Experimental Thermal and Fluid Science 74 (2016) 354–367

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Investigation of impinging single and twin circular synthetic jets flow field

C.S. Greco *, G. Castrillo, C.M. Crispo, T. Astarita, G. Cardone

Department of Industrial Engineering, University of Naples Federico II, Naples, Italy

ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 12 November 2015
Accepted 24 December 2015
Available online 12 January 2016

Keywords:
Synthetic jets
Impinging jets
Flow field
Particle image velocimetry
Vortex ring
Turbulence

ABSTRACT

Synthetic jets are largely used in the electronic cooling field; indeed their heat transfer performances have been widely investigated. The heat transfer performances have been enhanced through the design of innovative synthetic jet devices, as the twin synthetic jets device. Obviously the heat transfer performances of the classic and innovative synthetic jet devices are strictly related to their impinging flow field. Therefore the behavior of impinging single and twin circular synthetic jets in phase opposition is experimentally investigated by using Particle Image Velocimetry (PIV) at Reynolds and Strouhal numbers equal to 5100 and 0.024, respectively. Several nozzle-to-plate distances (H), ranging between 2 and 10 nozzle diameters (D), have been investigated. The time-averaged behavior of the velocity components has been reported and discussed. Their distributions, near the impinging plate, have been described. For the single jet, at short nozzle-to-plate distances ($H/D < 4$) the axial velocity profile near the impinging plate shows a double peak with a minimum on the jet axis. Instead, at high nozzle-to-plate distance ($H/D > 6$), the axial velocity profile is bell-shaped. This is ascribed to the adverse pressure gradient strength and the potential core-like region extension. External oscillations are observed in all the flow field quantities near the impinging plate at 2 diameters from the stagnation point due to a secondary counter rotating vortex ring generation. The presence of such a counter rotating vortex ring decreases as the nozzle-to-plate distance increases. Comparing the two synthetic jet configurations, higher axial velocity and turbulence level but lower axial phase-correlated organized contribution to velocity have been found for the twin case because of the jets interaction. The evolution of the flow field for both configurations has been explained through phase-averaged measurements. High turbulence is observed along the shear layer emanated by the nozzle edge and in the vortex ring core. During the suction phase the saddle point shows a different behavior in the two configurations. In the single case, the saddle point reaches the impinging plate causing injection of air from the plate into the device. Differently the twin configuration generates two saddle points which do not reach the impinging plate because of the presence of the other impinging synthetic jet.

1. Introduction

A synthetic jet device consists of a fixed actuator cavity bounded on one side by a membrane and on the other by an orifice or a nozzle. When the membrane vibrates, air is periodically pulled into and out of the cavity through the orifice generating a series of vortex rings. These vortices convect downstream and if the formation criterion is satisfied [1] a steady turbulent jet is created [2]. These jets are zero-net-mass-flux in nature; indeed they are synthesized from the ambient fluid in which the device is embedded. Although the net mass injection in the external ambient is zero, they transfer a positive net momentum without the need of an external piping making them very attractive in many fields such as: flow control [3], mixing [4], and heat transfer [5].

The governing parameters of the synthetic jet behavior are the Strouhal number and the Reynolds number defined as:

$$Sr = D/L_0 = fD/U_0 \tag{1}$$

$$Re = \rho U_0 D/\mu \tag{2}$$

where U_0 is the characteristic velocity of the jet, D is the exit diameter, f is the actuation frequency, ρ is the air density, μ is the air dynamic viscosity and L_0 is the stroke length (defined as U_0/f).

The characteristic velocity, according to Smith and Glezer [2], is defined as:

$$U_0 = \frac{1}{\tau}\int_0^{\frac{\tau}{2}} u_a(t)dt \tag{3}$$

* Corresponding author.
E-mail address: carlosalvatore.greco@unina.it (C.S. Greco).

http://dx.doi.org/10.1016/j.expthermflusci.2015.12.019
0894-1777/© 2016 Elsevier Inc. All rights reserved.

Nomenclature

b	jet width, m
D	nozzle diameter, m
f	actuation frequency, Hz
fs	sampling frequency, Hz
H	nozzle-to-plate distance, m
l	*twin* jets axes distance, m
L	nozzle length, m
L_0	stroke length, m
N	number of instantaneous flow fields at the same phase
n	natural number
r	radius, m
Re	Reynolds number
Sr	Strouhal number
T	time, s
u, v	x and y velocity components, m/s
$\tilde{u}$, $\tilde{v}$	phase-correlated organized x and y components contribution to velocity, m/s
u',v'	turbulent x and y velocity components, m/s
U_0	reference velocity, m/s
u_a	exit velocity on the jet axis, m/s
U_J	jet axis streamwise velocity, m/s
x, y	spatial coordinates, m

Greek symbols

φ	phase angle, °
μ	air dynamic viscosity, Pa s
ρ	air density, kg/m^3
Σ	dimensionless twin jets axes distance
τ	actuation period, s

Abbreviations

TSJ	Twin Synthetic Jets
SSJ	Single Synthetic Jet
PIV	Particle Image Velocimetry

where $\tau = 1/f$ is the actuation period and u_a is the exit velocity on the jet axis.

The first literature works on synthetic jets focused on the investigation of their fluid dynamic behavior [2,6,7] and the comparison with continuous jets [8,9]. Then researchers started studying the possibility of using synthetic jets as cooling device in an impinging configuration as done for continuous jets [10–13]. The heat transfer performances of such devices have been widely investigated [5,14–17].

Valiorgue et al. [16] studied synthetic jets impinging at nozzle-to-plate distance H equal to 2D and for various stroke lengths. The heat transfer rate, that obviously increases with increasing Reynolds number, was found to increase linearly with L_0/H up to $L_0/H = 2.5$, then being constant until L_0/H equal to 11. This effect is ascribed to the formation of a time-averaged recirculating vortex located at $r/D \simeq 2$ for $L_0/H = 2.5$. The promising performances of synthetic jets were later confirmed by the studies of Chaudhari et al. [5]. They carried out experiments on the cooling of a flat plate by using a synthetic jet generated through a circular orifice. Such experiments were undertaken at Reynolds number ranging between 1500 and 4200 and nozzle-to-plate distance ranging between 0 and 25D. The findings show that the heat transfer rate is comparable with that of continuous axisymmetric jets at low Reynolds number (up to 4000), expecting it to be higher at greater values of Reynolds number.

In the last years, researchers have also investigated the possibility of enhancing the heat transfer performance of these jets through the design of innovative configurations. Rylatt et al. [18] confined the impinging synthetic air jet in order to draw cold air from a remote location during the suction phase. This ducted configuration leads to achieve a heat transfer enhancement of 36% in the stagnation region. Chaudhari et al. [19] proposed a synthetic jet with the central orifice surrounded by multiple satellite orifices. Their experiments, carried out at $1000 < Re < 2600$ and $1 < H/D < 30$, show a heat transfer coefficient higher (approximately 30%) than the conventional single orifice synthetic jet.

A new generation of synthetic jet actuators consisting in two cavities sharing the same oscillating membrane (a piezoelectric) was proposed by Luo et al. [20]. A slide block was used to separate the two exit slots at an appropriate distance. They obtained, through a numerical simulation, a device which doubles the function of the existing synthetic jet with a single diaphragm leading to an increase of the energy efficiency with respect to the classical configuration [21]. In the near field Luo et al. [22] found, through PIV measurements, a flow field characterized by a "self-support" phenomenon between the two synthetic jets while in the far field the two jets merge into a single and more stable synthetic jet. Lasance et al. [23] replaced the classical circular single jet configuration with a double circular configuration. The double configuration is found to be advantageous because of noise reduction [24] and improvement of heat transfer performances.

The free flow field and the heat transfer performance of a twin circular configuration, compared to a single synthetic jet, was investigated by Greco et al. [25,26]. Their PIV experiments [25], undertaken using a device composed by two synthetic jets with a 180° phase shift, result in higher streamwise velocity component and lower jet width only for the configuration whose twin jets axes distance is equal to 1.1D. Moreover, a heat transfer enhancement is obtained in this twin configuration characterized by the two adjacent synthetic jets [26].

Although the heat transfer performances of the classical and innovative configurations of synthetic jet have been widely studied, the knowledge about the impinging flow field of synthetic jets [27–30], as also reported by Persoons et al. [31] and Badzizi-Therani et al. [27], is really insufficient.

For this reason the aim of the present work is to investigate and characterize the behavior of impinging flow field of single (SSJ) and twin synthetic jets (TSJ). Experiments are carried out at Reynolds number equal to 5100 and Strouhal number equal to 0.024, according to Eqs. (1)–(3). These governing parameters have been computed by using the first measurable axial velocity value (i.e. at 0.1D from the nozzle exit) during the expulsion phase along the jet axis. The twin jets axes distance is set equal to 1.1D, because of the strong jets interaction found in previous literature works [25,26], and the nozzle-to-plate distance ranges between 2 and 10 nozzle diameters. The paper has been divided as following: Section 2 describes the experimental apparatus employed in the present investigation, in Section 3 the triple decomposition analysis is presented, Section 4 discusses the results, for the single and twin impinging configurations and Section 5 draws final conclusions.

2. Experimental apparatus

A cross sectional sketch of the twin circular air synthetic jets device is represented in Fig. 1. A loudspeaker (CIARE®HS250) whose diameter is 270 mm, splits the cavity in two sub-cavities with a volume equal to 2 dm^3. Two nozzles, having a length $L = 210$ mm and an inner diameter (D) of 21 mm, are attached to