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Investigation of geometry and dimensionless parameters effects on the flow field and heat transfer of impingement synthetic jets

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ABSTRACT

In order to improve the cooling process in impingement synthetic jets, it is necessary to evaluate the influence of dimensionless parameters and the geometry of the flow field and heat transfer. In this paper, the effects of geometry (confined and unconfined impingement synthetic jets), and jet-to-surface spacings, Reynolds number and dimensionless stroke length on a three-dimensional unsteady impingement synthetic jet are studied. For this purpose, two types of turbulence models, namely the $v^2 - f$ and $SST/k - \omega$, have been employed. The simulation results have been indicated that the $v^2 - f$ model comparing to the $SST/k - \omega$ model has a close agreement with the available experimental data. The results show that the flow field and the corresponding heat transfer distribution of the impingement synthetic jet are affected by geometry such that an unconfined impingement synthetic jet is more efficient in a cooling process relative to the confined case. Also, increasing jet-to-surface spacing affects the vortex structure and consequently the heat transfer. The stagnation heat transfer rate reaches to the maximum value at an optimum impingement distance as a result of the appropriate ventilation and the coherence vortex structures. The stagnation heat transfer rate experiences several extrema as a result of the increasing stroke length and under the higher stroke length, the impingement synthetic jet acts similar to the impingement continuous jet.

1. Introduction

An appealing characteristic of impingement synthetic jets is the generation of vortex rings during cycles which has attracted researchers' attention in the field of electronic cooling, separation control, jet vectoring and mixing enhancement [1–4]. Synthetic jets are generated by oscillatory motions of an actuator with a certain frequency in a cavity and injected to a medium through an orifice. In a cooling application, an impingement synthetic jet without needing an extra energy source, can produce an oscillatory flow and has a much better efficiency in comparison with an ordinary impingement jet. The impingement synthetic jet consists of two strokes for the completion of a cycle: blowing and suction strokes. A vortex ring which is generated in the blowing stroke has to have enough energy to escape during the suction stroke. Then it impinges to the heated surface, moves radially along it and potentially can increase the heat transfer efficiency. In each cycle, a vortex ring is generated and leads to the set of vortex rings which moves toward the heated surface. The design and appearance of the impingement synthetic jets can improve the cooling process such that the impingement synthetic jets based on the appearance and design are categorized to the confined and unconfined impingement synthetic jets. The confined impingement synthetic jets are enclosed by two walls, around the orifice outlet (Fig. 1a). Although the unconfined impingement synthetic jets are similar to the confined ones, they do not have walls around the orifice outlet (Fig. 1b). However, this minor differentiation can affect extremely the heat transfer rate. A schematic of these types of synthetic jets and their components is shown in Fig. 1.

2. Literature review

Steady and oscillation flows have been considered in versatile applications namely, cooling of electronic devices and gas turbine blades, separation control, vectoring and mixing enhancement [1–6]. In the cooling process, employing steady or oscillation flow has been considered by researchers for many years. In the steady impingement jets and the impingement synthetic jets, several key dimensionless parameters affect the flow field and heat transfer rate. In an experimental study, Jambunathan et al. [7] have collated experimental data of impinging turbulent steady jets with Reynolds number in the range of 5000–124000. They found that existing correlations for local heat

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Nomenclature

D_c	Cavity diameter (^{mm})
D	Orifice diameter (^{mm})
D_T	Uniform temperature wall diameter (^{mm})
f	Frequency of diaphragm (Hz)
H	Jet-to-surface distance (^{mm})
h	Cavity height (^{mm})
h_c	Heat transfer coefficient ($W/m^2. K$)
L	Orifice height (^{mm})
L_0	Stroke length of synthetic jet (^{mm})
Nu	Nusselt number ($=h_c. D/\lambda$)
q''	convective heat flux (W/m^2)
r	Radial distance from the center of diaphragm (^{mm})
Re	Reynolds number ($=U_0. D/\upsilon$)
Sr	Strouhal number ($=f. D/U_0$)
St	Stokes number ($=\sqrt{f. D^2/\upsilon}$)
T	Time period of cycle (^{s})
t	Time (^{s})
$U(t)$	Instantaneous velocity (m/s)
U_0	Reference velocity (m/s)
$u(r, t)$	Instantaneous velocity at the diaphragm inlet boundary (m/s)
$\delta(r, t)$	Deformation of diaphragm (^{mm})
λ	Thermal conductivity ($W/m. K$)
Δ	Peak to peak displacement at the center of the diaphragm (^{mm})
θ	Local surface temperature (K)
θ_∞	Ambient temperature (K)
υ	Kinematic viscosity (m^2/s)
φ	Phase angle of oscillation (degree)
π	Pi number

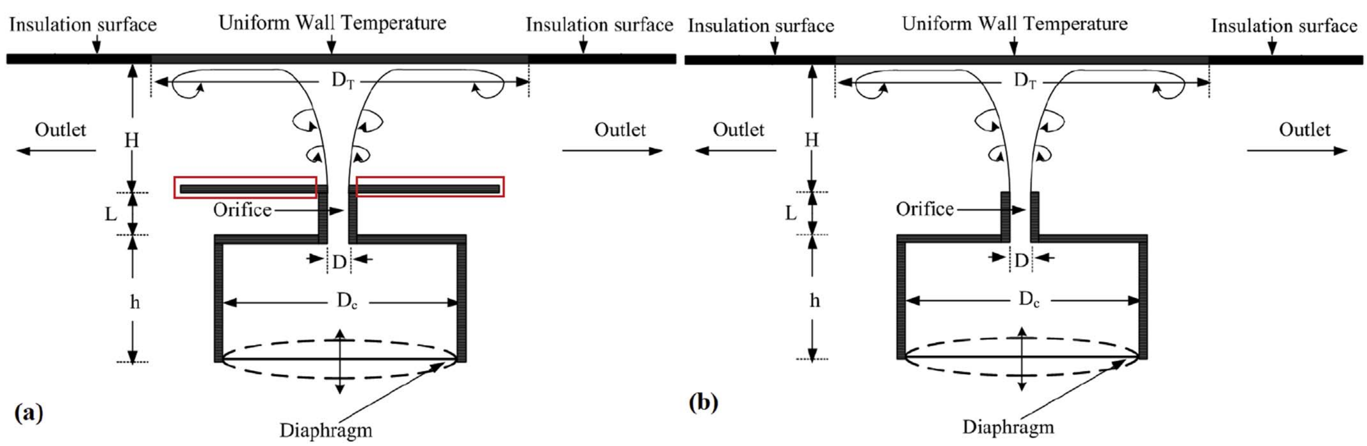

Fig. 1. A schematic of (a) confined (b) unconfined impingement synthetic jets.

transfer coefficient express Nusselt number as a function of Reynolds number raised to a constant exponent. However, the available empirical data suggest that this exponent should be a function of nozzle-to-plate spacing and of the radial displacement from the stagnation point. It is also suggested that the Nusselt number is independent of nozzle-to-plate spacing up to a value of 12 nozzle diameters at radii greater than six nozzle diameters from the stagnation point. Hoogendoorn [8], in an experimental study on heat transfer of the impinging steady jet, has shown the effect of turbulence on the stagnation zone. It has been reported that when a low turbulent jet is examined a Nusselt number value slightly higher than the stagnation point is observed. Colucci and Viskanta [9] have studied the effect of hyperbolic nozzle geometry on the local heat transfer coefficient for the confined impinging steady jets. Their experiments have been performed at the small nozzle to plate distances (between 0.25 and 6) and Reynolds numbers in the range of 10000–50000 on a uniformly heated impingement surface. It has been concluded that the local heat transfer coefficient for confined jets is more sensitive to Reynolds number and nozzle to plate spacing than that for unconfined jets. Xie et al. [10] have evaluated the application of ribs in gas turbine blade cooling process. For fixed mainstream and cooling flow Reynolds numbers, three ribs including continuous rib, centrally truncated rib and laterally truncated rib at two different blowing ratios (i.e., 0.5 and 1.0) are considered. They have reported that at lower blowing ratio, the result ensuing for each rib is identical but significantly outperforms the case without ribs. At higher blowing ratio, the heat transfer rate for the cases with ribs is lower than the case without ribs. Increasing efficiency with a synthetic jet firstly has been reported by Campbell et al. [1]. It has been shown through experimental studies that synthetic jets can improve the cooling process of a laptop processor. With an optimum combination of design parameters, they have shown that the synthetic jet can decrease the processor temperature rise by 22% in comparison with the uncontrolled case (i.e. without a synthetic jet). Nevins and Ball [11] have examined an oscillation impingement jet in a limited range of frequencies. The experiments have been repeated for several forms of waves: sinusoidal, quadratic, and triangular, however, in all cases, a significant impact has not been observed in the heat transfer rate. In the recent years, utilization of the synthetic jet for the improvement of heat transfer has grown significantly. The cooling process on a constant heat flux wall has been investigated by using a synthetic jet and the experimental results have been compared with a continuous jet [12]. In this study, the influence of several parameters namely, Reynolds number, orifice to surface distances and high and low frequencies have been examined. The results have shown that for small distances at high oscillation frequencies, the heat transfer coefficient is higher than low oscillation frequencies, whereas low frequencies have a better performance for lager distances. The performance of synthetic jets at small jet-to-surface spacings on a constant temperature surface has been addressed by McGuinn et al. [13]. The experimental observations have shown that the mean heat transfer distribution has a secondary peak for low jet-to-surface spacings due to high turbulent flow in the wall jet boundary layer. In another experimental study, Vukasinovic and Glezer [14] have proved that maximum heat transfer is not in the stagnation point; rather it is in a distance about half of the orifice radius. It has also been concluded that the heat transfer coefficient increases as a result of reducing jet-to-surface spacings and increasing frequency. The influence

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