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Numerical investigation of heat transfer characteristics of impinging synthetic jets with different waveforms

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ABSTRACT

Synthetic jet, potentially useful in electronic cooling, is numerically studied considering various waveforms for the purpose of heat transfer enhancement and compare to the corresponding steady air jet. In the present study, sinusoidal, rectangular and triangular synthetic jets are applied to a confined two-dimensional slot jet impinging on a heated plate adopting SST/k-ω turbulence model. The jet frequency is varied from 10 to 400 Hz for Reynolds numbers (Re) in the range of 1553–7766 (Strouhal number $0.012 \le St \le 2.4$) and jet-to-surface distances ranging from 2 to 8. Generally, the cooling performance is enhanced by increase in Re and with the increase in frequency and H/W, the cooling performance shows a first increase and then decrease trend. Results of simulation indicate that conditions at the turning frequency correspond to critical $St = 0.24$–0.48 have higher heat transfer rate than other cases at the same Re. When $St < 0.06$, the heat transfer performance of rectangular jets can be better than the other two jets. When St is close to the critical St, the comparison of heat transfer enhancement is that triangular jets > sinusoidal jets > rectangular jets. Time sequence of streamline and velocity contour image is presented to further explain this phenomenon. Moreover, most conditions show good heat transfer enhancement compare to the corresponding steady jet except conditions in which St is too high ($St > 1.2$) or H/W is too low, or H/W is too large ($H/W = 2$ or $H/W = 8$). The maximum heat transfer enhancement coefficient of synthetic jets is found to be 74.7% higher than that of the corresponding steady jet.

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1. Introduction

The miniaturization trends of electronic components lead to higher thermal power density but smaller space to remove the heat. Moreover, the failure of electronic components usually appears due to thermal overstressing, which shows an increasing need for efficient heat removal in closely packed systems. Impinging jets, the focus of this paper, providing higher local heat and mass transfer on the impinged surfaces than natural convection and parallel forced flow, can be used efficiently in cooling of electronic components [1].

Much work has been carried out on optimizing the heat transfer of steady impinging jets over the years. Numerous parameters affecting the flow field have been extensively studied, such as jet-to-surface spacing, Reynolds number, and orifice shape [2–5]. The authors [6–9] have studied the flow and heat transfer characteristics of single jet or jet arrays impinging onto dimpled/protrusioned surface. Compared with traditional steady jet, pulsating jet with time dependent inlet velocity can obviously disturb the flow field which shows potential for further enhancement [10]. Klein et al. [11] used piezoelectric (PZT) actuator causing jets to pulsate with Reynolds and Strouhal numbers in the ranges of $756 < Re < 1260$ and $0 < St < 0.052$, respectively. The heat transfer coefficients were enhanced by up to 34%. Synthetic impinging jets, special kind of pulsating jets, are commonly formed when the fluid is alternately sucked into and ejected from a small cavity by the motion of a diaphragm bounding the cavity, so that there is no net mass addition to the system [12]. Because synthetic jets do not need long input pipe and complex pumping, it is more efficient to cool electronic components balancing the demand of compact structure and good heat removal.

In the review of published literature, much work has been done in the past study about the formation, flow filed structure, flow control applications, actuators design, and heat transfer capabilities of synthetic jets [13–20]. Recently, Pavlova and Amitay [1] experimentally studied the effects of frequency and Reynolds number at different nozzle-to-surface distances H/d on synthetic jets. He found that for small H/d, the heat transfer of synthetic jets at

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Nomenclature

D	hydraulic diameter (m)
f	frequency of oscillation (Hz)
$f_{t\text{-}S}$	turning frequency of S-wave jet
$f_{t\text{-}R}$	turning frequency of R-wave jet
$f_{t\text{-}T}$	turning frequency of T-wave jet
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
H	height of nozzle-to-plate distance (m)
K	control parameter of waveforms
L	length of the target plate
Nu	Nusselt number based on nozzle diameter
q	wall heat flux ($W \cdot m^{-2}$)
R	the abbreviation of rectangle
Re	Reynolds number based on nozzle diameter
R-wave	the abbreviation of rectangular wave
S	the abbreviation of sine
St	Strouhal number based on frequency
S-wave	the abbreviation of sinusoidal wave
t	time (s)
T	period (s)
T	temperature (K)
T	the abbreviation of triangle
T_a	ambient temperature (K)
T_{wall}	wall temperature (K)
T-wave	the abbreviation of triangular wave
U_0	mean velocity at the nozzle exit ($m \cdot s^{-1}$)
$u(t)$	instantaneous velocity ($m \cdot s^{-1}$)
W	nozzle width (m)
x	coordinate parallel to plate (m)
y	coordinate normal to plate (m)

Greek symbols

α	thermal diffusivity of the fluid ($m^2 \cdot s^{-1}$)
λ	thermal conductivity of the fluid ($W \cdot m^{-1} \cdot K^{-1}$)
v	kinematic viscosity of the fluid ($m^2 \cdot s^{-1}$)
ρ	density of the fluid ($kg \cdot m^{-3}$)
β	enhancement coefficient
t	period (s)

Subscripts/superscripts

avg	average
uns	unsteady
s	steady
a	ambient

high frequency $f = 1200$ Hz is better than that of at low frequency $f = 420$ Hz, but at larger H/d, low frequency jets show more effective. What's more, synthetic jets are about three times more effective in cooling than continuous jets at the same Re. Chaudhari et al. [21] showed that the synthetic jet performance is found to be comparable with continuous axisymmetric jet at low Reynolds number (up to 4000). Liu et al. [22] experimentally studied a synthetic air jet impinged on a heated surface. They found that an optimal driven frequency of 600 Hz in this study provided the highest jet flow rates and heat transfer enhancement. Greco et al. [23] studied the effects of nozzle-to-plate distance ($H/D = 2$–10) and of the stroke length ($L_0/D = 5, 10, 20$) on the cooling performances of impinging synthetic jets. Valiorgue et al. [24] investigated the impinging synthetic jet flow structure for a small jet-to-surface spacing ($H/D = 2$) and dimensionless stroke length ($1 < L_0/D < 22$). A critical stroke length ($L_0/H = 2.5$) that marks two flow regimes has been identified. He et al. [25] have performed experimental studies on single-slot impinging steady and synthetic jets. The best heat transfer of synthetic jets is observed 40% enhancement compared with the steady jet. Ghaffari et al. [26] studied the synthetic impinging jet local flow field using the particle image velocimetry (PIV) technique. Heat transfer results show that the maximum cooling performance occurs with a jet-to-surface spacing of $5 \leqslant H/D \leqslant 10$. From the literature, it is noticed that synthetic impinging jets can indeed cool electronic components efficiently under the appropriate situation. Like the steady jets and pulsating jets, the heat transfer capabilities of synthetic jets are also highly sensitive to parameters such as Reynolds number, jet-to-surface distance and frequency.

To numerically simulate the synthetic jets, numerical methods such as Reynolds-averaged Navier-Stokes (RANS) model, large eddy simulation (LES), and direct numerical simulation (DNS) are adopted [27–30]. However, considering the CPU time consuming and simulation accuracy, SST/k-ω turbulence model based on RANS model are used most usually [31]. As for geometry model, the synthetic jet behaviors could be described enough by 2d treatment method. For example, Lv et al. [32] carried out 2D numerical computation using RANS model. The vibrating diaphragm moves in sinusoidal mode described by the coupled user definition function (UDF). Kral et al. [33] employed a velocity distribution along the orifice as the boundary condition, which could capture the essential outflow field features of the jet without modeling the details of the cavity flow. For the study of heat transfer characteristics, we draw main attention to the outfield flow, so a velocity boundary condition adopted in the present work is enough.

Many studies have been published concerning shape of waveforms in pulsating jets. For example, Esmailpour et al. [34] studied the heat transfer of pulsating impinging jet using sinusoidal waveforms and concluded that with an increase in the frequency and amplitude of oscillation as well as decrease in nozzle to plate distance, the cooling performance is enhanced. Under certain conditions, heat transfer of the pulsating jet shows lower than that of the steady jet so that the critical frequency was introduced in this study. Herwig et al. [35] experimentally investigated unsteady impinging jets by imposing various shapes (Sinusoidal, triangular, rectangular et al.) and frequencies (1.25 Hz–40 Hz) of unsteadiness. He found that heat transfer augmentations by periodically unsteady jets only occur for high frequencies. Geng et al. [36] conducted a series of experiments about unsteady impinging jets considering combination of sinusoidal, triangular and rectangular jets at frequencies ranging from 1.25 to 20 Hz, triangular signals with different symmetry and rectangular jets with variable duty cycle. They also found that enhancements of heat transfer appear when the frequencies increase. Xu et al. [37] numerically studied a slot impinging jet whose inlet velocity varied in an intermittent (on-off) fashion.

However, few attentions have been paid to oscillation shape of actuating signals in synthetic jets. To further enhance the heat transfer rate of synthetic jets, active flow control techniques about waveforms proving useful in pulsating jets will be employed. In this study, a numerical simulation was done to further explore the efficiency of a confined synthetic slot jet impinging on a heated surface under different shapes of waveforms considering parameters about Reynolds number, frequency, and nozzle-to-surface

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