International Communications in Heat and Mass Transfer 43 (2013) 81–89

Contents lists available at SciVerse ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Effect of synchronized piezoelectric fans on microelectronic cooling performance☆

S.F. Sufian [a,*], M.Z. Abdullah [a], J.J. Mohamed [b]

[a] School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia
[b] School of Material and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia

ARTICLE INFO

Available online 1 March 2013

Keywords:
Electronic cooling
Piezoelectric fan
Transient numerical simulation
Fluent
MpCCI
Heat transfer enhancement

ABSTRACT

This study reports on the influence of dual vibrating fans on flow and thermal fields through numerical analyses and experimental measurements. Two piezoelectric fans were arranged face to face and were vertically oriented to the heat source. 3D simulation was performed with FLUENT and ABAQUS with the use of code coupling interface MpCCI to calculate the velocity and temperature distribution on the horizontal hot plate. The fans' motion was described as deformable parts by ABAQUS at their first mode vibration. The effects of vibration phase difference between the fans corresponding to in-phase ($\Phi=0°$) and out-of-phase ($\Phi=180°$) vibrations were explored in terms of transient temperature and flow fields. The purpose is to enhance heat dissipation from the microelectronic component. Comparison with the performance of a single fan is made to assess the significance of the additional fan on thermal performance. Good comparison results were achieved through accurate modeling of the most important features of the fans and through heat transfer. Computed results show that the single fan enhanced heat transfer performance within approximately 2.3 times for the heated surface. By contrast, the dual fans enhanced heat transfer performance within approximately 2.9 for out-of-phase vibration ($\Phi=180°$) and 3.1 for in-phase vibration ($\Phi=0°$).

1. Introduction

Computers and portable electronic devices, such as cellular phones, laptops, and tablets, are rapidly emerging in lighter, slimmer, and more compact forms with high functionalities to meet consumer demands. However, the cooling requirements for such devices are crucial, and perhaps, traditional rotary fans have become impractical because of installation restrictions into limited space. Piezoelectric fans are microvibrating machines that have been recently proposed as airflow generators to help dissipate heat. They consist of a cantilever beam bonded with a piezoelectric material near their base ends. An input signal to the piezoelectric material causes oscillatory motion at the free end of the beam; this signal could induce the surrounded flow with low power consumption. Piezoelectric fans are also noise-free and adaptable in small spaces.

Numerous studies have been conducted on the cooling capabilities and flow schemes of piezoelectric fans. Toda [1,2] proposed the essential models for vibration and airflow by performing experimental and analytical analyses. A study on the local and average heat transfer coefficients on a vertical surface because of convection from a piezoelectric fan was performed by Schmidt [3]. Açıkalın et al. [4] examined the feasibility of placing fans in an actual laptop and cell phone enclosure. They determined a significant increase in heat transfer in both cases. 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 piezoelectric fan. 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 fan with an error of less than 12%. An experimental analysis design for the effects of fan amplitude, tip gap, fan length at resonance frequency, and fan offset from the center of 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 fan height on the performance of a single piezoelectric fan in microelectronic cooling horizontally oriented [12]. A 2D finite element method was reported by Florio and Harnoy to

☆ Communicated by W.J. Minkowycz.

* Corresponding author.
E-mail address: sufianfarid@gmail.com (S.F. Sufian).

0735-1933/$ – see front matter
http://dx.doi.org/10.1016/j.icheatmasstransfer.2013.02.013

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_u	length of un-patch piezofan (mm)
q°	heat flux (W m^{-2})
Q°	power input to the heat source (W)
$\overline{h}$	average heat transfer coefficient (W m^{-2} K^{-1})
$\overline{T}_s$	average temperature of heated surface (K)
T_a	ambient temperature (K)
$\overline{h}_{pf}$	average force convection (W m^{-2} K^{-1})
$\overline{h}_n$	average natural convection (W m^{-2} K^{-1})
$\vec{u}$	velocity vector
u	velocity (m s^{-1})
$\vec{u}_g$	local grid velocity
$\vec{f}$	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)
	traveling wave phase angle (degree)
ξ	heat transfer coefficient enhancement ratio
δ	dimensionless spacing between fan tip and heated surface
ρ	fluid density (kg m^{-3})
σ	Cauchy stress tensor
τ_{ij}	viscous stress tensor (N m^{-2})

enhance the natural convection cooling of a discrete heat source in a vertical channel with the use of a piezoelectric fan [13]. An enhancement of up to 52% in the local heat transfer coefficient was observed relative to that achieved by natural convection. Six piezoelectric fans 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 fan. They found that the heat transfer augmentation of the piezoelectric fan came from the entrained airflow during each oscillation cycle and the jet-like air stream at the fan 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 fans. They considered the proximity of surrounding walls with the use of three different enclosures. The aerodynamic interactions between two vibrating fans were explored by Kimber et al. [16]. They found that damping is significantly influenced by the proximity of neighboring piezoelectric fans 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 single and dual vibrating fans in free stream. Lin [19,20] recently analyzed 3D heat and fluid flow induced by a single piezoelectric fan on flat and cylindrical heat surfaces. His experimental and numerical results indicated that the piezoelectric fan improved the heat transfer coefficient by 1.2 to 2.4 times. Abdullah et al. [21] reported an orientation of multiple piezoelectric fans (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% may be achieved compared with natural convection.

In the literature, the thermal and flow behavior of single vibrating fans has been extensively studied. By contrast, characterizations on the thermal performance of dual piezoelectric fans, which have important practical applications, have not been sufficiently explored. Only Kimber and Garimella [10] experimentally investigated the thermal performance of dual vibrating fans in consideration of an identical vibration phase angle. Ihara and Watanabe's [5] experiments on the visualization of the flow field around dual vibrating fans established that the vibration phase angle significantly affected the flow field. However, further characteristics need to be determined to assess the influence of different phase angles between dual vibrating fans on the resulting heat transfer. Discussions are also lacking in the literature on the complexity of mechanisms such as dual fans with varying vibration phase angles. Therefore, this study explores experimental and numerical analyses on the flow and thermal performance of dual vibrating fans that are arranged face to face with different vibration phases. Two vibrometers (laser displacement sensors KEYENCE LK-G152) are employed to detect the phase angle and measure the vibration amplitude for each fan individually. 3D simulations based on a dynamic meshing scheme are performed in FLUENT and ABAQUS with the use of code coupling interface MpCCI to investigate transient changes on the temperature and flow fields achieved by dual vibrating fans with in-phase ($\Phi = 0°$) and out-of-phase ($\Phi = 180°$) vibration. The thermal performance of the dual fans is compared relative to the single fan, and the estimated results are also compared with experimental findings.

2. Experimental setup and procedure

A dual commercial piezoelectric fan consisting of a bimorph lead zirconate titanate patch bonded to a thin stainless steel blade was used in this study. The fan has high elongation properties at a relatively low power input (Table 1). The fans were arranged face to face with a spacing of 25 mm and were vertically oriented to the heated surface. Each fan was rigidly held by an adjustable stand to vary the tip gap. Two vibrometers (laser displacement sensors KEYENCE LK-G152) were set oppositely and positioned near the fans' tip to measure the vibration amplitude for each fan individually. The measurement points of the focal laser beam to the fan surfaces were (1 mm) from the fan tip. The error of the displacement sensor was −/+0.02%. Slightly different resonance frequencies existed between the fans because of discrepancy in manufacturing, which would occur as phase differences between their motions. Therefore, one of the main challenges in these

Table 1
Specifications of the piezoelectric fan (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_u)
Resonance frequency (Hz)	110
Power consumption (mW)	42
Weight (kg)	0.002