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Heat transfer and flow characteristics of a pair of adjacent impinging synthetic jets

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ABSTRACT

The local convective heat transfer rate of an impinging synthetic jet has been shown to rival that of an impinging steady jet. Recent research has demonstrated a significant degree of interaction between adjacent synthetic jets, especially when generated from rectangular orifices. When operated in an impingement setup, adjacent jet interaction has been shown to enhance the convective heat transfer performance in some cases. This paper presents the findings of an experimental study to determine the effect of the orifice-to-impingement surface distance, H, and orifice-to-orifice centre separation distance, S, of a pair of synthetic air jets formed by two rectangular orifices with a span-to-width aspect ratio of 27:1 and a slot width $D = 1.65$ mm. The local convective heat transfer coefficient is determined on an electrically heated thin metal foil using infrared thermography. Particle image velocimetry (PIV) measurements of the flow field between the jet orifices and the impingement surface were performed. The jets are maintained at a constant Reynolds number and stroke length ($Re = 300$, $L_0/D = 29$). For the parameter range considered ($6 < H/D < 24$, $3 < S/D < 12$), an optimum configuration of $H/D = 24$ and $S/D = 3$ operated at a phase difference of $60^\circ < \Phi < 120^\circ$ gives the highest average cooling performance. For hot spot cooling, a configuration of $H/D = 6$ and $S/D = 3$ operated at a phase difference of $135^\circ < \Phi < 180^\circ$ gives the highest local maximum heat transfer. These results demonstrate the potential of this double impinging synthetic jet arrangement for actively controlled heat transfer applications.

1. Introduction

Impinging synthetic jets have been identified as a promising alternative to conventional steady cooling jets (Pavlova and Amitay, 2006; Campbell et al., 1998; Mahalingam et al., 2007). The primary advantage is that synthetic jets recycle ambient fluid and hence have a zero net mass-flux (ZNMF). As a result, there is no need for an external pressurised supply of fluid.

The basic concept of a synthetic jet has been described concisely as a time-averaged fluid motion generated by sufficient strong oscillatory flow at a sudden expansion (Smith and Swift, 2003). The oscillatory flow is typically driven by an oscillating diaphragm or membrane inside a cavity which periodically entrains and expels ambient fluid through an orifice to form a train of vortices and hence a time-averaged jet. Round orifices have been shown to form a train of vortex rings (Glezer and Amitay, 2002; Pavlova and Amitay, 2006; Persoons et al., 2011; Shuster and Smith, 2007; Smith and Glezer, 2001; Valiorgue et al., 2009) whereas slot orifices form counter-rotating vortex pairs (Beratlis and Smith, 2003; Glezer and Amitay, 2002; Smith and Glezer, 2005). For an orifice diameter or slot width, D, the Reynolds number, $Re = \rho U_0 D/\mu$, and stroke length, L_0, govern the flow field of a free synthetic jet. The stroke length is defined as the distance that a slug of fluid travels away from the orifice during the ejection portion of the cycle (Holman et al., 2005). In terms of the average ejection velocity U_0, it is defined as:

$$L_0 = \int_0^{1/2f} U_m(t)dt = \frac{U_0}{f} \tag{1}$$

The variables $U_m(t)$ and f are the instantaneous area-averaged orifice velocity and the driving frequency of the synthetic jet, respectively.

In the case of impinging synthetic jets, the flow structure is further characterised by the orifice-to-impingement surface distance, H, which determines the propagation distance of the vortices and the level of confinement and recirculation. Both Zhang and Tan (2007), Silva and Ortega (2010) remarked that there is an optimal H/D value where maximum convective heat transfer is observed. Too low a H/D value can lead to a narrow under-developed jet. If the H/D value is too high, the flow reduces in intensity at the impingement surface since the vortices lose coherence and decay into turbulence. Campbell et al. (1998), Gillespie et al. (2006)

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Nomenclature

A	jet orifice cross-sectional area (m^2)
a	speed of sound (m/s)
Bi	Biot number of the impingement foil (ht_s/k_s)
D	orifice slot width (m)
f	jet actuation frequency (Hz)
H	orifice-to-impingement surface distance (m)
h	convective heat transfer coefficient ($W/(m^2\,K)$)
h_{nat}	heat transfer coefficient for natural convection
K	jet orifice damping coefficient
k, k_s	thermal conductivity of air and foil (W/(m K))
L, L'	jet orifice length (geometric and effective) (m)
L_0	jet stroke length (m)
Nu	Nusselt number (hD/k)
δNu	dimensionless heat transfer enhancement $\delta Nu = (Nu(\Phi)–Nu(\Phi = 0))/Nu(\Phi = 0)$
p_c	relative cavity pressure (Pa)
Pr	Prandtl number of air
q''	convective heat flux (W/m^2)
Re	Reynolds number ($Re = \rho U_0 D/\mu$)
S	orifice-to-orifice centre distance (m)
T, T_{jet}	heated surface and jet cavity temperature (°C)
t_s	impingement foil thickness (m)
t	time (s)

U, V	wall-normal (vertical) and transverse velocity (m/s)
V_{wall}	dimensionless near-wall transverse velocity magnitude ($V_{\text{wall}} = \lvert V(x \approx 0, y)\rvert/U_0$)
U_0	average orifice ejection velocity (m/s)
V_c	jet cavity volume (m^3)
x, y	wall-normal (vertical) and transverse coordinate (m)
z	out of plane transverse coordinate (m)

Greek symbols

α	jet orifice aspect ratio (span to width)
Φ	phase difference between jet actuators (°)
μ	dynamic viscosity of air (Pa s)
ρ	density of air (kg/m^3)
ϑ	phase angle in jet period (=360 ft) (°)

Subscripts

0	characteristic scale for synthetic jet flow
c	synthetic jet cavity
m	spatial average in orifice cross-section
max	local maximum at impingement surface
avg	spatially-averaged at impingement surface across $-35 < y/D < 35$ and $-13.5 < z/D < 13.5$

reported recirculation of heated fluid into the jet cavities for low values of H/D.

The distance travelled by coherent vortex pairs before they decay not only depends on how close the impingement surface is from the orifice or nozzle i.e. H but also on the amount of fluid ejected per stroke i.e. the stroke length L_0 (Pavlova and Amitay, 2006; Shuster and Smith, 2007; Silva and Ortega, 2010). Valiorgue et al. (2009) related both orifice-to-impingement distance and stroke length and found a critical $L_0 / H \cong 2.5$. For values below this, the heat transfer rates are significantly affected by stroke length and for values above, they are independent of stroke length. These findings have been extended by Persoons et al. (2011) to cover a wider range of stroke lengths and orifice-to-impingement surface distances. The authors developed a correlation for the stagnation Nusselt number for a single axisymmetric impinging synthetic jet, demonstrating a convective heat transfer rate similar to that of a steady impinging jet.

The flow field for a pair of *free* synthetic slot jets was examined by Smith and Glezer (2005), Luo and Xia (2008) using particle image velocimetry (PIV). Both authors reported an enhancing or enlarging effect on the overall jet when the two jets are operated in phase (i.e. zero phase difference). This effect is due to attraction and merging of adjacent vortex pairs. Smith and Glezer (2005) also reported that the flow rate is twice that of a single jet since each jet entrains fluid from one side. Other enhancements were also noted. Firstly, the merged vortex pair remains more coherent compared to a single jet. Secondly, there is a higher velocity further downstream compared to a single jet. Applying a phase difference Φ between the jet actuators causes vectoring of the overall jet field in the direction of the jet leading in phase. The vortex pairs, in this case, do not merge or coalesce but instead experience a vectoring mechanism which Luo and Xia (2008) call 'attract-impact causing deflection'. The vortex pair lagging in phase is attracted towards the leading vortex pair, impacting it and subsequently deflecting it. This causes the combined jet to be vectored in the direction of the jet leading in phase.

For a pair of *impinging* synthetic slot jets, this vectoring effect was shown by Persoons et al. (2009) to induce a cross-flow which provides fresh cooling fluid to the jets. This effect prevents recirculation of heated fluid to the cavity without the need for an external cross-flow (e.g. driven by a fan) and was shown to enhance the convective heat transfer performance of the jet pair. Heat transfer and PIV measurements by Persoons et al. (2009) suggest an optimum phase difference region of $90° < \Phi < 120°$ for constant values of $Re = 300$, $L_0/D = 29$ and an orifice-to-orifice centre separation of $S = 3D$. In this range of phase difference an effective cross-flow was set up whilst maintaining strong vortex mixing at impingement, resulting in the highest convective heat transfer rates.

There remains little literature on the effect of orifice-to-orifice distance S for adjacent synthetic slot jets. Recently, Greco et al. (2013) compared two round-orifice adjacent synthetic jets to a single round-orifice synthetic jet at a Reynolds number and stroke length of 6700 and $22D$ respectively. The orifice-to-orifice separation S was set to $1.1D$, $3D$, and $5D$. The authors observed little or no interaction for $S = 3D$ and $5D$. However, they observed a double vortex ring structure for $S = 1.1D$ which lead to a higher jet centreline velocity and a lower width.

Recently, as a follow-up to the work by Persoons et al. (2009), the authors have presented preliminary results in Fanning et al. (2013) for a wider range of S/D and H/D. The current paper employs PIV and infrared thermography heat transfer coefficient measurements in a wide range of geometric parameters, including the orifice-to-impingement surface distance ($6 < H/D < 24$) and the orifice-to-orifice distance ($3 < S/D < 12$). The local Nusselt number and near-wall flow characteristics are studied in detail, and the mechanism of cross-flow induced by the out-of-phase synthetic jets is discussed.

2. Experimental approach

2.1. Impinging synthetic jet facility

Fig. 1 illustrates the main components of the test setup. Two Visaton FR 8 speakers inside polyamide rectangular cavities force ambient air through an accurately machined acrylic orifice plate 10 mm in thickness with a slot width of $D = 1.65$ mm and span of