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High-frequency translational agitation with micro pin-fin surfaces for enhancing heat transfer of forced convection

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ABSTRACT

An advanced air cooling scheme that combines both active and passive cooling components is proposed and its thermal performance is demonstrated with single channel heat transfer experiments. The active cooling component, a piezoelectric translational agitator, generates strong air turbulence using a blade oscillating at a high frequency near either plain or micro pin-fin surfaces in the channel. The translational agitation of the blade is realized using an oval loop shell amplifier with a piezoelectric stack actuator. The micro pin-fin surfaces were fabricated by the LIGA photolithography technique. Single channel heat transfer experiments show promising results in the combined system with the micro pin-fin surface and the agitator. For instance, the combined system heat transfer coefficients were 250% of those on smooth surfaces without agitation. The channel flow rate was 40 LPM and the Reynolds number was 3300. Measurements are presented that assess, pin fin and agitation effects on thermal performance of the proposed active heat sink system for several channel flow rates. Based on these single channel test results, a multi-channel, full-size, active heat sink system utilizing micro pin fins and translational agitators is proposed, and its thermal performance is estimated.

1. Introduction

Effective cooling has been a critical issue for electronics from small portable devices such as smart phones to high power processing computers as failure of effective heat removal results in poor efficiency or damage to electronics systems. Large heat dissipation of several hundred Watts or even up to several kilowatts has led to implementation of complex liquid cooling schemes such as spray, boiling, etc. [1–6]. In spite of superior heat transfer performance of liquid cooling methods, air cooling is still an attractive thermal management scheme for its many advantages over liquid cooling, including simplicity, reliability, cost. These factors have been driving forces for development of many passive or active air cooling technologies to postpone transition to liquid cooling. A piezoelectric fan is one of the newly introduced methods for active air cooling. A piezoelectric ceramic generates a flapping motion of a thin elastic blade, usually at its resonance frequency, yielding air motion and turbulence from its flapping tip. A variety of piezoelectric fans of different configurations have been reported in the literature since Toda and Osaka [7] introduced the piezo fan as a cooling device. Yoo et al. [8] investigated the vibrational characteristics of bimorph piezoelectric fans operating at about 60 Hz. The lengths of the fans ranged from 28.6 to 69 mm. Different shim materials were tried and their structural responses were analyzed theoretically. The maximum peak-to-peak displacement of 35.5 mm was achieved from a phosphor bronze fan driven at 60 Hz with 220 V. Açikalin et al. [9] conducted a design study of piezo fans noting their utility in small portable electronics with their low noise and power consumption. The piezoelectric fan was 63.5 mm long and generated a peak-to-peak amplitude of 15 mm with an operating frequency of 20 Hz. They studied thermal performance of the fan with different mounting configurations relative to the heated surface achieving a largest heat transfer coefficient of 102 W/m^2 K. They also demonstrated the thermal performance of a fan in a laptop environment. Flow visualization was provided to support their measurements. Higher resonance modes of piezoelectric fans were investigated with finite element and experimental methods by Wait et al. [10]. They concluded that the second mode of operation is desirable, considering the electromechanical coupling factor for conversion from electrical to mechanical energy. However, higher mode operation was accompanied by increased power consumption. Açikalin and Garimella [11] predicted fundamental characteristics of piezoelectric fans, such as flow fields around the fans and associated fan curves as well as heat transfer performance. Kimber et al. [12] demonstrated

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Nomenclatures

A	convection surface area
A_b	carbon fiber blade area
A_c	cross sectional area of copper block
A_{sink}	convection surface area of the virtual active heat sink
d_b	hydraulic diameter of the blade
d_h	hydraulic diameter of the channel
f	friction coefficient
f_p	friction coefficient of plain surface
$f_{up,down}$	friction coefficient of upstream and downstream extensions of single channel
g	standard gravity
h	heat transfer coefficient
$K_{loss,inlet}$	inlet loss coefficient
k	thermal conductivity of copper
k_{air}	thermal conductivity of air
k_{tp}	thermal conductivity of thermal paste
Nu	Nusselt number
Nu_p	Nusselt number of plain surface
ΔP_{static}	static pressure drop
ΔP_{total}	total pressure drop
ΔP_{test}	pressure drop across the test section of the single channel
Pr	Prandtl number
p_b	perimeter of the agitator blade
Q_{sink}	volumetric flow rate of the virtual active heat sink
q	heat input of the single channel heat transfer
q_{sink}	heat input of the virtual active heat sink
Re_c	the channel Reynolds number
Re_a	the Reynolds number of PTA
Re_{tot}	the total Reynolds number
R_{th}	thermal resistance
St	Stanton number
T_{in}	single channel inlet temperature
T_{out}	single channel outlet temperature
T_{sink}	active heat sink base temperature
$T_{sink,in}$	air inlet temperature of the active heat sink
$T_{sink,out}$	air outlet temperature of the active heat sink
T_{sub}	temperature measured below the convection surface
T_{sur}	averaged surface temperature
ΔT_{LMTD}	log mean temperature difference
V_{con}	contraction velocity at the outlet adaptor
V_{in}	channel inlet velocity
ν	kinematic viscosity
z	manometer reading

Greek symbols

ε	performance index
ω	angular frequency
ρ_{air}	density of air
ρ_{water}	density of water

localized heat transfer enhancements with 60 Hz and 6.35–10 mm amplitude operation yielding heat transfer coefficients of about 100 W/m^2 K. They found that an optimal tip-to-surface gap is closely related to the vibration amplitude of the fans. Liu et al. [13] examined influences of fan geometry and arrangement with six different piezoelectric fans. Operating frequencies ranged from 28 to 53 Hz. The thermal enhancement ratios of their fans over natural convection were as high as three. Thus, the piezoelectric fan with an operating frequency of less than 100 Hz has various advantages, such as low noise level, low power consumption and compactness, for application to small-scale electronics. However, localized and confined heat transfer areas and low heat transfer coefficients make the flapping fans unsuitable for cooling of high power electronics.

Piezoelectric drives are used also in synthetic jets, devices that generate a net zero mass flow out of a cavity. Consisting of a drive, a diaphragm, a cavity and an orifice, they have gained much attention, recently, for localized cooling purposes. Beratlis and Smith [14] performed a numerical study to optimize a synthetic jet for cooling vertical cavity surfaces of a laser array. Their optimization parameters were the jet angle and distance from a heated surface. Mahalingam et al. [15] fabricated a synthetic jet ejector that generates secondary flows in a channel, then studied the effects of channel width on flow characteristics and thermal performance. An active heat sink combined with the synthetic jet ejector was tested to demonstrate 110 W dissipation of thermal energy while maintaining the heat sink temperature at 100 °C. This was a 350% improvement over natural convection. Wang et al. [16] embedded a synthetic jet into a printed wiring board used for the thermal management of microelectronics. A flexible polymeric diaphragm was driven by an electromagnetic driver. The synthetic jet achieved a peak jet velocity of 14 m/s with 60 mW of power and achieved heat flux removal of 3.6 W/cm^2 keeping the surface temperature below 70 °C. Pavlova and Amitay [17] found that synthetic jets are three times more effective than continuous jets operating at the same Reynolds number. They conducted a detailed flow visualization study to understand the cooling mechanism at different operating frequencies. Arik [18] investigated the localized heat transfer of a piezoelectric synthetic jet operating between 2 kHz and 6 kHz. They also studied the effects of applied voltages, frequencies, and heater lengths on cooling. One case provided 10 times natural convection heat transfer.

Combining these devices with a passive cooling system that provides increased heat transfer area (fins) may further enhance cooling capability. The passive method in the present study includes micro pin fin structures that can disturb the thermal boundary layers in addition to providing the increased heat transfer area. Intensive investigation on thermal and hydrodynamic aspects of pin fin structures is documented in the literature. Studies about heat transfer and pressure drop characteristics of conventional size pin fins with different array orientations [19–21] or cross sectional shapes [19,21–25] were reported. Overall, the studies suggested that a staggered array is superior to an in-lined array in terms of heat transfer capability. With technology advances in microfabrication, a remarkable size reduction of pin fin structures is possible. As a result, micro pin fins have recently gained considerable attention for thermal management. Marques and Kelly [26] demonstrated fabrication of micro pin fins onto planar or non-planar metal surfaces. Their results showed enhanced heat transfer performance over plain heat exchanger systems. Koşar et al. [27] documented pressure drop characteristics of laminar flow of water over micro pin-fin arrays of different orientations and shapes. Correlations for conventional pin fins were in need of modification for use with micro pin fins to account for the effects of pin fin height-to-diameter ratio, which tend to be smaller in micro pin fin arrays. Additionally, they showed that staggered and diamond-shaped pin fins generated higher friction factors than in-lined and circular-shaped fins. Peles et al. [28] documented heat transfer with a bank of micro pin fins and derived a correlation for total thermal resistance. Their results recommend that a dense