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# Development of a radial-flow multiple magnetically coupled fan system with one piezoelectric actuator

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## ABSTRACT

In recent years, piezoelectric fans and their feasibility for use in cooling electronic devices have been widely studied. However, there are few studies that address using a single piezoelectric actuator to generate radial air flow. In this study, a radial-flow multiple fan system (RMFS) was developed for the thermal management of high power LEDs. This system only used one piezoelectric actuator and a magnetic repulsive force to activate up to 20 fans, which featured low power consumption and a large cooling area. The RMFS was mounted in a circular heat sink to evaluate its thermal performance. To find the optimal design for the RMFS, the influence of some geometric parameters was investigated. The performance of different designs was compared with a commercially available axial fan. The results showed that design E had the best thermal performance among the designs because of its relatively large frequency and amplitude. The thermal resistance and percentage improvement under a 35 W heat flux were 0.86 K/W and 36.9%, respectively. In addition, a coefficient of performance (COP) was defined. The COP of design E was approximately 3.7 times that of the rotary fan. For the power consumption aspect, the RMFS is more efficient than the rotary fan.

## 1. Introduction

In recent years, light-emitting diodes (LEDs) have been used in many lighting devices because of their low power consumption and long life. With manufacturing process advancements, LED power levels have increased dramatically. Because the performance and the reliability of LEDs are highly dependent on the operating temperature, it is crucial for LEDs to dissipate waste heat [1–2]. A lower operating temperature leads to higher efficiency and longer life. Therefore, thermal management has become an important issue for high power LEDs. Typically, cooling technologies are categorized as passive or active. Passive cooling methods include a heat sink, a heat spreader or a heat pipe. Most of these methods likely have insufficient cooling capability for high power LEDs. Thus, it is necessary to use active cooling methods to maintain the operating temperature below a certain threshold. Among the active cooling methods, rotary fans are the most common means to remove waste heat. However, they might be unsuitable for high power LEDs due to their dust accumulation problem, high power consumption and high noise levels. To maintain good performance and a desirable lifetime for high power LEDs, alternative cooling technologies must be developed.

Cooling with a piezoelectric fan is a promising alternative method for use in LED thermal management because the piezoelectric fan features low power consumption, low cost, low noise and long life. These advantages are especially appropriate in high power LED applications. A piezoelectric fan is composed of a piezoelectric actuator and an extended blade. When an alternating current is imposed on the piezoelectric actuator, the piezoelectric fan deforms periodically by the piezoelectric effect. The piezoelectric fan can oscillate with large amplitude at its resonance frequency, thereby inducing significant air flow. The concept of a piezoelectric fan was first proposed by Toda [3–5]. The air flow was generated by a resonant vibrating cantilever structure, which featured maintenance-free operation with fairly low energy consumption. These characteristics make the piezoelectric fan viable for cooling some types of electronic devices. Kimber and Garimella [6] investigated the influence of some important parameters such as fan length, width, frequency, and amplitude. They suggested that the thermal performance was a little more dependent on frequency than amplitude. Acikailn et al. [7] studied different experimental configurations and several critical parameters of the miniature piezoelectric fan. In their best case, the heat transfer coefficient was 375% relative to the natural convection case. As a result, the temperature at the heat surface dropped more than 36.4 °C. They also indicated that frequency offset is a significant parameter to impact the thermal performance. A small frequency offset of 5% can decrease the cooling capability by more than 10 °C.

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## Nomenclature

| | |
|---|---|
| $A$ | amplitude of a fan (m) |
| $A_c$ | cross-sectional area of the copper slug (m$^2$) |
| $A_h$ | surface area of the heat sink (m$^2$) |
| $B_0$ | magnetic flux density (Tesla) |
| $d$ | distance between the centers of each magnet (m) |
| $E_c$ | Young's modulus of a carbon fiber plate (Pa) |
| $f_r$ | resonant frequency (Hz) |
| $Gr$ | Grashof number |
| $g$ | gravitational acceleration (m$^2$/s) |
| $H_h$ | height of the heat sink (m) |
| $h$ | convective heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $h_0$ | convective heat transfer coefficient under natural convection (W m$^{-2}$ K$^{-1}$) |
| $K_c$ | stiffness of a carbon fiber plate (N/m) |
| $K_{mag}$ | stiffness of the magnetic effect (N/m) |
| $k_a$ | thermal conductivity of the ambient air (W m$^{-1}$ K$^{-1}$) |
| $k_c$ | thermal conductivity of the copper slug (W m$^{-1}$ K$^{-1}$) |
| $L$ | distance between the thermocouples in the copper slug (m) |
| $L_c$ | length of a carbon fiber plate (m) |
| $L_f$ | characteristic length of a fan (m) |
| $m_c$ | mass of a carbon fiber plate (kg) |
| $m_{mag}$ | mass of a magnet (kg) |
| $N$ | the number of fans |
| $Q$ | heat flux through the heater (W) |
| $Q_r$ | resistive heat flux (W) |
| $R$ | thermal resistance (K/W) |
| $R_0$ | thermal resistance under natural convection (K/W) |
| $r_{mag}$ | radius of a magnet (m) |
| $T_a$ | temperature of the ambient air (°C) |
| $T_s$ | temperature of the heater surface (°C) |
| $\overline{T_h}$ | average surface temperature of the heat sink (°C) |
| $t_c$ | thickness of a carbon fiber plate (m) |
| $t_{mag}$ | thickness of a magnet (m) |
| $W$ | power consumption (W) |
| $W_c$ | width of a carbon fiber plate (m) |
| $W_m$ | width of a Mylar plate (m) |
| $\mu$ | permeability of air (H/m) |
| $\eta$ | percentage improvement of thermal resistance (%) |
| $\beta$ | thermal expansion coefficient of the ambient air (1/K) |
| $\nu_a$ | kinematic viscosity of the ambient air (m$^2$/s) |

Given that a single piezoelectric fan cannot provide sufficient flow to dissipate heat, a multiple piezoelectric fan system has been researched. Kimber and Garimella [8] used arrays of piezoelectric fans to cool a constant heat flux surface. Compared with a single fan, the area-averaged thermal performance of the fans at the optimal pitch was approximately 15% higher. Petroski et al. [9] examined a system of piezoelectric fans embedded in a heat sink. They proposed a volumetric coefficient of performance (COP) to assess the heat dissipating capacity. The COP of the fans' cooling system was up to five times greater than the COP under the natural convection condition. Sufian et al. [10] evaluated the thermal performance of an LED array system cooled by piezoelectric fans. The best performance decreased the thermal resistance of a single fan by 38%. In other research [11], they combined multiple piezoelectric fans and a heat sink to cool high power LEDs. Compared with natural convection, two fans enhanced the thermal performance by approximately 3.2 times, whereas four fans enhanced thermal performance by 3.8 times.

Although using multiple piezoelectric fans increases cooling capacity, power consumption and cost also increase. To address this problem, Ma et al. [12] developed a novel multiple fan system, which used only one piezoelectric actuator to drive the other passive fans. Permanent magnets were attached on the tips of the fans to magnetically couple each fan. When the piezoelectric fan was oscillating, the magnetic repulsive forces pushed adjacent passive fans and all the fans vibrated at the same time. The temperature drop of the heat sink can reach 17 °C with a power consumption of 0.03 W. The authors claim that the novel design can provide significant air flow without additional cost and power consumption. Further, they applied the multiple fan system to a pico projector [13]. The thermal resistance, the Nusselt number, and the Richardson number of their best model were 4.13 K/W, 81.25, and 0.018, respectively. Ma et al. [14] also proposed a dual-sided multiple fan system to cool two 30 W COB LED models. By using only one piezoelectric actuator, ten fans can vibrate simultaneously and generate air flow. In their study, a dimensionless heat convection number ($M_{D-MFPA}$) was defined to assess the thermal performance. The result showed that under the same power consumption, $M_{D-MFPA}$ was 3.92 for the dual-sided multiple fan system, but that of a single piezoelectric fan was only 2.82.

The feasibility of cooling with piezoelectric fans has been researched by many authors [15]. However, there are few studies addressing a multiple fan system which can produce radial air flow. Such a device is particularly aligned with thermal management of high power LEDs because LED lights are commonly circular with chips arranged radially. Therefore, a radial-flow multiple fan system (RMFS) was developed based on previous studies [12–14]. The system used only one piezoelectric actuator and the magnetic repulsive force to drive all the passive fans, which further reduced power consumption and provided a larger cooling area. During the experiments, the system was mounted inside a circular heat sink to evaluate its thermal performance. The influence of important parameters, such as the number of fans ($N$) and width of the carbon fiber plate ($W_c$), was investigated to find the optimal design. A comparison between a commercially available rotary fan and the RMFS was conducted under the same experimental setup.

## 2. Design and experimental setup

### 2.1. The radial-flow multiple fan system

As shown in Fig. 1, one of the fans was a piezoelectric actuator and the others were the carbon fiber plates that served as passive fans. The

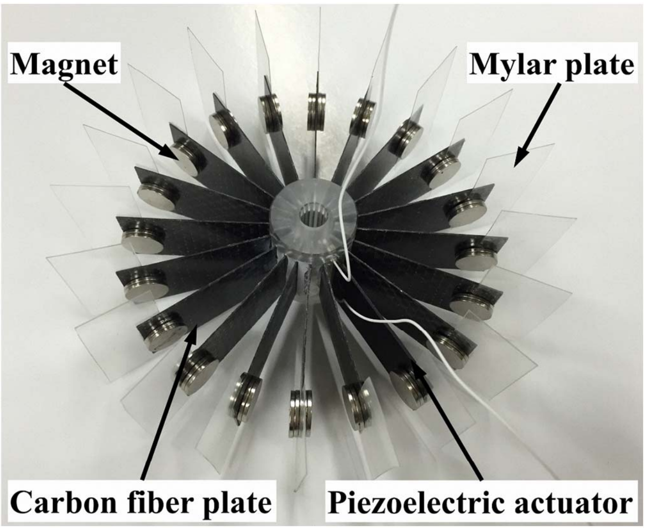

**Fig. 1.** Schematic view of the radial-flow multiple fan system with twenty fans.