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Moving-orientation and position effects of the piezoelectric fan on thermal characteristics of the heat sink partially filled in a channel with axial flow

Tzer-Ming Jeng *, Chi-Huang Liu

Department of Mechanical Engineering, Chienkuo Technology University, 500 Changhua, Taiwan, ROC

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ABSTRACT

This study 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. Total eight heat sinks, including square pin–fin heat sinks (Models A–C), plate-fin heat sinks (Models D–F) and aluminum-foam heat sinks (Models G and H), were employed. The relevant parameters were the Reynolds number of the mainstream (*Re*), the oscillating-movement orientation of the piezoelectric fan and the location of the piezoelectric fan (the relative horizontal distance $S/L = 0.25$ and the relative vertical distance $H_p/L = 0.22–0.62$). The smoke flow visualizations demonstrate that the oscillating movement of the piezoelectric fan did 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. The heat transfer results indicate that the heat sink gained more heat transfer enhancement at smaller *Re* when the piezoelectric fan was operating. For example, when the piezoelectric fan was operating with transverse oscillation at $Re = 850$, $S/L = 0.25$ and $H_p/L = 0.62$, the Nu/Nu_0 (Nu and Nu_0 separately mean the Nusselt number of the case with and without the piezoelectric fan) of square pin–fin heat sink Model C would exceed 2. The values of Nu/Nu_0 for various heat sinks would drop and approach to unity as increasing *Re*. In general, under the oscillating condition, the square pin–fin heat sink gained the best heat transfer enhancement; the longitudinal plate-fin heat sink gained slightly less heat transfer enhancement than the square pin–fin heat sink did; the aluminum-foam heat sink gained poor heat transfer enhancement. In addition, the transverse oscillation promoted slightly more heat transfer enhancement than the axial oscillation did. Finally, this study proposed reasonable and accurate empirical correlations of Nusselt number in view of the pure axial-flow, the pure piezoelectric-fan and the both-combined conditions.

1. Introduction

The piezoelectric fan is a cantilever-like structure composed of elastoplastic sheet covered with ceramic piezoelectric patch. When a voltage is imported, the piezoelectric effect makes the piezoelectric patch oscillate at a high frequency. Thus, the plastic sheet swings reciprocally driving nearby air, producing continuous and stable axial airflow. The piezoelectric fan is an air flow generating device with simple structure, low energy consumption and low noise, thereby meeting the cooling requirement of electronic products.

In recent years, using piezoelectric fan to enhance the convection heat transfer has become one of the topical subjects. Some studies conducted experimental observation and numerical simulation analysis of the air flow characteristics generated by piezoelectric fan. Some discussed the influence of the air flow generated by piezoelectric fan on the heat transfer of flat plate or the windward and leeward surfaces of cylinder. Others developed the cooling techniques combining piezoelectric fan with finned heat sink. Choi et al. [1] used smoke flow visualization technique and PIV (particle image velocimetry) to measure the air flow characteristics generated by one vibrating cantilever in the channel. They also used numerical simulation result to prove that the static pressure difference on both sides of the vibrating cantilever tip was the key to the formation and development of vortices. Choi et al. [2] used numerical method to simulate the air flow motion generated

* Corresponding author. Tel.: +886 4 7111111x3130; fax: +886 4 7357193.
E-mail addresses: tm.jeng@msa.hinet.net, tmjeng@cc.ctu.edu.tw (T.-M. Jeng).

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Nomenclature

A	area of heated surface (m^2)
A_{HT}	area of total heat-exchange surface (m^2)
C	top-bypass clearance (m)
f	dimensionless pressure drop, Eq. (3)
F	inertial coefficient
h	heat transfer coefficient ($W/m^2/K$)
h_{loss}	effective heat transfer coefficient of heat loss ($W/m^2/K$)
H	height of the test channel (m)
H_f	height of the heat sink excepting spreader (m)
H_p	vertical distance between the tip of piezoelectric fan and the bottom wall of test channel (m)
k	thermal conductivity (W/m/K)
K	permeability (m^2)
L	length of the heat sink (m)
N	numbers of pin fins or plate fins
Nu	Nusselt number, Eq. (2)
Q_{in}	total input heat (W)
Q_{loss}	loss heat (W)
Re	Reynolds number of mainstream, Eq. (1)
s	side length of the square pin fin (m)
S	horizontal distance between the tip of piezoelectric fan and the leading edge of heat sink (m)
t	thickness of the plate fin (m)
T	temperature (°C)
U_e	average air velocity through the test channel (m/s)
W	width of the test channel (m)
Δp	pressure drop (Pa)

Greek symbols

ε	porosity
μ	viscosity (kg/m/s)
ρ	density (kg/m^3)

Subscripts

0	axial flow only
b	bulk mean value
f	fluid
s	solid
pf	piezoelectric fan
w	heated wall
∞	ambient

by two vibrating cantilevers. They indicated that the phase angle difference between two cantilevers influenced the flow field significantly. The interaction between the paired counter-rotating vortices generated by each vibrating cantilever was changed by various phase angle differences, and the two vibrating cantilevers of opposite phase angle generated more air flow. Choi et al. [3] used 2-D numerical simulation to discuss the influence of the spacing between two vibrating cantilevers of opposite phase angle and inphase angle on the air flow characteristics. They found that if the spacing between two cantilevers was too small, the two cantilevers obstructed the formation of vortices mutually, which is disadvantageous for the cantilever to generate air flow. The performance of the air flow generated by two vibrating cantilevers of opposite phase angle was better than that by two vibrating cantilevers of inphase angle. The optimal spacing was twice as large as the completely grown vortex size generated by one vibrating cantilever. When the spacing was greater than three times, the vortex flow fields generated by various vibrating cantilevers would not affect each other. Abdullah et al. [4] used numerical and experimental methods to discuss the cooling performance of piezoelectric fan in the linearly arrayed two heat sources on horizontal plate. The piezoelectric fan was placed above the flat plate horizontally, and the swing direction was normal to the flat plate. The result showed that the heat source temperature was reduced when the piezoelectric fan was at an appropriate vertical distance to the heat source. Kimber and Garimella [5] conducted experiments to measure the cooling performance of oscillating piezoelectric fan in the vertical heating plane. The piezoelectric fan was normal to the heating plane, and the swing direction was identical with heating plane. The result showed that the heat transfer was maximized when the distance between the cantilever tip and the heating plane was at a specific value. At this specific spacing, the heat transfer was correlated only with the cantilever oscillation frequency and amplitude. Huang et al. [6] used business software to build a 3-D computation model, and discussed the optimum position of piezoelectric fan for the vertical heating surface. Lin [7] used 3-D numerical calculation and experimental measurement to discuss the heat transfer and flow characteristics of heating plane resulted from the piezoelectric fan. The piezoelectric fan was normal to the heating plane, and the cantilever swing direction was identical with the heating plane. The result indicated that under the interaction of the normal force of air applied by the piezoelectric fan to both sides of cantilever and the impinging jet flow generated by the cantilever tip. There was contrarotational helical recirculating flow on both sides of cantilever. The piezoelectric fan increased the heat transfer capacity of vertical heating plane by 1.6–3.4 times, and enhanced the heat transfer capacity of horizontal heating plane by 1.8–3.6 times. Sufian et al. [8] used numerical and experimental methods to discuss the heat transfer enhancement of two piezoelectric fans for the heating plane. The two piezoelectric fans were placed next to each other. The cantilever was normal to horizontal heating plane, and the cantilever swing direction was identical with the heating surface. The result showed that one piezoelectric fan enhanced the heat transfer by about 2.3 times, the two piezoelectric fans at opposite phase angle enhanced the heat transfer by 2.9 times, and enhanced the heat transfer by 3.1 times at inphase angle. Lin [9] used numerical and experimental methods to discuss the heat transfer enhancement of piezoelectric fan for vertical cylinder surface. The piezoelectric fan was normal to the axial direction of cylinder, and the swing direction was identical with the circumferential direction of cylinder. The result showed that the piezoelectric fan enhanced the heat transfer coefficient by 1.2–2.4 times. Lin [10] indicated that when the cylinder was put in forced convection, there was poor surface heat transfer in the leeward eddy zone. The piezoelectric fan was placed on the leeward side of cylinder. The cylinder surface heat transfer in that zone could be enhanced by the oscillating air flow generated by piezoelectric fan. The result indicated that the quasi-jet flow generated by piezoelectric fan interacted on the natural convection of cylinder heating surface and the mainstream vortex, the overall heat transfer was enhanced by 132%, and the leeward local heat transfer was enhanced by 214% at most. However, based on the specifications and position of the piezoelectric fan used in [10], when the mainstream Reynolds number exceeded 2200, the quasi-jet flow generated by piezoelectric fan reduced the overall heat transfer of cylinder on the contrary. Ma et al. [11] indicated that the length of cantilever, oscillating frequency and amplitude influenced the forced air flow generated by piezoelectric fan