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Effect of driven frequency on flow and heat transfer of an impinging synthetic air jet

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HIGHLIGHTS

- Synthetic air jet flow produced by the piezoelectric actuator operated in 200–800 Hz is reported.
- Best performance is obtained at an optimal operating frequency of 600 Hz.
- The best jet-to-surface spacing is 15.
- Higher driven frequency pushes flow downstream and leads to higher heat transfer coefficient.

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ABSTRACT

In this study, impingement heat transfer from a synthetic air jet on a heated surface was experimentally studied. A synthetic jet provides a high heat transfer coefficient and a compact design, which is suitable for the thermal management of electronic devices. The synthetic jet is produced by the high frequency oscillating motion (200–800 Hz) of a piezoelectric actuator, and a jet Reynolds number ranging from 500 to 1300. The instantaneous and time-averaged velocity profiles of the synthetic jet issuing from the jet hole were measured using a hot wire anemometer. The jet hole diameter was 3 mm and the jet-to-surface spacing (Z/d) ranged from 0 to 25. The excitation frequency effect, jet-to-surface spacing, and jet Reynolds number were tested. The heat transfer enhancement of the synthetic jet was at least double the natural convective heat transfer. At a small jet-to-surface spacing, the warm air circulates inside small spaces, jeopardizing heat transfer. An optimal driven frequency of 600 Hz in this study provided the highest jet flow rates and heat transfer enhancement.

1. Introduction

In accordance with the advancement of electronic devices, appropriate cooling schemes and thermal management is required for preventing failure and ensuring a longer service life. A synthetic jet is a viable cooling scheme featuring zero net mass flux, compact design, and low cost. It can be easily integrated into the existing thermal management systems. A synthetic jet is typically produced by a high frequency oscillating motion that draws the surrounding working fluid and generates a jet flow. The oscillation of the actuator induces flow ejection and suction, which induces a zero net mass flux through the orifice. Because the synthetic jet is created entirely from the surrounding working fluid, it does not require an external fluid source. The fundamentals of synthetic jets can be reviewed in Ref. [1]. Using the synthetic jet flows produced by the advection and interactions of trains of discrete vortices induces a remarkably distinctive spatial evolution in comparison with traditional continuous jets. The amplitude and the diaphragm motion period alter the celerity and characteristic length scale of discrete vortices. The time periodic reversal in flow direction along the jet centerline (between the blowing and suction strokes) produces a stagnation point on the centerline downstream of the orifice, confining the suction flow to a narrow domain in the orifice vicinity. A comparison between the continuous jet and synthetic jet was conducted by Smith and Swift [2] at a Reynolds number of approximately 2000. In comparison with continuous jets, synthetic jets entrained more fluids proximate to the orifice, and thus the jet width and volume flux were higher. Synthetic jets possess wider and slower velocity profiles, compared with continuous jets. Regarding the far field, synthetic jets resemble continuous jets because the self-similar velocity profiles are identical. Thus, the averaged Nusslet number is comparable to that of continuous jets at a larger jet-to-surface spacing.

Impingement cooling is achieved by sending the coolant flow directly to the target surface, thus producing high heat transfer rates.

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Nomenclature

A	Area of the copper plate [mm^2]
A_{hole}	Area of the jet hole [mm^2]
d	Diameter of the jet hole [mm]
f	Driven frequency [Hz]
h	Heat transfer coefficient [W/m^2·K]
I	Current [A]
k	Thermal conductivity of the air [W/m·K]
L_o	Stroke length
Nu	Nusselt number
Nu_c	Nusselt number predicted by the correlation
Nu_e	Experimentally measured Nusselt number
$\dot{Q}_{in}$	Heat input [W]
$\dot{Q}_{loss}$	Heat loss during heat transfer experiment [W]
r	Radial distance [mm]
R	Electrical resistance of the heater [Ω]
Re	Reynolds number
t	Thickness of the test plate
T_w	Wall temperature [°C]
T_∞	Ambient temperature [°C]
u	Local instantaneous velocity [m/s]
$\overline{u}$	Local time-averaged velocity [m/s]
U_o	Orifice centerline velocity [m/s]
$\overline{U}$	Spatially averaged velocity [m/s]
V	Voltage [V]
Z	Axial distance [mm]
ν	Kinematic viscosity [m^2/s]
τ	Period of the oscillation motion [s]

Thus, heat transfer coefficients are dependent on parameters such as the nozzle diameter, jet-to-surface spacing, and Reynolds number. Comparisons between cooling using synthetic jets and continuous jets were performed by Pavlova and Amitay [3]. The jet formation frequency effects and jet-to-surface distances (Z/d = 0–40) were investigated. High formation frequency (1200 Hz) synthetic jets were observed to remove heat more efficiently than low frequency (420 Hz) jets did for small Z/d, whereas low frequency jets were more effective at larger Z/d. Moreover, synthetic jets were approximately three times more effective at cooling than were continuous jets at the same Reynolds number. The particle image velocimetry results from their studies [3] indicated that the higher formation frequency jets had been associated with the breakdown and merging of vortices before they impinged on the surface. For the lower frequency jets, the wavelengths between coherent structures were larger such that the vortex rings impinged on the surface separately. Shuster and Smith [4] indicated the distance traveled by the jet flow scales by using the stroke length (L_o). The vortex ring formed during the ejection phase of the actuation cycle dominated the flow, and the flow field scaled exclusively with the actuator stroke length in the near field of the orifice. The flow field resembled a conventional, round turbulent jet for distances from the orifice that were greater than the stroke length.

Arik [5] used mesoscale synthetic jets for the cooling of electronic components and the heat transfer enhancement was 4–10 times higher than the natural convective heat transfer. The local and global heat transfer coefficients of this high frequency (4500 Hz) mesoscale synthetic jet were subsequently determined [6]. Valiorgue et al. [7] investigated the heat transfer mechanisms of impinging synthetic jets for a small jet-to-surface spacing of two, because few heat transfer studies have been conducted for $Z/d < 4$. A critical dimensionless stroke length (L_o/Z) of 2.5 was reported. Using this critical stroke length, two heat transfer regimes were identified. The stroke length substantially influenced the heat transfer at the stagnation point at a low stroke length, and while this influence diminished, the synthetic jets acted as a continuous jet at a high stroke length. This ratio of stroke length to jet-to-surface spacing is expected to characterize the flow regime.

The influence of frequency and amplitude on a flow created by a synthetic jet was investigated by Qayoum et al. [8]. Hotwire anemometry and Schlieren visualization techniques were used. The velocity fluctuations increased because of amplitude modulation, and the effect was more pronounced at low modulating frequencies. Qayoum et al. [8] also reported heat transfer enhancement accompanied by the cross-flow interaction between a synthetic jet and a flat plate laminar boundary [9]. Results showed that the average heat transfer coefficient increased with the excitation amplitude and a maximum of 44% enhancement was observed. A detailed investigation of heat transfer of a synthetic jet was conducted by Chaudhari et al. [10]. The oscillation frequency effects (100–350 Hz), jet-to-surface spacing (Z/d = 0–25), radial distribution, and length of orifice plate (1.6–5 mm) were investigated. A heat transfer correlation was proposed based on the jet Reynolds number, stroke length, jet-to-surface spacing, and heater size. Additional studies regarding the orifice shape effect and the multiple orifice synthetic jets have also been reported [11,12].

In addition to direct impingement cooling, a synthetic jet has been used for flow control to enhance convective heat transfer. Zhang et al. [13] measured the convective heat transfer of a synthetic jet driven by a piston actuator with horizontally forced flow. The effects of excitation frequency (8–24 Hz) and the orifice shape on the flow and heat transfer characteristics were explored. Regarding all the orifice shapes, the peak laterally averaged convective heat transfer coefficient increased up to 100% at an oscillation frequency of 24 Hz when compared with the forced flow only condition. Rylatt and O'Donovan [14] investigated a confined impinging synthetic jet with and without ducting. The ducting design improved heat transfer by drawing cold air from a remote location into the jet flow. The Reynolds number was set at 3000 and the dimensionless stroke length (L_o/d) was 15. Among the various tested parameters, ducting offered the maximal increase in heat transfer at Z/d = 1. Evidently the heat transfer performance of a synthetic jet is strongly related to its velocity profile. However, information regarding the connection between flow and heat transfer was generally unavailable. Hence, the objectives of this study were to measure the heat transfer and flow characteristics of synthetic jet impingement cooling driven by a piezoelectric actuator. Instantaneous and average flow velocities of synthetic jet flow produced by the piezoelectric actuator with the driven frequency ranging from 200 to 800 Hz were not reported in the literature. Synthetic jet impingement heat transfer was experimentally determined, with an emphasis on the effect of oscillation frequency and jet-to-surface spacing. Correlations for heat transfer were developed based on the jet Reynolds number and the jet-to-surface spacing.

2. Experimental setup

In this study, the velocity distribution of the synthetic jet and the impingement heat transfer were investigated. A schematic of the experimental setup is shown in Fig. 1. The operating frequency and the voltage of the piezo actuator were controlled using a power