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An investigation on convective heat transfer performance around piezoelectric fan vibration envelope in a forced channel flow

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ABSTRACT

An experimental and numerical investigation is performed in the current study to further explore the convective heat transfer performance by a vertically-oriented piezoelectric fan in the presence of channel flow. The effects of velocity ratio and fan tip-to-heated surface clearance are taken into considerations. It is illustrated that the presence of channel flow has an innegligible influence on the vibration amplitudes of the piezoelectric fan under large channel flow velocities. In the presence of channel flow, the vortical structures at the edges of vibrating fan are certainly suppressed, especially under large velocity ratios. On the other hand, the vortical streaming flow mixes with the channel flow to form a long stripe of vortical structure downstream of the fan vibration envelope. Under small velocity ratios, the impingement role of streaming flow along fan tip is still dominated and simultaneously the channel flow passing through the vibration envelope is effectively pulsated. Therefore, combined flows generally produce heat transfer enhancement around the fan vibration envelope related to the pure vibrating fan, especially at a small non-dimensional tip-to-surface gap. While under large velocity ratios, the impingement role of streaming flow induced by a vibrating fan is seriously weakened by the strong channel flow. The convective heat transfer produced by combined flows in the fan vibration envelope is generally reduced in comparison with pure piezoelectric fan. Related to the pure channel flow, the combined flows effectively improve the convective heat transfer, especially downstream of the fan vibration envelope.

1. Introduction

Piezoelectric fan is a solid-state device which employs the reversed piezoelectric effect to make the piezoelectric patch expand and contract periodically, driving the attached flexible blade to oscillate at the same frequency [1]. Due to the oscillatory motion of flexible blade, the neighboring fluid is periodically excited and thus a pseudo-jet or streaming flow is produced shedding along the fan tip. Previous investigations illustrated that the streaming flow induced by a piezoelectric fan is of vortical feature and the attainable flow rate is tightly dependent on the vibration parameters (such as vibration frequency, amplitude and mode shape) and geometric parameters of the piezoelectric fan [2–5]. Recently, the piezoelectric fan has gained much attention in the electronic cooling applications on account of its pseudo-jet impingement role [6].

Toda and Osaka [7] were the pioneers who promoted the exploratory research dealing with heat transfer enhancements by piezoelectric fans. Since the work of Toda and Osaka [7], considerable efforts had been paid to reveal the convective heat transfer performances induced by piezoelectric fans. Schmidt [8] experimentally investigated the local and average heat transfer coefficients on a vertical surface cooled by two piezoelectric fans. It was found that varying the distance between the fan and the surface noticeably changed the heat transfer coefficients for the system. Acikalin et al. [9–11] performed a series of studies on the thermal performance of piezoelectric fans. Their results demonstrated that an enhancement in convective heat transfer coefficient of more than 100% related to natural convection was achieved. The influence of main governing parameters such as fan tip-to-target distance, vibration amplitude and operating frequency on the heat transfer were also illustrated. Kimber and Garimella [12,13] experimentally investigated the local heat transfer performance of vibrating cantilevers. 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

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Nomenclature

A_p	vibration amplitude of fan-tip (m)
A_{pp}	peak to peak amplitude of fan-tip (m)
D	hydraulic diameter (m)
f	frequency (Hz)
G	fan tip-to-surface distance (m)
h	convective heat transfer coefficient (W/(m^2·K))
H	inner height of channel (m)
L_b	exposed length of fan (m)
L_p	PZT length (m)
L_y	lateral distance for average use (m)
Nu	Nusselt number
q	heat flux (W/m^2)
Re	Reynolds number
t	time (s)
T	temperature (K)
U	operation voltage (V)
u	velocity (m/s)
UR	velocity ratio
W	width of fan (m)
x	x-direction
y	y-direction
z	z-direction

Greek letters

ε	surface emissivity
λ_2	criterion for vortex structure identification
ν	kinematic viscosity (m^2/s)
σ	Stefan-Boltzmann constant

Subscripts

0	Stagnation point
a	relative to ambient
avx	laterally-averaged
b	relative to back surface of wall
c	relative to working fluid
CF	cross flow
PF	piezoelectric fan
w	relative to wall

distribution became elliptical in shape. Wait et al. [14] investigated the performance of piezoelectric fans operating at higher resonance modes. Both finite element analysis and experimental test demonstrated that the electromechanical coupling factor (EMCF) of a piezoelectric fan can be greater at higher resonance modes. However, this certain advantage of piezoelectric fan operating at higher resonance modes were offset by some serious disadvantages, such as increased power consumption and losses, as well as decreased bulk fluid flow. Liu et al. [15] made an experimental study concerning the influence of piezoelectric fan orientation on the thermal performance over a flat surface. It was illustrated that both vertical and horizontal arrangements have the same order of heat transfer enhancement magnitude. The heat transfer for the vertical arrangement showed a symmetrical distribution whereas the horizontal arrangement possessed an asymmetric distribution. Abdullah et al. and Fairuz et al. [16–18] performed a set of investigations concerning the effects of fan height, tip gap, vibrating amplitude and mode shape 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. Their results also showed that the increase of vibrating mode number decreases the attainable air flow velocity approaching to the target surface, thus impeding the cooling capabilities. Lin [19] performed a numerical simulation on three-dimensional flow induced by piezoelectric fans in the presence of an impinging target plate. Of particular was that the vibrating fan produced two air streams due to the presence of impinging target plate, namely a stream in the longitudinal direction and a stream in the transverse direction. The two streams interacted to form two counter-rotating screw-type flow structures on either side of the blade adjacent to the heated surface. Huang et al. [20] made an inverse problem investigation on determining the optimal position for piezoelectric fan. Experimental verifications were also made to justify the validity of the presented estimation of the optimal fan position. Tan et al. [21] performed a numerical investigation on the flow and heat transfer performances induced by vertically-oriented vibrating cantilevers in a confined space. It was found that 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.

To our knowledge, relatively little efforts had been devoted to reveal the flow and thermal performance of piezoelectric fans in the presence of a cross flow. For the conventionally continuous jet impingement, vast investigations had revealed that the initial cross flow has a significant influence on the convective heat transfer [22–25]. Lin [26] performed a numerical investigation on the heat transfer performance of cylindrical surface by the piezoelectric fan under forced convection conditions with an inlet velocity in the range of 0.46–2.30 m/s. It was found that the streaming jet induced by the vibrating fan mixes the free stream in the wake region and prompts an improved heat transfer performance. However, it was also noted that streaming jet induced by the vibrating fan can increase the wake region and reduce the local heat transfer from the cylindrical surface over the baseline case if the operational criteria beyond certain limits, such as under some specific situations with a large fan tip amplitude, a large fan tip-to-heated surface clearance and a high free flow velocity. Jeng and Liu [27] experimentally investigated the heat transfer and fluid flow behaviors of the heat sink partially filled in a rectangular channel with the axial mainstream interacted by the oscillating movement of the upstream piezoelectric fan. It was illustrated that the oscillating movement of piezoelectric fan strengthen the turbulent intensity of the mainstream at low Reynolds number, giving the additional disturbance momentum to the mainstream and making the fluid flow through the heat sink with turbulent flow characteristic.

In a common sense, due to the fluid-structure coupling nature, the presence of a cross flow will affect the fluid-structure interaction of piezoelectric fans and consequently the flow and thermal performance. For addressing further insights on convective heat transfer performance around piezoelectric fan vibration envelope in a forced channel flow, a series of experimental tests are made by varying the excitation voltage of piezoelectric fan and channel flow inlet velocity. The influences of the channel flow on the vibration amplitude of piezoelectric fan and convective heat transfer around the fan vibration envelope are illustrated. Besides, three-dimensional numerical simulations are also performed by using the dynamic meshing technique and sophisticated user defined functions describing the time-varying displacements of a vibrating fan. The instantaneous vortical structures and temperature contours on the heated surface are captured for illustrating the