Study on the Convective Heat Transfer Characteristic of a Horizontal Piezoelectric Fan

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Abstract. In this study, the horizontal cooling performance of piezoelectric fans was evaluated numerically. The flow field, average heat transfer coefficient and average temperature were estimated, and the best performance was found to be at (h/Lb=1/20). The experimental results showed that height reduction of the piezoelectric fan to a certain extent could improve the heat transfer performance. However, when the distance between the fan and the heating wall was too small (h/Lb<1/20), the heat transfer performance was negatively affected. The increase of vibration frequency and amplitude has a similar positive effect on the overall heat transfer capacity, and the increase of vibration frequency increases the heat dissipation capacity of the point heat source more significant. The increase of vibration amplitude has a greater effect on the heat dissipation range of the downstream area of the fan than the vibration frequency.

1. Introduction

As electronic devices are becoming smaller and more efficient with the rapid development of microelectronics technology, cooling and evacuation of the heat generated by these devices have gradually become a popular research topic. The most common traditional heat dissipation device is the rotary fan, whose heat dissipation capacity is largely determined by the size and speed of the fan blade. However, as the size of the blade increases, the volume of the fan increases accordingly, and increase in the blade speed also increases the noise level of the fan.

As a possible alternative, a piezoelectric fan can be used as a cooling device. The piezoelectric fan is made up of a vibrating plate and the piezoelectric material. When an AC voltage is applied, owing to the inverse piezoelectric effect, piezoelectric materials exhibit periodic compression-elongation behavior, to achieve cooling. Compared with rotary fans, piezoelectric fans are limited less by the space owing to the vibration mode. Moreover, a piezoelectric fan usually works at a low natural vibration frequency, which generates less noise. In addition, piezoelectric fans have longer service lives, lower power consumption, and smaller device sizes.

Till date, numerous studies have been conducted to evaluate the heat dissipation characteristics of piezoelectric fans. Kong et al. (2015) studies the influence of high natural vibration mode an two different arrangements of the piezoelectric fan on its performance; after calculating and measuring the distributions of various parameters in the flow field by simulating the motion process of the piezoelectric fan, they explored the influence of the frequency of the vibrating plate on the wind speed at the air outlet to estimate the length of the piezoelectric fan and the length ratio of the vibrating plate to the piezoelectric fan. Li et al. (2017) studied the vibration characteristics of a specific piezoelectric
fan and obtained the rule of the fan’s displacement to numerically investigate the characteristics of the vortex structure excited by the piezoelectric fan as well as its heat transfer. Li et al. (2017) studied the influence of the configuration and position of the piezoelectric fan and the size of the heat sink on thermal resistance experimentally. Shyu et al. (2014) studied the heat transfer of an n-type array cooled by a vibrating piezoelectric fan composed of four flexible rectangular blades. Huang et al. (2012) applied CF -ACE+ to construct a computational model of a three-dimensional piezoelectric fan and used the LMM (Levenberg-Marquardt Method) method to estimate its optimal position. Fairuz et al. (2014) explored the shapes of the first, second, and third modes driven at a certain frequency and the tip amplitude of the first mode using three-dimensional numerical methods to study the effects on heat transfer characteristics. Sufian et al. (2013) studied the influences of synchronized fans on flow and heat fields through numerical analyses and experiments. Li et al. (2016) experimentally studied the heat transfer characteristics of pin-fin heat sinks cooled by dual piezoelectric fans with detailed discussions about the influence of phase deviation, configuration, elevation of the piezoelectric fan and the size of the heat sink on heat dissipation performance. Açikalin et al. (2007) revealed the fan frequency, resonance, and fan amplitude offset as key parameters through design of experiment (DOE). Sufian et al. (2017) enhanced the heat transfer of high-power LEDs through a combination of piezoelectric fans and heat sinks and conducted experimental and numerical studies to evaluate the heat dissipation efficiencies of high-power LED packages operating under multiple vibrating fans. Sufian et al. (2014) also found the best configuration under the two fan arrangement. Ma et al. (2015) studied the thermal performance of a dual-side multi-fan piezoelectric actuator ("MFPA") system for thermal management of LEDs. Chen et al. (2007) applied the closed micro-jet cooling system to LED heat dissipation and experimentally studied the cooling and cooling effect of the system on high-power LEDs.

Among current studies on flow and heat transfer of piezoelectric fans, most studies focus on vertical cooling because the flow field generated in the vertical direction of the fan is similar to that of jet flow, resulting in relatively strong heat dissipation. However, piezoelectric fans are mainly used in microdevices such as chip radiators, which are usually limited by the vertical space. Therefore, it is necessary to study the heat dissipation characteristics of piezoelectric fans in the horizontal direction. In this study, the cooling effect of the piezoelectric fan at different heights, amplitudes and vibration frequency is examined on a constant heat flow surface.

2. Physical Model

2.1 Piezoelectric Fan

A commercially available piezoelectric fan was used for the numerical simulations. Figure 1 shows the structure of the piezoelectric fan, which is composed of a PZT patch and a stainless-steel blade. The PZT plate is adhered on one side of the blade. The fan length $L_p$, fan width $W$, and fan thickness $t_p$ of the PZT plate are 24 mm, 12 mm, and 0.4 mm respectively. The length of the elongated part of the flexible diaphragm $L_b$ is 23 mm, and its thickness $t_b$ is 0.1 mm. The fixed end of the piezoelectric fan is rigidly connected to the wall surface through a fixed base. A signal generator and power amplifier are used to provide sinusoidal excitation frequency for the fan to vibrate periodically and produce a series of vortices to disturb the fluid around the end of a string and to aggregate into the blade for continuous downstream jet transport. The maximum displacement of the blade tip (movement between the two limit positions) is $A_{pp}$, which is twice the amplitude of vibration $A_p$ of the blade tip.

![Figure 1. Schematic diagram of piezoelectric fan structure.](image)

The piezoelectric fan displacement function is obtained based on the cantilever beam theory. The first-order mode is the best vibration mode of the piezoelectric fan. (CHUNG et al. 2009). Therefore,
the first-order natural mode is selected for analysis.

3. Computing Method

3.1 Governing Equations

The governing equations used in the simulation software are as follows:

Continuity:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]  

\[ \text{Momentum Equation:} \quad \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (\tau_{ij} + \rho g_i + F_i) \]

where \( \rho \) represents the fluid density, \( \tau_{ij} \) the viscous stress tensor, and \( g_i \) the gravitational acceleration in the \( i \)-direction.

Energy Equation:

\[ \frac{\partial}{\partial t} (\rho c_p T) + \frac{\partial}{\partial x_j} (\rho c_p u_j T) = k \frac{\partial^2 T}{\partial x_i^2} \]

where \( T \) is the temperature, \( c_p \) the specific heat of air, and \( k \) the thermal conductivity.

3.2 SST k-omega governing equations

Turbulence Kinetic Energy:

\[ \frac{\partial}{\partial t} \bar{k} + \frac{\partial}{\partial x_j} (\bar{k} \bar{u}_j) = \rho S - \beta' \bar{k} - \frac{\partial}{\partial x_j} \left[ \frac{1}{2} \bar{k} \left( \bar{u}_j^2 \right) \right] \]

Specific Dissipation Rate:

\[ \frac{\partial}{\partial t} \bar{\omega} + \frac{\partial}{\partial x_j} (\bar{\omega} \bar{u}_j) = \nu S - \beta' \bar{k} - \frac{\partial}{\partial x_j} \left[ \frac{1}{2} \bar{\omega} \left( \bar{u}_j^2 \right) \right] + 2(1-r) \bar{\omega} \bar{k} \frac{1}{\bar{k}} \frac{\partial}{\partial x_j} \left( \bar{k} \bar{u}_j^2 \right) \]

3.3 Computational Domain and Boundary Conditions

In order to study the horizontal cooling characteristics of the piezoelectric fan, a computational domain and its size are established as shown in Figure 2. In the numerical calculation of the three-dimensional unsteady flow field, the piezoelectric fan was modeled as a thin sheet while its thickness is neglected. The horizontal cooling condition of the piezoelectric fan is as shown in Figure 2, the space between the fan and heating surface was selected as \( h/L_b = 1/40, 1/20, 1/10, 1/5 \) and 1/3 respectively, the amplitude was selected as \( A_p = 3 \text{mm}, 4 \text{mm}, 5 \text{mm}, 6 \text{mm} \) and 7 mm respectively, and the vibration frequency was selected as \( f = 50 \text{Hz}, 75 \text{Hz}, 110 \text{Hz}, 125 \text{Hz} \) and 150Hz. The heating surface was set as the no-slip velocity boundary, while the constant heat flux (1000W/m²) thermal boundary conditions and the remaining boundaries were treated as pressure boundaries with a pressure of 101325 Pa and a temperature of 300K.

4. Results and Analysis

4.1 Transient Flow Field Characteristics

In this work five piezoelectric amplitudes and vibration frequencies are analyzed. Figure 3 shows the turbulent intensity of the piezoelectric fans with different vibration amplitudes(a) and frequencies(b). The turbulent intensity are displayed for the middle plane of fan \( x=0 \).

It is seen from the figure that due to the maximum displacement of the fan tip, the maximum turbulent intensity is observed near the fan tip. And the turbulent intensity of fan at low amplitude is significantly higher than that at low vibration frequency. As the amplitude increases, the turbulent...
intensity downstream the fan increases, and the turbulence intensity near the constant heat flow surface is also increasing, it shows that the increase of amplitude effectively enhances the air flow near the wall. However, when $Ad>3\text{mm}$, increasing the amplitude did not significantly increase the maximum turbulent intensity, it shows that near the tip of the fan, low amplitude can bring relatively strong disturbance capability, increasing the amplitude has a limited effect on the flow intensity. Similar to Fig (a), the maximum turbulent intensity is also observed near the tip of the piezoelectric fan with different vibration frequencies, and the effect of vibration frequency on turbulent intensity is more significant. Different from increasing the amplitude, the increase of vibration frequency has a more significant effect on the turbulent intensity near the tip of the fan.

![Figure 3. Turbulence intensity at the middle plane of the piezoelectric fans with different vibration amplitude](image)

Fig 4 shows the turbulent intensity of the piezoelectric fans with different heights, as the fan height decreases, the area affected by the fan is constantly moving downstream of the fan, and the turbulent intensity is also increasing, when $h/L_b \leq 1/10$, the turbulence near the wall is strong, in the case of $h/L_b=1/20$ and $h/L_b=1/10$, the maximum turbulent region appears near the fan tip. However, when $h/L_b=1/40$, the position of the maximum turbulent region begins to move to the downstream region and becomes narrower and longer. As the height continues to increase, the core area of turbulent begins to move away from the wall, which indicates that reducing the fan height enhances the turbulent intensity. When $h/L_b \leq 1/20$, the turbulent intensity does not change significantly, lowering the height only results in an increase in the volume of the strong turbulent region. When $h/L_b > 1/10$, the core region of turbulent begins to move upward. The results show that the increase of height has a negative effect on the heat transfer capacity of piezoelectric fan.

![Figure 4. Turbulence intensity at the middle plane of the piezoelectric fans with different heights](image)

4.2 Transient Heat Transfer Analysis

In order to further compare and analyze the differences in the average heat transfer capacity of the surface at different heights, the laterally averaged convection heat transfer coefficient along the downstream direction of the fan was defined as

$$h_{av} = \frac{\int_{-L/2}^{L/2} \overline{\dot{q}}_{av} dx}{L}$$

$L_t$ is the reference length, take $A_{pp}$ and $2A_{pp}$ respectively.

Figure 5 present the laterally averaged convection heat transfer coefficient along the downstream direction of the fan with different amplitudes, vibration frequencies and heights respectively, the dotted vertical line in the figure represent the positions of the edges of the piezoelectric fan.
According to Figure 5, it shows that the increase of amplitude has a limited effect on the cooling capacity of both sides and the downstream outside of the fan area. As the amplitude increases, the overall heat transfer coefficient of the fan increases, however, the maximum heat transfer coefficient has little difference under different amplitudes. It shows that increasing the amplitude has a positive effect on the overall cooling capacity of the fan, but does not significantly enhance the cooling capacity near the fan tip. And the decrease of the attenuation speed of the downstream heat transfer coefficient shows that the cooling range of the downstream region can be increased significantly by increasing the amplitude.

For fans with different frequencies, it shows that the increase of frequency enhances the cooling capacity of both sides and the downstream outside area of the fan. The maximum heat transfer coefficient near the tip also increases significantly. However, the decay rate of the heat transfer coefficient in the downstream area of the fan is slow.

For a single fan at different heights, there were big differences in the average convection heat transfer coefficients. When $h/L_p=1/20$, $1/10$, $1/5$ and $1/3$, the maximum point of local convection heat transfer coefficient gradually shifted to downstream as the fan height increases.

Fig 6 shows the average surface heat transfer coefficients and surface temperatures of the heated wall. The overall heat transfer coefficient of the fan increases linearly with the increase of amplitude and frequency, while the maximum heat transfer coefficient increases relatively quickly with the increase of frequency. For piezoelectric fans of different heights, the overall heat transfer coefficient and the maximum heat transfer coefficient all appear at $h/L_p=1/20$.

5. Conclusion
In this work, the dynamic mesh technology was used to conduct numerical simulations of the unsteady flow and heat transfer characteristics of a single piezoelectric fan that cools a heated wall horizontally. The results are summarized as follows:
The increase of vibration frequency and amplitude has a similar positive effect on the overall heat transfer capacity, and the increase of vibration frequency increases the heat dissipation capacity of the point heat source more significant.

The increase of vibration amplitude has a greater effect on the heat dissipation range of the downstream area of the fan than the vibration frequency.

Reducing the fan height in a certain range also enhances the heat transfer performance, but too much height reduction has a negative impact on the heat transfer capacity.

The piezoelectric fan has the best heat transfer performance at $h/L_b = 1/20$.

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