International Communications in Heat and Mass Transfer 66 (2015) 40–46

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Thermal performance of a dual-sided multiple fans system with a piezoelectric actuator on LEDs☆

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ARTICLE INFO

Available online 16 May 2015

Keywords:
Piezoelectric fan
D-MFPA
LEDs
Arrangement
Thermal performance
Dimensionless analysis

ABSTRACT

With the advantages of lower power consumption and longer lifetime, piezoelectric fans have been widely investigated for use in electronic cooling for many years. However, the application of the piezoelectric fans for LEDs is seldom explored because of its insufficient cooling ability. In this study, a dual-sided multiple fans system with a piezoelectric actuator ("D-MFPA") is considered for use in the thermal management of LEDs. The obvious advantage is that the D-MFPA only uses one piezoelectric fan to drive eight passive magnetic fans vibrating simultaneously to provide sufficient cooling ability and two-directional air flows. Two 30-W chip-on-board (COB) LED models are adopted to investigate the thermal performance of the D-MFPA. The dimensionless heat convection number for the D-MFPA ($M_{D\text{ - }MFPA}$) is defined in this study to describe and quantify the thermal performance of the D-MFPA. Moreover, several horizontal orientations (x/S_l) and vertical orientations (y/S_h) are examined to investigate the effects of different arrangements. The results indicate that $M_{D\text{ - }MFPA}$ can be improved to 3.92 under the case of $x/S_l = 0$ and $y/S_h = 0.033$; however, the single piezoelectric fan can only improve $M_{D\text{ - }MFPA}$ to 2.82.

1. Introduction

As manufacturing processes continue to progress, high power light-emitting diodes (LEDs) are being widely used in many lighting devices, such as streetlights, lamps, and recessed lights. However, high power LEDs can also cause very high heat flux to influence their operating temperature. Because the lifetime of LEDs is extremely dependent on their operating temperature, overheating problems will decrease their performance and lifetime dramatically. In general, cooling technologies can be classified as active (e.g., rotary fan, liquid cooling, and air pump) and passive (e.g., heat sink, heat spreader, and heat pipe). For the thermal management of LEDs, on the other hand, passive approaches are usually adopted for cooling because of the operating environment of LEDs; the operating environment involves dust accumulation, which causes active methods to be unsuitable for LED thermal management. However, the problem of passive methods is lack of cooling ability for high power LEDs. Therefore, alternative cooling technologies must be developed to address the overheating problem in the thermal management of LEDs.

One of the cooling technologies that has been broadly investigated in the recent years involves the use of piezoelectric actuators. When an alternating signal inputs into a piezoelectric actuator, the piezoelectric actuator can vibrate periodically to drive air flow or liquid flow. A piezoelectric fan is one application of such oscillating piezoelectric actuators, which is comprised of the components of piezoelectric material and a vibrating blade, and its thermal performance can be optimized by operating at the resonance frequency. With the advantages of lower power consumption, longer lifetime and lower noise [1], several studies have been devoted to investigate the thermal characteristics of piezoelectric fans. One of the first concepts of piezoelectric fans was introduced by Toda [2]. The simplified flow field model induced by vibrating motion was developed to investigate the flow characteristics at the tip of the piezoelectric fan. The results indicated that the air flow velocity was almost equal to the fan edge vibrating velocity under different fan length cases. Moreover, because piezoelectric fans usually used either plastic or metal material as a blade to increase the vibrating amplitude, Yao et al. [3] further developed the lumped-mass model to analyze a composite vibrating cantilever beam, and the results showed that the vibrating amplitude was related with the stiffness and damping effect of the fan blade. Kimber et al. [4] studied several operational parameters of piezoelectric fans to investigate their thermal performance. In their study, dimensionless analyses were applied for exploring the relationship of heat transfer with the amplitude and frequency. The results indicated that the operating frequency was more influential than the vibrating amplitude on thermal performance. Liu et al. [5] conducted experiments of different placements of the piezoelectric fan on the flat heat source to determine the optimal operating parameters. For the horizontal placement cases, the optimum heat transfer occurred when the piezoelectric fan was placed at the center of the flat heat source. The best thermal performance under vertical cases occurred for a fan placed at the quarter region. Florio and Harnoy [6] developed the two-dimensional simulation model to explore the enhancement of the

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.05.008
0735-1933/

Nomenclature

A	vibration amplitude (mm)
A_{conv}	total area of the convection surface (mm^2)
d	diameter of the LED (mm)
h	thickness of the LED (mm)
D	diameter of the magnet (mm)
E_l	length of the Mylar (mm)
E_w	width of the Mylar (mm)
E_h	thickness of the Mylar (mm)
f	frequency (Hz)
f_{D-MFPA}	resonance frequency of the D-MFPA (Hz)
Gr	Grashof number
H	thickness of the magnetic fans (mm)
H_m	thickness of the magnet (mm)
$\bar{h}$	average convective heat transfer coefficient (W/m^2 °C)
k_{beam}	the stiffness of the cantilever beam (N/m)
Δk_{mag}	the stiffness of the magnetic effect (N/m)
L	fan length (mm)
L_p	length of the piezoelectric actuator (mm)
L_{PZT}	characteristic length of the fan (mm)
m_{beam}	the mass of the magnetic fans (g)
m_{mag}	the mass of the magnet (g)
M_{D-MFPA}	dimensionless heat convection number by the D-MFPA system
$\overline{Nu}_{D-MFPA}$	Nusselt number of the D-MFPA system
P	distance between each of the fans (mm)
Q_{heat}	thermal power dissipated from the LED (W)
Re_{D-MFPA}	Reynolds number of the D-MFPA system
Ri_{D-MFPA}	Richardson number of the D-MFPA system
S_h	fin height of the heat sink (mm)
S_l	fin length of the heat sink (mm)
$T_{ambient}$	ambient temperature (°C)
T_a	LED substrate temperature (°C)
T_0	initial temperature of the LED substrate (°C)
$\bar{T}_s$	average surface temperature of the heat sink (°C)
Γ	dimensionless temperature
W	fan width (mm)
W_p	width of a piezoelectric actuator (mm)
x/S_l	horizontal orientation of the D-MFPA
y/S_h	vertical orientation of the D-MFPA
ν	kinematic viscosity of the working fluid (m^2/s)

heat transfer by using a vibrating plate. The top surface-average heat transfer coefficient of a rectangular heat source can be improved by up to 40% compared with natural convection. Shyu et al. [7] developed the finger-like piezoelectric fan, which is comprised of four flexible rectangular blades to enhance the cooling efficiency.

For a high power electronic device, because one piezoelectric fan cannot provide sufficient cooling ability, the multiple-piezoelectric-fans cooling-system has been developed recently to improve its thermal performance. Abdullah et al. [8] investigated the thermal characteristics of the heat sink with three piezofans, and the results showed that the fan's effectiveness was increased to almost 4 times than the case without piezofans. Sufian et al. [9] investigated the thermal performance of two piezoelectric fans in multi-LED packages. Two configurations are discussed, and the results showed that when compared to the natural convection, the optimal thermal performance of two piezoelectric fans system can reach 2.4 times; however, a single piezoelectric fan system can enhance the same by only 1.8 times. Choi et al. [10,11] developed two dimensional unsteady numerical simulation model to investigate the characteristics of flow field induced by the vibrating cantilever pair. The results revealed that the cantilever pair vibrating in counter-phase can be more effective way to generate the airflow and perform better performance than the cantilever pair vibrating in-phase. Kimber et al. [12] investigated the thermal performance of arrays of vibrating cantilevers, and the results indicated that the aerodynamic loading from a fluid can have a large effect on both the resonance frequency and damping.

Although the multiple-piezoelectric-fans cooling-system can be widely applied for high power electronic devices, the cost and the power consumption of it can also significantly increase. To provide sufficient cooling ability without high power consumption and high cost, Ma et al. [13] first proposed a novel cooling device, the multiple fans system with a piezoelectric actuator ("MFPA"), which combined the piezoelectric effect, the magnetic effect and the resonance effect to drive more air flow for cooling by using only one piezoelectric actuator. Ma et al. [14] investigated the effects of the pitch of each fan and of the distance between fan and heat sink to optimize the thermal performance; moreover, Ma et al. [15] explored the multiple fans system embedded in an aluminum heat sink and applied the dimensionless analyses to explore the relationship of operating parameters and thermal characteristics. Based on previous studies, the dual-sided multiple fans system with a piezoelectric actuator ("D-MFPA"), which not only can drive more passive magnetic fans but can provide two-directional air flow, is applied on the thermal management of LEDs. Two 30-W COB LED models are used to assess and analyze the cooling ability of a D-MFPA. Some significant characteristics are discussed, including power input, vibrating amplitude, resonance frequency and the arrangements of the D-MFPA. Moreover, a comparison of the thermal performance between a single piezoelectric fan and a D-MFPA is also explored.

2. Experimental apparatus and procedure

The geometry of the D-MFPA is presented in Fig. 1(a). The fans of a D-MFPA can be separated into eight magnetic fans and a piezoelectric fan. The magnetic fans are made of a carbon fiber plate and a Mylar plate. The Mylar plate is used to increase the sweep area of the D-MFPA to drive more air flow. The length (L), width (W) and thickness (H) of

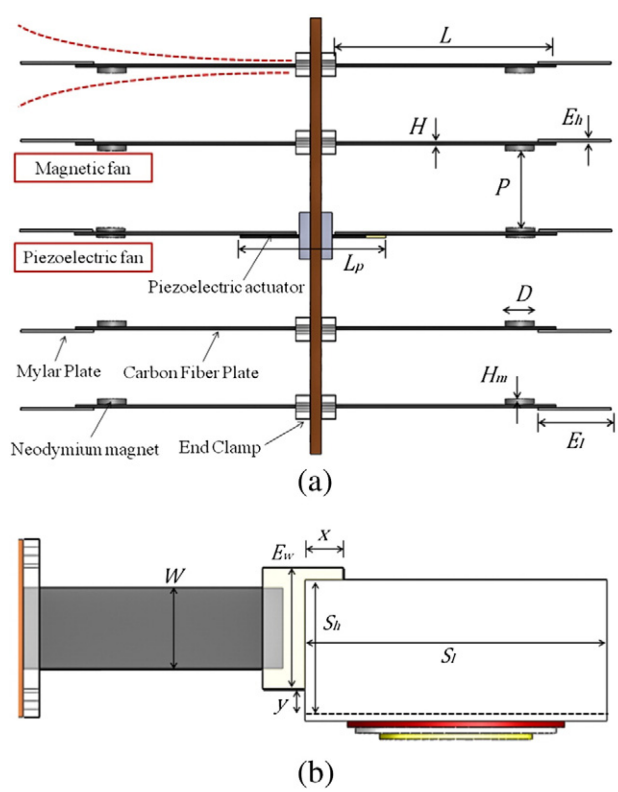

Fig. 1. (a) Geometries of the D-MFPA; (b) the arrangements of a D-MFPA in the heat sink.