ABSTRACT
This work experimentally investigated the fluid flow and heat transfer characteristics of specified finned heat sinks with the built-in piezoelectric fan and different configurations of flow-runner opens. Total three kinds of flow-runner opens were employed: the symmetrically lateral rectangular opens (Model A), the symmetrical lateral slot opens (Model B), as well as the bottom rectangular open (Model C) with/without bottom curved panel. The smoke flow visualization results indicate that various configurations of flow-runner opens resulted in different smoke flow fields. The Model C reduced the total thermal resistance by 10.4–21.3%; it was the optimal one to enhance cooling performance herein. The relevant results can be the base in designing such LED finned heat sink with a built-in piezoelectric fan.

KEYWORDS
Piezoelectric fan; finned heat sink; flow-runner opens; heat transfer; LED

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1. Introduction

The piezoelectric blade is a simple and low energy-consuming air flow-generating device. The ceramic piezoelectric patch cohering to the bottom plate covers the elastoplastic sheet to form a cantilever beam-like structure. When the voltage is imported, the back voltage effect of piezoelectric material results in high-frequency oscillation of piezoelectric chip, the plastic sheet swings up and down, driving nearby air fluid, generating permanent and stable axial air flow. The advantages of piezoelectric fan include low power consumption, compactness, and low noise, meeting various requirements of electronic product heat sinks.

In recent years, the piezoelectric blade for enhancing convection heat transfer has been studied by many scholars. Lin [1] discussed the heat transfer gain of piezoelectric blade for vertical cylinder surface. The piezoelectric blade was normal to the axial direction of cylinder, and the swing direction was the same as the radial direction of cylinder. The results indicated that the piezoelectric blade enhanced the heat transfer coefficient by 1.2–2.4 times. Ma et al. [2] indicated that the blade length, oscillation frequency, and blade amplitude influenced the effect of the forced air flow generated by piezoelectric blade strongly. They proposed a new type of cooling system combined with plate fin heat sink and piezoelectric blade, the piezoelectric blade was put between fins, the vibration direction of blade was normal to the fin surface, the generated oscillating airflow could damage the thermal boundary layer on the fin surface and enhance the forced convective cooling effectiveness of overall cooling system. The experimental and numerical simulation results indicated that the forced convection heat transfer coefficient generated by piezoelectric blade was 2.3 times of purely natural convection. Li et al. [3] used experimental method to discuss the heat flow characteristics of piezoelectric blade cooling plate fin heat sink. The piezoelectric blade was placed in the axial direction of fin, located in different positions of upper edge of heat sink. When the blade vibration direction was horizontal to the fin surface, the configuration of blade tip in the leading edge of heat sink had the best cooling effect, and the heat transfer gain of piezoelectric blade increased with the fin height. If the vibration direction of blade was normal to the fin surface, the heat sink with short fins had better heat transfer gain. The heat sinking of horizontal blade configuration was enhanced by increasing the spacing between fins; the influence on the heat transfer of vertical blade configuration was insignificant. Yu et al. [4] used numerical simulation to discuss the heat transfer gain of piezoelectric blade for finned heat sink. The piezoelectric blade was put vertically between two vertical plate fins, when the air flowed through the channel between two fins, the traverse motion of piezoelectric blade had transverse oscillation effect on the axial mainstream, which increased the overall heat transfer by 61%, and the increase in the blade oscillation frequency and amplitude could increase the heat transfer rate linearly. Abdullah et al. [5] observed the heat transfer enhancement effect of piezoelectric blade on the finned heat sink. Multiple piezoelectric blades were put between the fins of heat sink vertically or horizontally. The blades performed reciprocating oscillating motion horizontal to the fin surface. The vertical blade resulted in better heat transfer gain, the maximum heat transfer enhancement was 88% compared with natural convection. Ma et al. [6] designed a piezoelectric actuating system. Five blades could be oscillated synchronously by piezoelectric force and magnetic force. The five blades were put between the vertical plate fins in the axial direction of heat sink, performing oscillating motion normal to the fin surface. The results proved that the heat sink temperature was reduced by 17° only by consuming 0.03W. Shyu and Syu [7] designed a piezoelectric fan with four finger-like blades. The four blades could penetrate into the plate fin heat sink. The airflow generated by the oscillating motion of blades could enhance the overall heat transfer of heat sink effectively. Lin [8] indicated when the cylinder was put in forced convection; the surface heat transfer was very bad in the eddy zone of leeward. Therefore, he put a piezoelectric blade on the leeward side of cylinder; the cylinder surface heat transfer in the zone was enhanced by the oscillating airflow generated by the piezoelectric blade. The numerical and experimental results indicated that the quasi-jet flow generated by the piezoelectric blade interacted on the natural convection on cylinder heating surface and the vortices of mainstream, and the overall heat transfer was enhanced by at most 132%, the local heat transfer on the leeward side was enhanced by at most 214%. However, in the specification and position of the piezoelectric blade, if the mainstream Reynolds number exceeded 2200, the quasi-jet flow generated by the piezoelectric blade reduced the overall heat transfer of cylinder on the contrary. Jeng and Liu [9] used experimental method to discuss the effect of piezoelectric blade on the heat transfer of pin-fin heat sink with axial air flow in the channel. The piezoelectric blade was put in the front edge of heat sink. The experimental results showed in comparison to axial oscillating motion that the heat transfer gain proportion of transverse oscillation of piezoelectric blade was slightly higher. The heat transfer performance of different heat sinks was influenced by the piezoelectric blade to different extents. The oscillation of mainstream resulted from the piezoelectric blade swing increased the heat transfer of finned heat sink by at most two times. Fairuz et al. [10] used 3D numerical calculation to discuss
in different piezoelectric blade shapes, the effect of oscillation frequency and blade amplitude on the heat transfer characteristics. Ma et al. [11] built a cooling system which used piezoelectric magnetic force as vibration source to drive multiple piezoelectric blades. They proved that the thermal resistance of multi-piezoelectric electromagnetic fan system was only 76.7% of that in natural convection state. Sufian et al. [12] numerically simulated the heat transfer behavior of printed circuit board welded LED lamp array under the air flow driven by piezoelectric blade. The results indicated that one piezoelectric blade enhanced by heat transfer by 1.8 times, two piezoelectric blades enhanced the heat transfer by 2.3–2.4 times. Ma et al. [13] designed a casing to collect the air flow generated by multiple piezoelectric blades. The experimental results proved that the geometry of this casing really influenced the air velocity generated by multiple piezoelectric blades and the finned heat sink cooling performance. The piezoelectric blade is used for cooling heating surface and enhancing heat transfer of finned heat sink. However, the piezoelectric blade is mostly mounted outside the finned heat sink or between fins, the piezoelectric blade is mounted in the chamber inside the finned heat sink in this study, and a ventilation opening is designed for the air flow driven by the piezoelectric blade to flow out of the chamber (Figure 1). This type of application to heat transfer enhancement is scarce.

The aforesaid design is especially applicable to the conditions where the piezoelectric blade must be hidden, for example, to LED lamp heat sinking. This study uses experimental method to discuss the flow field and thermal resistance characteristics of the finned heat sinks with different ventilation opening configurations. There are three kinds of opening configuration: Model A — symmetric side opening rectangular double opening, Model B — symmetric side opening gap four opening, Model C — bottom opening rectangular single opening with/without air guide curved plate, the ventilation opening configuration sizes of finned heat

2. Experimental method

This study built appropriate heat transfer measuring system and test section, as shown in Figure 2. The experimental system consists of three parts, which are the thermal supply system, the test section, and the data acquisition system. In terms of the thermal supply system, a stainless steel film heating plate in diameter of 40 mm is pasted with heat conducting gel on the base made of low thermal conductivity Bakelite in the same diameter and in height of 55 mm. The DC supplier supplies electroheat to the heating plate to replace the waste heat from LED lamp panel. Two sets of Bakelite heating base are shown in Figure 3(a), stuck to both sides of heat sink test section symmetrically. The configuration dimensions of Bakelite heating base and heat sink test section are shown in Figure 3(b) and (c), respectively. The heat sink is made of aluminum alloy. Its basic configuration is a hollow rectangular chamber with two parallel plate fins on both sides. A piezoelectric blade is embedded in the heat sink to drive air flow, and a ventilation opening is designed for the air driven by the piezoelectric blade to flow out of the chamber. The photo and size of piezoelectric blade are shown in Figure 4. The RFN1-005 piezoelectric blade made by U.S. Piezo System Inc. is used. The power consumption is 30mW, the blade oscillation frequency is 60Hz, and the maximum air output is 2CFM. There are three opening configurations of heat sink: Model A symmetric side opening rectangular double opening, Model B symmetric side opening gap four opening, Model C bottom opening rectangular single opening with/without air guide curved plate, the ventilation opening configuration sizes of finned heat sink.
disturbing the accuracy of heat transfer experiment, all the tests are implemented in a 10-mm thick acrylic sheet confined space (400 × 400 × 300 mm). The temperature change within 0.2 °C within 15 min is identified as steady state temperature. Finally, the data are transferred to the computer for software monitoring and storage for subsequent parametric analysis and calculation.

An appropriate smoke flow field observation system is built in this study, as shown in Figure 6. One side of heat sink are shown in Figure 5. The data acquisition system uses 14 TT-T-30SLE T-type high-accuracy thermocouple wires for discharge balling, through two Bakelite heating bases and mounted on the back side of heating plate. There are other two thermocouples for measuring the ambient temperature. The thermocouples detect the micro voltage signal derived from temperature change. The data logger measures and converts the voltage signal into temperature value. In order to avoid the external environment disturbing the accuracy of heat transfer experiment, all the tests are implemented in a 10-mm thick acrylic sheet confined space (400 × 400 × 300 mm). The temperature change within 0.2 °C within 15 min is identified as steady state temperature. Finally, the data are transferred to the computer for software monitoring and storage for subsequent parametric analysis and calculation.

Figure 3. Configuration and dimensions of test section.
where \( T_w \) is the average temperature of heating surface, \( T_0 \) is the ambient temperature, \( Q_t \) is the total electric power imported into heating surface, \( Q_{\text{Loss}} \) is the heat loss. The heat loss (\( Q_{\text{Loss}} \)) can be estimated by the experiment on natural convection heat transfer of horizontal heated plate. In this experiment, the total electric power (\( Q_t \)) exported from DC power supply to the heating plate was dissipated in two parts: (1) natural convection heat via heated plate convection surface (\( Q_{\text{plate}} \)) and (2) heat loss (\( Q_{\text{Loss}} \)) transferred by Bakelite base on back side of heating plate.

\[
R = \frac{T_w - T_0}{Q_t - Q_{\text{Loss}}}
\]

(1)

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\[
Q_{\text{Loss}} = h_{\text{Loss}} \cdot A \cdot (T_w - T_0) = Q_t - Q_{\text{nc}} = (I \cdot V) - h_{\text{plate}} \cdot A \cdot (T_w - T_0)
\]

(2)
where \( V \) is the voltage imported into heating surface, \( I \) is the input current, \( A \) is the heating area, \( T_0 \) is the ambient temperature, \( h_{\text{plate}} \) is the natural convection heat transfer coefficient between cold air and vertical heated plate. This paper cites the empirical equations proposed by Ellison [14]:

\[
h_{\text{plate}} = 1.485 \left( \frac{T_w - T_0}{D/4} \right)^{0.25}
\]  (3)

In the experiment on heat loss in natural convection, importing different gross heating values (\( Q_t \)) into the heating plate resulted in different wall temperature and ambient temperature differences \( \Delta T \). The corresponding lost heat transfer coefficient (\( h_{\text{loss}} \)) can be derived from Equations (2) and (3), substituted in Equation (1) to obtain the total thermal resistance (\( R \)), so as to analyze the effect of the cancelation effect and enhancement effect between forced convection and natural convection in the mixed convection condition on the heat transfer characteristics of piezoelectric fan jet.

The experimental uncertainty was analyzed according to the uncertainty of single test of Moffat [15]. The total thermal resistance (\( R \)) and temperature \( (T) \) of this experiment were ±5.7% & ±2.4%, respectively.

### 3. Results and discussion

Figures 8–11 show the smoke flow field observations of four ventilation opening configurations, including Model A symmetric side opening rectangular double opening, Model B symmetric side opening gap four opening, Model C bottom opening, and Model C without bottom curve plate.

![Figure 7. Photos of test specimens for smoke flow visualization.](image)

![Figure 8. Flow visualizations of Model A with symmetrically lateral rectangular opens.](image)
According to Figures 7 and 8, when the piezoelectric blade is not actuated, the incense stick smoke trace of Model A shows a different path compared to when it is actuated.

**Figure 9.** Flow visualizations of Model B with symmetrically lateral slot opens.

**Figure 10.** Flow visualizations of Model C without flow-guiding curved panel.

**Figure 11.** Flow visualizations of Model C with flow-guiding curved panel.

**Figure 12.** Relationship between the total thermal resistance and the temperature difference.

rectangular single opening with air guide curved plate. According to Figures 7 and 8, when the piezoelectric blade is not actuated, the incense stick smoke trace of Model A
and Model B rises upward stably and integrally through the channel between fins. However, when the piezoelectric blade is actuated, the incense stick smoke trace of Model A and Model B is disordered by the transverse air flow generated by the piezoelectric blade, but the disordered smoke trace of Model A rises upward in general, the disordered smoke trace of Model B basically moves outward horizontally. According to Figures 9 and 10, when the piezoelectric blade is not actuated, the incense stick smoke trace of the bottom opening rectangular single opening without/with air guide curved plate rises from the lower opening into the chamber of heat sink, and then escapes downward along both sides of the opening and forms an eddy near both sides at the bottom. In the Model C configuration with air guide curved plate, under the guidance of air guide curved plate, the air flow rises stably and integrally through the channel between fins. However, when the piezoelectric blade is actuated, the incense stick smoke trace of the Model C configuration without air guide curved plate is disordered completely by the downward air from the piezoelectric blade. As for the Model C configuration with air guide curved plate, the smoke generated by the incense stick is driven by the downward air flow generated by the piezoelectric blade rapidly, and flows between fins along both sides of air guide curved plate and the gaps of heat sink, so there are a lot of disordered smoke traces rising upward among fins. Therefore, the embedded piezoelectric blade can drive air flow and disturb the originally stable incense stick smoke trace, and different opening configurations result in very different smoke flow field characteristics.

Figure 12 shows the relation between overall thermal resistance ($R$) of heat sink of various configurations and temperature difference ($\Delta T = T_w - T_0$). The control group is Model A without piezoelectric blade, the control group is Model A and Model B with piezoelectric blade actuation and Model C configuration with air guide curved plate. The results show that the $R$ value of Model A is lower than control group by 5.2–9.8%, the $R$ value of Model B is lower than control group by 4.4–7.8%, the $R$ value of Model C is lower than control group by 10.4–21.3%. The Model C reduces overall thermal resistance significantly, especially Model C with air guide curved plate, because the downward air generated by the piezoelectric blade takes the heat away from the chamber, and the air and natural convection form additive effect when it flows between fins along both sides of air guide curved plate and the gaps of heat sink. As for Model A and Model B, the smoke flow field observations show that the piezoelectric blade can drive air flow and disturb the original flow field, that should be helpful to heat transfer. However, as the ventilation opening is on the side, the air flow driven by the piezoelectric blade is opposite to the natural convection direction when it leaves the outlet, and the opening cross section area of the two models is much smaller than that of Model C. This explains why the ability of Model A and Model B to reduce overall thermal resistance is worse than Model C.

4. Conclusions

The piezoelectric blade is embedded in the chamber inside the finned heat sink. A ventilation opening is designed for the air driven by the piezoelectric blade to flow out of the chamber. The aforesaid design is especially applicable to the conditions where the piezoelectric blade must be hidden, for example, to LED lamp heat sinking. This study uses experimental method to discuss the flow field and thermal resistance characteristics of finned heat sink with different ventilation opening configurations. The results prove that the piezoelectric blade can drive air flow and disturb the original flow field, and the present heat sink of bottom opening rectangular single opening configuration with air guide curved plate can reduce the overall thermal resistance by 10.4–21.3%. Our future study will design the opening location and opening section size leading to the maximum heat transfer gain based on the flow field observations.

Nomenclature

- $A$: surface area of film heater ($\text{m}^2$)
- $D$: diameter of heating surface
- $I$: electrical current ($\text{I}$)
- $R$: thermal resistance ($\text{°C}/\text{W}$)
- $T_0$: temperature of the ambient ($\text{°C}$)
- $T_w$: average temperature of the heating wall ($\text{°C}$)
- $V$: electrical voltage ($\text{V}$)
- $Q_t$: total input power ($\text{W}$)
- $Q_{\text{Loss}}$: heat loss ($\text{W}$)

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