the vibrational amplitude and frequency, the fan dimension, and the fan tip-to-surface gap distance on heat transfer were discussed. A heat transfer contour envelope around the fan tip was observed to exhibit lobe-like, circular, and elliptical shapes when the gap distance was small, medium, and large compared with the vibration amplitude. The optimal gap distance changed with the vibrational amplitude. At the optimal gap distance, heat transfer increased with vibrational frequency and amplitude. Açıkalın et al. [11] developed a simplified 2-D CFD model to study the air flow field and heat transfer as induced by a piezo-fan. The heat transfer surface was perpendicular to the piezo-fan when it was at its neutral position. Vortices were clearly observed near the heat transfer surface for situations in which the vibrational amplitude was large and the gap distance was small, but the vortices were not found when the vibrational amplitude was small and the gap distance was large. The presence of vortices resulted in larger heat transfer enhancement in the former situation. Abdullah et al. [12] computationally studied heat transfer enhancement on a surface due to flow induced by a piezo-fan which was parallel to the surface when at its zero-deflection position. The vibration of the piezo-fan caused air movement next to the surface. The fluid vorticity and temperature contours were observed to begin near the fan tip and move downstream along the heat transfer surface. Liu et al. [13] experimentally compared heat transfer augmentation on a flat surface between piezo-fans that were arranged horizontally and vertically to the heat transfer surface. They reported that heat transfer augmentation levels by the two arrangements are similar. Petroski et al. [14] configured piezo-fans in an air-cooled heat sink. The flapping fan plates were parallel with the fin walls but perpendicular to the fin base when at their rest state. This arrangement allowed not only the fin walls but also the fin base to be cooled by the vibration of the flapping plate.

Synthetic jets (syn-jets) represent another efficient option for enhancing heat transfer in microelectronics cooling. A typical syn-jet consists of a piezo-material patch, a diaphragm, a cavity, and a nozzle. When the piezo-material patch contracts and expands, the diaphragm, which is attached to the patch, periodically deflects. The deflection causes periodical volume change of air in the cavity which, in turn, generates oscillatory air flow through the nozzle. The oscillatory air flow increases mixing of air next to the nozzle as the exit flow is an impinging flow and the returning flow is a sink flow. The net mass flow over an operational cycle is zero. Similar to the piezo-fans, the syn-jets generate large flow mixing but consume little power when operating at their resonant frequencies.

The following presents results from researches on fluid flow and heat transfer of syn-jets. Smith and Glezer [15] conducted an experimental study of the formation and evolution of syn-jet-induced flows. In the near field, a train of counter-rotating vortices was formed due to ejected flow from the nozzle, advected downstream in the nozzle flow. The flow field was relatively unaffected by flow drawn back into the nozzle as its path was sufficiently away from that of the nozzle flow. The jets and the vortices they carried then underwent transition to turbulence, slowed down, lost their coherency, and finally became indistinguishable from the mean jet flow in the far field. Smith and Swift [16] experimentally compared syn-jets and continuous jets at similar Reynolds numbers. Compared with continuous jets, syn-jets generated wider and slower flows in the near field, but, the induced flow in the far field bore much resemblance to that generated by continuous jets. Pavlova and Amitay [17] experimentally documented the effects of frequency and nozzle-to-surface distance, z/d, of syn-jets