Thermo-fluid-dynamic analysis of innovative synthetic jet devices

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Abstract. Synthetic jets are largely used, especially in the field of electronic cooling; indeed their heat transfer performances have been widely investigated and some of the work performed at University of Naples Federico II is herein described. Heat transfer coefficients have been enhanced through the design of innovative synthetic jet devices; in particular, twin synthetic jets and multi orifice nozzles are considered. Obviously, the heat transfer performances of both the classic and innovative devices are strictly related to their impinging flow field on the surface to be cooled. In this work, the behaviour of innovative impinging synthetic jets is experimentally investigated by using Particle Image Velocimetry (PIV) and IR thermography leading to both time average and phase average flow velocity and heat transfer measurements. Three-dimensional coherent vortex structures, time-averaged and phase-averaged means, as well as turbulent statistics of flow fields and wall heat transfer data are presented and discussed.

1. Introduction

The continuous technology improvement is causing a proliferation of electronic systems in our society. Nowadays human society is completely dependent on such electronic devices; hence, the reliability of these systems is mandatory. The failure of these systems can be caused by many factors such as high temperature, electrical overstress and material fatigue.

The system failure is mostly due to the thermal overstress caused by a continuous request of intense work. Although most of the electronic devices have a high efficiency, a continuous use can cause an increase in temperature which can affect the device performance until the failure. Electronic components are designed to operate within a certain temperature range thus need for a cooling system. Such a cooling system has to be designed to dissipate all the thermal power to maintain a suitable temperature and guarantee electronic component safety without affecting working performance.

According to Moore’s law [1], the number of transistors on an integrated circuit doubles every one and a half year and the transistor density is expected to be very high. Moreover, the size of these transistors decreases exponentially as silicon microfabrication processes are improved. These two components lead to an increase in the heat power which must be carried away by cooling devices in order to let the electronic systems work properly within a suitable temperature range.

Conventional cooling techniques such as heat sink, fans and liquid cooling need to be continuously optimized to face this continuous request of higher heat power dissipation and miniaturization. Such needs have led researchers to focus their efforts on the design of new cooling devices.
In the last decades, researchers discovered a new technology which has promising heat transfer performances. Such a new technology is the synthetic jet actuator, as named for the first time by Coe et al. [2] and then Allen and Glezer [3]. The synthetic jet actuator, depicted in Figure 1, is a device that releases a jet in the external environment without the need of an external piping. In particular, the synthetic jet is a zero-net-mass-flux jet which transfers linear momentum to the flow system without net mass injection across the flow boundary. It is usually produced by a sinusoidal oscillating membrane (e.g. piezoelectric or loudspeaker) or piston which alternatively forces the fluid through an orifice or a slot into the external flow field and entrain fluid back. In this periodic behavior, one can identify two stages that totally describes the phenomenon: the blowing phase, when fluid is ejected from the orifice, and the suction phase, when fluid is entrained back. During the blowing phase, the ejected fluid separates at the sharp edges of the orifice and rolls up to form a vortex ring or vortex pair, respectively in the 2D or 3D case. During the suction phase of the cycle, the vortex pair is quite far from the orifice and keeps on propagating away due to its self-induced velocity. However, the vortex pair is not entrained into the cavity only if its convection velocity is larger enough than the averaged velocity during the suction cycle. In this case [4] the vortex structure will propagate downstream and dissipate at some distance from the exit, synthesizing a jet with momentum transfer to the embedding flow. Thus, a train of vortex structures is created by the actuator and, in the mean, the velocity profile appears like a steady jet. Over a single period of oscillation of the membrane, there is, therefore, zero net mass-flux into or out of the cavity, yet there is a non-zero mean jet velocity. The parameters that govern the synthetic jet behaviour are the Reynolds number and the Strouhal number defined as:

\[
Re = \frac{U_0 D}{v} \\
St = \frac{D}{L_0} = \frac{D}{f U_0}
\]

where \(D\) is the characteristic length, \(v\) is the fluid kinematic viscosity, \(f\) is the actuation frequency, \(U_0\) is the characteristic velocity [5] and \(L_0\) is the stroke length (equal to \(f U_0\)).

Since these actuators are easy to be miniaturized and are low-cost devices, they have been widely used in many fields of application such as: flow control [6], jet vectoring [7], mixing enhancement [8], thrust generation [9] and electronic cooling.

In the last decades, the application of this technology in the electronic cooling field has been widely investigated. The first literature work on synthetic jets used as cooling devices was presented in 1982 by Gutmark et al. [10]. They presented a work where synthetic jet were used to enhance both natural and forced convection. They obtained an increase of 400% of the overall heat transfer coefficient with this acoustically excited airflow. Later Mahalingam and Glezer [11] designed a heat sink with synthetic jet impingement for high power dissipation in electronics. They studied the thermal performances of this device obtaining a temperature decrease from 71.5 to 36°C with synthetic jets operation and a power dissipation of 20-40% higher with respect to the same heat sink with a fan in the flow rate range of 3-5 cubic feet per minute. Chaudhari et al. [12] studied the thermal performance of synthetic jets, issued by a circular orifice, used to cool a flat plate. Such experiments were undertaken under the following operating conditions: Reynolds number in the range 1,500-4,200 and nozzle to plate distance in the range 0-25\(D\). The results show that the Nusselt number is comparable with that of continuous axisymmetric jets at low Reynolds number (up to 4,000), expecting it to be higher at greater values of Reynolds number. Valiorgue et al. [13] studied the influence of the stroke length on the thermal behaviour of impinging synthetic jets. They found a critical stroke length which is a boundary between two different flow regimes. This critical stroke length is \(L_0/H\) equal to 2.5. The heat transfer rate (that obviously increases with Reynolds number increasing) is found to be linearly proportional with \(L_0\) up to \(L_0/H = 2.5\) than constant for increasing \(L_0\) values.

As for steady jets, heat transfer correlations have been developed also for synthetic jets [14,15]. Arik and Icoz [14] found an empirical correlation to determine the heat transfer coefficient of impinging synthetic jets. Such a correlation depends on several parameters: Reynolds number, axial distance, orifice size and jet driving frequency. In particular, the range of validity of this correlation are \(Re < \)
2,900, \( 5 < H/D < 20 \) and actuation frequency between 0.16 times the resonance frequency and the resonance frequency. Persoons et al. [15] accounts, in their general correlation, for several scaling parameters such as Reynolds number \((500 < Re < 1,500)\), jet to surface spacing \((2 < H/D < 16)\) and stroke length \((2 < L_0/D < 40)\). Based on this study, they defined four heat transfer regimes, each one identified by a different range of values acquired by the ratio \(L_0/H\), whose flow field characteristics were later described by McGuinn et al. [16]. They [16] undertook high speed PIV and single point hot wire anemometry experiments to understand the influence of the dimensionless stroke length on the impinging synthetic jet flow field for a wide range of nozzle-to-surface spacing \((2 < H/D < 16)\) and a single Reynolds number \((1,500)\).

Early studies on synthetic jets, in the heat transfer field, were focused on the assessment of the effects of all the characteristics parameters on their heat transfer behavior. Differently, the most recent research is aimed at the design of innovative configurations in order to further enhance the cooling rate. Rylatt et al. [17] proposed a confined synthetic jet device stating that, with such a configuration, cold air is drawn from a remote location into the jet flow during the suction phase. Such a configuration was experimentally found to achieve a heat transfer enhancement of up to 36\% in the stagnation region. Chaudhari et al. [18] designed a new synthetic jet characterized by a centre orifice surrounded by multiple satellite orifices. They tested this device varying both the Reynolds number \((1,000 < Re < 2,600)\) and the normalized axial distance \((1 < H/D < 30)\). This innovative configuration achieves a heat transfer of approximately 30\% higher than that of the conventional single orifice jet. Luo et al. [19] proposed a new generation of synthetic jet actuators consisting in two cavities sharing the same oscillating piezoelectric diaphragm with two exit slots located at an appropriate distance. The numerical simulation showed that this innovative device doubles the function of the existing single synthetic jet and also solves the problems of pressure loading and energy inefficiency. Luo et al. [20] also carried out PIV measurements of this new device at Reynolds number and Strouhal number equal to 2500 and 0.17. The results reveal, in the near field, a more complex flow field characterized by a “self-support” phenomenon between the two synthetic jets, while, in the far field, the two jets merge a single and more stable synthetic jet. Persoons et al. [21] studied two adjacent synthetic jets, with slot orifice, which allows to direct the flow by changing the phase between the jets. They studied the flow field and the heat transfer performances of this device through PIV and IR thermography experiments. The device was characterized by a Reynolds number of 600 and a dimensionless stroke length equal to 29. Several values of phase and jet-to-surface spacing \((6, 12, 24)\) were investigated. The results showed a 90\% enhancement of the maximum and overall cooling rate, compared to a single jet, for a phase equal to 120\° and a jet-to-surface spacing \(H/D\) equal to 12. Also Lasance et al. [22] investigated a device belonging to the new synthetic jet generation proposed by Luo et al. [19]. Lasance et al. [22] device has a double circular exit. Such a double configuration is found to be advantageous because it improves the heat transfer performances [24] and, above all, it reduces the noise emission [23].

One of the main drawbacks of synthetic jet actuators is the generation of noise due to the membrane oscillation and to the aerodynamic noise generated by the synthetization of the jet. Among the several solutions proposed in literature are modification of the orifice shape and use of multiple interacting jets. Chaudhari et al. [25] investigated, for the first time, the influence of the orifice shape on the heat transfer performances of synthetic jets. Three configurations were analysed (square, circular, and rectangular exits) and the synthetic jet was characterized by a Reynolds number between 950 and 4500 and normalized impingement distance between 1 and 25. They found that the square orifice is more effective than the other shapes at \(H/D > 5\) at the same exit flow conditions, while rectangular orifices with aspect ratio between 3 and 5 gives the best performance at smaller distances. Bhapkar et al. [26] experimentally investigated the acoustic aspects and average heat transfer characteristics of the elliptic shape and found that the latter performs better than the square, circular, and rectangular only at low \(H/D\). Jeyalingam and Jabbal [27] studied the acoustic and flow behaviour of synthetic jets with 4-lobed and 6-lobed orifices and showed that the 6-lobed orifice offers a good broadband noise reduction over mid to high frequency range with respect to the baseline circular orifice.

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Multiple jet configurations are by far the most efficient technique towards aerodynamic noise abatement: this goal may be achieved by phasing neighboring jets in such a way to obtain acoustic destructive interference. For this reason, at the University of Naples Federico II the design of innovative synthetic jet devices involving multiple jet configuration has been developed. In particular, two innovative devices have been investigated through Particle Image Velocimetry and InfraRed Thermography: twin synthetic jets [27-29] and multi orifice nozzles [30-31]. In the present work, the flow field the heat transfer performances and enhancement provided by these two devices is analysed and discussed.

2. Experimental setup and technique

In this section, the two innovative devices, the setup for the flow field and heat transfer measurements are described.

2.1. Twin synthetic jets device

Figure 1 shows the schematic of the twin circular synthetic jets (TSJ) device. The oscillating membrane is a loudspeaker (CIARE HS250), with a diameter of 270 mm. This loudspeaker splits the cavity in two sub-cavities with the same volume ($V=2\times10^{-3}\text{m}^3$). Two pipes are attached to these sub-cavities. The pipe’s length $L$ is equal to 210 mm and their thickness and their inner diameter $D$ are 1 mm and 21 mm, respectively. The parameter $l$ is the jet axes distance and its corresponding non-dimensional parameter is $\Sigma$, defined as $l/D$. Such jet axes distance is varied between 1.1 and 5 nozzle diameters. The configuration $\Sigma=1.1$ corresponds to the condition for which the two pipes are adjacent. The two sub-cavities have the same resonance frequency, because the pipe length and diameter are equal. The same volume of the two sub-cavities is achieved by filling the upper and the bottom sub-cavity using particular geometrical items. The single synthetic jet is obtained by using a bended tube at the pipe exit in order to deflect one of the two synthetic. The device is operated at a frequency of 4Hz by supplying the loudspeaker with a sinusoidal input signal, which is generated by a wave generator (Digilent Analog DiscoveryTM), coupled with a power amplifier. Under these operating conditions, the synthetized jet has a Reynolds number of 5100 and a Strouhal number of 0.024.
2.2. Quadruple synthetic jet device

A schematic of the quadruple synthetic jet (QSJ) device is shown in Figure 2a. The device consists of an aluminum cubic box of 115 mm side with four recesses in its lateral faces. In these recesses, four loudspeakers (CIARE PA065) are located and, therefore, four cavities are formed. These four cavities are connected to the upper face of the aluminum box by four identical L-shaped interior nozzles. The speakers, screwed on the bottom of the box recesses, cause the formation of synthetic jets at the nozzle outlets through their oscillation. The nozzles are placed at an axis-to-axis distance $l$ of $1.1D$ ($D=10$ mm) in order to cause a strong near-field interaction between neighboring synthetic jets [27]. The four loudspeakers are supplied with 120 Hz sinusoidal input signals by using the same equipment employed for the other device. In the following, the four cavities and the corresponding nozzles and synthetic jets are named after the cardinal points. Moreover, each jet is associated with a phase angle, which is indeed the phase angle of the corresponding cavity pressure response.

Figure 2b shows the four investigated quadruple synthetic jet configurations: monopole-like (MP), dipole-like (DP), quadrupole-like (QP), and 90-degrees-circularly-shifted-jets (CSP) in analogy with acoustics (more details are reported in Paolillo et al. [30]). Each of the four single synthetic jets have the same Reynolds (4000) and Strouhal numbers (0.2). In order to obtain identical exit conditions for the single synthetic jets, a calibration of both the amplitudes and the phases of the speaker driving signals is performed, because of the slightly different mechanical features of the employed commercial speakers. All the details about the calibration procedure can be found in Paolillo et al. [30].

![Figure 2. Quadruple synthetic jet actuator: a) schematic of the device, b) investigated configurations: the jet phase angles are relative to that of the jet in the $Z > 0$ hemispace (north jet).](image-url)

2.3. Particle Image Velocimetry setup and data reduction

The impinging TSJ flow field has been investigated by using the experimental apparatus sketched in Figure 3. The operating conditions are: Reynolds number equal to 5100, Strouhal number equal to 0.024 and the jet-axes-distance of 1.1, and 3 nozzle diameters for five different values of dimensionless nozzle-to-plate distance $H/D$ (2, 4, 6, 8 and 10). Illumination is provided by a Quantel Evergreen laser (Nd-YAG, 200 mJ/pulse) while particle images are acquired with a Zyla 5.5 sCMOS camera lens with 50 mm focal length and with a relative aperture $f/\#$ equal to 11 (more details are reported in Greco et al. [29]). In order to perform phase average measurements, the imaging system is synchronized with the synthetic jet. The synthetic jet is sampled at each $12^\circ$ and the average of each phase is performed on 400 instantaneous flow fields. All the 12000 double frame images taken for each test are used to obtain reliable turbulence statistics. The vector field has been obtained processing images with a multiple pass algorithm with window deformation by using the Blackman weighting windows.
according to Astarita and Cardone [32] and Astarita [33-35]. The detailed employed process is clearly described by Greco et al. [29].

Differently from the TSJ device, the QSJ impinging flow field has not investigated yet. Anyway, important information, to deeply understand the heat transfer behaviour of this innovative device, can be inferred by its free flow field. This flow field is experimentally investigated by using the stereoscopic particle image velocimetry (SPIV). A sketch of the SPIV apparatus is illustrated in Figure 4. The employed equipment (cameras and laser) is the same used in the previous described experiment. In this experiment, the cameras work with two different relative apertures (f-stop): 5.6 for camera 1 and 8 for camera 2. Furthermore, the cameras are arranged in an angular displacement configuration with an angle, between the two optical axes, of about 50°. The Scheimpflug condition is satisfied with the installation of tilt-axis adapters. The two-dimensional (2D) two-components (2C) displacement fields in each image plane of the two cameras are computed through a multiple-pass algorithm with window deformation. The employed PIV algorithm is the same previously used. The PIV process details are described by Paolillo et al. [30].

All the velocimetry measurements are then analysed by applying the triple decomposition technique [36]. For further details, the reader is referred to Greco et al. [29, 37].
2.4. Heat transfer measurements setup and data reduction

Figure 5 shows a schematic of the classic thermal test apparatus. The heat flux sensor can be a constantan foil of 50 μm thickness, 200 mm width and 450 mm length (employed in QSJ’s experiments) or a stainless steel foil 243 mm wide, 715 mm long and 40 μm thick (used in TSJ’s experiments). The foil is clamped with two copper conducting bars pairs, mounted on the shortest side of the foil and provided with a constant voltage using a 0 V to 250 V DC stabilized power supply. The stabilized current control ensures uniform and constant heating by Joule effect. The very large equivalent cross section of the bus bars, with respect to that of the heated foil, ensures that the voltage drop along them is very small.

![Figure 5. Schematic of thermal test apparatus.](image)

The foil is positioned horizontally with the synthetic impinging on its lower (QSJ) or upper (TSJ) face. The distance \( H \) between the nozzle exit plane and the target foil (impingement distance) is adjusted by means of a linear slide and varied between 2.5\( D \) and 20\( D \) (QSJ case) with a spacing of 2.5\( D \) or between 2\( D \) and 10\( D \) (TSJ case) with a spacing of 2\( D \).

In the QSJ device, four waterblocks are employed to cool the speakers. Such waterblocks are connected with a thermostatic bath to avoid the jet temperature increase due to the Joule heating caused by the electric currents flowing through the speaker coils. This effect is not negligible for this device because the cavity (volume delimited by the speaker cone and the bottom of the recess in the box face) is very small compared to the overall box dimensions and thus the aluminum body acts to insulate the heat dissipated in the speaker coil and transferred to the cavity.

An infrared camera (FLIR SC6000 for QSJ case while CEPID JADE III for TSJ) measures the temperature of the foil face, imaged by means of a mirror, that is opposite to that where the synthetic jet impinges. Temperature across the foil is considered constant as the Biot number (\( Bi = \frac{hs}{\lambda_f} \) where \( h \) is the time-averaged convective heat transfer coefficient and \( s \) and \( \lambda_f \) are the foil thickness and thermal conductivity, respectively) and the inverse of modified Fourier number (\( Fo = \frac{\alpha}{\pi fs^2} \) where \( \alpha \) is the thermal diffusivity) are small with respect to unity. The imaged foil face is coated by high-emissivity black paint (hemispherical emissivity \( \varepsilon \) = 0.95) in order to increase the accuracy of temperature measurements. The IR camera is used in conjunction with the unsteady [38] and steady [39] heated thin foil heat transfer sensor, whose details, not reported here for the sake of brevity, can be found in Greco et al. [28].

The experimental data are reduced in dimensionless form in terms of time average Nusselt number \( \overline{Nu} = \frac{hD/k} \) (\( k \) is the thermal conductivity of air at film temperature), phase average Nusselt number \( Nu(\varphi) = \frac{h(\varphi)D/k} \), standard deviation of Nusselt number phase averaged fields \( Nu' \) and percentage area-weighted standard deviation of the Nusselt number \( \sigma_{\overline{Nu}} \) (non-uniformity parameter).
3. Results

3.1. Twin Synthetic Jets device: impinging flow field and heat transfer

In this section, for the sake of brevity, only the impinging flow field of SSJ and TSJ at $\Sigma=1.1$ are analysed and discussed. This configuration (i.e. $\Sigma=1.1$) is that which shows the strongest interaction of the two synthetic jets giving a completely different behaviour with respect to the classic single synthetic jet. Indeed, the configurations at $\Sigma$ equal to 3 and 5 show the behaviour of two superimposed SSJ whose exit centres are shifted of $3D$ or $5D$, respectively. Anyway, for all the other configurations, the reader is referred to Greco et al. [29].

In Figures 6 all the velocity components are depicted for $H/D$ equal to 2. For the sake of brevity, only eight phase-average flow fields (representing the ejection phase) are reported. The phases range from $\phi = 0°$ up to $\phi = 168°$. For each phase the velocity vector arrows are placed every 0.08 $D$ in $x$ and $z$ direction.

In Figure 6a) the phase-average axial and radial velocity maps are shown. At $\phi = 0°$ the synthetic jet starts being issued by the nozzle and at $\phi = 24°$ the vortex ring is formed. Then the synthetic jet impinges and spreads over the plate as observable at $\phi = 48°$. For this phase, it is possible to detect the formation of a counter rotating vortex ring near the impinging plate and also two regions of high radial velocity at $x/D$ equal to about 0.75 (where the complete rotation of the impinging synthetic jet occurs) and at the position of the convective primary vortex ring. From this phase to $\phi = 120°$ the effect of the impinging plate on the impinging synthetic jet is clearly observable. Indeed, the morphology of the axial velocity is characterized by a hemispherical axial velocity decreasing, near the plate, caused by the strong adverse pressure gradient. For $48° \leq \phi \leq 96°$, the vortex ring continues sweeping the impinging plate and the position of high radial velocity is always located at $x/D$ equal to 0.75 (while the second region shifts towards higher radial position with the vortex ring and its value decreases). For this range of phases the axial velocity attains the maximum value. For $\phi > 96°$ the vortex ring is out of the measurement zone and the values of axial and radial velocity start decreasing.

In Figure 6b) the phase-average mean-squared axial and radial turbulent velocity maps are depicted. At $\phi = 0°$ the axial values are zero because, obviously, the synthetic jet is coming out. At $\phi = 24°$ the axial turbulent velocity acquires non-zero values on the front boundary of the vortex ring while the radial one attains its maximum near the vortex ring core. At $\phi = 48°$ the maximum value for both components are located in the middle between the vortex ring and the counter rotating one. Moreover, for the axial turbulent velocity a value different from zero is also detected at $x/D$ equal to -0.5 and along the shear layer (only for $z/D > 1$). The radial turbulent velocity shows high values also along the last
zone ($z/D > 1$) of the shear layer. At $\varphi = 72^\circ$ the axial component has maxima located in the vortex ring core, near the impinging wall at $x/D$ between 1.5 and 2 and along all the shear layer up to the nozzle exit. Differently, the radial component shows a zero turbulent value near the nozzle ($0 < z/D < 0.4$) and maxima along the wall ($1 < x/D < 2.25$) and ahead of the vortex ring (near the wall) at a radial position equal to approximately 3.3 $D$. At $\varphi = 96^\circ$ the vortex ring is completely detached from the impinging plate (as visible from the peak of axial and radial turbulence) but near the plate still high value of axial ($1.5 < x/D < 2.5$) and radial ($1 < x/D < 2.5$) are observable. For $\varphi > 96^\circ$ the two maxima, located in vortex ring core, are out of the measurement zone and the other high values start decreasing (still visible is the maximum of axial turbulence near the impinging plate at $x/D$ equal to approximately 2). It is important to highlight that for this nozzle-to-plate configuration, from $\varphi$ equal to 48$^\circ$ until $\varphi$ equal to 120$^\circ$ the zone between -0.5 $< x/D < 0.5$ is characterized by no turbulence and a constant value of the velocity, resembling the potential core behaviour of a continuous jet (defined as a potential core-like region).

In Figure 7 all the velocity components are depicted for $H/D$ equal to 6. In Figure 7a) the phase-average axial and radial velocity maps are reported. It is possible to see how the vortex ring is generated (by the roll-up of the shear layer sheet) and convects downstream (first three phases). Then (at $\varphi = 72^\circ$) it impinges on the plate and still generates a smaller counter rotating vortex ring (than that generated in the shortest nozzle-to-distance configuration, as also visible in Figure 6). For this latter phase, it is possible to highlight that a maximum in the radial velocity, near the impinging plate, is detectable at a
radial position of about 1.3 $D$ from the jet axis. The axial velocity, approaching the impinging plate, shows a bell-shape distribution that is completely different from the behaviour detected for the shortest configuration. At $\phi = 96^\circ$ the vortex is sweeping the plate and a local radial maximum is located between the vortex ring and the impinging plate. Differently from the shortest case, the second radial velocity peak has approximately the same value of the first one. At this phase, the axial component shows a region of high value that has the greatest extension (toward the impinging plate). As $\phi$ increases, the radial and axial values decrease.

In Figure 7b) the phase-average mean-squared axial and radial turbulent velocity maps are shown. The behavior, in the first two phases, is similar to what shown for the case at $H/D$ equal to 2. Then, at $\phi = 48^\circ$, high value of the axial turbulence is located mainly along the shear layer and near the front boundary of the vortex ring. The radial turbulence shows its maximum along the shear layer, as well, and near the vortex ring core. At $\phi = 72^\circ$ it is possible to point out that the mean-squared axial turbulent velocity has high value all along the shear layer (until the nozzle exit) and in the counter rotating vortex ring. The radial turbulence shows, basically, the same characteristics of the axial one. Differently from the shortest nozzle-to-plate configuration, the axial and radial turbulence start merging on the jet axis at $z/D$ equal to about 3.8. That zone, featured by a zero-turbulence value, is the so-called potential core-like region. At $\phi = 96^\circ$ the axial turbulence has its maximum along the shear layer and in the vortex ring core but, differently from $H/D$ equal to 2, the zone of high turbulence near the wall at $x/D$ equal to about 2 shows lower values. The radial turbulence still shows (as for $H/D$ equal to 2) a high value region near the plate (which covers the zone between the shear layer and the vortex ring) apart from the maxima present along the shear layer and inside the vortex ring core. At $\phi \geq 120^\circ$ the turbulence values start decreasing and the vortex ring is moved out of the measurement region.

The phase-average axial and radial velocity are shown in Figure 8. At $\phi = 0^\circ$ the right synthetic jet starts coming out but, differently from the SSJ case, at $\phi = 24^\circ$ the vortex ring is not fully formed because the starting suction phase of the left synthetic jet delays such a formation (only the right vortex ring footprint is observable). At $\phi = 48^\circ$ the right synthetic jet impinges but it is slightly deflected towards $x/D$ equal to 0. Indeed, near the plate the negative radial velocity is higher and more extended (in the axial direction) than the positive one. At $\phi = 72^\circ$ the axial distribution is not symmetric with respect to the right synthetic jet centreline (located at $x/D$ equal to 0.55) but the maximum is attained along $x/D$ equal to 0. This is due to the interaction of the two jet which is stronger near the $x/D$ equal to 0 axis. The radial velocity still presents two maxima: the first near the plate where the jet has its complete rotation and the second between the plate and the sweeping vortex ring. At $\phi = 96^\circ$ the right synthetic jet seems to be less stretched by the left one because the interaction starts decreasing. For $\phi \geq 120^\circ$ the values become lower.

![Figure 8. Phase-average axial (left) and radial (right) velocity maps at $H/D$ equal to 2.](image-url)
In Figure 9 the phase-average mean-squared axial and radial turbulent velocity are shown respectively. At \( \phi = 0^\circ \) no zero values of axial and radial turbulence are still present due to the trailing part of the left synthetic jet. At \( \phi = 24^\circ \) the axial turbulence attains high value on the front of the vortex ring while the radial one is located in the vortex ring core and between the two jets. At \( \phi = 48^\circ \) the axial turbulence shows high values along the internal shear layer which are higher than the external one. This is due to the interaction of the two 180° phase-shift jets. Indeed, the extension of the turbulence of the internal shear layer arrives until the nozzle exit, differently from the external one. Moreover, the axial turbulence of the left vortex ring footprint is lower than the right one because of the suction phase of the left synthetic jet. The same considerations can be drawn for the radial turbulence. Moreover, a region of high turbulence, connecting the left nozzle exit and the internal shear layer, is present (above all for the radial component). At \( \phi = 72^\circ \) the turbulence along the internal shear layer increases and is still higher than the external one. The axial turbulence attains also high value in the vortex core and in the zone near the plate between the vortex ring and the shear layer. The radial component acts as the axial one apart from the region near the vortex ring. Indeed, here the maximum is attained near the plate where the counter rotating vortex is located. At \( \phi = 96^\circ \) the behaviour of turbulence is the same, indeed, maxima are located along the shear layer, in the ring vortex centre (on the vortex ring left side near the impinging plate for the radial component) and near the impinging plate. For \( \phi > 96^\circ \) the values start decreasing. In all the phases, it is possible to see that, as previously described, the right synthetic jet is deflected towards the \( x/D \) equal to 0 axis. Furthermore, even in this TSJ configuration a potential core-like region is detectable.

**Figure 9.** Phase-average mean–squared axial (left) and radial (right) velocity maps at \( H/D \) equal to 2.

In Figure 10 the phase-average axial and radial velocity components are depicted. At \( \phi = 0^\circ \) the footprint of the trailing part of the left synthetic jet is still present. At \( \phi = 24^\circ \) the right synthetic jet is issued and the behaviour is similar to what shown in the shortest nozzle-to-plate case. At \( \phi = 48^\circ \) the jet is going to approach the impinging plate but, as it is possible to observe, the ring vortex is deflected because of the interaction with the left synthetic jet which is acting like a sink. At \( \phi = 72^\circ \) the jet is impinging and the axial profile is bell-shaped, differently from the \( H/D \) equal to 2 case. Moreover, the jet is considerably deflected toward the \( x/D \) equal to 0 axis. Focusing our attention to the radial component it is possible to see that the negative velocity is higher than the positive one because of the previously described deflection. For \( \phi = 96^\circ \) the left radial value does not show a high peak (as in the previous phase) because the vortex ring is sweeping and for \( \phi \geq 120^\circ \) the velocity values decrease and the vortex ring goes out of the measurement zone. Furthermore, the radial velocity over the plate, for these phases, does not show a peak where the impinging jet rotates. Indeed, this value has the magnitude of the one created between the sweeping vortex ring and the impinging plate (differently from the \( H/D \) equal to 2 configuration).
In Figure 11 the phase-average mean-squared axial and radial turbulent velocity, respectively, are shown. At $\varphi = 0^\circ$ no-zero values of turbulence are still present because of the trailing part of the impinging left synthetic jet. At $\varphi = 24^\circ$ the axial turbulence shows values different from zero along the shear layer and on the front boundary of the jet. The radial turbulence has a peak in the vortex ring core. At $\varphi = 48^\circ$ the axial turbulence along the internal shear layer has increased and is thicker than the external one. Furthermore, the two shear layers start merging at $z/D$ equal to about 3.8 and coalesce with the axial turbulent developed on the front boundary of the convecting vortex ring. Also the radial turbulence seems to start merging but still shows its peak in the vortex ring core. It is necessary to point out that the axial value, as the radial one, of the right vortex ring footprint is higher than the left one. This could be related to the fact that the left part of the vortex ring is affected by the suction phase of the left synthetic jet which damps partially the oscillations. At $\varphi = 72^\circ$ the turbulent axial component shows higher value along the internal shear (than the external one) and also a maximum located in the vortex ring core (with a greater value in the right footprint). The turbulent radial component acts as the axial one along the shear layer but, near the impinging plate, shows a maximum between the plate itself and the convecting vortex ring (where the counter rotating is placed). Furthermore, both components start merging at an axial position of about 3.8 diameters from the nozzle exit. Such a zone is the so-called potential core-like region. At $\varphi = 96^\circ$ the vortex ring continues sweeping the impinging plate, featured by a decreased axial turbulence maximum in the core. Moreover, a high value zone of radial turbulence, which spans from the vortex ring core until the impinging shear layer, is observable. For $\varphi \geq 120^\circ$ the values start decreasing. The deflection and the wider internal shear layer (with high values) presented in these turbulent components is the reason why in the time-average measurement the extension of the potential core-like region seems to be lower (up to 2 diameters).
Regarding the heat transfer behaviour of this device, Figure 12 shows the phase average Nusselt number maps for the SSJ at $H/D = 2$ and 6, starting from $\phi = 0^\circ$ up to $\phi = 168^\circ$.

At $H/D=2$, the jet reaches the target plate at $\phi = 0^\circ$ and starts spreading over the foil, as visible at $\phi = 24^\circ$. At $\phi = 48^\circ$ the jet is sweeping the surface and the inner ring shaped region arises at radial distance ($r$) from the stagnation point of $0.5D$ from the centre of impingement. This result agrees with DNS simulation of a continuous circular impinging jet by Rohlfs et al. [40]. This inner ring shaped region is caused by the radial wall acceleration [40, 41].

According to Rohlfs et al. [40] this radial acceleration generates an increase of the spatial gradient of axial velocity near the impinging plate (for the continuity equation) which leads fresh air
near the plate itself. This agrees with the no bell-shaped profile of the axial velocity near the impinging plate which can be inferred from Figure 6. At \( \varphi = 72^\circ \) the \( N_u \) value at inner ring location increases its value, likely because synthetic jet continues impinging over the foil causing an increase of the wall radial acceleration, and an outer ring shaped region can be detected at a radial distance of 1.9 \( D \). The outer ring shaped region can be ascribed to unsteady separation and later reattachment due to the formation of the secondary counter rotating vortex on the wall, generated by the passage of the primary vortex ring and subsequently vortex rings caused by the Kelvin-Helmholtz instability. Hence the delay between the appearances of the two ring shaped regions can be ascribed to the travelling time necessary to the primary vortex ring to assume the requested vorticity in order to generate, for the first time, the secondary counter rotating vortex. Indeed, such ring structures is already present at \( \varphi = 48^\circ \) but is not so clearly visible as in the next phases. At \( \varphi = 48^\circ \) the outer ring is the one formed by the passage of the sweeping vortex ring which creates the counter rotating one (as seen in PIV experiments). After the ring vortex is passed (indeed the zone featured by high heat transfer is widening) the outer ring shaped region is still present. This one could be ascribed to the column of fluid which follows the ring vortex (as described for a \( L_0/D \) higher than 4 in McGuinn et al. [16]). The higher is the dimensionless stroke length \( (L_0/D) \), the longer is the following column of fluid. Hence in this case \( (L_0/D = 42) \) this column of fluid acts like a turbulent continuous jet generating vortex rings, because of the Kelvin-Helmholtz instability. Such vortex rings are the cause of the counter rotating vortex rings near the wall and, consequently, the cause of the continuous presence of the outer ring shaped region of Nu number maxima. The outer ring shaped region moves from \( r/D \) equal to about 1.8 to \( r/D \) equal to approximately 2. Such a motion is caused because the synthetic jet is still impinging, indeed vortex ring is still travelling, so the location of the secondary vortex ring separation is moved towards higher radial position. At \( \varphi = 96^\circ \) the \( N_u \) number acquires its maximum value. After \( \varphi = 96^\circ \), phase-average Nu number values in this region decrease and the two ring shaped regions weaken probably because the biggest part of the incoming flow (for the cycle) has already impinged. The map for \( H/D \) equal to 4 (not shown herein for the sake of brevity but present in the attached movie to Greco et al. [28]) presents result similar to those at \( H/D = 2 \).

At \( H/D = 6 \) (Figure 12), differently from the case at \( H/D = 2 \), the two ring shaped regions are not present. The absence of the inner ring shaped region is caused by two main features: the value of \( H/D \) which is greater than the synthetic jet potential core-like region (shown in PIV measurements); the ring vortex does not have enough vorticity to generate a strong enough secondary counter rotating vortex (as depicted in Figures 9 and 11). It is possible also to note that the maximum value of \( N_u \) is attained around \( \varphi = 72^\circ \) for \( H/D \) equal to 6 while it is attained at around \( \varphi = 96^\circ \) for \( H/D \) equal to 2. Moreover, the heat transfer rate is more spatially concentrated near the stagnation point for \( H/D = 6 \) than the case with \( H/D = 2 \) where such a cooling occurs inside the area enclosed by the outer ring shaped region. For all the \( H/D \) values, the phase-average Nu number maps for \( \varphi > 168^\circ \) (not shown herein for the sake of brevity but present in the attached movie 1 to Greco et al. [28]) present a decreasing value of the heat transfer, with respect to the map at \( \varphi = 168^\circ \) and have all a similar spatial distribution.

The phase-average Nu number maps for the TSJ with \( \sum = 1.1 \) at \( H/D \) equal to 2 and 6 are reported in Figure 13. The phase-average Nu number maps for the configuration with \( \sum = 3 \) and 5 have not been reported because their behaviour is very similar to that of two superimposed synthetic jets. (All phase-average Nu number maps are attached to Greco et al. [28] as video sequences in movie 2, 3 and 4 for \( \sum = 1.1, 3 \) and 5, respectively). The phase-average Nu maps (Figure 12) of TSJ for \( \sum = 1.1 \) at \( H/D \) equal to 2 show a different behaviour with respect to SSJ. During the ejection phase, at \( \varphi = 0^\circ \), a higher heat transfer \( (N_u \) in the stagnation point is about double with respect to the single synthetic jet), is shown mainly due to the strong jet interaction. At \( \varphi = 24^\circ \) the phase-average \( N_u \) map of TSJ already shows, with respect to SSJ, a strong inner ring shaped region; at \( \varphi = 48^\circ \) such a map shows a higher value of \( N_u \) at the inner ring shaped region and a strong presence of the outer ring shaped region differently from SSJ. These phenomena are caused by the higher centreline velocity of the TSJ with respect to SSJ (as reported PIV measurements). In fact, such a higher velocity generates a faster spreading of the impinging synthetic jet over the foil, hence a greater wall radial
acceleration. Furthermore, at $\phi = 72^\circ$ the TSJ $N_u\phi$ map shows a higher value at inner and outer ring regions with respect to SSJ. In the following phases the value acquired by the phase-average Nusselt number for TSJ are comparable (at $\phi = 96^\circ$) or slightly lower (at $\phi = 120^\circ$) than those of SSJ in the same phase. Finally, the inner and outer ring shaped regions disappear approximately at the same phase for both configurations. For $H/D$ equal to 6 the outer and inner ring shaped regions for both configurations (Figures 12 and 13) are not detected because, as in the case of the single synthetic jet, the nozzle-to-plate distance is much higher than the potential core-like region of the synthetic jet. Moreover, it is possible to highlight that also for this value of $H/D$ the phase-average Nusselt number map of TSJ, for the first four phases, attain a higher value with respect to the SSJ due to the higher impinging axial velocity and axial fluctuations. On the other hand, the behaviour, in the last four phases, is the same for both configurations.

![Phase-average Nusselt number for TSJ with $\sum$ equal to 1.1 at $H/D$ equal to 2 (left) and 6 (right).](image)

In order to have a comprehensive overview of the heat transfer behaviour of the TSJ device, the time average Nusselt number and the standard deviation of the phase average Nusselt number, are shown in Figure 14 and they are compared with those of the SSJ case.

At short distance from the nozzle (inside the potential core-like region), many physical features can be considered as in analogy with continuous jets (Jambunathan et al. [42]) impinging within the length of their potential core (i.e. $H/D = 2$ and 4). At $H/D = 2$ an inner ring shaped region with local $N_u$ maximum appears at $x/D \approx 0.5$ and an outer region with local $N_u$ maximum appears at $x/D \approx 1.9$. Maximum values of $N' u'$ are also obtained approximately in the same regions where inner and outer ring shaped structures are located as easily detectable in $N' u'$ map. The $N_u$ values, measured in the first ring shaped region, are slightly higher than the values obtained in the stagnation region. This can be related to the behaviour of the time-average axial velocity component and the mean-squared phase-correlated organized contribution to the velocity component. Indeed, a peak of these parameters, for this nozzle-to-plate configuration, is observable at $x/D$ equal to 0.5. This ring shaped region is not present for nozzle-to-plate distances higher than 4 (after the end of the potential core-like region), as detectable from $N_u$ and $N'u'$ profiles.

The second peak (outer ring shaped region) is present for $H/D$ lower than 4 while for $H/D$ equal to 6 only a change in the $N_u$ slope is visible. For $H/D$ greater than 6 such a peak disappears. The presence of this peak, as previously stated, can be ascribed to the formation of the secondary counter rotating vortex on the wall which is generated by the passage of the ring vortex. In these experiments the formation of the counter rotating vortex is visible until $H/D$ equal to 6. The size and vorticity of this counter rotating vortex decreases as $H/D$ increases. This behaviour agrees with the heat transfer profiles. It has to be point out that such a second heat transfer peak is not only related to the phase-average measured counter rotating vortex caused by the primary vortex ring. Indeed, others counter rotating vortex are generated by the vortex ring caused by the Kelvin-Helmholtz instabilities of the column of
the fluid following the primary ring vortex (because the Strouhal number is equal to 0.024). At a nozzle-to-plate distance equal to 6 diameters the maximum heat transfer in the stagnation point is detected, in agreement with what happens for continuous jets.

$Nu'$ resembles the $\bar{Nu}$ profile and is strictly related to the axial fluctuating velocity profile (phase-correlated and turbulent components). Moreover, the value of $Nu'$ map becomes more uniform and its maximum value decreases at high $H/D$ because, as the distance from the nozzle increases (Shuster and Smith [43]), synthetic jets act like turbulent continuous jets. As matter of fact all the fluctuating velocity values decrease for $H/D$ higher than 6.

The $\bar{Nu}$ profile for twin synthetic jets with $\Sigma = 1.1$ show two distinct stagnation points only for $H/D = 2$. As a matter of fact, the relative $\bar{Nu}$ profile shows a first peak at $x/D = 0$ and a symmetric second peak at approximately $x/D = 1.05$. The first and the second peak are related to the existence of the inner ring shaped region. Such a ring occurs around the two stagnation points, located at $x/D = 0.55$, and shows a diameter equal to $1D$. The superimposition of the two inner ring shaped regions at $x/D = 0$ is the reason why the first peak is higher than the second one. This can be related to the behaviour of the time-average axial velocity component and the time-average phase-correlated organized contribution to the velocity axial component (not presented here).

![Figure 14. Phase-average Nusselt number for TSJ with $\Sigma$ equal to 1.1 at $H/D$ equal to 2 (left) and 6 (right).](image)

The $Nu'$ maps and profile clearly show the effect of the unsteady passage of the vortex ring. Due to the superimposition of the two inner ring shaped regions, the value of $Nu'$ acquired at $x/D = 0$ is not equal to the one attained at $x/D \approx 1.05$. As $H/D$ increases the strong interaction between the two adjacent jets produces a different heat transfer behaviour characterized by a maximum $\bar{Nu}$ value at $H/D = 4$ as visible in Figure 14. For $\Sigma = 1.1$ and $4 \leq H/D \leq 8$ $Nu'$ presents a different behaviour from the $\bar{Nu}$ profile. In fact, at $H/D$ equal to 4 the $Nu'$ profile shows the peak relative to the inner ring shaped region but the second peak is strongly reduced. Such a second peak disappears for $H/D$ higher than 4 differently from the first one. This could be related to the presence of the second wall jet which passes over the same zone of the plate (already swept by the vortex ring) causing a change in the variables value, differently form the SSJ configuration. Indeed, only small later oscillations, approximately in the same radial position, can be barely seen. The first $Nu'$ peak shifts toward the centre as $H/D$ increases because
the jet, as previously explained, starts acting as a turbulent continuous jet. At $H/D$ equal to 10 the $N_u$ profile is very similar to the one of a single synthetic jet. At all the nozzle-to-plate-distances the values of $\overline{N_u}$ measured are higher than the SSJ case. Moreover, it is worth nothing that the values attained by $N_u$ for such a twin synthetic jets configuration are lower than the one acquired by the single synthetic jet. This is related to the presence of two impinging synthetic jets. Indeed, in this configuration there is always a heat transfer caused by the impingement. This condition leads to a decreasing variation of the Nusselt number ($N_u$') as also occurs for the phase-correlated velocity contributions in the TSJ case (with respect to SSJ case).

Regarding the twin synthetic jets with $\Sigma = 3$ the Nusselt number maps show two clearly distinct stagnation regions, approximately at $x/D \approx 1.5$ with its inner and outer ring shaped regions. In this configuration, for $H/D = 2$, the peak located approximately at $x/D \approx 1$ is higher than the peak at $x/D \approx 2$. This effect is related to the fact that the peak which is closer to the centre is more affected by the presence of the other jet and a beneficial effect is attained. Such a phenomenon decreases with $H/D$ increase, disappearing already for $H/D = 4$. Also in this case $N_u$' and $\overline{N_u}$ maps and profiles present a similar behavior. As matter of fact at $H/D = 2$ the $N_u$' profile shows two peaks at approximately $x/D \approx 2.1$ and $x/D \approx 3.5$ showing the presence of the inner and outer shaped regions. The relationship between the velocity component and the heat transfer behaviour is the same previously explained for the SSJ case. As $H/D$ increases, the inner and outer structures disappear. Moreover the maxima in $N_u$' profile merge in a unique maximum located at approximately $x/D \approx 1.5$, where the synthetic jet impinges. The behaviour of twin synthetic circular air jets with $\Sigma = 5$ is very similar to the one shown for $\Sigma = 3$.

3.2. Quadruple Synthetic Jets device: free flow field and heat transfer

The quadruple synthetic jet flow field is deeply characterized by the formation and convection of large-scale coherent vortex structures (CVSs). These structures originate during the ejection stroke after the separation of the flow at the edges of the jet outlet and then move downstream under their self-induced velocity. As the CVSs propagate, they develop inertial instabilities that cause their break down and, finally, they decay to turbulence. Therefore, two different flow field region can be defined: near and far (velocity) fields. The near (velocity) field is that part of the field characterized by the passage of the CVSs, while the far (velocity) field is the region where the CVSs have completely dissipated and the synthetic jet has turned into a steady turbulent jet flow. The QSJ is characterized by $L_v/D = 5$, so no significant trailing jet is expected. Therefore, the near field of the QSJ is dominated essentially by the dynamics of the CVSs. These CVSs show a complex evolution since they result from the interaction of fours vortex rings issued by the four nozzles. As expected, this interaction strongly depends on the initial phases of the single synthetic jets and, thus, on the considered configuration. In order to explain the behaviour of such structures in the four investigated configurations, the phase-averaged fields of the out-of-plane vorticity are considered and analyzed.

In Figure 15 (left), contours of the non-dimensional phase-averaged $\zeta D/2U_0$ in the N/S plane for the MP configuration are reported. Four different phases are presented, corresponding to the beginning and the middle of the ejection part of the cycle (phases $\varphi = 0^\circ$ and $\varphi = 90^\circ$, respectively) and to the beginning and the middle of the suction part ($\varphi = 180^\circ$ and $\varphi = 270^\circ$, respectively).

At the phase $\varphi = 0^\circ$, two CVSs can be detected at $x/D = 8$ and $x/D = 4$, named CVS1 and CVS2, respectively. No coherent structures can be observed in the downstream region of the flow field, while the phase-averaged vorticity field shows irregular small-scale variations that is a usual characteristic of unsteady turbulent motions. From $\varphi = 90^\circ$, another structure (CVS3) is forming at the beginning of the field of view and, then, it continues its propagation. Indeed, CVS1 and CVS2 can be considered as the evolution of CVS3. It is important to remark that these CVSs are generated by the coalescence of the four separated vortex rings, which are simultaneously issued from the four nozzles. Figure 15 clearly shows that the original vortex rings merge causing a larger structure whose diameter (defined as the
distance between the two points with the highest $\zeta$ value) is approximately 2.5 times the nozzle diameter. Such a structure slowly weakens moving downstream, and, at $x/D \approx 12$, it completely dissipates (CVS1 definitively loses its coherence between $\phi=180^\circ$ and $\phi=270^\circ$).

Figure 15. Contours of the non-dimensional phase-averaged out-of-plane vorticity $\zeta D/2U_0$ in the N/S plane for the MP configuration (left) and in the NE/SW plane for the DP (right) configuration. $Re$ 4000, and $Sr$ 0.200.

To better analyse the behaviour of the DP configuration, the phase evolution of the out-of-plane vorticity field in the NE/SW plane is discussed (Figure 15 - right). At $\phi=0^\circ$, the ejection strokes of the north and east jets begin and two CVSs can be observed in the near region ($x/D<6$). These structures seem to have an elongated shape and they are tilted toward the centreline. This particular shape is ascribed to the interaction between the two vortex rings generated by the two nozzles (in the blowing phase) and the influence of the suction phase of the other two nozzles. North and east vortex rings merge in the CVS1 which is distorted by the suction forces of the south and west nozzles. Indeed, the structure denoted as CVS3, observed within the field at $\phi=180^\circ$ and already detectable at $\phi=90^\circ$, represents the early stage of the evolution of CVS1. Analogously, the merging of the vortex rings, ejected by the south and west nozzles and affected by the suction phases of the north and east nozzles, generate the CVS2 structure. Its evolution can be followed in a straightforward way as the time phase increases in Figure 15. Anyway, it is important to note that the phase evolution, in the NE/SW plane, during the second half of the period, is specular with respect to the x axis to that in the first half. From Figure 15, it is clear that these CVSs propagate along directions inclined with respect to the x axis (CVS1 and CVS3 toward the negative y direction and CVS2 toward the positive y direction). This oblique propagation of the CVSs is the cause of the greater spreading of the DP jet in this plane than in the other investigated ones. The CVSs preserve their coherence up to $x/D=6$, differently from MP configuration.

The phase-averaged of the out-of-plane vorticity fields of the QP configuration in the N/S plane is illustrated in Figure 16 (left). At $\phi=0^\circ$, the ejection stroke of the north and south jets begin. For this configuration, two different CVSs in the near region, denoted as CVS1 and CVS2, can be observed. As in the DP case, such structures are ascribed to the coalescence of the two vortex rings formed at the exit of the ejection nozzles (which are opposite to each other in this configuration), and their evolution is affected by the suction phase of the other two nozzles. Passing from $\phi=0^\circ$ and $180^\circ$, it is possible to observe that the CVS1 firstly widens and then decays. On the opposite, CVS2 appears to shrink between $\phi=180^\circ$ and $270^\circ$ and then loses its coherence. Indeed, at $\phi=270^\circ$, such a coherent vortex structure is observed at $x/D=4$, while at $\phi=0^\circ$, no coherent structures are detected downstream of this position. Anyway, these structures lose coherence and dissipate very quickly leaving no evidence of them.
downstream of $x/D=5$.

Finally, in Figure 16 (right), the phase-averaged fields of the out-of-plane vorticity component in the N/S plane for the CSP case are shown. The phase $\phi=0^\circ$ represents the beginning of the ejection stroke of the north jet. At this phase, two CVSs (CVS1 and CVS2) are observed in the near field region ($x/D<6$). Following the phase evolution, four more CVSs appear in the field of view. CVS3, CVS4, CVS5, and CVS6 are the vortex rings ejected from the north, west, south, and east nozzles, respectively, while CVS1 and CVS2 are advanced stages of the evolution of CVS5 and CVS6, respectively. Indeed, in the CSP configuration, no merging of the vortex rings occurs because the ejection strokes of the four jets are shifted by $90^\circ$ (one-quarter of period) with respect to each other. Nevertheless, a mutual interaction occurs between these structures because of their closeness. Each vortex moves substantially along the axis of the corresponding nozzle and dissipates completely within eight diameters from the nozzle exits (for instance, CVS1 disappear between $\phi=90$ and $180^\circ$ approximately at this location).

**Figure 16.** Contours of the non-dimensional phase-averaged out-of-plane vorticity $\zeta zD/2U_0$ in the N/S plane for the QP configuration (left) and for the CSP (right) configuration. $Re$ 4000, and $Sr$ 0.200.

The evolution of such coherent vortex structures deeply influence the heat transfer behaviour of the QSJ. In order to have a clearer overview of how such structures evolve, their behaviour is schematically shown in Paolillo et al. [45]. Considering these structures and their evolution, the heat transfer results can be analysed and discussed in an easier way. Figure 17 shows the distribution of the time-averaged Nusselt number for all the impingement distances in all the investigated configurations.

At $H/D = 2.5$ the MP jet attains the lowest values of the time-averaged Nusselt number. This could be due to the frequency of generation of the CVSs in the MP configuration that is smaller than that of the other cases. Interestingly, the Nusselt number spatial distribution reflects the shape of the impinging CVSs. Indeed, the pattern of the inner region, characterized by the highest values of the Nusselt number, has the same shape of the footprint of the impinging CVS. In the MP case at $H/D = 2.5$ such a region has a four-lobe shape with the major axes aligned with the diagonal directions and the minor axes aligned with the longitudinal Y and Z directions. Outside of the high-Nu region, it is possible to observe four regions with relatively high Nu values, which form a cross shaped pattern. Such a distribution evidently suggests that the wall jet develops mainly along the Y and Z directions. Moving from the stagnation region along the Y - and Z-axes, it is possible to note a minimum and a subsequent maximum of $Nu$ located at $2D$ and $2.8D$ from the centre respectively. Such features are typical of impinging jets at short $H/D$ and their origin has been widely investigated and documented in literature (see Carlomagno and Ianiro [44] for instance): local minima are caused with vortex-induced separation, while subsequent local maxima are related to the following reattachment of the wall jet.
At $H/D = 5$ the MP jet exhibits a completely different $Nu$ distribution. In particular, the Nusselt number increases and the four lobe pattern has its major and minor axes switched. In this case, the wall jet likely develops mainly in the direction of the minor axes of the four-lobe shape (i.e. $Y = Z$ and $Y = -Z$,) since $Nu$ shows high values over a longer distance when moving away from the plate centre along these directions.

At $H/D = 7.5$ the four-lobe shape disappears and an ovoid pattern is observed, while at higher $H/D$ pattern becomes circular. Such a behaviour is ascribed to the CVS shape oscillations that ceases at these nozzle-to-plate distances assuming a circular shape. Indeed, for $H/D \geq 12.5$ the CVSs do not reach the wall because they dissipate before. Therefore, at these $H/D$ values, a turbulent jet, generated by the breakdown of the CVSs, reaches the impingement plate. Such a flow is self-preserving in its downstream development and characterized by a Gaussian crosswise velocity profile. Consequently, the $Nu$ distribution is bell-shaped, with the maximum value in the plate centre. At higher $H/D$, the bell-shaped distribution is smoothed out and becomes more uniform because of the jet spreading and deceleration.

The DP configuration shows, at any impingement distance, an elliptical Nusselt number pattern because of the elongated shape of the CVSs and their oblique propagation. Although the CVSs lose their coherence within the first eight diameters (Figure 15), the $Nu$ map preserves an elliptical shape at high impingement distances, opposite to the MP configuration behaviour. This is due to the fact that, despite the decay of the CVSs, the DP jet continues spreading in the streamwise plane containing the trajectories of the CVSs at a faster rate than in the other planes. At $H/D = 2.5$ minimum $Nu$ values are observed on the symmetry line ($Y=Z$) in the central part of the plate between two regions of maximum heat transfer. Such a distribution is due to the particular shape of the impinging CVSs, which are, at this stage, two-lobe shaped. Moving far enough from the centre, the Nusselt number decreases along the direction normal to the symmetry line. At higher $H/D$, the heat transfer attains high values on the
symmetry line and in the direction normal to it. Furthermore, the highest value of $Nu$ is always detected in the centre of the plate because in its proximity the CVSs impinge and then spread around keeping approximately their shape. The highest $Nu$ values are reached at $H/D = 5$; for greater distances, the heat transfer values monotonically decrease.

In the QP configuration, the $Nu$ distribution attains a rhomboidal pattern for $H/D \leq 10$ and a circular pattern for greater distances. The rhomboidal pattern is ascribed to the CVSs behaviour: before the vortex reconnection and splitting, the CVSs have a structure elongated along Y or Z direction. Even after the splitting, the two new formed vortex rings move away from each other along one of these two directions. Only after the dissipation of the CVSs, the Nusselt number map shows a more axisymmetric distribution, similar to the MP configuration. As in the DP configuration, the maximum $Nu$ values are attained at $H/D = 5$.

The CSP configuration achieved the highest values of Nusselt number and the widest high-$Nu$ region at $H/D = 2.5$. At larger impingement distances, the $Nu$ distribution seems to continuously rotate in the counterclockwise direction. Such a rotation continues until $H/D = 12.5$, then no further rotation is observed. At this nozzle-to-plate distance (i.e. $H/D$), the Nusselt number pattern is ovoid shaped with its major axis slightly rotated counterclockwise with respect to the diagonal line $Y = -Z$. It is worth noting that the $Nu$ distribution resembles that obtained by impinging swirling jets at low swirl numbers (Ianiro and Cardone [46]). In particular, at $H/D = 7.5$, the Nusselt number distribution of the CSP configuration looks very similar to the lozenge shape with rounded edges observed by Ianiro and Cardone [46] at $H/D = 6$ in the case of swirling jets (swirling number equal to 0.4). Clearly, these similar patterns are caused by very different flow topology. Swirling jets are characterized by multiple precessing spiral vortex structures (Cala et al. [47]), while the CSP jet consists of a train of vortex rings arranged in a helicoidal structure along the jet centreline. In the CSP jet case, the significant swirling velocities are generated by the successive vortex rings in their intermediate regions, because of their closeness. Consequently, at the arrival of the vortex rings to the wall, the incoming flow has an azimuthal velocity component in addition to axial and radial velocities. On the other hand, the rotation of such a pattern up to $H/D = 12.5$ is surely related to the helicoidal structure of the vortex train. At greater $H/D$ the pattern does not rotate because the CVSs have already dissipated. Finally, it can be noted that the $Nu$ values, differently from the other configurations, monotonically decreases with $H$ in each point of the plate.

4. Conclusions

The synthetic jet technology has been widely applied in several fields of application because of their main advantages: easy miniaturization and low-cost manufacturing. The scientific community has employed this new technology also in the electronic cooling field because of the continuous request of higher heat power dissipation and miniaturization of the cooling devices. Therefore, the heat transfer capability of impinging synthetic jets has been experimentally and numerically investigated in these last decades. These devices have found to be promising from the heat transfer viewpoints. Many works have underlined the benefits and improvements of synthetic jets, compared with a classic electronic cooling as fan, such as: better efficiency, design-friendly, intrinsic higher reliability, easier miniaturisation, simple noise cancellation.

Early studies on synthetic jet, in the heat transfer field, were focused on the assessment of the effects of all the characteristics parameters on their heat transfer behaviour. After that their heat transfer capabilities were proved and the influence of the characteristic parameters were understood, the researchers paid their attention on the design of innovative configurations in order to further enhance the synthetic jet cooling rate. At the University of Naples Federico II, two new synthetic jet devices were designed in order to achieve a heat transfer enhancement and also a noise reduction, which is one of the main drawbacks of the synthetic jet technology. The heat transfer performances of these two
devices have been evaluated through the IR thermography. Obviously, the heat transfer performances of both the innovative devices are strictly related to their fluid dynamic behaviour. For this reason, also the flow field of these two devices has been experimentally investigated through the Particle Image Velocimetry technique (planar and stereo configurations).

The twin synthetic jets device has shown, in the side-by-side condition, higher values of axial velocity and turbulent kinetic energy than the single classical configuration. The other two cases (jet-axes-distances equal to 3 and 5) have shown a behaviour similar to the single case. Moreover, a potential core-like region of low turbulence has been defined and the evolution of the synthetic jet flow field has been described through the phase-average measurements.

Under these results the heat transfer behaviour of this device, always compared to the single case, has been evaluated. The twin synthetic jet device (in its side-by-side configuration) has shown a heat transfer enhancement for all the nozzle-to-plate distances. The time-average heat transfer behaviour of the single and twin synthetic jets has been explained through the results obtained in the impinging flow field study. A strong correlation between the axial velocity components and the heat transfer distribution has been found. Some aspects of the heat transfer behaviour (as the inner and outer region shaped of heat transfer maxima) have been explained through the potential core-like region and the vortex ring behaviour near the plate. The evolution of the heat transfer over the impinging plate has been described through the phase-average measurements.

The quadruple synthetic jet device has shown a complex flow field where the behaviour and the evolution of the coherent vortex structures is fundamental for the explanation of the heat transfer process. The footprint of the CVSs is clearly recognizable in the heat transfer maps at low values of H/D. Therefore, in the MP configuration a four-lobe pattern is detected, which exhibits an axis switching before assuming a circular shape. In the DP configuration, the heat transfer distribution is elongated in the direction of the major dimension of the impinging elliptical CVSs and preserves such a shape also at higher impingement distances. The QP heat transfer map is rhomboidal at small H/D and turns into a circular distribution as H/D is increased. The CSP configuration is characterized by a swirling jet-like heat transfer distribution (consisting in a pattern that rotates with H/D up to a H/D = 12.5).

In particular, the MP configuration exhibits the lowest values of heat transfer rate at small impingement distances and slightly better performance at larger distances. The CSP configuration offers very high heat transfer rates at H/D = 2.5. Intermediate values are attained with the DP and QP configurations, with the latter slightly outperforming the former. The obtained findings and previous acoustic investigation suggest that the CSP configuration is the most performing one for the purpose of electronics cooling, because it combines the lowest noise level with a thermal performance equivalent to that of the other configurations (even better at low impingement distances).

References
[1] Moore G.E., 1965, Cramming more components onto integrated circuits, Proceedings of the IEEE, 86(1), 114-117.
[2] Coe D.J., Allen M.G., Trautman M.A. and Glezer A., 1994, Micromachined jets for manipulation of macro flows, Solid-State Sensor and Actuator Workshop, 243–247.
[3] Allen M.G. and Glezer A., 1995, Jet vectoring using zero mass flux control jets, AFOSR contractor and grantee meeting on turbulence and internal flows.
[4] Holman R., Utturkar Y., Mittal R., Smith B.L. and Cattafesta L., 2005, Formation criterion for synthetic jets, AIAA J., 43(10), 2110-2116.
[5] Smith B.L. and Glezer A., 1998, The formation end evolution of synthetic jets, Phys. Fluids, 10(9), 2281-2297.
[6] Buchmann N.A., Atkinson C. and Soria J., 2013, Influence of ZNMF jet flow control on the spatio-temporal flow structure over a NACA-0015 airfoil. Exp. Fluids, 54(3), 1485.
[7] Smith B.L. and Glezer A., 2002, Jet vectoring using synthetic jets. J. Fluid Mech., 458, 1-34.
[8] Wang H. and Menon S., 2001, Fuel-air mixing enhancement by synthetic microjets. AIAA J., 39(12), 2308-2319.
[9] Müller M.O., Washabaugh P.D., Bernal L.P., Moran R.P., Parviz B.A. and Najafi K., Micromachined acoustic resonators for micro jet propulsion. *AIAA Paper*, 2000, 200-2404.
[10] Gutmark E., Yassour Y. and Wolfshein M., 1982, Acoustic enhancement of heat transfer in plane channels, *Proceedings of Seventh International Heat Transfer Conference*, 441–445, Munich, Germany.
[11] Mahalingam R. and Glezer A., 2005, Design and thermal characteristic of a synthetic jet ejector heat sink, *J. Electron. Packaging*, 127, 172-177.
[12] Chaudhari M., Puranik B. and Agrawal A., 2010, Heat transfer characteristics of synthetic jet impingement cooling, *Int. J. Heat Mass Tran.*, 53, 1057-1069.
[13] Valiorgue P., Persoons T., McGuinn A. and Murray D.B., 2009, Heat transfer mechanisms in an impinging synthetic jet for small jet-to-surface spacing, *Exp. Therm. Fluid Sci.*, 33, 597-603.
[14] Arik M., Icoz T., 2012, Predicting heat transfer from unsteady synthetic jets, *J. Heat Transfer*, 134, 1-8.
[15] Persoons T., McGuinn A. and Murray D.B., 2011, A general correlation for the stagnation point Nusselt number of an axisymmetric impinging synthetic jet, *Int. J. Heat Mass Tran.*, 54, 3900-3908.
[16] McGuinn A., Farrelly R., Persoons T. and Murray D.B., 2013, Flow regime characterization of an impinging axisymmetric synthetic jet, *Exp. Therm. Fluid Sci.*, 47, 241–251.
[17] Rylatt D.I. and O’Donovan T.S., 2013, Heat transfer enhancement to a confined impinging synthetic air jet, *Appl. Therm. Eng.*, 51, 468-475.
[18] Chaudhari M., Puranik B. and Agrawal A., 2010b, Effect of orifice shape in synthetic jet based impingement cooling, *Exp. Therm. Fluid Sci.*, 34, 246-256.
[19] Luo Z.B., Xia Z.X. and Bing L., 2006, New generation of synthetic jet actuators, *AIAA J.*, 44(10), 2418-2419.
[20] Luo Z.B., Deng X., Wang L. and Xia Z.X., 2011, Experimental technique based on delay phase angle and PIV measurements of a dual synthetic jets actuator, *Proceedings of the 2011 Symposium on Piezoelectricity, Acoustic Waves and Device Applications*, 1-5, Shenzhen, China.
[21] Persoons T., O’Donovan T.S. and Murray D.B., 2009, Heat transfer in adjacent interacting impinging synthetic jets, *Proceedings of 2009 ASME summer heat transfer conference*, 1-8, San Francisco, California.
[22] Lasance C.J.M. and Aarts R.M., 2008, Synthetic Jet Cooling Part I:Overview of Heat Transfer and Acoustic, *24th Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, 20-35, IEEE.
[23] Russell D.A., Titlow J.P. and Bemmen Y.J., 1999, Acoustic monopoles, dipoles, and quadrupoles: An experiment revisited, *Am. J. Phys.*, 67, 660-664.
[24] Lasance C.J.M., Aarts R.M. and Ouwelijes O., 2008, Synthetic jet cooling part II: experimental results of an acoustic dipole cooler, *24th Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, 26-31, IEEE.
[25] Bhapkar U.S., Srivastava A. and Agrawal A., 2014, Acoustic and heat transfer characteristics of an impinging elliptical synthetic jet generated by acoustic actuator, *Int. J. Heat Mass Tran.*, 79, 12-23.
[26] Jeyalingam J. and Jabbal M., 2016, Optimization of synthetic jet actuator design for noise reduction and velocity enhancement”. In *Proceedings of 8th AIAA Flow Control Conference. Washington, D.C.*, United States, AIAA paper 2016-4236.
[27] Greco C.S., Ianio A., Astarita T. and Cardone G., 2013, On the near field of single and twin circular synthetic air jets, *Int. J. Heat Fluid Fl.*, 44, 41-55.
[28] Greco C.S., Ianio A. and Cardone G., 2014, Time and phase average heat transfer in single and twin circular synthetic impinging air jets, *Int. J. Heat Mass Tran.*, 73, 776-788.
[29] Greco C.S., Castrillo G., Crispo C.M., Astarita T. and Cardone G., 2016. Investigation of impinging single and twin circular synthetic jets flow field. *Exp Therm Fluid Sci.*, 74, 354-
367.

[30] Paolillo G., Greco C.S. and Cardone G., 2017, Novel Quadruple Synthetic Jet Device: Flowfield and Acoustic Behavior, *AIAA J.*, **55**(7), 2241-2253.

[31] Paolillo G., Greco C:S: and Cardone G. 2017, Time-averaged heat transfer in confined impinging quadruple synthetic jets, *9th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, 12-15 June, 2017, Iguazu Falls, Brazil.

[32] Astarita T. and Cardone G., 2005, Analysis of interpolation schemes for image deformation methods in PIV, *Exp. Fluids*, **38**, 233-243.

[33] Astarita T., 2006, Analysis of interpolation schemes for image deformation methods in PIV: effect of noise on the accuracy and spatial resolution, *Exp. Fluids*, **40**, 977-987.

[34] Astarita T., 2007, Analysis of weighting windows for image deformation methods in PIV. *Exp. Fluids*, **43**, 859-872.

[35] Astarita T., 2008, Analysis of velocity interpolation schemes for image deformation methods in PIV, *Exp. Fluids*, **45**, 257-266.

[36] Hussain A.K.M.F. and Reynolds W.C., 1970, The mechanics of an organized wave in turbulent shear flow, *J. Fluid Mech.*, **41**(02), 241-258.

[37] Greco C. S., Cardone G. and Soria J., 2017, On the behaviour of impinging zero-net-mass-flux jets, *J. Fluid Mech.*, **810**, 25-59.

[38] Golobic I., Petkovsek J. and Kenning D.B.R., 2012, Bubble growth and horizontal coalescence in saturated pool boiling on a titanium foil, investigated by high-speed IR thermography, *Int. J. Heat Mass Tran.*, **55**(4), 1385-1402.

[39] Carломagno G.M. and Cardone G., 2010, Infrared thermography for convective heat transfer measurements, *Exp. Fluids*, **49**, 1187-1218.

[40] Rohlfs W., Haustein H.D., Garbrecht O. and Kneer R., 2012, Insights into local heat transfer of a submerged impinging jet: Influence of local flow acceleration and vortex-wall interaction, *Int. J. Heat Mass Tran.*, **55**(4), 1385-1402.

[41] Gordon R. and Akfirat J., 1965, The role of turbulence in determining the heat-transfer characteristics of impinging jets, *Int. J. Heat Mass Tran.*, **8**(10), 1261–1272.

[42] Jambunathan K., Lai E., Mossand M.A. and Button B.L., 1992, A review of heat transfer data for single circular jet impingement, *Int. J. Heat Fluid Fl.*, **13**, 106-115.

[43] Shuster J.M. and Smith D.R., 2007, Experimental study of the formation and scaling of a round synthetic jet, *Phys. Fluids*, **19**, 045109.

[44] Carломagno G.M. and Ianiro A., 2014, Thermo-fluid-dynamics of submerged jets impinging at short nozzle-to-plate distance: A review, *Exp. Therm. Fluid Sci.*, **58**, 15-35.

[45] Paolillo G., Greco C.S. and Cardone G., 2017, The evolution of quadruple synthetic jets, *Exp. Therm. Fluid Sci.*, **89**, 259-275.

[46] Ianiro A. and Cardone G., Heat transfer rate and uniformity in multichannel swirling impinging jets, *Applied Thermal Engineering*, **49**, 89–98.

[47] Cala C., Fernandes E., Heitor M. and Shlork S., Coherent structures in unsteady swirling jet flow, *Experiments in Fluids*, **40**(2), 267–276.