THERMAL PERFORMANCE OF VERTICAL HEAT SINKS WITH DIFFERENT PIEZOFAN ARRANGEMENTS

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ABSTRACT
This study examines various effects on the heat transfer enhancement of several vertical heat sinks with a running piezofan. Both plate-fin heat sink and pin-fin heat sink having a 10-mm-high or 30-mm-high fin array were tested with either a vertical or a horizontal piezofan. Results show that the piezofan tip located at $x/L = 0.5$ usually yielded the highest heat transfer enhancement. Besides, heat transfer enhancement factors ranged from 1.2 to 2.4 for the present 10-mm-high plate-fin heat sink, and from 1.1 to 2.6 for the 10-mm-high pin-fin heat sink.

Keywords: thermal; piezofan; Mylar; heat sink; arrangement.

PERFORMANCE THERMIQUE DE PUITS DE CHALEUR VERTICAUX AVEC DIFFÉRENTS ARRANGEMENTS DE PIEZO-VENTILATEURS

RÉSUMÉ
Cette étude examine les différents effets de l'augmentation du transfert thermique de quelques puits de chaleur verticaux munis d'un piezo-ventilateur. Les échangeurs thermiques à ailettes en plaque et les dissipateurs de chaleur à ailettes ayant 10-mm de hauteur ou 30-mm de hauteur d'aire de surface ont été testés avec un piezo-ventilateur vertical ou horizontal. Les résultats montrent que la pointe du piezo-ventilateur situé à $x/L = 0.5$ produit habituellement un transfert de chaleur plus élevé de l'ordre de 1.2 à 2.4 pour l'actuel échangeur thermique à ailette de 10-mm de hauteur, et de 1.1 à 2.6 pour le dissipateur de chaleur.

Mots-clés : thermique ; piezo-ventilateur ; puits de chaleur ; arrangement.

NOMENCLATURE

A_0	total surface area of heat sink (m^2)
$\bar{h}$	average heat transfer coefficient (W/m^2K)
Q_c	convective heat transfer rate (W)
T_a	ambient temperature (°C)
T_b	average base temperature of heat sink (°C)
Greek symbols	
η_0	overall fin efficiency
ξ	heat transfer enhancement factor
Subscripts	
n	natural convection
pf	piezofan

1. INTRODUCTION

A piezofan, which induces air flow by oscillating a flexible cantilever blade bound together with the piezoelectric patch operated at a certain resonant frequency, has received increasing attention in the application of cooling portable electronic devices due to numerous advantages, such as its absence of noise, low power consumption, and, above all, small volume. Beginning with Toda's work [1, 2], over 25 years of analytical and experimental work have resulted in numerous patents for piezofan applications.

Acikalin et al. [3] conducted a flow visualization experiment to understand the physics of piezofan operation. An enclosure to simulate a cellular phone and a commercially available laptop computer were used to demonstrate the cooling feasibility of such fans. They found that piezofans offered an enhancement in convective heat transfer coefficients of 100%.

Kimber et al. [4] measured the local heat transfer coefficients induced by piezofans for a fan vibrating close to an electrically heated stainless steel foil, and observed the entire temperature field by means of an infrared camera. Three distinct two-dimensional contours of the local heat transfer coefficient were shown in their experiment, depending on the distance between the fan tip and the heated surface. They also developed correlations with appropriate definitions of Reynolds and Nusselt numbers to estimate the area-averaged thermal performance.

Acikalin et al. [5] considered various effects to assess the cooling potential of piezofans. A design of experiments (DOE) analysis revealed the critical parameters to be the fan frequency offset from resonance and the fan amplitude. In the best case, an enhancement in convective heat transfer coefficient exceeding 375% relative to natural convection was observed. Effects of the flow on convection heat transfer for different fan-to-heat source distances and boundary conditions were analyzed.

Kimber and Garimella [6] investigated the heat transfer achieved using piezofan arrays vibrating in their first resonant mode. The convection patterns observed were strongly dependent on the fan pitch. Correlations were developed to describe this enhancement in terms of several governing parameters. The best thermal performance was obtained when the fan pitch was 1.5 times its vibration amplitude.

Kimber and Garimella [7] investigated the influence of each piezofan operational parameter and its relative impact on thermal performance. Of particular interest are the vibration frequency and amplitude, as well as the geometry of the vibrating cantilever beam. With a piezofan mounted normal to a constant heat flux surface, temperature contours on the surface, captured with an infrared camera, were used to determine the forced convection coefficient due to the fluid motion generated from the fan. Results showed that the performance of the fans was maximized at a particular value of the gap between the fan tip and the heated surface. It was found that when a fan operates at this optimum gap, the heat transfer rate is dependent only on the frequency and amplitude of oscillation. Correlations based on appropriately defined dimensionless parameters were developed and found to successfully predict thermal performance across the entire range of fan dimensions, vibration frequency, and amplitude.

Liu et al. [8] examined the influence of geometric parameters, including horizontal/vertical arrangement and location of the piezofan, on the thermal performance of piezofans on a flat plate. They found that the heat transfer augmentation of the piezofan comes from the entrained airflow during each oscillation cycle and the jet-like air stream at the fan tip, yet these two modes are of the same order of magnitude. The heat transfer performance for vertical arrangement shows a symmetrical distribution and peaks at the center region, whereas the horizontal arrangement possesses an asymmetrical distribution and shows an early peak at $x/L = 0.25$.

Abdullah et al. [9] investigated the cooling capability of a horizontally oriented piezofan for two inline arranged heat sources by both numerical and experimental analyses. The flow measurements were carried out at different piezofan heights by using a PIV system. They reported that the height of a vibrating piezofan of $hp/lp = 0.23$ could reduce the temperature of the heat source surface by as much as 68.9°C.

Petroski et al. [10] proposed a cooling system incorporating piezofans with a heat sink as a more efficient cooling system. The heat sink not only provides surface area but also shapes the flow for the unusual 3-D flow field driven by the piezofans. Their results demonstrated a cooling capability of 1 °C/W over an area of about 75 cm^2. They reported that the COPv of a piezofan-heat sink system was five times higher than that of a similar heat sink under natural convection. A 3-D flow field of the proposed cooling scheme with a piezofan was obtained with a flow visualization method. Velocities at the heat sink on the order of 1.5 m/s were achieved through this critical shaping. Finally, the overall system characterization of different heat loads and fan amplitudes was also discussed.

Although so many studies have been conducted to investigate the heat transfer of piezofans with a cantilever normal to a heated flat plate, few studies have examined the thermal performance of heat sinks with piezofans with a cantilever parallel to a heated flat plate. A vibrating piezofan with a cantilever parallel to the heat source could be a more space-saving design for cooling electronics. Therefore, the objective of this study is to investigate the effects of different piezofan arrangements and locations on heat transfer enhancement of commonly used plate-fin and pin-fin heat sinks with two different fin heights, 10 mm and 30 mm, at two fan heights, 12 mm and 16 mm.

2. EXPERIMENT

The experimental setup consisted of a signal generator, an amplifier, an oscilloscope, and a test heat sink, as well as a piezofan, as shown in Fig. 1. The piezofan was fabricated by bonding a commercially available 30-mm-long and 12-mm-wide piezoelectric patch (Piezo Systems, Inc.) to a 0.18-mm-thick, 70-mm-long, and 12-mm-wide Mylar blade for testing. A signal generator (Picotest G5100A) was used to provide a sine wave of a specified frequency for the amplifier (Piezomechanik Gmbh SVR500-3) to generate a 50-V voltage for both the oscilloscope (Tektronix TDS10001B) and the piezofan.

Two plate-fin heat sinks with 11 plates and two pin-fin heat sinks with 10 × 10 pins, shown in Fig. 2(a), were tested. Each heat sink is made of aluminum alloy 6061, which has a thermal conductivity of 170 W/mK. Each has a 2-mm-thick base, on which are mounted 30-mm-high or 10-mm-high fins. The base area of those heat sinks is 45 mm × 45 mm, and each has five thermocouples beneath the base plate. A 45 mm × 45 mm Kapton heater, powered by a DC power supply (Gwinstek GPS-3030DD), was placed below the heat sink to eliminate the spreading resistance. In the present study, the distance between static piezofan and fin tip, denoted as fan height, was fixed at either 12 mm or 16 mm. Five fan positions relative to the heat source, denoted as x/L = 0, 0.25, 0.5, 0.75 and 1, with either a vertical or a horizontal running piezofan, were tested, as shown in Fig. 2(b).

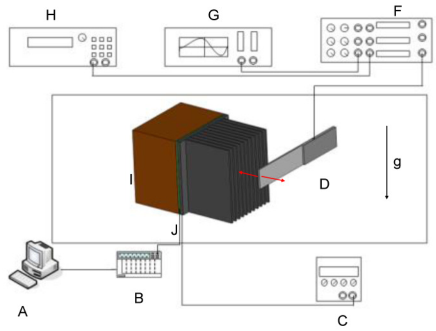

Fig. 1. The present experimental setup having (a) a vertical piezofan, and (b) a horizontal piezofan on a tested heat sink; the red arrow indicates the piezofan vibration direction, and the black arrow indicates gravity.

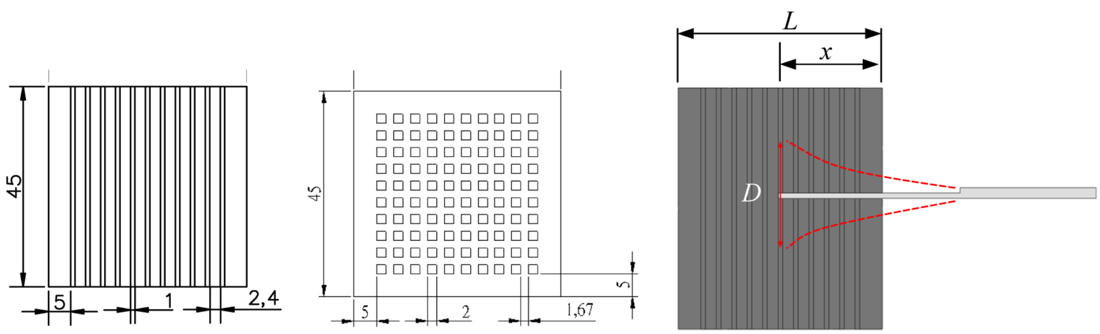

Fig. 2. Schematic diagrams of (a) present plate-fin heat sink having 11 plates and pin-fin heat sink having 100 square pins, (b) a piezofan having horizontal vibration over a heat sink and the definition of both x and L.

In order to maintain a constant and uniform ambient temperature within quiescent air during the experiment, all tests were performed inside an environmental chamber having a volume of 0.86 m (L) $\times$ 0.86 m (W) $\times$ 1.16 m (H). To simulate the natural flow condition, no air ventilator was used, in order to maintain a constant ambient temperature of 30 °C with a controlled resolution of 0.2°C during the experiment. An insulation box made of Bakelite with a low thermal conductivity of 0.44 W/mK was placed beneath the heater to reduce the conduction heat loss. In addition, thermal grease of high thermal conductivity (2.1 W/mK) was used to connect the heat sink and the heater. Several T-type thermocouples were inserted into the insulation base below the test heat sink for estimation of both conduction heat loss and average heat transfer coefficient.

The average heat transfer coefficient can be calculated as follows:

$$\bar{h} = \frac{Q_c}{A_0 \eta_o (T_b - T_a)} \tag{1}$$

where Q_c is convective heat transfer rate obtained by subtracting conduction heat loss and radiation heat transfer from the input power of 3 W; η_0 is the overall fin efficiency; A_0 denotes total exposed surface area of the heat sink; and T_b and T_a are the average temperature over heat sink base and the ambient temperature, respectively.

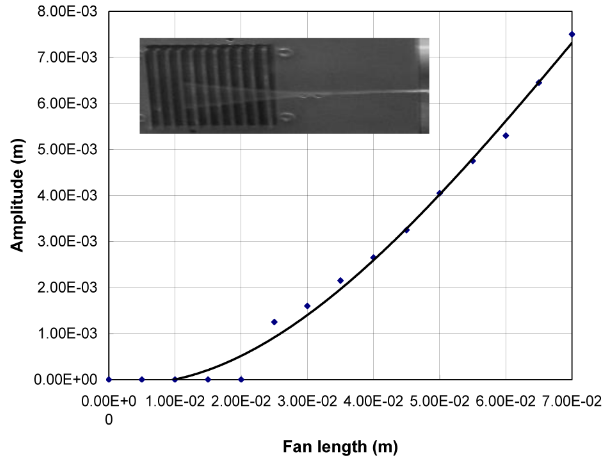

Fig. 3. Displacement of the present 70-mm-long vibrating piezofan at different positions operated at resonant frequency.

Alternatively, the heat transfer enhancement factor with the presence of a piezofan relative to that without a piezofan, is defined as follows:

$$\xi = \frac{\bar{h}_{pf}}{\bar{h}_n} \tag{2}$$

where subscripts pf and n denote the heat transfer coefficient obtained under a running piezofan and under natural convection conditions, respectively.

3. RESULTS AND DISCUSSION

The photo in Fig. 3 shows the present piezofan running on a plate-fin heat sink. The amplitude of the present 70-mm-long piezofan at different positions is also reported in Fig. 3. Note that the mean-to-peak amplitude is defined as the tip displacement from the farthest fan deflection to its static position, namely $D/2$ in Fig. 2(b). It can be found that the mean-to-peak amplitude of the present fan is about 7.2 mm at the fan tip when the fan operates at its resonance frequency, 31 Hz. The fan amplitude, which is a major factor that influences induced air flow rate and air velocity, depends on the properties of the fan blade material, blade size, voltage, and so on.

For purposes of comparison, test results, in terms of Nusselt number for the present 30-mm-high vertical plate-fin heat sink under natural convection condition at various input powers, are compared with those estimated by the correlation proposed by van de Pol and Tierney [11] in Fig. 4. The satisfactory agreement between measurements and the correlation substantiates the reliability of the present measured data based on the test system.

Figure 5 shows a comparison of heat transfer enhancement factor, ξ, due to a vertical-running piezofan between two different kinds of heat sink, having fin heights of either 10 mm or 30 mm. It can be found that the enhancement factor by a vertical running piezofan of a heat sink having longer fins is less than that of a heat sink having shorter fins. In addition, for heat a sink having longer fins, the difference in heat transfer enhancement between plate-fin heat sink and pin-fin heat sink by a vibrating piezofan is slight in Fig. 5 at various fan locations. For a heat sink having shorter fins, the heat transfer of the pin-fin heat sink can be enhanced more than that of the plate-fin heat sink. A logical explanation is that the longer fin array partially blocks the airflow induced by a vibrating piezofan from being blown into the array, thus reducing the heat transfer enhancement.

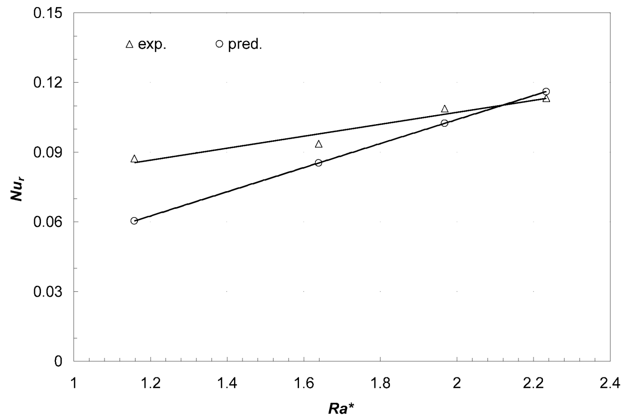

Fig. 4. Comparison of natural convection heat transfer of 10-mm-high plate-fin heat sink between the present measurement and the calculated value by the correlation proposed by Van De Pol and Tierney.

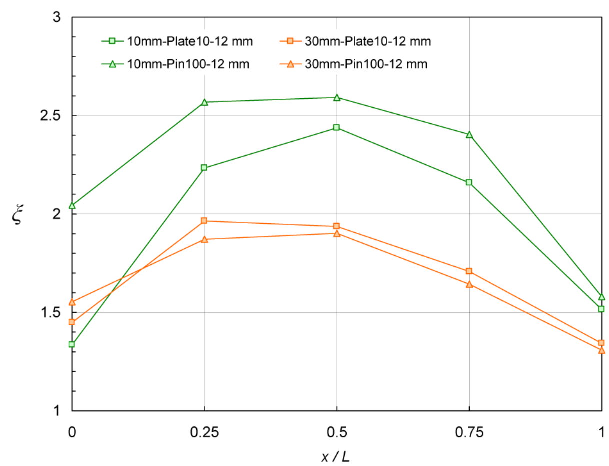

Fig. 5. Heat transfer enhancement of 10-mm-high and 30-mm-high heat sinks with a vertical piezofan at various fan positions.

In terms of heat transfer enhancement factor, the corresponding thermal performances of the 10-mm-high plate-fin heat sink and the 10-mm-high pin-fin heat sink at various dimensionless piezofan locations, x/L, are shown in Figs. 6 and 7. It can be found in Figs. 6 and 7 that different fan locations resulted in different amounts of heat transfer enhancement for the piezofan with either vertical or horizontal vibration. The heat transfer of a 10-mm-high plate-fin heat sink with a piezofan at $x/L = 0.5$ was enhanced by a factor ranging from 1.7 to 2.4, as shown in Fig. 6, while the heat transfer enhancement factor of a 10-mm-high pin-fin heat sink ranged from 1.9 to 2.6 in similar conditions, as shown in Fig. 7. In addition, a higher fan height usually enhanced heat transfer less, as shown in Figs. 6 and 7.

The fan with a vertical arrangement enhanced heat transfer more greatly than did the horizontal-running piezofan, as shown in Figs. 6 and 7. It could be that, besides the entrained airflow, the jet-like flow ejecting from the piezofan tip [8, 12, 13] also penetrates into the fin array as the piezofan tip deflects toward the heat sink. However, horizontal piezofan oscillation above a heat sink mainly provides the heat sink with entrained air flow.

Similar to the heat transfer results on a flat plate proposed by Liu et al. [8], the fan locations providing the greatest heat transfer enhancement of the present plate-fin and pin-fin heat sinks occurred either at x/L

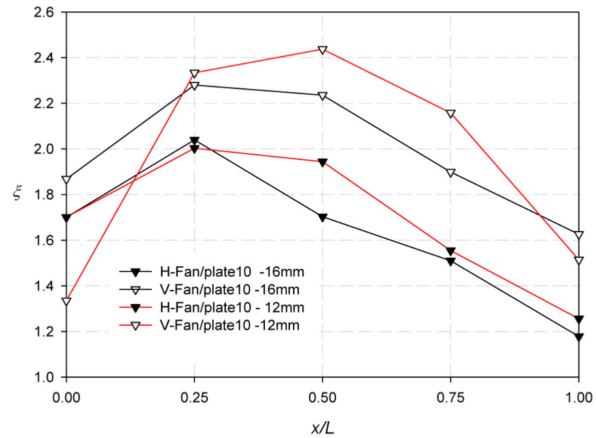

Fig. 6. Heat transfer enhancement by vertical and horizontal piezofans of the present 10-mm-high plate-fin heat sink with fan heights of 12 mm and 16 mm.

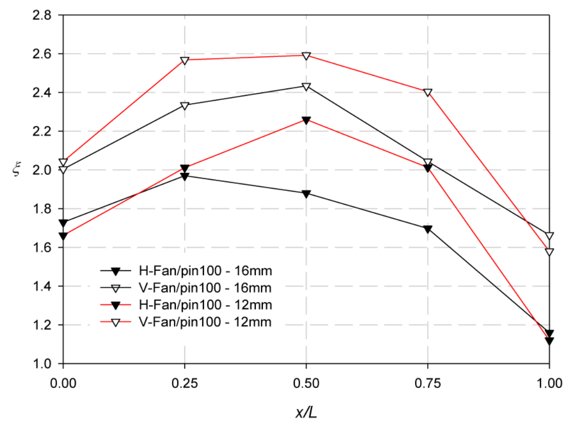

Fig. 7. Heat transfer enhancement by vertical and horizontal piezofans of the present 10-mm-high pin-fin heat sink with fan heights of 12 mm and 16 mm.

= 0.5 or at x/L = 0.25, while the least heat transfer enhancements, in Figs. 6 and 7, usually occurred at x/L = 1. One of the major causes of differences in heat transfer enhancement for both vertical and horizontal fan arrangements at different positions would be the differences in air flow over the heat sink induced by the piezofan. Since the one of the major air streams induced by a running piezofan is a jet-like flow originating from the fan tip, the airflow rate that can effectively cool the heat sink is reduced as x/L increases. Consequently, the vibrating piezofan with a fan tip located at $x/L > 0.5$ showed a dramatic reduction in heat transfer enhancement in both Figs. 6 and 7. The lowest heat transfer enhancement was 1.1 at $x/L = 1$, for a horizontal piezofan vibrating above a 10-mm-high pin-fin heat sink. With a running piezofan, the discrete fins in a pin-fin heat sink lead to less constraint on the airflow. Thus the airflow induced by a piezofan is able to pass over a pin-fin heat sink more freely than it can over a plate-fin heat sink.

4. CONCLUSIONS

The objective of this study was to examine various effects of piezofan height, arrangement, and location on heat transfer enhancement of two typical types of heat sink, namely plate-fin and pin-fin heat sinks. Both 10-mm-high and 30-mm-high heat sinks having 11 plate-fins and 100 square pin-fins were tested with a running 12-mm-wide and 70-mm-long piezofan having a Mylar blade. The influence of piezofan position and arrangement on the thermal performance of four vertical heat sinks was investigated. The heat transfer coefficients were measured with either a vertical running piezofan or a horizontal running piezofan located at five different locations with distances of 12 mm or 16 mm above the fin tip. The tip of the present piezofan had a mean-to-peak amplitude of 7.2 mm at its resonant frequency, 31 Hz. The following results are concluded based on the foregoing discussions:

1. The heat transfer enhancement factor by a running piezofan of a heat sink having longer fins is usually less than that of a heat sink having shorter fins.

2. The piezofan with a vertical arrangement enhanced heat transfer more than did that with a horizontal arrangement in the present study.

3. For a given heat sink, a piezofan located at $x/L = 0.5$ has the highest heat transfer enhancement factor, while a piezofan located at $x/L = 1$ has the worst heat transfer enhancement factor.

4. At $x/L = 0.5$, the heat transfer of a 10-mm-high plate-fin heat sink with a piezofan can be enhanced by a factor ranging from 1.7 to 2.4, while the heat transfer of a 10-mm-high pin-fin heat sink can be enhanced by 1.9 to 2.6 in similar conditions.

5. A vibrating piezofan with fan tip located at $x/L > 0.5$ showed a dramatic reduction in heat transfer enhancement.

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