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Influence of Reynolds number synthetic jet dynamic in crossflow configuration on heat transfer enhancement

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ABSTRACT

The influence of synthetic jets on heat transfer rate along a flat plate has been studied for laminar and turbulence cross-flow and at several exciting frequencies ($0 < f < 12.8$ Hz). To better understand such interactions, both cross-flow field without and with synthetic jets in a quiescent environment were preliminarily reviewed. The influence of their confrontation on flow structure was studied, particularly for a frequency of 12.8 Hz and the roles of this frequency as well as four others on heat transfer coefficient were determined. Lastly, the influence of cross-flow velocity with its fluctuating activity on synthetic jet development was closely observed.

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1. Introduction

Synthetic jets or zero-net-mass-flux jets correspond to dedicated flows controlled in two distinct phases; a suction phase of the surrounding fluid through a given orifice and an ejection phase of the same mass flow through the same orifice. As a consequence, upward and downward motions are unsteadily induced while time-averaged velocity is equal to zero. Synthetic jets can be induced from several different actuators or devices such as a Helmholtz resonator from a loudspeaker excitation [1], a piezoelectric device driving a membrane [2] or a mechanical here-and-there piston motion [3]. Synthetic jets are mainly characterized by a given velocity and following Holman et al. [4], the governing parameters for a synthetic jet are stroke length (L_0), the corresponding Reynolds number (Re_j) and the Strouhal number (St), based on the average velocity ($\overline{W}$) along the ejected mid-period and total exit surface A:

$$\overline{W} = 2f\frac{1}{A}\int_A \int_0^{1/2f} W(t,X)dt\,dA = 2W_0 \quad (1.1)$$

$$W_0 = fL_0 = f\int_0^{1/2f} W_c(t)dt \quad (1.2)$$

$$Re_j = \frac{\overline{W}D}{\nu} \quad (1.3)$$

$$St = \frac{2\pi fD}{\overline{W}} \quad (1.4)$$

Although synthetic jets have not been as extensively studied as continuous jets, they have aroused increased interest over the last few decades. In this context, the flow mechanisms induced [5,6] and their interaction with a potential cross-flow need to be better understood. Glezer and Amitay [7] presented a comprehensive review of the flow field behaviors involved in synthetic jets. Without cross-flow and in an open environment, Tescar and Kordík [8] developed an analytical model to depict synthetic jets. Based on a quasi-similarity transformation, the model can estimate spatial distribution of most variables of interest, turbulent parameters included. In an experimental analysis, Smith and Swift [9] compared synthetic and continuous jets; synthetic jets favor entrainment of surrounding jet close to the orifice, and turbulence is highlighted more than in a continuous jet. Far away from the injection area, however the two jet topologies are similar in a quiescent environment. As clearly pointed out by Glezer and Amitay [7], interactions between synthetic jets and the main flow have direct influence on the characteristic scale of jets. Other authors such as Milanovic and Zaman [10], Jahori [11], and Welch et al. [12] have characterized synthetic jet in cross-flow topologies numerically and experimentally. Straight and pitched orifices in a wide range of Reynolds numbers of cross-flow, as well as the momentum ratio between the jet and main flow, have been extensively studied by

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Nomenclature

a	piston stroke [m]
A	jet orifice area, [m^2]
D	orifice diameter, [m]
f	jet actuation frequency, [Hz]
h	convective heat transfer coefficient, [W/(m^2 K)]
L_0	jet stroke length, [m]
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]
X, Y, Z	horizontal, longitudinal and vertical coordinate, [m]

Greek symbols

ε	wall emissivity, [–]
λ	fluid thermal conductivity, [W/(m K)]
υ	kinematic viscosity of air, [m^2/s]
φ	flux density, [W/m^2]

Dimensionless number

Re	Reynolds number
St	Strouhal number
Nu	Nusselt number

Subscripts

∞	main flow air parameter
rad	radiative
rms	root mean square velocity
$conv$	convective
$cond$	conduction
$elec$	electrical dissipation power
w	flat plate
–	average velocity component
★	coordinate report to orifice diameter D

Welch et al. [12], who showed that the trajectories of synthetic jets are well-represented by the continuous jet correlation available in the literature.

For synthetic jets, the time-averaged flow field can be compared to turbulent continuous jets in a crossflow configuration (JICF) and common features can be emphasized: (1) normal to the crossflow in the near field of orifice, to being (2) aligned with the crossflow in the far field part. Along this baseline, a pair of counter-rotating vortices are created. Additional vortex structures near the jet exit are created, due to the interaction of the crossflow boundary layer and the orifice, as the horseshoe structures behind the orifice or the wake-vortex connecting the jet to the boundary layer along the wall in the wake of the jet. Essential parameters such as the velocity ratio between the jet and the cross-flow [13], the orifice shape [14] or the cross-flow boundary layer [13] are exhibited.

During the ejecting phase of the cycle without crossflow a ring vortex is created. Following several cycles, a train of vortex rings is induced and far away from the orifice they decay at their own self-induced velocities. In a boundary layer flow, i.e. with cross-flow, the ring vortex are combined with the shear boundary layer to created three-dimensional complex vortex structures, as hairpin vortex or tilted vortex rings. Downstream from the orifice with low jet-to-freestream-velocity ratio, hairpins vortex close to the wall are created. With the increase of this ratio the confrontation between the crossflow and the synthetic jet created tilted vortex with a pair of trailing secondary vortex as described by Jabbal and Zhong [15].

Fundamental studies have elucidated flow dynamics, and some features of synthetic jets have shown promise in several dedicated applications such as heat transfer enhancement and flow control. In this domain, these actuators offer an easy way to control flow behind an obstacle such as an aircraft wing [16–18]. With this objective in mind, Xu et al. [18] studied design optimization of backward-facing step flow control with a synthetic jet and found an optimal configuration for the reduction of the attachment zone at a given frequency and a given injection angle. Several authors [19–27] have tried to increase heat transfer rate using synthetic jets in an impinging configuration. Fanning et al. [27] studied two synthetic jets impinging upon a flat wall and underlined the influence of several geometrical parameters for a given and constant Reynolds number. Nozzle-to-plate distance is an important heat transfer parameter and the optimal cooling point along the plate has been reached at a distance equal to 24D. In addition, the distance between the two jets and phase shift between the two actuators help to determine heat transfer rate [28–30]. Other studies have been conducted on impinging synthetic jets in micro channel configuration in presence of a cross-flow [31–35], and synthetic jet impingement leads to more than a fourfold increase in heat dissipation. Indeed, at a given frequency, the increased amplitude of the synthetic jet significantly improves heat transfer. Conversely, as shown by Chandratilleke et al. [35] cross-flow speed significantly damps down heat transfer efficiency. Few works were devoted to the development of synthetic jet in cross-flow with heat transfer at the same level from the orifice. Qayoum et al. [36], for instance, studied such a configuration under laminar flow conditions with a piezoelectric device functioning as synthetic jet actuator; a 44% increase of the convective heat transfer downstream from the orifice for the higher amplitude was achieved. Jabbal and Zhong [37] similarly studied the development of synthetic jet generated by a diaphragm in laminar water cross-flow; a crystal-based thermochromics liquid was used to view the thermal evolution. The authors showed that the thermal footprint was similar to that of oil flow pattern downstream from a cylinder.

Focusing on the effects of synthetic jets in cross-flow, an experimental test section was developed to depict the influence of synthetic jet frequency on heat transfer. In a closed thermally controlled wind loop tunnel, the mean velocity (U_∞) ranged from 0 to 6.6 m/s and five synchronized synthetic jets were positioned perpendicular to the main flow. Frequency ranged from 0 to 12.8 Hz while piston stroke was equal to 22 mm. Consequently, average velocity ($\overline{W}$) reached levels ranging from 0 to 2.1 m/s. A five jet row configuration was chosen to reduce edge effect around the central jet.

One of our objectives is to explore the link between heat transfer enhancement of a given flow field along a flat plate and synthetic jets. For this reason, the latter were located within a given cross-flow. For comparison, wind flow was initially studied alone (without synthetic jets). Two main velocities were imposed: U_∞ = 1.9 m/s and 6.6 m/s corresponding to low and high fluctuation flows respectively, while synthetic jet in a quiescent environment (U_∞ = 0) was analyzed dynamically to understand the flow during its different phases. Synthetic jet row was studied with the two main cross-flows and for the different frequencies presented in Table 1 (in particular 3.2 and 12.8 Hz), both dynamically and

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