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Numerical investigation of convective heat transfer on a vertical surface due to resonating cantilever beam

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A R T I C L E I N F O

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A B S T R A C T

In this article a simplified vibrating cantilever beam model is made to simulate the piezoelectric fan. The flow and heat transfer performances induced by the vibrating cantilever beam operating at different flexural modes and opening inlets are studied by numerical simulation. The fluid domain is meshed using a dynamic meshing scheme in order to model the displacement and deformation of the vibrating cantilever beam over time. The results show that the flow patterns generated at different resonance modes change with the deformation of the cantilever beam. The gap between the cantilever beam tip and the heated wall has significant effect on the flow and heat transfer features. By comparison with natural convective heat transfer, heat transfer augmentation ratios by the pseudo-jet induced by vibrating cantilever beam are 1.7–3.1 at the first mode and 1.7–2.7 at the second mode, respectively. For the confined space, the interaction of vortex induced by the vibrating beam and wall jet formed by the pseudo-jet impingement makes the intensity of vortices strong and pushes the vortex core upwards or downwards, contributing for higher heat transfer. Once the gap between the cantilever beam tip and the heated wall is larger than 4 times of vibrating amplitude of the cantilever beam tip ($G/A = 4$), the effects of opening inlet on pseudo-jet heat transfer are very weak.

1. Introduction

Air cooling is the simplest method of thermal control, most widely used in variety of electronic systems ranging form portable electronics to large business systems. In this field, a lot of researchers are looking for improvements or replacements of current rotary fans because there are still many issues such as fan noise, power consumption, size, and the life issue due to wear of the bearing. Piezoelectric fans are preferred as alternative for conventional fans because they have features of low noise and low power consumption, as well as easily be fabricated to suite specific applications.

Piezoelectric fan is a solid-state device that uses piezoelectric excitation to drive a thin blade for cooling. This fan generally consists of a patch of piezoelectric material attached to a flexible blade as illustrated in Fig. 1. When an alternating voltage is applied to the piezoelectric patch, it expands and contracts in the lengthwise direction, causing bending moments at both ends of the patch. These moments drive the attached blade to oscillate at the same frequency. The amplitude of oscillation reaches a maximum when the input voltage is applied at the resonance frequency of the fan. Consequently, this oscillatory motion drives a pseudo-jet flow which can be exploited for cooling.

A number of studies on the flow features driven by piezoelectric fans have been reported in the literature. Toda [1] performed a theoretical and experimental investigation into the air flow generated by a resonant-type PVF2 bimorph cantilever fan. He developed a simplified model for vibration prediction and investigated the factors affecting the performance of piezoelectric fans. The results showed that the air volume flow rate produced by the vibrating fan was proportional to the blade width and thickness, and the blade length had only a minor effect on the flow rate. Yorinaga et al. [2] investigated the construction of the bimorph that was suitable for the fan. They also examined the air volume flow rate and the noise level of a fan placed between two fixed plates. Ihara and Watanabe [3] performed a visualization study on the flow field driven by single and double oscillating plates for in-phase and counter-phase vibration, and also made a numerical study to simulate the air flow around flexible plates by using a numerical discrete vortex method. They found that the normal flow in the

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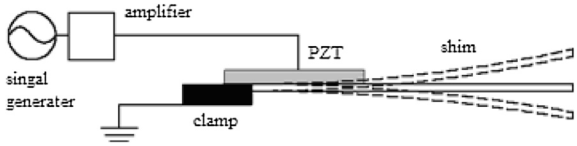

Fig. 1. Schematic of a piezoelectric fan [15].

downstream direction was greatly affected by the distance between two plates for counter-phase oscillation, but such flow was scarcely affected for in-phase oscillation. Yoo et al. [4] considered the piezoelectric fan used in cooling applications for portable electronics devices. They investigated the flow field characteristics of various piezoelectric ceramic bimorph cantilevers. Acoustic streaming in flexural plate wave devices was investigated by Nguyen and White [5]. They developed 2-D and 3-D numerical models of acoustic streaming and investigated the influence of wave amplitude and back pressure on time-averaged velocity in the flow field. Acikalin et al. [6] developed a closed-form analytical solution to predict the two-dimensional streaming flow from an infinite vibrating beam. The solution was used to develop a computational flow model for a baffled piezoelectric fan vibrating at its first mode of resonance in an infinite medium. Experimentally mapped flow patterns were found to closely match those predicted by the model for the baffled fan. Kim et al. [7] investigated the flow field generated by a vibrating cantilever plate mounted between two endplates by using phase-resolved particle image velocimetry as well as a smoke visualization technique. They found that the flow was quite complicated in nature. During each vibration cycle a pair of counter-rotating vortices was generated and a high velocity region was formed between these two counter-rotating vortices. The flow field was two-dimensional near the cantilever tip, but became more complex and three-dimensional further downstream. Parameters of the vortices induced by the vibration of cantilever were also estimated using the theory of oscillating deformable airfoils and compared against experiments. Wait et al. [8] studied the characteristics of piezoelectric fans running at higher resonance modes with numerical simulation and flow visualization. The results revealed certain advantages, such as greater fluid mixing and electro-mechanical energy conversion, of the piezoelectric fan being operated at higher resonance modes were offset by the increased power consumption and decreased flow delivery. Kimber et al. [9] made an experimental study on the pressure and flow rate performance of piezoelectric fans. Their results showed that the attainable flow rate exhibited a nearly quadratic dependence on the tip velocity, and the vibration frequency was more influential in determining the attainable pressure compared to the vibration amplitude. In addition, the inlet flow was found to be drawn primarily from above and below the portions of the vibrating fan experiencing the largest amplitude and these portions should remain uncovered to ensure the largest flow rate possible. Choi et al. [10] presented a comparative investigation between numerical flow simulations and the experimental data of a vibrating cantilever. The unsteady flow fields were observed with smoke visualization, and the unsteady velocities were measured by high resolution PIV. It was found that the static pressure difference across the tip plays an important role in the formation and development of each individual vortex.

Many numerical and experimental investigations on the thermal performance of piezoelectric fans have also been reported in the literature. Toda and Osaka [11] pioneered the research dealing with heat transfer enhancements from piezoelectric fans targeting a heated surface. They found that placing a piezoelectric fan on either side of a power transistor panel of the television receiver resulted in a 17 K decrease in temperature on the panel surface. Schmidt [12] used the naphthalene sublimation technique in experiments to determine the local and average transfer coefficients on a vertical surface cooled by two piezoelectric fans resonating out of phase. They found that varying the distance between the fans and the surface and from one fan to another noticeably changed the transfer coefficients for the system. The potential convective heat transfer capability of an ultrasonic flexural wave generated by direct and inverse piezoelectric effect was experimentally investigated by Loh et al. [13] and Wu et al. [14]. The feasibility of using piezoelectric fans in small scale electronic cooling applications was investigated by Acikalin et al. [15]. The thermal performance of piezoelectric fans was investigated in two different experiments: a custom-built setup was used to quantify the cooling enhancement from a heat-dissipating component due to piezoelectric fans in an enclosure simulating a cellular phone, and a commercially available laptop computer was utilized to demonstrate the viability of using piezoelectric fans for localized cooling. In the first setup, the piezoelectric fans were found to offer enhancements in convective heat transfer coefficients of more than 100% relative to natural convection, while in the latter, a 6–8 K temperature drop was observed in the electronic components within the laptop. Acikalin et al. [16] also performed a rigorous parametric study of a fan vibrating near a small discrete heat source in order to document the influence of governing parameters such as distance to target, vibration amplitude, and whether or not the fan was operating at resonance. They revealed the fan frequency offset from resonance and the fan amplitude as the critical parameters. For the best case, an enhancement in convective heat transfer coefficient exceeding 375% relative to natural convection was observed. Kimber et al. [17] presented the local heat transfer coefficients induced by piezoelectric fans by using the infrared camera technique. They found that the local heat transfer coefficient transition from a lobed shape at small gaps to an almost circular shape at intermediate gaps. At larger gaps, the heat transfer coefficient distribution became elliptical in shape. Florio and Harnoy [18] used a two-dimensional finite element scheme to study the heat transfer enhancement obtained by the transverse oscillations of a thin short plate. An improvement of up to 52% in the local heat transfer coefficient was observed relative to that achieved by natural convection. Abdullah et al. [19] conducted a 2-D numerical simulation to predict the heat transfer coefficient and flow fields around a piezoelectric fan with two heat sources. Their results showed that a best arrangement of fan and heated surface could reduce the temperature of the heat source surfaces by as much as 68.9 K. Besides the natural convection flow, the forced convection heat transfer enhanced by the oscillating fans was investigated by Dey and Chakrborty [20]. Their numerical results depicted that the oscillating fans interrupted the development of thermal boundary layer on the heated surface. A correlation of Nusselt number with the fan tip amplitude was proposed in their study. Kimer and Garimella [21,22] studied experimentally the thermal performance of vibrating cantilevers arrays. They revealed that the area-averaged heat transfer coefficient of the fan array was greater than that of a single fan. Their work quantified the influence of each operational parameter and its relative impact on thermal performance. Of particular interest were the vibration frequency and amplitude as well as the geometry of the vibrating cantilever beam. Liu et al. [23] presented an experimental work concerning the heat transfer by a piezoelectric fan on a flat surface subject to the influence of horizontal/vertical arrangement. It was found that the heat transfer augmentation of the piezoelectric fans came from the entrained air flow during each oscillation cycle and the jet-like air stream at the fan tip, yet these two modes were of the same order of magnitude. Lin [24] analyzed numerically and experimentally the heat and flow fields around the