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Thermal analysis of dual piezoelectric fans for cooling multi-LED packages

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ABSTRACT

This paper reports on the dissipation of heat generated by a high power LED array using piezoelectric fans. Both numerical and experimental studies were carried out to evaluate the heat dissipation efficiency of high power LED package operating under multiple vibrating fans. Two vibrating fans were vertically oriented to the LED package and arranged according to configuration A (for edge to edge arrangement), and configuration B (for face to face arrangement). The junction temperature (T_j), thermal resistance (R) and average heat transfer coefficient $\bar{h}$ were estimated. The results show that the single fan enhanced heat transfer performance approximately 1.8 times for the LED package. On the contrary, the dual fans enhanced heat transfer performance approximately by 2.3 times for configuration A and 2.4 for configuration B. A significant decrease in the thermal resistance was observed for all the configurations when fan separation distance δ was reduced. The best performance relative to natural convection was found to be at ($\delta = 0.1$) which decreased the thermal resistance using single fan by about 38%, whereas the dual fan accounted for 49.5% in case of configuration A, and 50.6% for configuration B.

1. Introduction

Over the last few years, light emitting diode (LED) has seen a tremendous surge in its application as new generation lighting technology, replacing the conventional general lighting (gas lights), such as incandescent and fluorescent lamps. Light emitting diode (LED) is a solid state semiconductor device that converts electrical energy into a visible light. Several applications such as the LCD back light source, television, automotive and general lighting use LEDs on account of its compact size, low power consumption, long lifetime, short response time and environmental protection.

Only a minor portion of the LED power input converts into a visible light of particular wave length, and the rest appears as unwanted heat which adversely affects the maintainability of low LED die temperature. Accordingly, most of the applications that require very high lumens necessitate multi-chip LED module. Thermal characterization of LEDs packages in an array is very different from that of single LED package. The junction temperature of LEDs packages will be significantly influenced not only by ambient temperature but the side effect from multiple chips [1]. Sustaining LEDs in lower junction temperature results in higher luminous efficacy, longer lifetime, and stable emission wavelength of the light output [2]. Thus, in order to extract maximum benefits from LEDs, heat dissipation solutions become crucial. The commonly methods of cooling used for the present applications of LEDs in the market are mostly confined on heat sinking techniques (passive cooling) [3]. However, the passive cooling relatively has very low cooling efficiency and therefore, higher heat dissipation solutions are urgently needed.

Many heat dissipation solutions have been investigated for the thermal management of LEDs. Jang et al. [4] optimized the cooling performance and mass of a pin-fin radial heat sink for LED lighting applications. They reported that the system was sensitive to the number of fin arrays, as well as the length of the long and middle fins. Their design for the optimum radial heat sink reduced the mass by more than 30% while maintaining a similar cooling performance to that of a plate-fin heat sink. Ha and Graham [5] developed a thermal resistance model for chip-on-board packaging of high power LED arrays. They proposed an analytical thermal resistance model for the LED array and validated by comparing it with finite element analysis (FEA) results.

Kim et al. [1] reported the thermal characterization of high power LED arrays cooled by a heat pipe. They used thermal transient methods to measure the junction temperature and calculate the thermal resistance with and without heat pipe. Also, Lu et al.

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Nomenclature

A_{pf}	amplitude of piezoelectric fan (mm)
A_b	exposed surface area of MCPCB (m^2)
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)
q	heat flux ($W\ m^{-2}$)
Q	LED array heat input (W)
$\bar{h}$	average heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
T_j	LED array device junction temperature (K)
T_s	LED array solder point temperature (K)
T_b	board (MCPCB) temperature (K)
T_a	ambient temperature (K)
$\vec{u}$	velocity vector
u	velocity ($m\ s^{-1}$)
$\vec{u}_g$	local grid velocity
$\vec{f}$	volume force
x, y, z	space coordinates
n	number of LED chips
R	total thermal resistance ($K\ W^{-1}$), $R = R_{js} + R_{sb} + R_{ba}$
R_{js}	thermal resistance from device junction to solder point on the MCPCB top ($K\ W^{-1}$)
R_{sb}	thermal resistance from solder point to MCPCB bottom ($K\ W^{-1}$)
R_{ba}	thermal resistance from MCPCB bottom to the ambient ($K\ W^{-1}$)
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

δ	dimensionless spacing between fan tip and heated surface
ρ	fluid density ($kg\ m^{-3}$)
σ	Cauchy stress tensor
τ_{ij}	viscous stress tensor ($N\ m^{-2}$)

[6], Lin et al. [7], and Li et al. [8] proposed a combination of heat pipe with heat sink as a cooling technique for carrying out thermal analysis of high power LED. Shyu et al. [2] studied the thermal characterization of shrouded plate fin array (heat sink) on an LED backlight panel consisting of 270 1-W LEDs in an acrylic housing. Their results showed that the heat transfer coefficient slightly reduced with the rise of shroud clearance from 0 mm to 5 mm, followed by a notable rise. However, the heat transfer coefficient peaks at a shroud clearance between 10 and 20 mm and any further increase of shroud clearance leads to a marginal decrease of heat transfer coefficient. Thermal performance of three kinds of LED vapor chamber-based plates comparing the experiments, theories, and simulation thermal resistances were discussed by Wang [9]. His results showed that the thermal performance of the LED vapor chamber-based plate was better than that of the LED copper-based plate. Yung et al. [10] presented thermal analysis and experimental validation of natural convective air cooling of a high brightness 3×3 LED array package on a printed circuit board (PCB) during operation from 0° to 180° inclinations. Their analysis results revealed that the effect of position and inclination plays an important role in the heat dissipation of the LED package. Refrigerating liquid for LED's thermal management integrated within a fabricated prototype was proposed and investigated by Faranda et al. [11]. Their experimental results reported that the refrigerating liquid reduces the junction temperature, and can positively influence the luminous radiation performances. An active cooling solution using liquid metal as the coolant was proposed for high power (LEDs) by Deng and Liu [12]. Besides, Xiaobing and Sheng [13] and Liu et al. [14] proposed a microjet array cooling system for thermal management of high-brightness LEDs demonstrating excellent performance.

On the other hand, several researchers [15–22] have recently proposed the vibrating fans (piezoelectric fans) as potential cooling technique on account of its compact size, low power consumption, noise-free operation and adaptability in small spaces. Piezoelectric fans are micro-vibrating machines used 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 surrounding flow.

Acikalin et al. [22] 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 considered different experimental configurations, and the effect of varying the fan amplitude, distance between the fan and heat source, 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 piezoelectric fans. They found that applying piezoelectric fan resulted in a temperature drop at the heat source by more than 36.4 °C.

Although, many researchers focused on the thermal and flow analysis of vibrating fans over a single heat source (single chip) in microelectronic applications, the thermal analysis of vibrating fan for cooling LED package (multi-chips) is still lacking in the literature. Only Acikalin et al. [22] experimentally investigated the thermal performance of single vibrating fan in context of LED. This calls for further investigations into the study of characteristic influence of multiple vibrating fans on the resulting heat transfer associated with LED heating.

Therefore, in this work the thermal behavior of LED array system cooled by means of piezoelectric fans is carried out. Experimental and numerical analysis on the thermal characterization of LED package under natural and forced convection conditions are explored. Furthermore, dual vibrating fans are vertically oriented to the LED package and arranged in two different ways namely: configuration A (for edge to edge arrangement), and configuration B (for face to face arrangement). Vibrometers (laser displacement sensors KEYENCE LK-G152) are employed to measure the vibration amplitude fans. 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. The thermal performance of the dual fans is compared relative to the single fan, and the estimated results are also compared with the experimental findings.