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Research Paper

Heat transfer enhancement of an impinging synthetic air jet using diffusion-shaped orifice

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HIGHLIGHTS

- Synthetic air jet was produced using a diffusion-shaped orifice.
- The effect of the opening angle and driven frequencies were studied.
- The diffusion-shaped orifices produced higher heat transfer enhancement.

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ABSTRACT

Impingement heat transfer from a synthetic air jet through a diffusion-shaped orifice was investigated in this study. The effect of the opening angle (60° and 90°), orifice thickness (1–3 mm), and driven frequencies (400–800 Hz) were examined. Hot-wire anemometry was used to measure the instantaneous and average flow velocities ejected from the jet holes. At a small jet-to-surface spacing, synthetic jets from a diffusion-shaped orifice produced higher heat transfer than that from a round orifice. The highest heat transfer enhancement from using a diffusion-shaped orifice was approximately 30% compared with the round orifice at an opening angle of 60°. The diffusion-shaped orifice achieved the highest area-averaged heat transfer coefficient and Nusslet number of 80 W/m^2·K and 8.9, respectively. When the opening angle increased to 90°, heat transfer enhancement was degraded because of increased flow circulation and reduced ejection flow velocity. The effect of orifice configuration on the heat transfer diminished as the jet-to-surface spacing increased.

1. Introduction

Normally the high-power electronic systems generate significant amount of heat and requires ingenious compact cooling designs for heat removal. In general, either active or passive cooling can be employed but active cooling is more attractive when space is especially limited. Active cooling utilizing a synthetic jet can be applied to small systems and is especially attractive in concentrated local hot spots. Synthetic jets are generated by an oscillating diaphragm to induce suction and ejection from the surrounding fluid. The coalescing and breaking down of vortices occur as synthetic jets move in a downstream direction. Its heat-transfer enhancement is superior to that of natural convective cooling.

Mahalingam and Glezer [1] determined that the cooling of the high-power heat sinks with synthetic jets. The synthetic jets can significantly lower the case temperature from 71.5 °C to 36 °C. At a flow rate of 3–5 CFM, the synthetic jets dissipated approximately 20%–40% more heat than that of fan cooling. Arik et al. [2] used infrared thermography to investigate the impingement heat transfer of a meso-scale synthetic jet. The flow velocity was measured using hot-wire anemometry at a distance of 0.5 mm from the jet hole. The flow velocities varied with the driven frequency of the actuator, and the noise level was between 30 and 73 dB. The heat transfer was 10 and 4.5 times higher than that of natural convection at the driven frequencies of 3000 and 4500 Hz, respectively. Further investigation showed decreasing heat transfer enhancement with increasing heater size [3]. Lasance et al. [4] investigated synthetic jet cooling, emphasizing the principles of heat transfer and acoustics. An acoustic dipole cooler was built and tested, with superior synthetic jet performance for heat transfer, noise level, and dissipated power [5].

For short jet-to-surface distances, synthetic jets with high driven frequencies were more effective in heat removal than those with low driven frequencies [6]. The effect of excitation amplitude on the flow field also depended on the driven frequency [7]. The velocity fluctuations increased because of amplitude modulation, and the effect became more pronounced at low modulating frequencies. A maximal increase of heat transfer with a coefficient of 44% was achieved by increasing the excitation amplitude [8]. An extensive study of synthetic-jet heat transfer was subsequently performed [9],

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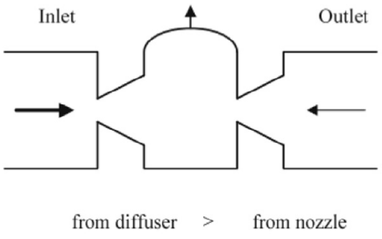
including jet-to-surface spacing (Z/d = 0–25), oscillation frequency (100–350 Hz), orifice thickness (1.6–5 mm), and the length of the orifice plate to the orifice diameter (8–22). Heat transfer was impaired by using a thicker orifice plate because of increased fluid friction and decreased flow velocity. In addition, small jet-to-surface spacing (Z/d < 5) promoted the circulation of warmer fluid and decreased the Nusselt number. Chaudhari et al. [10] had examined the effect of orifice shape, showing that a higher heat-transfer enhancement of a square orifice than that of an orifice with a rectangular or circular shape at a larger Z/d. At a small Z/d, a rectangular orifice with an aspect ratio between 3 and 5 provided the optimal performance. In addition, multiple-orifice synthetic jets were tested with a center orifice surrounded by multiple satellite orifices [11]. The satellite orifices with the center orifice reached a high heat transfer at a lower Z/d, which can be desirable for compact cooling designs. At a lower axial distance (Z/d = 2), two orifices provided optimal performance.

Valiorgue et al. [12] investigated an impinging synthetic jet for a small jet-to-surface spacing of Z/d = 2. The critical dimensionless stroke length ($L_0/Z = 2.5$) can be used to identify heat transfer regimes. Trávníček et al. [13] studied an axisymmetric impinging synthetic jet by applying flow visualization, hot-wire anemometry, PIV, and naphthalene sublimation techniques. The Reynolds number ranged from 1600 to 5000. The effect of excitation at higher frequencies on the jet mixing and spreading was observable, but its effect on heat transfer was not noticeable. Zhang et al. [14] investigated convective heat transfer on a flat plate subjected to normally synthetic jets and horizontally forced flow. With the peak laterally averaged, convective heat-transfer coefficient increased to 100% in relation to the individual action of the forced flow when the piston was operated at 24 Hz. Rylatt et al. [15] reported heat transfer enhancement of a confined, un-ducted and ducted, impinging synthetic air jet, with experimental parameters that included the spacing of the jet to the impingement surface (Z/d = 0.5–3), ducting outlet diameter (1.2, 1.6, and 2 jet diameter), and length of the confining plate (90–200 mm). The ducting improved the heat transfer by drawing cold air from a remote location into the jet flow, with the highest increase in heat transfer occurring at Z/d = 1.

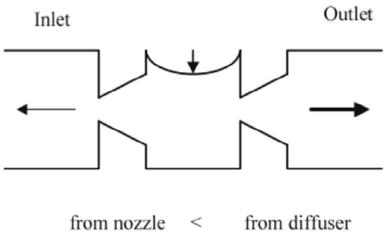
In a micropump system, flow control is achieved using a nozzle and diffuser (Fig. 1). In supply mode, the inlet serves as a diffuser, as the diaphragm moves upward. The outlet serves as a nozzle, which hinders the flow from entering the system. When in pump mode, the inlet and outlet function in an opposite manner. Yang et al. [16–18] investigated enhancement structures on heat transfer in micro nozzle/diffuser systems. The pressure drop increased as the Reynolds number increased, and the pressure drop in the nozzle was higher than in the diffuser. For the diffuser, the flow separation was promoted by widening the opening angles. The micro nozzle/diffuser system has inspired striving for a less pressure loss and implementing a larger opening area for the diffuser, which may contribute to a beneficial design for improving synthetic jet performance further. Thus far, a synthetic jet produced through a diffusion-shaped orifice to enhance impingement heat transfer has not been studied. The fundamental study on a synthetic jet by using a piezoelectric actuator was reported in a previous study [19], and an extended investigation on further enhancing synthetic-jet heat transfer by using a diffusion-shaped orifice was conducted in this study.

2. Experimental setup and procedure

Impingement heat transfer from a synthetic jet on the surface was experimentally determined using the setup shown in Fig. 2. The synthetic jet was produced by a piezoelectric actuator. A function generator adjusted the driven frequency of the piezoelectric actuator from 400 to 800 Hz. The flow velocity of the synthetic jet was measured by a hot-wire anemometer. The test plate comprised a copper plate, resistance heater, and support frame. The 3-mm thick copper plate and the heater were fastened to a balsa wood plate. Thermocouples were used to measure the temperature of the test plate and the ambient temperature. The thermocouple signals were recorded using a thermocouple module (NI-9213). The jet-to-surface spacing (Z/d) was controlled by using a linear translation stage. During the heat transfer experiment, a transparent acrylic enclosure (45 cm × 30 cm × 30 cm) shielded the test plates to prevent surrounding flow disturbance.

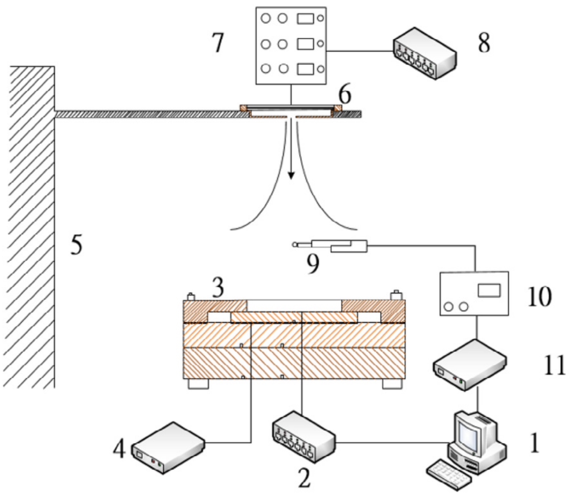


(a) Supply mode



(b) Pump mode

Fig. 1. Supply and pump modes in a micro nozzle/diffuser.



1. Computer
2. Thermocouple Module
3. Test Plate
4. Power Controller
5. Linear Translation Stage
6. Piezoelectric Actuator
7. Variable Transformer
8. Function Generator
9. Hot Wire Probe
10. Hot Wire Anemometer
11. Hot Wire Module

Fig. 2. Schematic of the experimental setup.