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Influence of multi-perforation synthetic jet configuration on heat transfer enhancement

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ABSTRACT

The multi-perforated wall of synthetic jets bas been analyzed to enhance heat transfer under laminar and turbulence cross-flow and for several dynamic configurations. To study the role of cross-flow and synthetic jet interactions, a dedicated experimental set-up was developed with convective heat transfer coefficients along the wall. Multi-perforated results were directly compared to single synthetic jet data. Sensitive parameters such as jet frequency, piston amplitude displacement and cross-flow velocity were determined. Heat transfer from the synthetic jet device can be amplified from 23 to as much as 175% depending on experimental conditions. The role of multi-perforating plate with regard to the single row configuration is clearly demonstrated. It is reinforced by continuous interaction between the main flow and synthetic jets.

1. Introduction

A synthetic jet device is mainly used to control flow field [1–4] without adding mass flow rate, jets being characterized by an ejecting and a suction phase. As a consequence, such a device is a zero-net-mass-flux; Holman et al. [5] have characterized the jet dynamically by the $\bar{W}$ average velocity level during the ejection phase. Synthetic jets enhance heat transfer for mostly impinging configurations; the jet output is located perpendicular to the wall in order to cool it down. In a synthetic jet without cross-flow and impingement configuration, Ghaffari et al. [6] emphasized the influence of the distance between the wall and the orifice. They also showed that the optimal space for cooling ranged from 5D to 10D and demonstrated the role of coherent vortex structures in the thermal process. Greco et al. [7,8] underlined the role of vortex ring on the flow field [7] and heat transfer [8] depending on the distance from orifice to the heated plate. In cross-flow and perpendicular configurations the role of synthetic jets in heat transfer has been studied [9–11]. Qayoum et al. [9], and Jabbal and Zhong [10] underlined, in a laminar flow condition, a maximum of 44% increase of convective heat transfer downstream from the orifice [9] and showed that the thermal footprint was similar to the flow pattern downstream from a cylinder [10]. On the other hand, in our dedicated test bench [11] we have focused on local and unsteady velocity disturbances during a synthetic jet period, the effectiveness of the resulting averaged jets being determined by the velocity ratio of the characteristic ejected velocity to the U_∞ cross-flow; as soon as U_∞ is strong enough to confine arising jet, its effect on heat transfer efficiency is significantly reduced. In the configurations studied, an increase of +20% on convective heat transfer was obtained along a characteristic distance downstream from the orifice; away from 2.8D, no significant effect of the synthetic jets was identified (i.e. an increase less than +20%). Multi-perforation was then necessary for spatially enhanced heat transfer.

Multi-perforation of non-synthetic jets has been widely studied [12–18], principally because of its applications in turbojet engine cooling. More precisely, combustion chamber and turbine blades are protected through cold air injected through multiple perforations. Many parameters have been shown to influence heat transfer: angle of jet injection, jet injection Reynolds number, velocity ratio M, distance between jets in a given row and distance between rows or pattern of jet injection (inline or staggered). Few studies have analyzed the development of the flow issuing from the jets along the plate. The closest study to the present one is Petre et al. [14]. In this study, for perpendicular injections, the authors observed that velocity profiles and heat transfer rate do not evolve significantly after the fifth row. However, this position could change due to the inclination of the injections [13]. Coulthard et al. [17,18] have studied the influence of multi-pulsating jets in heat transfer enhancement compared to the same cases with continuous jet. They underlined the increase of heat transfer coeffi-

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Nomenclature

a	piston stroke [m]
D	orifice diameter [m]
f	jet actuation frequency [Hz]
h	convective heat transfer coefficient [W/(m^2·K)]
M	velocity ratio, $M = \frac{\bar{W}}{U_\infty}$
r_p	distance between the motor axis and the rod attachment (a /2) [m]
T	temperature [K]
t	time [s]
U, V, W	horizontal, longitudinal and vertical velocity component [m/s]
$\bar{W}$	synthetic jet mean ejection velocity, $\bar{W} = 2f\int_0^{1/2f} W(t)dt$
X, Y, Z	horizontal, longitudinal and vertical coordinates, [m]

Greek symbols

λ	fluid thermal conductivity, [W/(m·K)]
φ	flux density [W/m^2]

Dimensionless number

Re_j	Reynlods number of the synthetic jet, $Re_j = \frac{\bar{W}D}{\nu}$
St	Strouhal number, $St = \frac{2\pi f D}{\bar{W}}$
Nu	Nusselt number, $Nu = \frac{hD}{\lambda}$

Subscripts

∞	main flow air parameter
elec	electrical dissipation power
exp	experimental results
cond	conduction
conv	convective
j	synthetic jet air parameter
rad	radiative
rms	root mean square velocity
the	theoretical results
$-$	average component
$*$	coordinate relative to orifice diameter D

cient with the pulsating compared to the non-pulse case; the higher the frequency the stronger the heat enhancement.

Nevertheless, all of the above multi-perforation studies have involved non-synthetic jets. To our knowledge, no studies have dealt with a multi-perforated plate of synthetic jets and their influence on heat transfer. However, such a configuration could be encountered in industrial configurations. In particular, in turbofan, synthetic jets are produced throughout the duct behind the fan.

To depict the role of multi-perforation in heat transfer, an existing experimental test section was equipped with 10 synchronized rows of 5 synchronized synthetic jets. To underscore multi-perforation influence, the configurations previously investigated for a one-row case [11] were subsequently examined for a 10-row configuration, and new parameters were added. Cross-flow velocity ranged from U_∞ = 1.9 to 12.8 m/s; the Reynolds number was consequently large and facilitated depiction of both laminar and turbulent cross-flow conditions. Similarly to multi-perforation injection plates [19–21], the momentum ratio between jets and cross-flow is a significant parameter in synthetic jets [11]; in a previous article, we explicitly underlined the role of synthetic jet development during each phase, particularly around the orifice, on unsteady local flow and, consequently, on heat transfer enhancement. The effect of multi-perforated synthetic jets was then parametrically studied and amplitude of piston motion and frequency were dynamically and thermally analyzed.

2. Experimental facility and measurement techniques

The experimental set-up consists mainly of a synthetic jet system located within a closed wind loop tunnel; along with the measurement techniques, it was extensively described in a previous work [11] and hereinafter only the main issues will be mentioned.

2.1. Experimental facility

As seen in Fig. 1, experiments were conducted in a closed loop wind tunnel that was controlled in both mass flow rate and temperature, with a test section at 80D × 80D × 400D (with D the orifice diameter equal to 6.25 mm). Except for the lower section, the wall tunnel was made in Plexiglas for velocity measurements. Part of the upper wall could be replaced by an IR window for thermal measurements. On the ground level of the test section, a 27.2D × 48D plate (in black in Fig. 1) i.e. the measurement area, was located 192D away from the beginning of the wind loop tunnel.

Fifty orifices were uniformly distributed in ten rows of 5 holes. They were positioned at 8D downstream from the beginning of the measurement region and perpendicular to the tunnel flow. Each row, like each line, was spaced by 2.8D. All synthetic jets were created by 50 pistons (Fig. 2, A) sliding inside a multi-perforated bronze block (B). From this block to the wind tunnel, the orifice air volumes were linked by a plastic pipe (C) through a polyurethane block as well as the electrical plate designated as D and E respectively in Fig. 2. An electrical motor was used to produce piston motion and a disk was installed to accurately control motion amplitude. Synthetic jet frequency was established by the up-and-down piston motion frequency through the motor speed controller.

2.2. Measurement techniques

As explicitly detailed in the experimental facility section, an electrical plate was located all around the fifty orifices along the 27.2D × 48D (170 × 300 mm^2 in real size) plate. Generating constant heat flux density dissipation, the plate was made of 0.4 mm epoxy glass thickness engraved by a thin copper foil circuit. A FLIR titanium infrared camera was used to measure wall surface temperature through an IR window. The electrical plate was linked

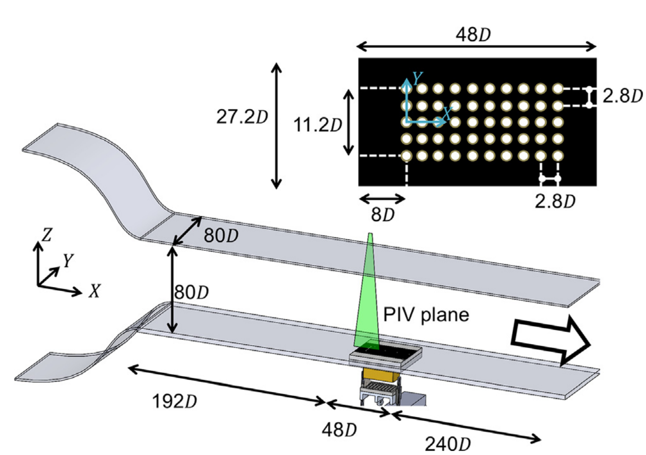

Fig. 1. Wind loop tunnel and electrical heated plate dimensions.