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Optimum thermal resistance of the multiple piezoelectric–magnetic fan system[☆]

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ABSTRACT

An innovative cooling technology vibrating fans with a piezoelectric–magnetic source is investigated for the thermal management of electronic devices. The objective of the present work is to establish a cooling system that uses a piezoelectric–magnetic force as a vibrating source to drive multiple fans for cooling. The vibration driving force is generated by a piezoelectric material actuator coupled with multiple magnetic resonance forces. The cooling performance in terms of thermal resistance is evaluated and measured with different configurations, including the aspect ratio of the fan pitch (P/L) that ranges from 0.167 to 0.333 and the ratio of the gap between the fan tip and the heat sink (G/L) that ranges from 0.0167 to 0.0833 with different fan input powers ranging from 0.15 W to 0.25 W. The results indicate that multiple piezoelectric–magnetic fan ("MPMF") system is efficient consuming low power with an improved thermal resistance performance (76.7%) compared with natural convection. In addition, the optimum P/L can be found at 0.233 with different fan input powers. Furthermore, the optimum G/L is 0.05 whereas the optimum P/L is 0.233. The MPMF system can apparently enhance thermal resistance with the advantage of lower power consumption.

1. Introduction

Piezoelectric fans which are composed of piezoelectric material and plates have recently been studied as a thermal management device.

Toda [1] proposed the concept of piezoelectric fans and developed a simplified theory for vibration prediction and flow field behavior. The results indicated that theoretical analysis matched with the experimental findings. Toda [2] also performed thermal experiments and demonstrated that piezoelectric fans can cool a power transistor panel in a TV cabinet. Several types of piezoelectric fans for cooling electronic devices were constructed and experimented with Yoo et al. [3,4]. Analyses of series and parallel piezoelectric bimorphs with different widths of metal shims at different resonant frequencies were performed. The results indicated that the resonance frequencies of the fans were mainly determined by the length of the vibrating plate. In addition, the wind velocity had a nearly linear relationship with the applied voltage and displacement of plate tip. The displacement of the plate tip was related to the material of the vibrating plate and the fan geometry. Yao et al. [5] developed analytical solutions by modeling composite piezoelectric cantilevers that coupled a piezoelectric bimorph to a thin elastic plate. They concluded that the damping effect played a dominant role in the vibrating elastic plate. Loading a mass at the tip of the elastic plate led to an increased deflection magnitude at a lower frequency. Açıkalın et al. [6] presented a piezoelectric fan theory and a numerical simulation, with flow visualization applied using a mobile phone and laptop computer. The results were aimed at thermal improvement using piezoelectric fans at different locations and of different types. Schmidt [7] achieved local and average mass transfer on a vertical surface cooled by a piezoelectric fan that consisted of two plastic blades vibrating back and forth and moving 180° out of phase cooling a nearby vertical surface. Two dimensions were defined to measure mass transfer: the spacing of the blades and the separation distances measured from the blade tips in the resting state to the vertical surface. The most effective cooling occurred at the midpoint of the fan blade and increasingly diminished as the distance increased. There was an approximately 50% drop compared with midpoint of the fan. In addition, the mass transfer was relatively insensitive when the fan-to-surface distance increased. A piezoelectric fan with two symmetrically placed piezoceramic patches was investigated through analytical modeling by Bürmann et al. [8]. The results revealed the optimum patch-beam thickness ratio and the patch-beam length ratio for maximizing the dynamic electromechanical coupling factor. Specifically, a thickness ratio of approximately 0.8 and a length ratio of approximately 0.6 maximized the dynamic electromechanical coupling factor for this choice of material combination and for a fixed clamp-patch distance.

Açıkalın et al. [9–11] developed a single piezoelectric fan cooling system that can be used to cool a heated surface. The results revealed that the enhancement in the convective heat transfer coefficient

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Nomenclature

A	vibration amplitude (mm)
D	magnet outer diameter (mm)
f	fan resonance frequency (Hz)
G	gap between the fan tip and the heat sink (mm)
G/L	ratio of the gap between the fan tip and the heat sink
H_T	distance between two measuring points inside a copper slug (mm)
L	fan length (mm)
L_P	length of the piezoelectric actuator (mm)
P	fan pitch (mm)
P/L	aspect ratio of the fan pitch
P_w	fan input power (Watts)
Q	dummy heat source input power (Watts)
R	thermal resistance (°C/W)
R_0	thermal resistance in natural convection (°C/W)
t	thickness of the fan (mm)
$T_{ambient}$	ambient temperature (°C)
T_{case}	temperature of the copper slug (°C)
t_m	thickness of the magnet (mm)
W	fan width (mm)
η	efficiency of the MPMF system (%)

exceeded 375% relative to natural convection, resulting in a temperature drop at the heat source of more than 36.4 °C. Prototypes of the fans were also investigated to assess their feasibility and cooling performance, and the optimal locations for the fans were determined. It was apparent that the largest heat transfer enhancement was obtained when the fan covered half of the heat sink. A laptop computer was used to demonstrate the cooling feasibility of the fans. Piezoelectric fans were found to offer significant localized cooling, exceeding enhancements in the convective heat transfer coefficients by 100%. Different experimental configurations were also considered, and the effect of varying the fan amplitude, the distance between the fan and the heat source, the fan length, its frequency offset from resonance, and the fan offset from the center of the heat source were studied to assess the cooling potential of the fans. As shown by the results, the temperature difference reached the highest value when the fan was placed vertically in front of the heat source. In addition, this difference was more strongly dependent on the fan distance and the fan amplitude than on the fan offset. Kimber et al. [12] analyzed the performance of two fans operating simultaneously. Heat transfer characteristics were determined experimentally for a pair of piezoelectric fans in horizontal vibration and vertical vibration orientations. Only in-phase and out-of-phase vibration were considered with horizontal vibrations during heat transfer experiments. The vibration amplitude increased for in-phase vibrations, whereas a negative effect was observed for out-of-phase vibrations because of a fan coupling effect that further augments the heat transfer obtained. The optimal heat transfer performance appeared when the fan pitch was approximately equal to the vibration amplitude. Piezoelectric fans were also analyzed under vacuum and atmospheric conditions. In a vacuum environment, the fan vibrated at much larger amplitudes, nearly double that observed in air. When the fan pitch was decreased, only a small-frequency up shift occurred. Kimber et al. [13] conducted local heat transfer coefficients experimentally for a fan vibrating close to the heat source and the entire temperature field was observed by means of an infrared camera. Four vibration amplitudes ranging from 6.35 to 10 mm were considered for selected distances between the heat source and the fan tip which varied from 0.01 to 2 times the amplitude. The optimum gap was dependent on the vibration amplitude for the convection coefficient. The optimum gap was small for large amplitudes and increased as the amplitude decreased. Kimber et al. [14] investigated the heat transfer achieved by using arrays of vibrating cantilevers. Two piezoelectric fans were mounted near a constant heat flux surface to determine the local convection coefficients. The results revealed the convection patterns were strongly dependent on the fan pitch and the best thermal performance was obtained when the fan pitch was 1.5 times its vibration amplitude.

Ma et al. [15] studied the piezoelectric fan cooling system, which included an aluminum heat sink and a piezoelectric fan. Several parameters, such as the inclined angle, the resonance frequency and the location of piezoelectric fan, were studied to evaluate the efficiency of heat dissipation by piezoelectric fans. Compared with natural convection, the results revealed that piezoelectric fans can break the thermal boundary layer effectively to enhance the heat dissipation efficiency. Ma et al. [16] demonstrated an innovative piezoelectric–magnetic fan that can generate stronger air flow to increase thermal performance by using one piezoelectric actuator. Ma et al. [17] developed the T-shape multiple-vibrating fan cooling system to enhance cooling ability. The experimental results revealed that the temperature can decrease from 86.9 °C to 55.6 °C when a heat source operates at 25 W.

In this study, the heat sink is cooled by a multiple piezoelectric–magnetic fan ("MPMF") system that is composed of one actuating piezoelectric fan and two passive magnetic fans. The parameters of fan pitch, fan gap between MPMF and heat sink at various fan input powers are studied. A smaller fan pitch yields a smaller combined cooling envelope but a higher repulsive magnetic force and a larger fan pitch yields a larger combined cooling envelope but a lower repulsive magnetic force. Therefore, the cooling performance in terms thermal resistance of the MPMF system is optimized. An effective fan input power usage is also investigated to obtain better cooling performance output.

2. Experimental setup and theoretical analysis

2.1. Experimental setup

The experimental apparatus is shown in Fig. 1, including a dummy heat source that provides a constant heat flux source; a DC power supply; a programmable AC power supply, Chroma 61501, which provides AC source and frequency output; a digital power meter, Chroma 66201, which measures AC power signals and related parameters; a data acquisition system, Agilent 34970A; and a MPMF system.

The dummy heat source is constructed by attaching two stainless steel cartridge heaters. Before installation into the dummy heat source, the resistance of the heater is ensured to be the same at 37 Ω in order to maintain uniform heat flux in the dummy heat source. The heaters are inserted and fixed into a copper slug — C11000. The thermally conductive compound – Dow Corning TC-5022 with thermal conductivity 4.0 W/m°C – is used to fill the gap between the heaters and the copper slug. A cross-section view and the dimensions of the dummy heat source are shown in Fig. 2. There are three Omega 36-gauge type T thermocouples attached inside the copper slug. Two thermocouples are used to calculate the heat source power by following Fourier's law heat conduction equation. H_T is the distance between two measuring points, which is 10 mm. The thermal conductivity of a copper slug is 386 W/m°C. One thermocouple is placed on the top of the heat source to record the upper surface temperature of the copper slug. The upper surface of the copper slug, which simulates a CPU integrated heat spreader, has a length (L_S) of 32 mm × 32 mm with 2 mm round areas at the four corners to simulate the heat source. The copper slug is embedded in the insulation system, which is made of bakelite. The insulation system is designed with some gaps between the copper slug and the bakelite because of low thermal conductivity property of air of 0.026 W/m°C to minimize heat losses from a copper slug to an outside environment.

The MPMF system includes an aluminum base, a piezoelectric actuator, passive magnetic fans and magnetic bases, as shown in Fig. 3.