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Effects of blade shape on convective heat transfer induced by a piezoelectrically actuated vibrating fan

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ABSTRACT

An experimental and numerical investigation is performed to explore the effects of blade shape on the convective heat transfer performance induced by piezoelectric fans. Five blade types are taken into consideration corresponding to the ones presented by Lin et al. [28], including one baseline type with a rectangular shape (Type-A), two rectangular shapes with wider widths (Type-B and Type-C), and two trapezoidal shapes in divergent (Type-D) and convergent (Type-E). All the blades are attached to the same piezoelectric patch and have the same exposed length. The vibration tests show that the blade shape has a significant influence on the vibrating characteristics of piezoelectric fan. Related to the baseline Type-A, Type-B and Type-C make the first-order resonance frequency a little descent. Type-D makes its first-order resonance frequency far less than the baseline type but Type-E is opposite. From the numerical simulations, the vortical structures induced by different blades vibrating at their respective resonance frequencies are illustrated. It is found that Type-B and Type-C produce stronger vortical flow although they have a little less vibrating frequency than the baseline Type-A. For Type-E, as its vibration frequency is obviously larger than Type-A, the scale of vortex shedding from the vibrating fan seems much stronger. In comparison with baseline type of piezoelectric fan, the location of highly local heat transfer zone moves from the center to both edges of fan-tip vibration envelope of fan-tip vibration envelope with the increase of blade width. In general, the blade types like Type-C and Type-E are suggested to be the favorable shapes for achieving better convective heat transfer performance. However, a little larger power consumption for actuating the piezoelectric fan is paid in relative to the baseline blade shape.

1. Introduction

Efficient heat removal of electronics systems is a critical issue for avoiding poor efficiency or damage. Although the air-based cooling technique is generally not capable of providing the same powerful cooling capability as the liquid-based cooling, it is still an important concern in the thermal management of electronics systems on account of its native advantages, such as high reliability, low cost and simplicity. In order to improve the thermal dissipation capability of an air-based heat sink, considerable efforts have been devoted in the past decades. Among the heat transfer enhancement techniques, an advanced active means by using the piezoelectric fans attracts much attention recently. It is a smart solid-state device which generally consists of a patch of piezoelectric material and a flexible blade. Relying on the reversed piezoelectric effect, the piezoelectric patch expands and contracts in the lengthwise direction, driving the attached blade to oscillate at the same frequency. Consequently, this oscillatory motion of flexible blade produces a pseudo-jet flow and results in highly local convective heat transfer.

Toda and Osaka [1,2] promoted the exploratory research dealing with the use of a piezoelectric fan as an air flow generator in the rear of 19th century. Excited by its potential applications in the active flow control and heat transfer enhancement, considerable efforts had been paid for revealing the streaming flow features induced by a resonating piezoelectric fan and optimizing the actuated parameters. For instances, Ihara and Watanabe [3] performed a study on the flow around the ends of oscillating flexible cantilevers. Kim et al. [4] investigated the flow field generated by a vibrating cantilever by using the phase-resolved particle image velocimetry and smoke visualization technique. It was revealed that a pair of counter-rotating vortices was generated during each vibration cycle and a high velocity region was formed between these two counter-rotating vortices, making the flow field of two-

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dimensional nature near the cantilever tip but more complex and three-dimensional further downstream. Wait et al. [5] studied the influence of resonance mode on the performances of piezoelectric fans. It was illustrated that the electro-mechanical energy conversion in higher resonance modes could be greater than in the first bending mode. However, losses in the piezoceramic were also shown to be higher at those modes. Therefore, the first resonance mode was suggested to be more favorable due to its minimum overall power consumption. Kimber et al. [6] 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. Kim et al. [7] and Choi et al. [8] made further investigations on the flow field generated by a vibrating cantilever using phase-locked particle image velocimetry. The vortical structures generated by a vibrating cantilever were identified and characterized by using the continuous wavelet transform. It was found that the static pressure difference across the tip played an important role in the formation and development of each individual vortex. Jeffers et al. [9] and Agarwal et al. [10] presented phase locked PIV results of an unconfined piezoelectric fan operating in its first vibration frequency mode. A three-dimensional λ_2 criterion isosurfaces were constructed from interpolated PIV measurements to identify the vortex core in the vicinity of the fan. These results clearly identified the formation of a horse shoe vortex that turned into a hairpin vortex before it broke up due to a combination of vortex shedding and flow along the fan blade. It was also clearly identified that a horse shoe type vortex was initially formed around the fan blade as it accelerated from zero velocity at maximum deflection. As the fan blade advanced beyond a certain phase angle, the horse shoe vortex begun to separate from the fan tip and a hairpin vortex was formed. Lin [11] performed a numerical simulation of three-dimensional heat and fluid flow induced by piezoelectric fans in the presence of an impinging target plate. Of particular was the illustration of interaction between the pseudo-jet flow and the target surface. Due to the presence of impinging target plate, the vibrating fan produced two air streams, namely a stream in the longitudinal direction and a stream in the transverse direction. The longitudinal stream was generated by the impingement jet effect at the fan tip, while the transverse stream was produced by the normal force exerted on the air by the vibrating fan. These two streams interacted to form two counter-rotating screw-type flow structures on either side of the blade adjacent to the heated surface.

By using the pulsating feature of a pseudo-jet flow produced by the piezoelectric fan, the local convective heat transfer enhancement was achieved [12]. Acikalin et al. [13] demonstrated the feasibility of using piezoelectric fans in small scale electronic cooling applications. In a commercially available laptop computer, a 6–8 K temperature drop was observed in the electronic components within the laptop. Acikalin et al. [14] also performed a parametric study to illustrate the influence of governing parameters including fan tip-to-target distance, vibration amplitude, and operating frequency on the heat transfer of miniature piezoelectric fans. It was revealed that the fan frequency offset from resonance and the fan amplitude were the critical parameters. For the best case, an enhancement in convective heat transfer coefficient exceeding 375% related to natural convection was observed. Kimber and Garimella [15,16] experimentally investigated the local heat transfer performance of piezoelectric fan. The local heat transfer coefficient distribution for a single fan was found to change from a lobed shape at small fan tip-to-surface gaps to an almost circular shape at intermediate gaps. At larger gaps, the heat transfer coefficient distribution became elliptical in shape. Their work quantified the influence of each operational parameter and its relative impact on the thermal performance. Of particular importance were the vibration frequency and amplitude of the vibrating cantilever beam. Liu et al. [17] made an experimental study concerning the influence of piezoelectric fan orientation on the thermal performance over a flat surface. It was illustrated that the heat transfer for the vertical piezoelectric fan showed a symmetrical distribution whereas the horizontal piezoelectric fan possessed an asymmetric distribution. The heat transfer augmentation of the piezoelectric fans came from the entrained airflow during each oscillation cycle and the jet-like air stream at the fan tip. Both the vertical and horizontal piezoelectric fan arrangements produced the same order of heat transfer enhancement magnitude. Abdullah et al. [18,19] performed experimental investigations concerning on the effects of tip gap and amplitude of piezoelectric fan vibration on the heat transfer characteristics of finned heat sinks. Among the tested ranges, the case with least tip gap and highest amplitude was confirmed to be the best. Tan et al. [20] and Fairuz et al. [21] performed numerical investigations to illustrate the effect of piezoelectric fan mode shape on the heat transfer characteristics. Their results suggested that the fundamental resonance mode was favorable for the practical piezoelectric fan application. Sufian et al. [22] studied the influence of dual vibrating fans on flow and thermal fields through numerical analyses and experimental measurements. Ma et al. [23] as well as Li and Wu [24] investigated experimentally the heat transfer of pin-fin heat sinks cooled by dual piezoelectric fans. It was found that the vibration phase difference between the fans had a great influence on the thermal and flow performance of double fans. Yeom et al. [25] and Li et al. [26] proposed a concept of active heat sink system that combined micro pin-fin surfaces and translational agitators. By using high-frequency translational agitation to aid existing channel flow generated by an external blower, the heat transfer coefficients were confirmed to be 250% of those on smooth surfaces without agitation.

To our knowledge, a lot of efforts have been paid to reveal the influence of geometric and operational parameters on the heat transfer performance of piezoelectric fan, such as fan tip-to-target distance, vibration amplitude, operating frequency and mode shape, etc. However, little attention was focused on the effect of fan-blade shape. Recently, Shyu et al. [27] presented a novel finger-like piezoelectric fan comprising four flexible rectangular blades. This design enhanced the fin array heat transfer and reduced cooler volume by embedding multiple vibrating beams into the fin array. Lin et al. [28] performed an experimental and numerical investigation on the flow fields induced by variously shaped piezoelectric fans. Five blade types were examined in their work, including three rectangular with different widths and two trapezoidal blades with divergent and convergent shapes. These piezoelectric fans were actuated at their respectively first resonant frequencies for ensuring the same vibration amplitude. It was demonstrated that a blade with a larger width had a larger velocity in general. The blade with a convergent shape was suggested to be better for hot spot heat sources than those with divergent and rectangular shapes. Excited by the work of Lin et al. [28] in the exploration of an effective heat-dissipating piezoelectric fan for high heat density devices, an experimental and numerical investigation is performed in the current study to further illustrate the influencing mechanism of fan-blade shape on the flow field in the presence of a target surface as well as the convective heat transfer performance. Totally three aspects of research contents are involved in the current study, including the vibration test, three-dimensional flow simulation and convective heat transfer analysis.

2. Piezoelectric fans and vibration tests

2.1. Brief description of piezoelectric fans

Totally five piezoelectric fans are designed in the current study. They have the same piezoelectric patch size but different blade shapes. As seen in Fig. 1(a), the piezoelectric patch is rectangular with a fixed width (W_0) of 12.7 mm, length (L_0) of 29 mm and thickness (t_p) of 1 mm, which is made of piezoelectric ceramic packaged with electric cords. The blade attached to the piezoelectric patch is made of stainless steel with a thickness (t_b) of 0.1 mm. Its length is 51 mm and the