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Experimental study of mixed convection heat transfer on the heated plate with the circular-nozzle synthetic jet

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ABSTRACT

This study experimentally examined the mixed convection heat transfer characteristics of a horizontal heated plate with the impinging cooling of down-blowing (Model 1) or up-blowing (Model 2) synthetic jet. The synthetic-jet device was made of a loudspeaker and a cylindrical acrylic chamber. The signal function generator and amplifier imported electric voltage at different frequencies and amplitudes to the loudspeaker, so that the loudspeaker's membrane surface vibrated at different displacements and frequencies. Then, the 3 mm-diameter circular nozzle on the end face of cylindrical chamber generated synthetic jet. The ratio of nozzle diameter (d) to the heated-plate diameter (D) was 0.06. The variable parameters included mean jet Reynolds number ($Re_j = 230$–4593), Grashof number ($Gr = 1.25 \times 10^5$–5.51×10^5) and relative impingement distance ($c/d = 1$–11). The experimental results showed that at a specified Re_j, the Nu of various models basically increased with c/d. However, some cases showed that Nu declined as c/d exceeded some critical value. In addition, when the impingement distance was short ($c/d = 1$) and in a small Reynolds number range ($Re_j \leqq 1155$), Model 1 generated the cancelation effect (forward impinging jet and natural convection are opposite in direction) and enhancement effect (deflected wall jet intersects natural convection transversely) of mixed convection heat transfer at the same time. When c/d increased (e.g. $c/d = 11$), there was a large forward impingement contact area due to the diffusion effect of jet, and the cancelation effect of forced convection and natural convection of Model 1 was more significant. The enhancement effect of mixed convection heat transfer was formed in Model 2. When Re_j was small, the Nu of Model 2 was larger than that of Model 1. When $Re_j \geqq 2105$, both models had similar Nu, and it did not vary with Gr, meaning the overall heat transfer was dominated by forced convection. Finally, this study established an empirical Nu correlation of mixed convection in terms of Re_j and Gr at various c/d for Model 1 and Model 2, applicable to heat transfer analysis and optimal design of synthetic-jet device.

1. Introduction

The synthetic-jet device is characterized by light weight, low energy consumption, quick actuation and simple structure. It is very promising in active pneumatic control of aerial vehicles and cooling management of electronic modules. Differing from blade fans, it uses the displacement formed by vibrating elastic slice or reciprocating-motion piston in cylinder to generate air jet. The flow field is approximately divided into developing, full development and dissipation regions. The air mass blown from the synthetic-jet device is approximately identical with that sucked into the device in operation, so it is also known as Zero-Net-Mass-Flow. However, the flow field still keeps forward momentum, and it has been applied to enhanced heat transfer.

Mallinson et al. [1] analyzed the mean velocity data of hot-wire anemometry and compared it with numerical result. The measured velocity was along the center-line of a synthetic jet flow. They suggested the computational meshes should be refined, especially in the near orifice region. Wang et al. [2] designed a microelectromechanical active cooling device, which could make synthetic jet on printed circuit board to enhance thermal control. They used Fluent computing software to simulate related thermal and flowing behaviors. The turbulence model was Large Eddy Simulation (LES), and the simulation result was consistent with experimental data. Agrawal and Verma [3] used numerical simulation to discuss the similarity between plane (Cartesian coordinates) and axisymmetric (cylindrical coordinates) synthetic jets. They found that, at

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Nomenclature

A	heated area (m^2)
c	impingement distance between jet nozzle and heated plate (m)
d	diameter of jet nozzle (m)
D	diameter of heated plate (m)
g	acceleration of gravity (m/s^2)
Gr	Grashof number, Eq. (4)
H_{Loss}	effective heat transfer coefficient for heat loss ($W/m^2/K$)
h_{plate}	natural convection heat transfer coefficient between cold air and horizontal heated plate ($W/m^2/K$)
I	input current to the film heater (A)
k	thermal conductivity (W/m/K)
Nu	Nusselt number, Eq. (5)
Q_t	total input heat (W)
Q_{Loss}	loss heat (W)
Q_{plate}	heat from the heated plate to cold air via natural convection (W)
Re_j	mean jet Reynolds number, Eq. (3)
T	temperature (°C)
V	input voltage to the film heater (V)
V_j	mean air velocity at the nozzle exit (m/s)
V_{rms}	root-mean-square input voltage to the loudspeaker (V)
Z	axis along the center line from the jet nozzle (m)

Greek symbols

β	thermal expansion coefficient of air (1/K)
μ	viscosity (kg/m/s)
ρ	density (kg/m^3)

Subscripts

0	ambient
f	fluid
j	jet nozzle
r	referred
w	heated wall

the region far from the synthetic-jet nozzle, the center velocity and vortex ring diffusivity of these two synthetic jets were similar. Qayoumet et al. [4] used experimental method to discuss the interaction between flat-plate boundary layer of transverse mainstream and synthetic jet. They adjusted the amplitude and frequency of piezoelectric actuator to control the synthetic jet, and measured the heat transfer enhancement for the flat plate. They used hot-wire anemometer to measure the flow field characteristics, and used transient liquid crystal method to measure the heat transfer coefficient. They found that the heat transfer enhancement was at most 44% by increasing the amplitude. Even if at a low frequency, the effect of increasing amplitude on heat transfer was still obvious. The experimental results showed that the flow pattern of the synthetic jet was similar to the vortex generated by the fluid flow cross an obstacle block (e.g. rib). Therefore, the synthetic jet could be used as heat transfer enhancement device within the boundary-layer region. Chandratilleke et al. [5] used numerical simulation method to discuss the effect of synthetic jet in the micron channel with transverse flow on heat transfer characteristics. The simulation results indicated that compared with the case without synthetic jet, the synthetic jet could enhance the heat transfer by 4.3 times. Chaudhari et al. [6] built an experimental platform to measure the heat transfer capability of synthetic jet impinging on heated plane, as well as the changes in radial distribution of jet velocity and static pressure. The jet Reynolds number and impingement distance were changed in their experiment. They found that compared with natural convection, the synthetic jet could increase the heat transfer coefficient of impinging cooling by at most 11 times. Chaudhari et al. [7] also used experimental method to discuss the impinging cooling effect of single-chamber multi-orifice synthetic jet on the heated plane. They found that compared with previous single-orifice synthetic jet, the multi-orifice synthetic jet could enhance the heat transfer by at most 30%, and the spacing between jet orifices influenced the heat transfer distribution and overall cooling effect. Persoons et al. [8] experimentally measured the impinging cooling of axisymmetric synthetic jet. The variable parameters included the Reynolds number, the impingement distance and the displacement of diaphragm of synthetic-jet device. They proposed the empirical correlation of Nusselt number at the stagnation point according to the experimental results. Trávníček et al. [9] installed four synthetic-jet devices around an axisymmetric air-jet nozzle to make the main jet flow form spiral or bifurcation pattern. The experimental results showed that the heat transfer enhancement was at most 40% at the stagnation point of impinging cooling. Lee et al. [10] used three-dimensional numerical simulation to observe the mutual effect of synthetic jet and transverse flow on microchip cooling in micron channel. The changed parameters included the amplitude of diaphragm of synthetic-jet device and the heating of microchip. The simulation results indicated that the synthetic jet enhanced the heat transfer apparently. Lin [11] observed the synthetic jet generated by the resonances of the loudspeaker's membrane surface. The frequency was 40 Hz, the input amplified voltage and signal waveforms were changed. They indicated that the amplified voltage was the main factor influencing the velocity of synthetic jet, and the jet velocity was linearly proportional to the ratio of membrane-surface displacement to the chamber length. In addition, the jet pressure formed by forward membrane surface impelled the nozzle edge to generate a pair of forward spiral airflows. The suction force formed by backward membrane surface did not draw the jetted airflow. They also observed that after the synthetic jet being blown out, the central speed of the jetted airflow could be divided into 5 regions from nozzle to remote downstream. Zhang et al. [12] experimentally explored the effect of synthetic jet on heat transfer under the interaction of pure impinging cooling and cross flow. The synthetic-jet device generated synthetic jet at different frequencies by reciprocating motion of piston-cylinder device. The reciprocating motion of piston at higher frequency generated higher mean jet velocity, and there was relatively strong convection heat transfer enhancement effect. The jet-orifice shape had limited effect on the mean jet velocity, but affecting the interacted flow field of synthetic jet and cross flow. Rylatt and O'Donovan [13] experimentally investigated the heat transfer of confined, un-ducted and ducted impinging synthetic air jets. They depicted that increasing the length of the confining plate reduced the heat transfer capacity due to recirculation of heated air and reduced entrainment of cooler ambient air. Therefore, a ducted synthetic jet was introduced. That ducted configuration was demonstrated to increase heat transfer obviously by drawing cold air from a remote location into the jet flow. Greco et al. [14] used the membrane-surface vibration characteristic of loudspeaker to make synthetic-jet device, and used experimental method to investigate the flow characteristics of single and twin synthetic jets. The blowing and sucking actions of twin synthetic jets were designed oppositely. The results showed when the spaces between the jet orifices were 3 times and 5 times of jet-orifice