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# Flow field and heat transfer characteristics of impingement based on a vectoring dual synthetic jet actuator

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ABSTRACT

An innovative cooling technology based on a vectoring dual synthetic jet (DSJ) actuator is proposed, and then flow field and heat transfer characteristics are experimentally investigated. The deflection angle of vectoring DSJ can vary bilaterally and linearly with the movement of the adjustable slide. This novel feature makes the installation more flexible to obtain a maximum heat transfer coefficient and the effective heat transfer area is greatly extended, comparing to a conventional DSJ. The sweeping-flow capability can prevent the marginal region from working continuously at a high temperature. This cooling technology is expected to have important practical implications in space-constrained and large-area electronic cooling. Moreover, a model predicting the heat-transfer influence domain is established based on the vectoring angle of DSJ. The predicted results are validated to be in good agreement with the experimental results in the normal impingement region and the cross-flow region. It can provide a guide for properly arranging electric devices to improve the convective heat transfer.



## 1. Introduction

Increases in power levels coupled with reductions in feature sizes have resulted in continuously increasing heat fluxes of electric devices. When operating, these devices produce much heat that needs to be readily dissipated to prevent the thermal failure. Therefore, a high-efficiency and compact cooling solution is crucial to keeping the reliability of electric devices, and this need is predicted to grow continually in the foreseeable future.

Synthetic jet has been identified as a promising technique featuring no complex plumbing, compact design, low power consumption and high reliability [1,2]. Therefore, synthetic jet has been studied as a flow control technology for decades, such as jet vectoring control [3,4] and separation control [5–13]. In response to the increasing power density of electric chips, synthetic jet has been investigated as a cooling technology. The vortical structures can create a strong entrainment of surrounding air and a vigorous mixing near the heated surface, which are beneficial to heat transfer enhancement [14,15]. Synthetic jet is the interaction of a train of vortices that are formed by alternative ejection and suction of fluid across an orifice [16,17]. As a result, synthetic jet can substantially enhance the local heat transfer due to the vortex roll-up that disrupts the thermal boundary layer. Synthetic jet impingement cooling has received much attention from both industrial and academic points of view, because it can potentially extend the envelope of air cooling at a relatively high heat transfer rate. Synthetic jet was validated about three times more efficient than the continuous jet for impingement cooling at a same Reynolds number [18]. Valiorgue et al. [19] investigated the relation between the convective heat transfer and the flow field characteristics of impingement synthetic jet at a small jet-to-surface spacing. They elucidated the influence of impinging vortex on the distribution of time-averaged heat transfer coefficient. Chaudhari et al. [20] also studied the heat transfer characteristic of impingement synthetic jet. It was found that the maximum heat transfer coefficient of impingement synthetic jet was up to 11 times more than that of the natural convection. Persoons et al. [21] comparatively analyzed the heat transfer performances of axisymmetric impingement synthetic jets and steady jets at the stagnation point. They proposed a general correlation of Nusselt number at the stagnation point including the effect of all appropriate scaling parameters. Arik and Icoz [22] developed a closed form correlation as a function of jet geometry, position, and operating conditions of impingement synthetic jet based on experimental data. The predicted heat transfer coefficient was within 25% accuracy in a wide range. Greco et al. [23] found that a single impingement synthetic jet had a behavior similar to that of a continuous jet. At a low jet distance the heat transfer distribution showed an inner and an outer ring shaped region with a

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**Nomenclature**

| | |
|---|---|
| $A$ | effective area of heated surface ($m^2$) |
| $d_1$, $d_2$ | width of two slots (mm) |
| $d_o$ | slot width when the adjustable slider is at center (mm) |
| $H$ | slot-to-plate spacing (mm) |
| $h$ | convective heat transfer coefficient ($W/(m^2K)$) |
| $h_n$ | slot depth (mm) |
| $I$ | current through the foil (A) |
| $l$ | slot length (mm) |
| $Ma$ | Mach number |
| $Nu$ | local Nusselt number |
| $Q_{ele}$, $Q_{loss}$ | input power and total heat loss (W) |
| $q_{conv}$ | net removed heat flux ($W/m^2$) |
| $T_s$, $T_j$ | impingement surface and jet temperature (°C) |
| $V$ | voltage across the foil (V) |
| $x_s^*$ | dimensionless displacement of adjustable slider toward right |
| $Z_0$ | distance between cone apex and impingement surface (mm) |

*Greek symbols*

| | |
|---|---|
| $\theta$ | vectoring angle (deg) |
| $\theta_L$, $\theta_S$ | half-cone angles along long and short axis (deg) |
| $\lambda$ | thermal conductivity of air (W/(mK)) |
| $\sigma_T$ | standard deviation of temperature (°C) |

*Subscripts*

| | |
|---|---|
| max | local maximum at impingement surface |
| avg | spatially-averaged |

*Acronyms*

| | |
|---|---|
| CCD | charge-coupled device |
| DSJ | dual synthetic jet |
| PIV | particle image velocimetry |
| PZT | piezoelectric ceramic transducer |

local maximum, while for a higher jet distance such a feature disappeared. Mangate and Chaudhari experimentally investigated the effect of orifice shape with a same hydraulic diameter on the heat transfer and acoustic characteristics of impingement synthetic jet [24]. It was indicated that the maximum value of average heat transfer coefficient using diamond and oval shape orifices were 17% and 7% higher respectively with respect to the circular orifice at 200 Hz. An optimal driven frequency was attained to provide the highest jet flow rate and the best heat transfer of impingement synthetic jet [25]. Heat transfer characteristics of single-slot impingement steady jet and synthetic jet were comparatively analyzed by He et al. [26]. They concluded the synthetic jet exhibited up to a 40% increase in the heat transfer coefficient with respect to the steady jet. Chandratilleke et al. [27] proposed a novel thermal enhancement strategy for micro-scale heat transfer applications by combining a synthetic jet and a microchannel flow. Simulation results indicated that the combination cooling method increased the heat dissipation by about 4.3 times and the pressure drop did not increase than that of the channel flow without synthetic jet. Zhang et al. [28,29] found synthetic jet impingement cooling was much better than a continuous jet at a larger jet-to-surface spacing, and the orifice shape had a moderate effect on the convective heat transfer. A normal synthetic jet combining with a horizontally forced flow could enhance the heat transfer, especially at a high excitation frequency. Yu et al. [30] proposed a cooling method of air-cooled heat sinks integrated with piezoelectric-driven agitators and synthetic jets. It was shown that the combination cooling method increased the heat transfer coefficient by 82.4% with respect to the single channel flow. Recently, a pair of adjacent impingement synthetic jets was investigated on the heat transfer and flow characteristics [31]. An optimum configuration of slot-to-plate spacing and orifice-to-orifice center distance was obtained for the highest average cooling performance at a phase difference between 60° and 120°.

Dual synthetic jet (DSJ) actuator is a novel kind of synthetic jet actuator. A typical DSJ actuator consists of two slots and two cavities separated by a shared vibrating diaphragm [32,33]. The diaphragm vibration induces inverse changes of two cavity volumes, and then two synthetic jets are alternately generated from two slots with a phase difference about 180°. Comparing to a conventional piezoelectric synthetic jet actuator [3], the energy utilization efficiency and the jet frequency of a DSJ actuator are doubled due to the alternate formation of two synthetic jets. Vectoring DSJ actuator is a new generation of DSJ actuator, based on which an adjustable slider is introduced to control the vectoring deflection of DSJ [32,34]. This vectoring feature implies that the vectoring DSJ actuator is great useful for the large-area electronic cooling. Moreover, synthetic jet was been proven to be used at an optimum impingement angle in space-constrained applications without serious reduction in average heat transfer coefficient [35]. Therefore, the vectoring DSJ actuator will be beneficial to space-constrained cooling in an inclined layout with a normal impingement.

The present paper proposes an innovative cooling technology based on a vectoring DSJ actuator. The corresponding flow field and the heat transfer characteristics are analyzed experimentally using a particle image velocimetry (PIV) system and an infrared thermal camera, respectively. Moreover, a predicted model of the heat-transfer influence domain is established based on the vectoring angle, and it is validated with the experimental results.

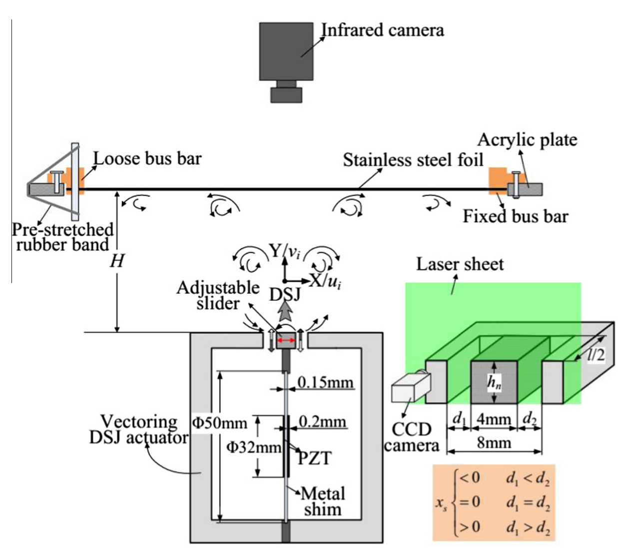


**Fig. 1.** The schematic of the experimental setup.