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Thermal performance of plate-fin heat sinks with piezoelectric cooling fan

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ABSTRACT

An experimental method was used to study the thermal-fluid characteristics of plate-fin heat sinks cooled by a piezoelectric fan. The fan configuration, the fan location, and the heat sink dimensions were evaluated in terms of effects on thermal resistance. The experimental results show that, when the piezoelectric fan is vertical, thermal performance is the best with the tip of the fan blade at the center of the heat sink. When the piezoelectric fan is horizontal, thermal performance is the best with the tip of the fan blade at the front edge of the heat sink. In most cases, a vertical piezoelectric fan performs best with low fin heights. When the piezoelectric fan is horizontal, the thermal performance enhances as the fin height increases for three-fin heat sinks. For two-fin heat sinks, however, the correlation with fin height depends on the fin width. Heat transfer efficiency does not increase with fin width when the piezoelectric fan is vertical. However, thermal resistance usually decreases with fin width when the piezoelectric fan is horizontal.

1. Introduction

Rapid advances in MEMS manufacturing process have enabled reductions in the sizes of electronic products such as laptops, mobile phones, PDAs and GPS devices. As a result, heat flux continues to increase during the running period because the power requirements of electronic components continues to increase even as their size decreases. To ensure that electronic products can operate stably at high heat fluxes without diminished life expectancy, the size of the cooling system must be decreased, and the efficiency must be increased.

Development of the underlying theory and applications of piezoelectric materials has continued for the past 100 years. These materials are widely used for actuator and sensor components because they have both electrical and mechanical characteristics. However, their use for cooling is a relatively new application. Advantages of piezoelectric fans include their light weight, small volume, low energy consumption, low noise, and long life expectancy. They can be manufactured in sizes small enough to cool microelectronic components. Some researchers have begun studying the potential applications of piezoelectric fans for heat transfer.

Acikalin et al. [1] reported that piezoelectric fans are a feasible technology for cooling electronic devices because of their small size, low noise, and low energy consumption. Piezoelectric fans are also easily machined and easily installed in cooling system. Although piezoelectric fans cannot replace rotary fans currently used for heat transfer, they can provide even better cooling performance in high temperature areas or in areas where rotary fans are inefficient. This study used flow visualization technique to analyze the flow field distribution of a piezoelectric fan and evaluated the use of this technology for cooling mobile phones and laptops.

Wait et al. [2] simulated and measured the flows of piezoelectric fans with three different blade lengths to compare the effects of different resonance frequencies on flow field and energy consumption. Their simulation and experimental results showed that, although a high resonance frequency improves heat exchange by providing the complex flow field needed for sufficient mixing of the cooling fluid, it also increases energy consumption. Mobile electronic devices focus a lot on the consumption of electric energy. Therefore, a piezoelectric fan for mobile electronic devices requires an appropriate resonance frequency.

Abdullah et al. [3] numerically and experimentally investigated the effects of piezoelectric fan height on fluid flow and heat transfer for electronic cooling application. Two different heights of the piezoelectric fan are set up above the heat source. Numerical comparisons showed that the piezoelectric fan farthest from the heat source conferred the best heat transfer effect and lowered the heat source temperature by 68.9 °C.

Kimber et al. [4] used infrared thermography to perform experiments. The experiments are performed by placing a stainless steel sheet in front of a piezoelectric fan. Different vibration amplitudes of the piezoelectric fan and different distances between the fan and the stainless steel sheet are compared to determine their effects on heat transfer. The comparison results indicate that the best dis-

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Nomenclature

A	cross-sectional area of heating element (mm^2)	R_{th}	thermal resistance (°C/W)
A_t	heat transfer area of heat sink (mm^2)	T_{ave}	average temperature of top surface of heat sink base plate (°C)
b	thickness of base of heat sink (mm)	T_l	temperature of lower measuring point in heating element (°C)
d	distance between the measuring points in heating element (mm)	T_u	temperature of upper measuring point in heating element (°C)
G	inter-fin spacing (mm)	T_∞	temperature of cooling air (°C)
H	fin height (mm)	U	overall heat transfer coefficient (W/°C mm^2)
H_{fan}	distance between piezoelectric fan center and top surface of the heat sink base plate (mm)	V_t	heat sink volume (mm^3)
k_{al}	thermal conductivity of aluminum alloy (W/mK)	W	fin width (mm)
L	length of heat sink base plate (mm)	X	piezoelectric fan location (mm)
n	fin number		
Q	heating power (W)		

tance between the piezoelectric fan and the heated stainless steel sheet depends on the vibration amplitude. As vibration amplitude increases, heat transfer improves as the distance between the piezoelectric fan and the stainless steel sheet decreases; accordingly, the optimal distance increases as the vibration amplitude of the piezoelectric fan decreases.

In heat transfer experiments performed by Liu et al. [5], a piezoelectric fan was positioned horizontally or vertically above a flat surface. Experimental tests of six piezoelectric fans showed that heat transfer was increased by the entrained airflow during each oscillation cycle and the jet-like air stream at the fan tip. The heat transfer augmentation depicted a symmetrical distribution with a peak at $x/L = 0.5$ when the piezoelectric fan is placed vertically but an asymmetrical distribution with a peak at $x/L = 0.25$ when the fan is placed horizontally. The experiments also showed that the heat transfer in the horizontal case is not necessarily inferior to the vertical case.

Kimber and Garimella [6] measured the cooling characteristics of a piezoelectric fan mounted perpendicular to a constant heat flux surface. The resonance frequencies of the six piezoelectric fans used in the experiments range from 60 Hz to 250 Hz. The experimental results show that influence of vibration frequency on the heat transfer rate is larger than that of vibration amplitude.

Yoo et al. [7] indicate that the piezoelectric fan is a very suitable replacement for the rotary fan in some noise-sensitive devices. Different piezoelectric fans are constructed and tested. The vibrating plate of the piezoelectric fan is made of brass, aluminum, or phosphor bronze, and the operating frequency is 60 Hz. The experiments show that, if the length of the piezoelectric ceramic bimorph is fixed, the resonance frequency of the piezoelectric fan increases as the vibrating plate length decreases. Moreover, the vibrating plate, which is made of phosphor bronze, is more efficient; although the aluminum plates have lower efficiency, their material costs are lower.

Acikalin et al. [8] investigate the thermal performance of three different configurations of the piezoelectric fan and the heat source. Their experimental results indicate that the frequency offset, the fan amplitude, and the distance between the fan and the heat source have the greatest influence on the thermal performance of the fans.

A study by Petroski et al. [9] focused on the optimal design of a heat sink cooled by a piezoelectric fan. The volumetric coefficient of performance, COPv, is used to compare the cooling capability. The results show that the piezoelectric fan system is five times more efficient than natural convection in terms of COPv and has the cooling capability of about 1 °C/W over an area of about 75 cm^2. Moreover, velocities in the heat sink reach 1.5 m/s.

Huang et al. [10] apply the Levenberg–Marquardt method to determine the optimal location of the piezoelectric fan to minimize the maximum fin temperature. Comparisons of four different original fan positions show that the optimal fan position occurs at about 3.5 mm below the center point of the fin.

While the studies analyzed piezoelectric fans in terms of electronic cooling focused mostly on the heat transfer of flat surfaces, only few works were reported on the combinations of piezoelectric fans and heat sinks [1,8–12] which have important practical applications. The above studies indicate that piezoelectric fans are effective for cooling electronic components because of their light weight, low energy consumption, low noise, and long life expectancy; they can also be fabricated in small sizes to fit applications that require cooling. In cases where rotary fans are ineffective for dissipating heat or where local cooling is required, the piezoelectric fan provides an effective and reliable alternative approach to heat transfer. However, many factors affect the performance of the piezoelectric fan. In this study, the thermal performance of plate-fin heat sinks cooled by a piezoelectric fan is analyzed by infrared thermography. Particle image velocimetry (PIV) is used to acquire the flow fields induced by the piezoelectric fan. The effects of the piezoelectric fan configuration and location and the effects of the heat sink dimensions on thermal resistance are investigated.

2. Experimental apparatus and methods

Fig. 1 shows the experimental apparatus used in the research, which includes the infrared thermographic system, the piezoelectric fan, the heating system, the temperature measurement device, and the heat sink. The infrared camera used in the experiments is the FLIR A325, which has an un-cooled focal plane array detector with 320×240 pixels and can receive a wavelength from 7.5 μm to 13 μm. It covers the temperature measurement range from −20 °C to 350 °C and has an accuracy of ±2%. The field of view is $25° \times 19°$/0.4 m; the thermal sensitivity is 0.05 °C at 30 °C. The images are recorded and analyzed by the ThermaCAM Research Pro 2.9 software. The AC piezoelectric fan used in the experiments, which is manufactured by Piezo system, weighs only 2.8 g and has a maximal air velocity up to 2 m/s. Table 1 and Fig. 2 show the detailed dimensions and specifications of the experimental apparatus.

The heating system includes the DC power supply and the heating element, which is completely wrapped with insulating material except in areas where it is in contact with the base of the heat sink. The heating power of the system is

$$Q = \frac{k_{al}A(T_l - T_u)}{d} \tag{1}$$