THERMAL AND FLOW ANALYSIS OF PIEZOELECTRIC FANS FOR COOLING LEDS PACKAGES

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UNIVERSITI SAINS MALAYSIA

2014

THERMAL AND FLOW ANALYSIS OF PIEZOELECTRIC FANS FOR COOLING LEDs PACKAGES

By

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Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

August 2014

DEDICATION

This thesis is dedicated to my beloved parents for their tremendous sacrifices. They are always a constant source of inspiration and motivation in my life. Their support and love have pulled me throughout my difficult times. Not to forget my brothers, Mr. Nathir and Mr. Muhammad and my sisters and also other family members for their continuous support in my life.

SUFIAN FARID SHAKER

August 2014

ACKNOWLEDGEMENTS

First and foremost, I am highly grateful and thankful to the almighty ALLAH who gave me the opportunity to accomplish my studies.

I would like to express my highest gratitude and appreciations to my supervisor, Prof. Dr. Mohd Zulkifly Abdullah for his precious guidance, assistance and endless encouragement throughout my candidature period of Msc. and PhD. Special thanks to my co-supervisor Dr. Julie Juliewatty Mohamed for her help to develop this research work. Special thanks also must be given to all academic and technical staff especially Mr. Amri**,** and Mr. Hashim for their help on my research work. Special thanks must be given to my friends Dr. Zubair, Dr. Elnaggar, Dr. Khalil, and Mr. Kamal for their cordial assistance, encouragement and suggestions during my research.

I would like to extend my gratitude to my colleagues in electronic cooling lab, (Mr. Fairuz, Mr. Sofwan, Mr. Nazmi), Vibration lab (Mr. Najib, and Mr. Tan) and all my friends as well for their moral support and help during my research work. I am highly grateful to the University Science Malaysia for the opportunity to complete my research work during my Msc. and PhD and for the financial support through RU grant number 1001/PMEKANIK/814163.

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August 2014

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SYMBOL	DESCRIPTION	UNIT
A_{pf}	amplitude of piezoelectric fan	(m)
A_{mc}	surface area of the microelectronic component	(m^2)
A_b	the board exposed surface area to the fans	(m^2)
A_{hs}	the heat sink exposed surface area to the fans	(m^2)
c_p	specific heat of air,	$J\ kg^{-1}K^{-1}$
q	rate of heat flux	($W\ m^{-2}$)
Q	power input of microelectronic component	W
Q	power input of LEDs	W
$\bar{h}$	average heat transfer forced coefficient	($W\ m^{-2}\ K^{-1}$)
$\bar{h}_n$	average heat transfer natural coefficient	($W\ m^{-2}\ K^{-1}$)
Nu	Nusselt number	–
R	thermal resistance	(°C. W^{-1})
Re_l	local Reynolds number	–
Re	Reynolds number	–
ξ	enhancement ratio	–
k	thermal conductivity	$W\ m^{-1}\ K^{-1}$
λ	thermal conductivity of air	$W\ m^{-1}\ K^{-1}$
T	temperature	K
$\bar{T}_S$	average temperature of heated surface	K
T_j	device junction temperature	K
T_s	solder point temperature	K
T_b	MCPCB temperature	K
T_{hs}	sink temperature	K
T_a	ambient temperature	K
t	time	s
l_{Pf}	length of piezoelectric fan	(mm)
D_{pf}	Width of piezoelectric fan	(mm)

t_{pf}	Piezoelectric fan thickness	(mm)
l_u	length of un-patch piezoelectric fan	(mm)
P	separation distance	(mm)
P	static pressure	(N m $^{-2}$)
$\vec{v}$	velocity vector	_
u	velocity	(m s $^{-1}$)
$\vec{v}_g$	local grid velocity	_
$\vec{f}$	volume force	_
x, y, z	space coordinates	_
S	Source term	_

Greek

Φ	vibration phase angle	(degree)
Θ	traveling wave phase angle	(degree)
$\O_y$	total luminous flux of an LED	(l W^{-1}
$\boldsymbol{\delta}$	dimensionless spacing between fan tip and heated surface	_
$\boldsymbol{\rho}$	fluid density	(kg m $^{-3}$)
σ	Cauchy stress tensor	_
τ_{ij}	viscous stress tensor	(N m $^{-2}$)
τ_w	Wall shear stress	(N m $^{-2}$)
Γ	Diffusion coefficient	_
ω	Ratio of ε to k	_
ω	the angular velocity of the wave	Rad.s^{-1}

LIST OF ABBREVIATION

2D	Two dimensional
3D	Three dimensional
AC	Alternate current
ALE	Arbitrary Lagrangian-Eulerian
CCD	Charge-coupled device
FEM	Finite element method
FSI	Fluid structure interaction
FVM	Finite volume method
LED	Light emitting Diode
LES	Large eddy simulation
MCPCB	Metal core of printed circuit board
PCB	Printed circuit board
PIV	Particle image velocimetry
PZT	Lead zirconate titanate
RANS	Reynolds average Navier Stokes
RMS	root mean square
SEM	Scanning electron microscope
SIMPLE	Semi-implicit pressure-linked equations
SST	Shear stress transport
TIM	Thermal interface materials
VAC	Voltage alternating current

LIST OF PUBLICATIONS

Sufian S. F., Abdullah M. Z. & Mohamed J. J. 2013. Effect Of Synchronized Piezoelectric Fans On Microelectronic Cooling Performance. *International Communications in Heat and Mass Transfer,* 43**,** 81-89.

Sufian S. F., Abdullah M. Z., Abdullah M. K. & Mohamed J. J. 2013. Effect of Side and Tip Gaps of a Piezoelectric Fan on Microelectronic Cooling*Components, Packaging and Manufacturing Technology, IEEE Transactions on,* 3**,** 1545-1553.

Sufian S. F., Fairuz Z. M., Zubair M., Abdullah M. Z. & Mohamed J. J. 2014.Thermal analysis of dual piezoelectric fans for cooling multi-LED packages. *Microelectronics Reliability,* 54, 1534-1543..

Fairuz Z.M., **Sufian S.F.**, M.Z. Abdullah, M. Zubair, M.S. Abdul Aziz, Effect of piezoelectric fan mode shape on the heat transfer characteristics, International Communications in Heat and Mass Transfer, 52 (2014) 140-151.

ANALISIS TERMA DAN ALIRAN BAGI KIPAS PIEZOELEKTRIK UNTUK PENYEJUKAN PAKEJ LED

ABSTRAK

Komputer, pakej LED dan alatan elektronik mudah-alih, seperti komputer riba mini, tablet, telefon sel, meningkat dengan ketara dari segi bentuk, ringan, nipis, dan lebih padat dengan fungsi yang tinggi bagi memenuhi permintaan pelangan. Pertumbuhan yang ketara ini dalam elektronik termaju memerlukan penyelesaian moden bagi menyesuaikan dengan cabaran baru pengurusan terma. Salah satu daripada penyelesaian terma terbaru adalah kipas piezoelektrik, yang mana baru-baru ini dianggap sebagai alat yang amat sesuai bagi penyejukan generasi hadapan dalam alatan mikroelektronik umum.

Kipas piezoelektrik (kipas getaran) adalah mesin getaran mikro yang berpotensi digunakan sebagai penjana aliran udara bagi membantu membebaskan haba dalam alatan mikroelektronik. Alat ini adalah kebolehpercaya, jangka hayat yang panjang, menggunakan kuasa rendah, tidak bising dan boleh digunakan dalam ruang yang kecil. Dalam kajian ini, kombinasi analisis eksperimen dan berangka (CFD) telah dijalankan bagi mengkaji prestasi kipas piezoelektrik ke atas fungsi haba terbebas. Kajian vibrometer laser telah digunakan bagi menentu frekuensi resonan kipas getaran. Kajian velocimetri imej zarah menunjukkan medan aliran terhasil daripada kombinasi beberapa susunan kipas-kipas bergetar. Simulasi 3D berdasarkan skim jaringan dinamik telah dijalankan dalam FLUENT dan ABAQUS dengan

menggunakan perantara gabungan kod MpCCI bagi mengkaji perubahan fasa keatas suhu dan medan aliran yang terhasil daripada kipas-kipas bergetar.

Keputusan kipas bergetar berorientasi tunggal menunjukkan bahawa orientasi menegak pada permukaan panas memberikan peningkatan yang ketara keatas pemindahan haba. Kesan perbezaan getaran fasa di antara kipas-kipas mengaitkan dengan getaran dalam fasa (Φ=0°) dan luar fasa (Φ=180°) telah diterokai dengan sebutan suhu fana dan medan aliran. Keputusan yang dikira menunjukkan kipas tunggal meningkatkan prestasi pemindahan haba sebanyak lebih kurang 2.9 bagi getaran luar fasa (Φ=180°) dan 3.1 bagi getaran dalam fasa (Φ=0°).

Kaedah yang berjaya ini telah digunakan sebagai alat penyejukan bagi membebaskan haba pada pakej LEDs berkuasa tinggi. Pakej LEDs telah dipasang dengan dua kipas bergetar tersusun mengikut konfigurasi A (bagi susunan bucu ke bucu kipas), dan konfigurasi B (bagi susunan muka ke muka). Ia mendapati dua kipas telah meningkatkan kadar prestasi pemindahan haba lebih kurang 2.3 kali ganda bagi konfigurasi A dan 2.4 bagi konfigurasi B. Kombinasi penyerap haba dengan dua dan empat kipas bergetar untuk menyejuk pakej LEDs digunakan bagi memaksimum haba terbebas telah diterolai. Kipas bergetar empat dengan penyerap haba menunjukkan penurunan ketara pada suhu simpang LEDs (T_j = 319K) berbanding kipas berdua (T_j= 324K), perolakan tabie dengan penyerap haba (T_j= 344K) dan perolakan tabie tanpa penyerap haba (T_j = 390K). Kajian ini telah menunjukkan kemampuan kipas piezoelektrik dalam pengurusan terma LEDs pelbagai susunan dan mencadangkan ianya diguna sebagai penyejukan komersial bagi cip LEDs.

THERMAL AND FLOW ANALYSIS OF PIEZOELECTRIC FANS FOR COOLING LEDs PACKAGES

ABSTRACT

Computers, LED packages and portable electronic devices, such as mini-laptops, tablets, and cellular phones, are rapidly emerging in lighter, slimmer, and more compact forms with high functionalities to meet consumer demands. This tremendous growth in advance electronics necessitates modern solutions to be adapted with the new challenges of thermal management. One of the recent thermal solutions is piezoelectric fans, which recently considered as a very strong candidate for cooling the next generation in general microelectronic devices.

Piezoelectric fans (vibrating fans) are microvibrating machines that can be potentially used as airflow generators to help dissipate heat in microelectronic devices. They are reliable, have longer life span, consume low power, noise-free and it's adaptable in very small spaces. In this work, a combination of experimental and numerical analyses (CFD) was performed to investigate the performance of piezoelectric fans on heat dissipation function. Laser vibrometer study was carried out to determine the resonance frequency of vibrating fans. Particle image velocimetry study presented the flow field induced by combination of different vibrating fans arrangements. 3D simulations based on a dynamic meshing scheme were 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 vibrating fans.

The results of single vibrating fan orientations showed that the vertical orientation to the heated surface had significant enhancement on the heat transfer. The effects of vibration phase difference between the fans corresponding to in-phase (Φ=0°) and out-of-phase (Φ=180°) vibrations were explored in terms of transient temperature and flow fields. 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 (Φ=180°) and 3.1 for in-phase vibration (Φ=0°).

This successful approach was then exploited as a cooling device to dissipate heat from high power LEDs package. The LEDs package were directly exposed to the dual vibrating fans arranged according to configuration A (for edge to edge fans arrangement), and configuration B (for face to face fans arrangement). It was found that the dual fans enhanced heat transfer performance approximately by 2.3 times for configuration A and 2.4 for configuration B. Combination of heat sink with dual and quadruple vibrating fans to cool the LEDs package for maximizing the heat dissipation was also explored. The quadruple vibrating fans with heat sink demonstrated significant reduction in the junction temperature of the LEDs (T_j = 319K) over a dual fans (T_j = 324K), natural convection with heat sink (T_j = 344K) and natural convection only MCPCB substrate without heat sink (T_j = 390K). This research has established the ability of piezoelectric fans for thermal management of LEDs arrays and recommends it for use as commercial cooling of LEDs chips.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Modern day gadgets such as computers, LED packages and portable electronic devices (mini-laptops, tablets, and cellular phones) are rapidly emerging in lighter, slimmer, and more compact forms with high functionalities to meet consumer demands. This tremendous growth in advance electronics necessitates modern solutions to be adapted with the new challenges of thermal management. Currently, the thermal management for such commercially available devices is mostly confined to passive cooling because of its typical simplicity in implementation. One such example is the thermal management of LED packages.

LED is based on the principle of solid-state lighting (SSL) technology which converts electricity into visible light using semiconductors. Over the last 10 years, LED technology has seen tremendous progress on account of its numerous advantages over the traditional lighting sources. This success of LED will continue to dominate the lighting market; completely replace the traditional lighting and outperform the incandescent and the fluorescent lighting in future. Only a small portion of the LED power input converts into a light of particular wave length, and the rest appears as unwanted heat which adversely affects the maintainability of low LED die temperature.

Approximately 80% of the LED applied power is converting to heat which greatly reduces the luminosity of the device and therefore must be dissipated to the ambient (Petroski, 2002). Therefore, thermal management has become the major issue related to high-power LEDs. In order to achieve longer lifetime, higher luminous efficacy and stable emission wavelength of light output, LEDs should be sustained in lower junction temperature (Shyu et al., 2011). Thus, in order to exploit these advantages, heat dissipation solutions for LEDs become crucial.

It is well known that cooling efficiency is very low for passive cooling mechanism. Moreover, the modern electrical devices need higher heat dissipation requirements and their demands have significantly increased over time, which draws out attention towards more effective cooling techniques. Presently, the heat transfer enhancement methods are broadly classified as either active (e.g. piezoelectric fans, surface vibration, electric or magnetic fields, and so on) or passive (e.g. extended surfaces, swirl flow devices, vortex generators) (Lin, 2012). The piezoelectric fan stands out amongst all the methods due to its operational simplicity, small size and low power consumption.

The piezoelectric fan is an airflow generator that induces the flow with a vibrating flexible blade. It has recently been proposed as an alternative device for microelectronic cooling. It consists of a flexible blade bonded with piezoelectric material near its base end. An input signal applied to the piezoelectric material causes an oscillatory motion at the free end of the blade. This signal can induce the surrounding flow with low power consumption. Piezoelectric fan has several advantages and is an attractive thermal management alternative. It consumes very little power and can be typically operated in the range of 1-40 mW. This makes it an ideal choice for applications where power consumption is a key issue particularly for use in cell phone, PDA, or other mobile device. Another important advantage is that it can easily fit into any geometric constraint and make use of available volume. Significantly, this device is driven at frequencies under 100 Hz. Consequently, their acoustic energy and noise levels were very low to an extent that their first mode of resonance was outside the range of frequencies audible to the human ear. This ensured near silent operation thereby avoiding unnecessary noise in the system. Another major advantage of this device when compared to a traditional rotary fan was that it had no moving parts, which ultimately led to longer life and better reliability.

Presently, LED cooling has been carried out using heat sinks and other passive cooling methods. Jang et al.(2012) optimized the cooling performance and mass of a pin-fin radial heat sink for LED lighting applications. Dehuai et al. (2012) improved the thermal characteristics of high-power LED package by using phase change heat sink. Kim et al.(2007) reported the thermal characterization of high power LED arrays cooled by a heat pipe. In another work, Li et al.(2013b) proposed a combination of loop heat pipe heat sink with dual complete parallel condensers for high power integrated LED cooling. These methods have limited scope and they are not very efficient.

The use of piezoelectric fan based cooling of LED's has not been carried out in any of the previous work. Addressing the use of piezoelectric fans as cooling devices for LEDs is expected to highly contribute to the knowledge of the thermal and flow characteristics of these fans. It is also well established that the performance of LED based electronic devices can be considerably improved at lower junction temperatures. The LED itself being low power consuming device, the use of conventional cooling techniques requiring higher power inputs is not justifiable. On the other hand, the piezoelectric fan based cooling technique has been proven to be very useful in several microelectronic cooling applications requiring very minimal power (Açıkalın et al., 2004).

1.2 Problem Statement

The exponential increase in miniaturization of electronic components and the growing demand for small scale tablet PC has put the focus on thermal management engineers. The heat dissipated from modern electronic devices is a major concern and is the driving force behind thermal management research. The conventional way to dissipate heat was to employ fan based forced convection technique. The small size electronic devices, increased heat flux on the processing platform and impetus on clean operation with minimal or no noise has propelled the need for improved cooling techniques that suit the modern electronic industries. Traditional rotary fans are no longer practical as it has reached their utmost limit in size reduction. Moreover, it requires large space, high power consumption, and the high speed moving parts cause noise and vibrations. Thus, it is very crucial to develop newer cooling techniques suiting the modern electronic devices for dissipation of associated heat generated.

Presently, piezoelectric fans, surface vibration, electric or magnetic fields are most widely used active cooling methods (Lin, 2012). Among all these methods, piezoelectric fans are very strong candidate for cooling the next generation microelectronic devices. It stands out amongst all the methods due to its operational simplicity, small size and low power consumption. Many studies have demonstrated its usefulness and discussed the related flow and thermal analysis of single piezoelectric fan (Liu et al., 2009). Despite the simple structure of piezoelectric fans, the airflow patterns developed by these fans have not been completely understood. Not much has been reported about the flow field induced on account of piezoelectric fan orientation.

Although, some studies on multiple piezoelectric fans have been carried out, but the underlying flow interaction and their optimized arrangement for best possible heat dissipation have not been given importance (Kimber and Garimella, 2009a). The flow field induced by two neighboring piezoelectric fans can be highly influenced by the vibration phase (Ihara and Watanabe, 1994). This calls for further investigations into the study of characteristic of multiple vibrating fans to assess the influence of different phase angles between two vibrating fans on the resulting flow and heat transfer. In addition to this, most of the researches with respect to multiple piezoelectric fans were based on the findings of dual fans. There is much to be realized on the appropriate arrangement of these fans for best possible heat transfer capabilities. Besides, the use of quadruple fans and their combination with heat sinks and performance of these fans at different power inputs have not been explored yet. In addition to this, most of the researchers focused the use of vibrating fans to cool a single heat source, whereas studies involving multiple heat sources (such as LEDs packages) have found no takers.

LED is an application of solid-state lighting (SSL) technology which converts electricity into a visible light by utilizing semiconductors. It is anticipated that LED will dominate the lighting market and outperform the incandescent and the fluorescent lighting in future, thereby replacing the traditional lighting sources completely. Light output of the conventional incandescent and newer compact fluorescent light bulb is much higher than the single LED output. As a result, multiple numbers of LEDs are used to be packaged in arrays to provide the preferred lighting for various applications of general illumination systems.

Although, LED’s have high luminous efficiency, about 80% of the power supplied is lost in the form of waste heat. It is highly recommended to maintain the junction temperature below 398K (125°C) to run the LED's for maximum lifetime(OSRAM, 2005). Therefore, the thermal problem caused by the heat generated within the LED itself constitutes an obstacle and limits the stability, reliability and lifetime of high power LED. It has been reported that, the average time to failure for most high power LED devices would reduce approximately by 50% when the specific operating junction temperature increases by an excess of 10 °C above the specific operating junction temperature (Zou et al., 2007). On the other hand, thermal behavior of LEDs packages is essentially affected by ambient temperature and multiple chips. Moreover, packaging the LED chips in small space causes increase in the thermal stresses. Therefore, it is necessary to develop LED packages with effective thermal design having very low thermal stresses in order to enhance the performance of LED.

The advantages of dual piezoelectric fans in dissipate heat from LEDs package have not been studied. In addition to this, quadruple piezoelectric fan design for cooling of LEDs chips and their effectiveness in heat dissipation needs further investigation. Combining these two major power saving devices not only would add to the efficiency of the LED's but would also reduce the overall power consumption to a very large extent. This is the basic thrust of this research and as a part of this work several studies are carried out to evaluate the effect of using vibrating fans to cool LED arrays.

1.3 Research Objective

The present study aims at describing the behavior of the convection transfer coefficients of flows generated from piezoelectric fans. Addressing details in this subject is essential for providing guidelines related to these fans and it may helps in their practical application. However, the main objectives of the present research are:

1. To investigate the flow characteristics induced by single and dual piezoelectric fans.
2. To develop and validate 3D numerical simulation to estimate the transient flow and temperature field of piezoelectric fans.
3. To study the cooling capability of the piezoelectric fan with different orientations over single heat source.
4. To examine the characteristics of different phase angles between dual vibrating fans on the resulting flow and heat transfer.
5. To investigate the thermal characteristics of high power LED array cooled by multiple vibrating fans.

1.4 Scope of the Research

This research reports on the piezoelectric fans as cooling technique for microelectronic applications. The thermal and flow performance of single and multiple piezoelectric fans were examined over imitated microelectronic component (heated surface). The piezoelectric fan was targeted to heated surface in different orientations with aim of enhancing the heat transfer. In particular, the interactions of coupled piezoelectric fans set in array and their effect on resulting heat transfer were characterized. These fans were ultimately combined with heat sink and utilized for cooling LEDs package. Several experimental investigations conducted for understanding the underlying physics of piezoelectric fans. The studied variables were the fans' amplitude, frequencies, fans' tip separation distance, separation distance between dual fans (pitch), vibration phase angle, and different fans configurations. The experimental measurements were represented by the numerical simulations. The estimations of transient thermal and flow of the developed model were then compared with measurements results to assess the cooling ability of the vibrating fans.

1.5 Thesis Outline

This thesis is organized in five main chapters. Chapter 1 addresses the needs of thermal solutions for electronic devices, LEDs applications, piezoelectric fans, the problem statement and research objectives. In Chapter 2, a comprehensive review of experimental and numerical studies on various types of cooling electronic devices, studies on the piezoelectric fans and LEDs cooling methods are explored and the need for further research in this area was summarized. Chapter 3 gives a detailed account of the materials and methods used in the current research. Chapter 4 presents the results of experiments and numerical simulation. A detailed discussion is provided on flow analysis and thermal performance for both single fan and multiple piezoelectric fans and its applicability for LEDs cooling. It is basically divided into two main sections which addresses the flow and the thermal characteristics. The thermal part includes the study of basic heat transfer with single and dual piezoelectric fans on a single heat source and application of multi piezoelectric fans on an array of LED chips. This is followed by chapter 5 which concludes the research and includes suggestions for future work.

CHAPTER 2

Literature Review

2.0 Overview

This chapter presents a thorough review of the heat transfer modalities especially related to electronic cooling employing piezoelectric fan. The effect of single and multiple piezoelectric fans on the flow and heat transfer characteristics were studied. Thereafter, the combination of piezoelectric fan with heat sink is explored. The findings of both numerical and experimental studies are presented in this review to justify the significance of using piezoelectric fan in heat dissipation and power savings. Finally, the use of piezoelectric fan for LED cooling application and its related studies are presented in this work.

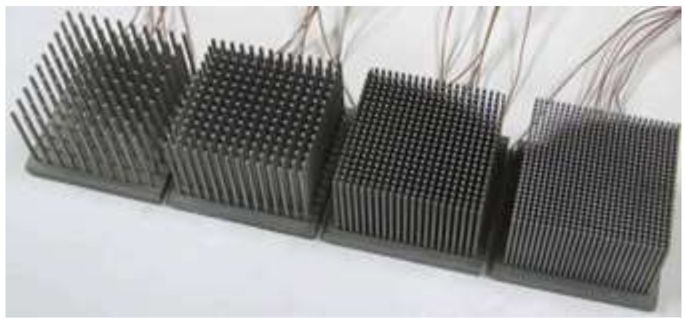
2.1 Cooling Methods of Electronic Devices

About 30% of the computer's printed circuit board (PCB) area is stashed with power delivery components which makes it susceptible to high heat generation. With increasing attempt to reduce the size of the electronic devices, it is expected that the power delivery components would cover the PCB area exceeding the present 30% margin. This is expected to create higher heat flux and therefore requires more efficient thermal module for proper functionality. Moreover, it is also expected that the anticipated transistor density will be more than 1010 per die (Stanford, 2006) by

2015. This dramatic increase in heat flux needs to be transferred elsewhere to maintain lifetime of future microelectronics. Therefore, research in better thermal management of electronic devices is inevitable in order to overcome the adverse affect of excessive heat generated due to this miniature phenomenon. It is well known that, the failure rate of electronic equipment increases exponentially with temperature (Cengel, 2002). Increased demand for higher functionality and higher power dissipation has increased the need for better thermal solutions. Accordingly, three common techniques are extensively employed to dissipate heat from the electronic devices.

First, is the passive air cooling method which dissipates heat on account of the airflow generated by difference in temperature; second type is the forced air cooling (active cooling) which requires the air to be forced over the heat source by means of fans and blowers, and finally the forced liquid cooling which involves the coolants like water to pass over the heated surface (Suzuki, 1998). Amongst all the methods, the air cooling is very useful for thermal management of electronic devices because of its simplicity and easy operation (Ledezma and Bejan, 1996, Chih-Peng et al., 2009). The passive air cooling technique (see Figure 2.1) is preferable for low power dissipating devices due to advantage of low-cost, energy-free, and silent operation (Tou et al., 1999, Adams et al., 1999, Chih-Peng et al., 2009). Although, the advance design of heat spreaders and heat sinks can also enhance passive cooling but it is still confined for only lower heat flux dissipation (Mehrtash and Tari, 2013, Li and Chao, 2009, Kim et al., 2009, Li and Chen, 2007).

(a)



(b)

Figure 2.1. Heat sinks used for passive cooling: (a) plate-fin heat sink, (b) pin-fin heat sink (Kim et al., 2009).

Thus, when the passive thermal solutions no longer provide the performance required for a proper functionality, the integration of an active cooling solution may become an attractive option (Miner and Ghoshal, 2006, Zhou and Yang, 2008, Egan et al., 2008, Ismail et al., 2008, Arularasan and Velraj, 2008). Forced air cooling (active cooling) techniques offer higher heat dissipation compared to passive air cooling which can be obtained by using flow accelerators. Conventional rotary fans and blowers are the most widely used as active cooling techniques in several power electronic systems (Blinov et al., 2011, Sauciuc et al., 2006). For several decades, thermal management solutions for most consumer electronics relied extensively on the operation of conventional rotary fans derivatives, such as fan-heat sink combinations and fan-heat pipe combinations (Wang et al., 2013, Elnaggar et al., 2013) as shown in Figure 2.2.

(a) (b)

Figure 2.2. Combinations of (a) heat sink with rotary fan and (b) heat pipes with rotary fan (http://hardwaretexpert.files.wordpress.com).

Developing heat transporter cooling technologies such as heat pipes (Elnaggar et al., 2011, Choi et al., 2012a), microchannels (Chen and Garimella, 2011, Determan and Garimella, 2011, Wälchli et al., 2010, Chiu et al., 2011), and micropumps (Darabi et al., 2001, Singhal and Garimella, 2005), are focused on local high heat flux dissipation and local hot spot cooling applications. However, the conventional rotary fans and heat sinks dominate the overall heat transfer performance which is more desirable for thermal management of packages (Wang et al., 2013). Although conventional rotary fans can work efficiently in large form electronics, their major disadvantages are the noise level, high power consumption, and accumulation of dust on the entire structure after long periods of operation. Besides, the current electronic devices are oriented towards miniaturization. The conventional rotary fans are no longer useful for thinner and smaller consumer electronics. As a result, there is an urgent need for efficient compact cooling techniques that ensure functionality of small form electronic devices in terms of size, low power consumption, reliability, acoustic level, and heat transport capability.

One of the potential solutions strongly recommended in thermal management for compact form electronics is the piezoelectric fans (Mochizuki M, 2011, Açikalin and Garimella, 2009). The advantages of piezoelectric fans are simple structures, low acoustical noise, and efficient control of air speed and airflow (see Figure 2.3). Furthermore, a reasonable lifetime longer than 25,000 hrs (Yoo et al., 2000, Mochizuki M, 2011) and low device power consumption (Yoo et al., 2000, Garimella, 2006) are essential features over other competitive airside cooling technologies. Besides, piezoelectric fans are also efficient when they are used to increase heat transfer rate of finned heat sinks (Petroski et al., 2010, Abdullah et al., 2012b). There is wealth of literature detailing the use piezoelectric fan in configuration of either single or multiple fans in the study of heat transfer as well as their characteristic flow patterns that facilitate heat removal.

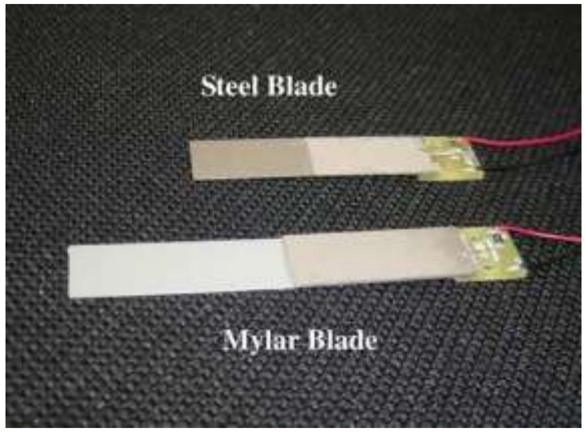


Figure 2.3. Two piezoelectric fans (mylar and steel blades) tested to characterize the influence of operating parameters (Kimber et al., 2009b).

2.2. Thermal and Fluidic Analysis of Piezoelectric Fans

Several studies have postulated the advantages of using piezoelectric fans for applications in electronic cooling. In general, the studies can be broadly categorized in a number of ways. In this chapter, research on piezoelectric fan has been categorized based on single fan or multiple fans and its effect of flow developed and its related heat transfer abilities have been discussed in detail.

2.2.1 Single Piezoelectric Fan

One of the earliest studies on heat transfer enhancements using single piezoelectric fans was conducted by Toda (1979). Simplified models for airflow and vibration were presented and experiments were conducted to judge the accuracy of these models with six-layer PVF2 bimorph fans. It was demonstrated in this work that the observed resonance frequency was larger than the value predicted from theory, and this difference increased as shorter fans were considered. However, results showed fairly good agreement with theory for airflow from longer fans (lower frequencies).

Material used in manufacture of piezoelectric fans had definitive impact on its flow and heat transfer properties. This was investigated by Yoo et al. (2000), who developed and investigated many types of piezoelectric fans. Fans were constructed using bronze, brass, aluminum with PZT patches and had lengths from 32 to 35 mm. All fans operated at 60 Hz and at two voltage levels, 110 and 220 VAC, which produced different vibration amplitudes and airflow rates. The measured air velocity was found to be highly dependent on the maximum tip velocity. They also found that the most effective fan was made from a phosphor bronze shim and with PZT in a bimorph configuration whose width was equal to that of the piezoelectric patch.

Loh et al.(2002) investigated the cooling performance of acoustic streaming from an ultrasonically vibrating fan. They performed analytical model based on Nyborg's formulation along with computational fluid dynamics CFD simulation for the vibrating fan. The flow was assumed as laminar and incompressible. They found that the vortical flows, observed by experiment and predicted by acoustic streaming theory, could be reproduced. However, it was observed that streaming velocities calculated from CFD simulations were greater than estimates from the theory. This discrepancy was attributed to the incompressible flow assumption made in the CFD simulations. The heat transfer enhancement was attributed to 30K reduction by the fan nearby the surface of heat source.

The motion of a piezoelectric fan with two symmetrically placed piezoelectric patches was described with closed-form analytical developed by Burmann et al. (2003). They used this model to optimize the electromechanical coupling factor (EMCF), which was a measure of the electrical energy that could be converted into mechanical energy. They found optimum values for patch-to-beam length ratio, thickness ratio, and patch thickness ratio.

One of the major studies in the field of piezoelectric fan was carried out by Açikalin and Garimella (2003) who presented an analytical, computational, and experimental investigations of the incompressible two-dimensional streaming flows induced by resonating thin beams Closed-form analytical streaming solutions were presented first for an infinite beam. These were used to motivate a computational scheme to predict the streaming flows from a baffled piezoelectric fan. They found good qualitative agreement between the predicted flow patterns and experimental visualizations. However, according to the authors the effect of 3D enclosure was negligible and therefore this study required further attention.

In another study, analysis of the two-dimensional flow field generated by a vibrating cantilever was investigated by Kim et al. (2004) using phase-resolved particle image velocimetry (PIV) measurements and smoke visualization techniques.

They were able to detect precise counter-rotating vortices and were observed to be shed each time the blade passed the natural position, *i.e.*, at twice the vibration frequency. Between these two vortices and just beyond the tip, a region was formed where the maximum fluid velocity occurred, and was found to be roughly four times that of the maximum tip velocity. In addition, they observed that the flow field was two-dimensional near the cantilever tip and became more complex and three-dimensional further downstream.

In continuation of his previous work, Açıkalın et al. (2004) examined the feasibility of placing piezoelectric fans in an actual laptop and cell phone enclosure. Thermocouples were placed at various locations within the laptop, and it was shown that in certain areas the temperature dropped an additional 6K due to the presence of the piezoelectric fans. They also attempted to place the piezoelectric fan in a simulated cell phone enclosure with the fan vibrating at 20 Hz and vibration amplitude of 1.5 cm. The fan was placed in various positions relative to a small heat sink and enhancements over natural convection were quantified. The best performance was observed when the fan covered half of the heat sink, yielding a 100% increase in the heat transfer coefficient clearly showing the usefulness of piezoelectric fan in such applications. Basak et al.(2005) carried out analysis on a beam with a piezoelectric patch and developed the equations of motion required to accomplish optimization. The results from this analytical solution were compared to finite element predictions and both methods found to match closely for the same optimal configurations.

The use of the local effects of the imposed transverse oscillations of a rigid plate to augment pure natural convection cooling of a rectangular heat source was investigated by Florio and Harnoy (2005, 2007). The heat source was attached to a mounting board in a vertical channel. They developed a two-dimensional laminar flow using finite element method concerned the oscillation parameters, the oscillating plate-heat source mean clearance spacing, and the oscillating plate position varied. The results obtained suggested that a parameter and configuration dependent optimum clearance space existed for a given displacement amplitude and frequency that was related to the degree of constriction of the flow around the heat source caused by the positioning of the plate near the heat source.

Açikalin and Garimella (2004) experimentally investigated the optimal design of single piezoelectric fan for extracting heat from a heat source and proposed its possibility for cooling light emitting diodes (LEDs). They simulated a typical heater which was consistent with a high-power LED package of similar size. Several parametric studies were carried out using different experimental configurations. Some of the studies involved varying the fan amplitude, fan length, distance between the fan and heat source, frequency offset from resonance, and the fan offset from the center of the heat source. About 36.4^{o}C drop in temperature was reported at the heat source on using the piezoelectric fan.

In another of their work, numerical modeling of the flow field and heat transfer induced by a piezoelectric fan was carried out (Açıkalın et al., 2007). The flow field induced by these fans was found to be highly complex and dependent on the distance from the fan tip to the heat source, and the presence of other boundary conditions such as sidewalls also showcased significant impact. Investigations were also made with a single piezoelectric fan vibrating near a small heat source to estimate the optimization conditions of the average heat transfer. Figure 2.4 shows the three different configurations of the piezoelectric fan and heat source that were studied.

Experiments were carried out by varying the position of the fan relative to the heat source in the first two configurations, whereas the third configuration was identical with the first type but had fin attached to the heat source. Based on their analysis, DOE revealed that the piezoelectric fan frequency offset from resonance, and the piezoelectric fan amplitude was the critical parameter. The critical considered factors were fan length, vibration amplitude, frequency offset and distance from the heat source. Optimal conditions occurred when the fan operated at resonance and was oriented normal to the heat source. This provided an enhancement over 375% in the heat transfer coefficient relative to natural convection.

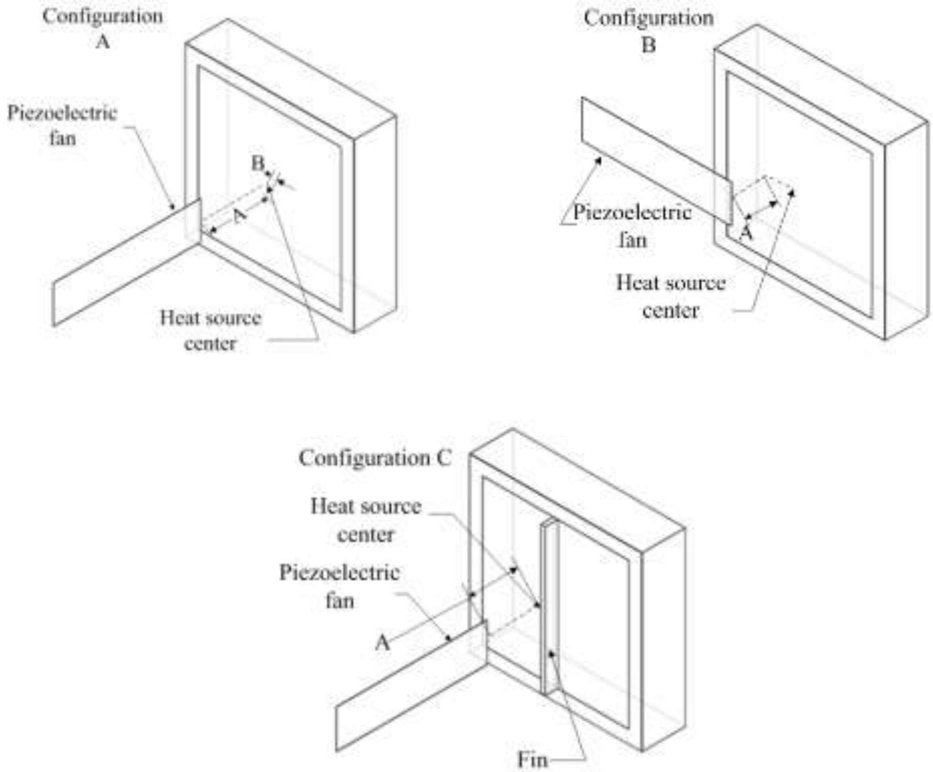


Figure 2.4. Schematic of piezoelectric fan with heat source in different configurations conducted experimentally by Açıkalın et al. (2007).

In a recent work, Açikalin and Garimella (2009) analyzed and predicted the effect of amplitude of the piezoelectric fan. A seventh-order least squares polynomial fit was used to represent the mode shape given in Açıkalın et al. (2007) and describe the location of the piezoelectric fan in time. They used CFD-ACE with special feature of structured mesh having deforming mesh modules. The domain automatically remeshes itself by estimating the new location of the fan at every time step. They used a transfinite interpolation scheme to estimate the new locations of the nodes at every time step. Except in the case with smallest amplitude and largest gap, the predictions were well within ±20% of the heat transfer experiments.

Zaitsev et al.(2009) reported the first analysis using turbulent flows around a vibrating fan in 3D numerical simulation. They used a parallel CFD technique to estimate fluid structure interaction problems. . The deforming mesh approach based on the arbitrary Lagrangian-Eulerian (ALE) formulation was employed to compute the flow around vibrating bodies whereas the hydrodynamic force calculated predicted the body motion/deformation. The RANS/LES vortex-resolving model was utilized to include turbulence. It was shown that 2D simulation was inadequate. Therefore, in the cylinder case characterized by two-dimensional geometry, the spanwise periodicity conditions imposed for 3D simulation. The simulation was performed with one month CPU time, using 11 processors of an Opteron-based cluster.

The effect of different piezoelectric fan amplitudes and tip gap from the heat surface are an important parameter that would define the effectiveness of heat removal ability of the devices. Kimber et al.(2007) experimentally investigated local heat transfer coefficients for a single piezoelectric fan at various vibration amplitudes and gaps. The fan was vibrating close to an electrically heated stainless steel foil, and the entire temperature field was observed by means of an infrared camera as shown in figure 2.5. Four vibration amplitudes ranging from 6.35 to 10 mm were considered, with the distance from the heat source to the fan tip chosen to vary from 0.01 to 2.0 times the amplitude. It was seen that the thermal maps exhibited a lobed-contour behavior at large gaps, transitioning to nearly circular (or rounded square) contours at intermediate gaps, and finally elliptical contours at small gaps. An optimal gap was noted both in the horizontal centerline profiles of local heat transfer coefficient and in the stagnation-region performance; the value of optimum gap was dependent on the vibration amplitude. Specifically, the optimum gap was small for large amplitudes and increases as the amplitude decreases. Predictive correlations were proposed for stagnation-region and area-averaged local Nusselt numbers. Correlations developed with appropriate Reynolds and Nusselt number definitions described the area-averaged thermal performance with a maximum error of less than 12%.

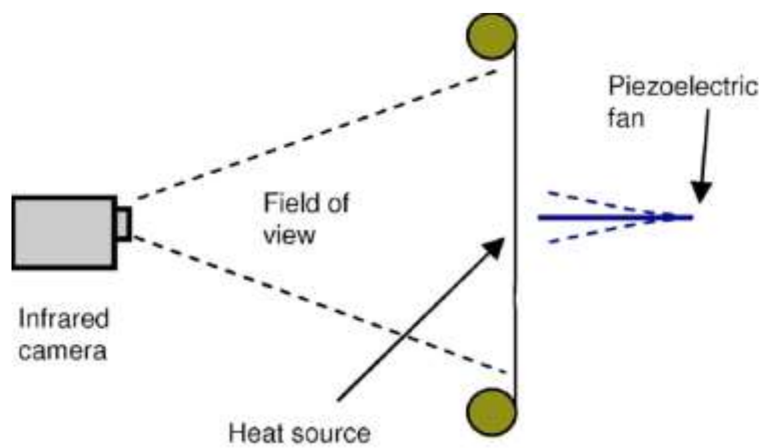


Figure 2.5. Schematic of thermal camera setup for heated foil cooled by piezoelectric fan (Kimber et al., 2007).

In another study, Kimber and Garimella (2009b) investigated the vibration frequency, amplitude and the geometry of the vibrating cantilever beam. The experimental setup consisting of a piezoelectric fan was mounted normal to a constant heat flux surface. Infrared camera was used to capture the temperature contours on this surface and subsequently the forced convection coefficient due to the fluid motion generated from the fan was estimated. A total of six fans of different geometries, with fundamental resonance frequencies ranging from 60 to 250 Hz, were considered. These fans were individually tested over a range of vibration amplitudes, frequencies and gaps. Results showed improved performance of the fans a particular distance between the fan tip and the heated surface. It was also observed that the heat transfer rate was dependent only on the frequency and amplitude of oscillation when the fan operates at this optimum gap. Specific correlations were developed based on appropriately defined dimensionless parameters to predict the thermal performance across the entire range of fan dimensions, vibration frequency and amplitude. This enabled improved understanding of the dependence of thermal performance on the governing variables and consequently helped improve the design of piezoelectric fans for enhancing heat transfer.

Besides, Kimber et al.(2009b) also presented an experimental measurement of the pressure and flow rate characteristics of piezoelectric fans. They considered two fans having blades made from different materials (mylar and steel) with operating frequencies of 60 and 113 Hz. They also explored the effects of fan installation details on fan performance. They determined the pressure using (Novasina PascalVision with accuracy ± 0.05 Pa), the flow rate using mass flow meter (accuracy ± l/min), and the amplitude using a laser displacement sensor (Keyence LK-G150) which captured the vibration signal of the fan tip. The output of these fans was then compared with two commercially available axial fans. They were evaluated