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Research Paper

Heat transfer enhancement to an array of synthetic air jets by an induced crossflow

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HIGHLIGHTS

- Higher heat transfer was achieved by operating the synthetic jet array out of phase.
- Strong dependence between jet vectoring, axial spacing and stroke length.
- Vectoring occurs at stroke lengths and axial spacing.
- Maximum jet vectoring occurs at & lowest overall heat transfer at.
- Vectoring is achievable in arrays of more than two adjacent synthetic jets.

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ABSTRACT

Jet vectoring and crossflow enhanced heat transfer to a modular synthetic air jet array consisting of six individually controllable parallel slot jets is investigated. When applied in a multi-jet array, jet vectoring can be implemented to operate as an adaptive, modular heat exchanger capable of dynamically targeting hot spots and enhancing local cooling. Time averaged surface heat transfer distributions are presented for varying Reynolds number, stroke length and axial spacing. It is shown that crossflow is achievable for an array of jets; however vectoring performance is dictated by inter-jet phase delay and limited by axial spacing and stroke length. All operating parameters showed increased levels of heat transfer are produced by operating the array out of phase. In particular, at small axial spacings this is attributed to crossflow generated by the out of phase jet pulsation.

1. Introduction

A synthetic jet is a relatively new technology which has shown great potential for applications in a number of fields such as aerodynamics where it can be used to delay the boundary layer transition and control flow separation. Other applications include providing propulsion for automated underwater vehicles (AUV) and for heat transfer applications such as microprocessors and manufacturing processes. Synthetic jets are based on an established, robust, reliable and scalable technology which can be assembled into modular heat exchanger arrays. It is for these reasons that they're particularly attractive for applications in extreme environments.

A single synthetic air jet is created when a periodically reversible flow is established across an orifice located on a wall of an enclosed chamber. The periodic flow produces a non-zero mean stream-wise pulsating jet in front of the orifice. To achieve oscillatory flow, one wall must be formed using a flexible membrane which is commonly excited by a motor, piezoelectric or electromagnetic actuator. The resulting streamwise pulsating jet emanating from the orifice can be directed at a heated object to provide cooling. For any given synthetic jet there are two key parameters which govern the synthetic jet flow field. These parameters are Reynolds number $Re = \rho U_0 d/\mu$ (d is the characteristic length scale, slot width) and stroke length and can be calculated from the average jet exit velocity U_0:

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

where f is the actuation frequency and $U_m(t)$ is the mean exit velocity.

Many studies have been undertaken into heat transfer to single impinging synthetic jets [1–4] which demonstrate how effectively they can remove heat. Due to their periodicity synthetic jets produce high level of turbulence within the jet flow. The resulting

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Nomenclature

A	orifice cross-sectional area (m^2)
A_{surf}	foil surface area (m^2)
c	speed of sound (m/s)
d	characteristic lengths scale (mm)
f	actuation frequency (Hz)
f_0	Helmholtz frequency (Hz)
h	heat transfer coefficient (W/m^2 K)
h_o	orifice height (mm)
h^*	local heat transfer enhancement (–)
h'	effective orifice height (mm)
H	axial spacing (mm)
I	current (A)
k	thermal conductivity (W/m K)
K	orifice pressure loss constant (–)
L_0	dimensionless stroke length (–)
P	total actuation power (W)
$\|p_a\|$	acoustic cavity pressure (Pa)
q_{ohm}	heat flux (W/m^2)
s	inter-jet spacing (mm)
t	time (s)
T_{surf}	local surface temperature (°C)
Re	Reynolds number (–)
U_0	average jet exit velocity (m/s)
U_m	mean jet exit velocity (m/s)
$\|U_{avg}\|$	orifice velocity amplitude (m/s)
V	voltage (V)
V_c	cavity volume (m^3)
x	x-coordinate (mm)
y	y-coordinate (mm)
α	slot aspect ratio (–)
β	orifice correction factor (–)
ε	emissivity (–)
θ	phase angle (°)
ρ	density (kg/m^3)
μ	dynamic viscosity (Ns/m^2)

small scale mixing is highly effective at stripping heat from hot surfaces and has been shown capable of outperforming similar continuous air jets [5]. However, a limitation of the technology is their ineffectiveness in highly confined situations [6,7], including array configurations [8,9]. Under these conditions, ambient fluid becomes continuously re-circulated and as the fluid temperature increases the jet's ability to remove heat is impaired [10]. Many applications also produce uneven or intermittent heat flux distributions. It may be possible to negate this problem through the implementation of an adaptive, modular heat exchanger, capable of dynamically targeting hot spots and inducing crossflow, thereby providing a constant stream of cooler air with which to remove heat. Rylatt and O'Donovan [11] implemented ducting between the jet exit and confined impingement surface in order to entrain cooler ambient air into the jet flow during the suction phase of the cycle. The authors reported that an area averaged enhancement in heat transfer of up to 36% was achievable. Trávníček et al. [12] investigated the possibility of enhancing synthetic jet flow by implementing a more complex valve-less pump. The authors reported that the generated jet is comparable with a conventional axisymmetric fully developed turbulent jet for large distances from the nozzle. However, no confined impingement data was reported upon.

A number of authors have reported on synthetic jet arrays for heat transfer purposes [8,9,13], however all have been driven by a single actuator producing multiple in-phase jets. Campbell et al. [8] concluded that multiple jets were capable of cooling a greater area while Chaudhari et al. [9] found that at lower axial spacing an array provided up to 30% better cooling performance compared to a single orifice. Both studies reported on jets formed by an array of round orifices, and while no flow visualisation was undertaken, neither study noted any significant inter-jet interaction.

Reporting on free, adjacent, synthetic jet pairs with slot geometry both Zhen-Bing and Zhi-Xun [14] and Smith and Glezer [15] showed that controlled jet vectoring is possible by operating the jets out of phase. All investigations into synthetic jet vectoring have implemented a dual adjacent slot jet arrangement. Such an arrangement optimises the available area for inter-jet interaction and therefore maximises the ability to achieve jet vectoring. Flow visualisation data in both studies showed that vectoring is influenced by the inter-jet interaction in both the blowing and suction cycles. Zhen-Bing and Zhi-Xun [14] presented data showing that jet vectoring tends towards the leading jet, with the strongest vectoring occurring for a phase delay of approximately 60–90°. The authors also showed that jets operating in-phase but at varying relative amplitudes also produced jet vectoring. This study reported that flow was vectored towards the jet with higher driving amplitude. Combined flow visualisation and heat transfer data presented by Persoons et al. [16] and Fanning et al. [17] showed how a vectoring jet pair producing cross flow can enhance heat transfer from a heated impingement surface. As with Smith and Glezer [15], the authors operated the jet at a stroke length of $26d$ as well as the shorter stroke length of $10d$, the axial spacing, H was varied between $6d$ and $24d$. Peak heat transfer was observed at a phase delay of between 60° and 120° producing a 50% increase in heat transfer compared to a jet with zero phase difference. While these preliminary results are promising and show that it is possible to establish a cross-flow capable of increasing surface heat transfer, much remains unknown about the overall performance and operational limitations of the jets at various axial spacings, dimensionless stroke lengths, Reynolds numbers and inter-jet spacings. More recently Greco et al. [18] showed that heat transfer enhancement can be obtained by operating a pair of adjacent synthetic jets 180° out of phase, however no vectoring was reported. To date, no studies have been undertaken investigating whether it is possible to establish jet vectoring or cross flow using more than two jets. This paper sets out to show that a modular synthetic jet array operating a significant number of adjacent jets can function as an adaptive heat exchanger in order to achieve similar or greater rates of heat transfer to one operated in phase.

Synthetic jets contain no wear components such as bearings, brushes, seals, sliding surfaces, require no lubrication, and operate using an acoustic speaker which is an established, reliable technology with very few modes of failure. This reliability makes them ideal for operation in extreme environments. The most common failures in defence-related electronic systems as experienced by the US Air Force are dust, humidity, vibration and temperature [19]. With no moving parts it is expected that a speaker would last significantly longer, with ultimate failure more likely caused by power electronics rather than mechanical failure. It is for these reasons it is ideally suited to being implemented as a heat exchanger technology in extreme environments.