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Effect of piezoelectric fan mode shape on the heat transfer characteristics☆

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ABSTRACT

Piezoelectric fans with their low noise and power consumption, are an effective means of enhancing heat transfer and is a viable alternative to the natural convection process. Several studies have been extensively carried out at the fundamental resonance mode. In this work, three-dimensional numerical studies on the effect of first, second and third mode shapes driven at frequency and the tip amplitude of the first mode are accomplished to investigate their effects on the heat transfer characteristics. The experimental and numerical model of the first mode shows a reasonably good agreement between them. The results showed that the increase in the mode number decreased the induced air flow velocity on the top of the heated surface, thus impeding the cooling capabilities at higher mode number. The vibrating blade of the first mode produced a pair of asymmetric vortex of opposite circulation around front and the back the piezofan tip, which disappear with the increase of mode number. It is thus established from this work that higher mode of vibrations is ineffective and therefore the fundamental resonance mode is suggested for all practical piezofan applications.

1. Introduction

Recent advances in the field of electronics have maximized the density integration, clock rates, and miniaturization of modern electronics. This has tremendously increased the dissipation of heat flux, which might in turn cause thermal failures such as mechanical stresses, thermal debonding and thermal fracture. Therefore, it is of significant importance for any electronic engineer to manage temperature and its adverse effects on electronic packages to ensure optimal performance and reliability.

Piezoelectric fans can be used to generate airflow for cooling microelectronic devices. Their outstanding features include noise-free operation, low power consumption and suitability for confined spaces which make them easy replacement to the conventional rotary fan. It consists of a thin flexible cantilever blade bonded with a piezoelectric patch near its base end. When an alternating input signal is applied to the piezoelectric material it contracts and expands periodically in the lengthwise direction at the frequency of the input voltage. This causes bending moment at the beginning and end of the patch, which can be effectively used to replicate the necessary oscillatory motion at the free end of the blade. When frequency of the input signal is applied at the resonance frequency of the piezofan, the amplitude of the oscillation is maximized resulting in a more complex flow field suitable for use as a practical cooling application.

A number of studies have been carried out to study the cooling capabilities and flow characteristics of piezoelectric fans under first mode orientations. Toda [1,2] proposed the basic models for vibration and airflow and demonstrated a significant reduction in the temperature on placing the piezofan on either side of the transistor panel. Schmidt [3] studied the local and average heat transfer coefficients on a vertical surface cooled by two piezoelectric fans resonating out of phase. It was observed that change in the distance between the fans or between the surface and the fans effected the heat transfer coefficients. Meanwhile, Açıkalın et al. [4] examined the feasibility of placing piezofans in an actual laptop and cell phone enclosure. They determined a significant increase in heat transfer in both cases. On the other hand, Ihara and Watanabe [5] investigated quasi 2D flows around the free ends of a flexible single plate and two plates, both oscillating with a large amplitude. Ro and Loh [6] studied the feasibility of using ultrasonic flexural waves as a cooling mechanism. Analytical, computational, and experimental investigations on incompressible 2D streaming flows induced by resonating thin beams were conducted by Açıkalın et al. [7]. Closed-form analytical streaming solutions were presented for an infinite beam; these solutions were also used to motivate a computational scheme to predict the streaming flows from a baffled piezofan. The predicted asymmetric streaming flows were in good agreement with the experimental flow profiles. Kimber et al. [8–10] experimentally investigated single and arrayed piezoelectric fans vibrating near an electrically heated stainless steel foil. The temperature field was measured by an infrared camera. 2D contours of the local heat transfer coefficient were presented for different vibration amplitudes and gaps. Moreover, correlations were developed with appropriate Reynolds and Nusselt number definitions that described the area average thermal performance of the piezoelectric piezofan with an error of less than 12%. An experimental analysis design for the effects of piezofan amplitude, tip gap, piezofan length at resonance frequency, and piezofan offset from the center of

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Nomenclature

A_{pf}	Amplitude of piezofan (mm)
A_{mc}	Exposed surface area of the microelectronic component (m^2)
l_{pf}	Length of piezofan (mm)
D_{pf}	Width of piezofan (mm)
t_{pf}	Piezofan thickness (mm)
l_{vb}	Length of un-patch piezofan (mm)
q°	Heat flux (W m^{-2})
Q°	Power input to the heat source (W)
	Average heat transfer coefficient (W m^{-2} K^{-1})
	Average temperature of heated surface (K)
T_a	Ambient temperature (K)
	Average force convection (W m^{-2} K^{-1})
	Average natural convection (W m^{-2} K^{-1})
	Velocity vector
u	Velocity (m s^{-1})
	Local grid velocity
	Volume force
x, y, z	Space coordinates
i, j, k	Coordinate indices
t	Time (s)
P	Static pressure (N m^{-2})
g	Gravitational acceleration (m s^{-2})
c_p	Specific heat of air, J kg^{-1} K^{-1}
T	Temperature, K
k	Thermal conductivity, W m^{-1} K^{-1}
CCW	Counter-clockwise
CW	Clockwise

Greek symbols

Φ	Vibration phase angle (degree)
Θ	Traveling wave phase angle (degree)
	Heat transfer coefficient enhancement ratio
δ	Dimensionless spacing between fan tip and heated surface
ρ	Fluid density (kg m^{-3})
	Cauchy stress tensor
τ_{ij}	Viscous stress tensor (N m^{-2})

the heat source was reported by Açıkalın et al. [11]. The heat transfer coefficient could be enhanced by as much as 375% with appropriate specifications of the design parameters. 2D computational fluid dynamics simulation and experimental analysis were performed by Abdullah et al. on the effect of piezofan height on the performance of a single piezoelectric fan in microelectronic cooling system placed in horizontal orientation [12]. A 2D finite element method was reported by Florio and Harnoy to enhance the natural convection cooling of a discrete heat source in a vertical channel with the use of a piezoelectric piezofan [13]. An enhancement of up to 52% in the local heat transfer coefficient was observed relative to that achieved by natural convection. Six piezoelectric piezofans with various blade geometries were made and tested on a flat heated surface by Liu et al. [14]. They experimentally investigated the influence of geometric parameters, including horizontal/vertical arrangement and location of the piezoelectric piezofan. They found that the heat transfer augmentation of the piezoelectric piezofan came from the entrained airflow during each oscillation cycle and the jet-like air stream at the piezofan tip. The heat transfer performance for the vertical arrangement showed a symmetrical distribution and peaked at the center region, whereas the horizontal arrangement possessed an asymmetrical distribution and showed an early peak. The heat transfer performance for the horizontal arrangement was not necessarily lower than that of the vertical arrangement. Kimber et al. [15] experimentally determined the relationship between the pressure and flow rate generated by miniature piezoelectric piezofans. They considered the proximity of surrounding walls with the use of three different enclosures. The aerodynamic interactions between two vibrating piezofans were explored by Kimber et al. [16]. They found that damping is significantly influenced by the proximity of neighboring piezofans and by vibration phase difference. A comparative investigation between 2D numerical flow simulations and experimental data on particle image velocimetry was conducted by Choi et al. [17,18]. They observed the vortex formation and unsteady flow fields around a single and dual vibrating piezofan in free stream. Lin [19,20] recently analyzed 3D heat and fluid flow induced by a single piezofan on flat and cylindrical heat surfaces. He showed that vibrating blade produced a pair of contour-rotating screw type flow structure on either side of the blade and a pair of asymmetric vortex was formed around the piezofan tip. His experimental and numerical results indicated that the piezoelectric piezofan improved the heat transfer coefficient by 1.2 to 3.6 times. Abdullah et al. [21] reported an orientation of multi-piezoelectric piezofan (set in edge-to-edge arrangement) to enhance the heat transfer of finned heat sink in microelectronic cooling with 3D numerical simulation. Their results showed that an enhancement in convective heat transfer coefficient exceeding 88% can be achieved in comparison to that with only natural convection. Sufian et al. [22] reported the influence of single and face to face dual vibrating piezofans, on flow and thermal fields through numerical analyses and experimental measurements. Computed results show that the single piezofan enhanced heat transfer performance by approximately 2.3 times the heated surface. On the contrary, the dual piezofans enhanced heat transfer performance by 2.9 times for out-of-phase vibration and 3.1 for in-phase vibration.

It can be observed from the literature that most studies using numerical and experimental investigations were accomplished while operating at their first resonance mode. There is lack of evidence with regards to the cooling capabilities of piezofan operating at its higher resonance mode. Therefore, in this work attempt has been made to carry out numerical investigation, in order to understand the effect of piezofan mode shape operating at first, second and third mode on the airflow behavior and thermal performance. In addition to this, the experimental results of the first mode obtained using the thermocouples are utilized to compare it with the findings of numerical simulations.

2. Experimental and numerical methods

2.1. Experimental procedures

A commercial piezoelectric piezofan consisting of a bimorph-lead zirconate titanate patch bonded to a thin stainless steel beam and resonating at its first mode natural frequency was used in this investigation. This type of piezofan is ideal for cooling application because of its high elongation properties at relatively low power input requirements (Table 1).

The piezofans was arranged vertically oriented to the heated surface with a spacing of 1.8 mm. A vibrometer (laser displacement sensors KEYENCE LK-G152) was utilized and positioned near the piezofan tip to detect the piezofan-tip deflection and measure the amplitude.

Table 1
Specifications of the piezoelectric piezofan (Piezo Systems Inc., USA).

Specification	Value
Material	Stainless steel
Size (mm)	47 (l_{pf}) × 12 (D_{pf}) × 0.4 (t_{pf})
Length without patch (mm)	23 (l_{vb})
Resonance frequency (Hz)	110 (first mode of vibration)
Power consumption (mW)	42
Weight (kg)	0.002