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Visualization of a Small Jet Synthetic Using a Particle Image Velocimetry and Background-Oriented Schlieren Techniques

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Visualization of a Small Jet Synthetic Using a Particle Image Velocimetry and Background-Oriented Schlieren Techniques

M Faruoli, G Abbruzzese, RM Di Tommaso and E Nino
Scuola di Ingegneria, Università degli Studi della Basilicata,
Viale Ateneo Lucano 10, 85100 Potenza, Italy

E-mail: enrico.nino@unibas.it

Abstract This work reports the results of experimental investigations carried out on a submerged synthetic jet obtained through the use of a headset speaker piloted with an appropriate sinusoidal signal at a frequency of 380 Hz. The study begins with the construction of a device that, exploiting the well-known transport properties of impacting jets, was able to improve local ventilation and the removal of excess moisture, due to the natural transpiration of human skin in people forced to assume the same position for prolonged periods such as professional drivers; bedridden patients; etc... Subjects are substantially forced to have parts of their own body in contact with fabrics and coverings that hinder the normal conditions of skin transpiration. The experimental activity was first based on the study of the structure of the synthetic jets, then moving on to the creation of a sponge mat equipped with 80 individual jets. On this sponge mat, semi-empirical tests were carried out in order to remove moisture from a fabric soaked in distilled water. The experimental investigations were first carried out using the PIV technique, and, subsequently, the synthetic jet was visualized using the Background-Oriented Schlieren (BOS) technique which allowed to test the presence of the jets, installed directly on the mattress, in a relatively simple and fast way, requiring a very simplified set-up.

Keyword: Moisture Removal; Synthetic Jet; PIV; Background-Oriented Schlieren.

1. Introduction

The recent development of the so-called "synthetic jets" has allowed the identification of new and interesting applications such as active control of gaseous flows, including reactive ones; control of the cooling of mechanical and electronic components; etc… The so-called "synthetic jets" are non-stationary jets obtained using a special cavity equipped, at one end, with a suitably shaped duct capable of putting the cavity itself in contact with the external environment. The other end is generally closed by using a membrane or by means of a piezoelectric element, both of these elements are able to oscillate if operated by appropriate signals. The membrane, or the piezoelectric element, is operated in such a way to make it oscillate and cause a variation in the internal volume of the cavity (figure 1). The fluid surrounding the device (air if exposed to the environment) is first sucked into the cavity and, in the subsequent semi-oscillation, expelled. By shaping the duct (and the cavity) in an appropriate way, it is possible to obtain a pulsed jet, with good properties of mass and energy transport (heat), even if there is a zero average mass flow rate. Obviously, the effectiveness with which the aforementioned mass and energy transports are obtained strongly depends on the coupling of the cavity, the oscillating element, and the discharge duct.

Starting from these well-known properties of synthetic jets, widely described and studied in the literature [1 to 16], in the present work, we have focused on an application distributed over a relatively large surface to exploit the mass transport properties of an array of "synthetic jets", suitably incorporated into elements of more or less padded fabric. The purpose of making such a device is to obtain a manufact that can improve human comfort, in cases where there is prolonged contact of parts of the human body with fabric and/or padding such as, for example, in the case of professional drivers or in the case of patients immobilized in bed for long periods and who may develop sores from decubitus. According with [17], the normal production of vapor of the human skin at room temperature (~20 °C) is of the order of magnitude of the $2.9\cdot10^{-3}$ kg/m^{2}hour. This amount of vapor produced by the skin can cause, in the worst cases, an increase in problems related to the formation of bedsores [18, 19] in long-term patients, or, in the most common cases, situations of discomfort in subjects forced to have parts of the body in contact with fabrics and padding that limit the normal transpiration. Several works have been carried out to mitigate and/or control the stagnation of skin moisture through the study and development of appropriate tissues [20, 21]. Our proposal is to improve comfort by increasing the transpiration of the parts of the human body, subjected to a prolonged obstacle of natural transpiration, through application of "synthetic jets", or through devices that, in fact, can "move the air" simply by sending an electrical signal. The same effect, if obtained by sending external air, could be obtained by using a source of pressurized air (compressor) and a series of ducts capable of distributing the pressurized air in the various contact areas. Neglecting the noise that a compressor or ventilator would introduce into the environment, the product would be crossed by a series of pipes that would reduce its flexibility, therefore its comfort, and would be subject to progressive obstruction and/or soiling caused by dust, which would be however creep into the ducts. The use of an array of "synthetic jets" substantially simplifies the system by eliminating the air transport ducts and the compressor or external fan, replacing them with simple connection cables, much less bulky and more flexible.

2. Synthetic jet

A synthetic jet is a fluid jet generated by the periodic motion of a diaphragm that closes a cylindrical cavity on one of the two base surfaces; the opposite base surface shows one or more orifices or slots, through which the cavity communicates with the external environment (figure 1). The movement of the diaphragm generates the alternation of two phases, one of ejection of the fluid contained in the cavity (blowing phase) and one of suction phase, which follow one another alternately. In the ejection phase, when the diaphragm is forced to move upward, part of the fluid contained in the cavity is expelled through the orifice; in the suction phase, on the other hand, the retrograde movement of the membrane causes a depression in the cavity, with a consequent recall of external fluid. Thus, a flow characterized by two macro regions is established: the area close to the outlet hole, in which the fluid mass affected by continuous expulsions and sucks is confined, and the region adjacent to it, in which there is a continuous flow with turbulent characteristics and with speed constantly directed upwards.

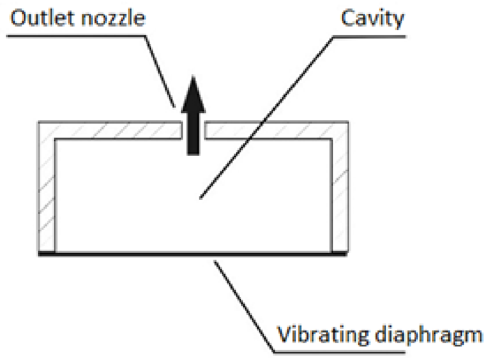

Figure 1. Schematic representation of a device for synthetic jet generation.

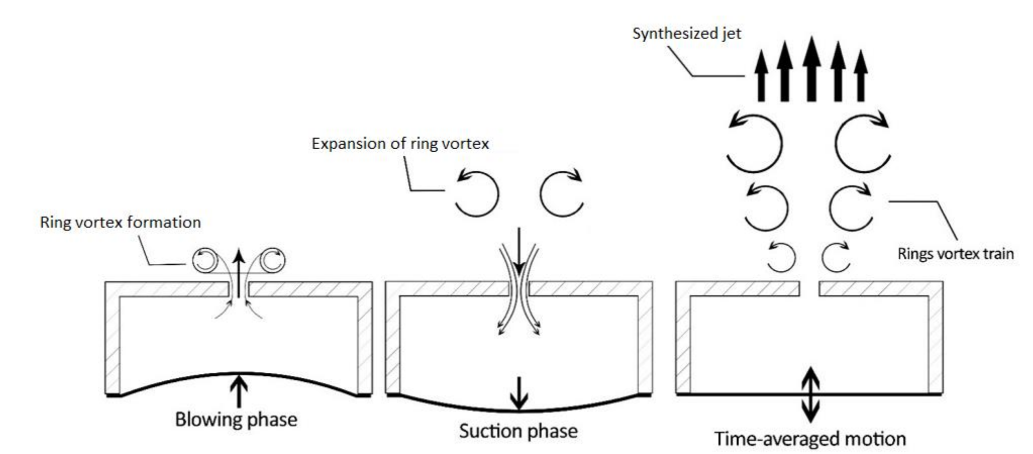

Figure 2. Qualitative description of the formation of synthetic jet.

Thus, a continuous turbulent jet can be obtained at different diameters away from the orifice without any contribution of mass from the outside through the interface surface of the system. In other words, the jet is synthesized by the same fluid that constitutes it: hence the name of synthetic jet. It should also be noted that the flow rate through the outlet nozzle is on average equal to zero as it is characterized by flows that, in an ejection-suction cycle, are periodically inverted.

A brief qualitative analysis of the period of oscillation of the diaphragm will allow us to understand the phenomena for which a synthetic jet is created. During the ejection phase, we witness the crucial phenomenon for the formation of this particular jet: the separation of the boundary layer at the edges of the orifice. As can be seen in figure 2, this leads to the generation of a ring vortex that moves upward and evolves due to the coalescence of smaller vortex structures. In particular operating conditions, during the suction phase, the vortex is sufficiently distant from the orifice and, therefore, theoretically not influenced by the entrainment of the fluid in the cavity. In this way, in several work cycles, a train of annular vortices (rings vortex train) is created away from the orifice; in the central part of these annular vortices, the counter-rotating motion of the same drags fluid mass upwards, generating the aforementioned turbulent flow.

The possibility of generating gaseous jets with the total absence of ducts and pumping systems makes synthetic jets the natural choice for our application.

In general, a synthetic jet with a cavity-diaphragm configuration can be seen as a double system, consisting of an electromechanical (diaphragm) and a fluid/acoustic (cavity-orifice) domain. The diaphragm, belonging to the electro-mechanical domain, is forced to oscillate, and reaches the maximum deflection at its resonant frequency. These oscillations are followed by the same amount of pressure signals which affect the fluid present in the cavity and which propagate towards the orifice and then escape, resulting in the synthesis of the jet. The oscillations of the fluid inside the cavity are associated with the fluid-acoustic domain, which is maximized at the resonant Helmholtz frequency of the cavity. Therefore it is understood that the resonance frequency of the synthetic jet intended as a double system is a combination of the two frequencies just mentioned.

In general, the resonant frequency of the diaphragm depends on the material, the mass, the dimensions of the membrane and the amplitude of the vibration. Assuming that the vibrating diaphragm is modeled as a circular disk, rigidly fixed to the edges, the solution to this problem is well documented [22] and the first two resonance frequencies $f_{1,2}$ are given by the following equation:

$$2\pi f_{1,2} = K_{1,2}\sqrt{\frac{4Et^3}{3(1-\upsilon^2)m_a D^4}} \quad (1)$$

Where:
K_1 and K_2 are constants;
E elastic modulus of the diaphragm;
t thickness of the actuator disc;
v mass per unit area of the actuator disc;
D the diameter of the vibrating disc.

The Helmholtz resonant frequency f_H [23] is presented; under a series of hypotheses (isentropic expansion, ideal gas law) he obtained the following equation:

$$2\pi f_H = \left[\left(\frac{4\rho h}{3\pi r_0^2} + \frac{8\rho}{3\pi^2 r_0}\right)\left(\frac{V}{\rho c^2}\right)\right]^{-0.5} \quad (2)$$

Where:
ρ density of the fluid contained in the cavity;
c speed of sound at operating conditions;
h thickness of the orifice;
r_0 radius of the orifice;
V volume of the cavity.

The application of what has been described so far has led, at the beginning of the research activity, to the creation of an actuator for the generation of synthetic jets visible in figure 3 and constituted by a suitable cavity closed by a piezoelectric actuator.

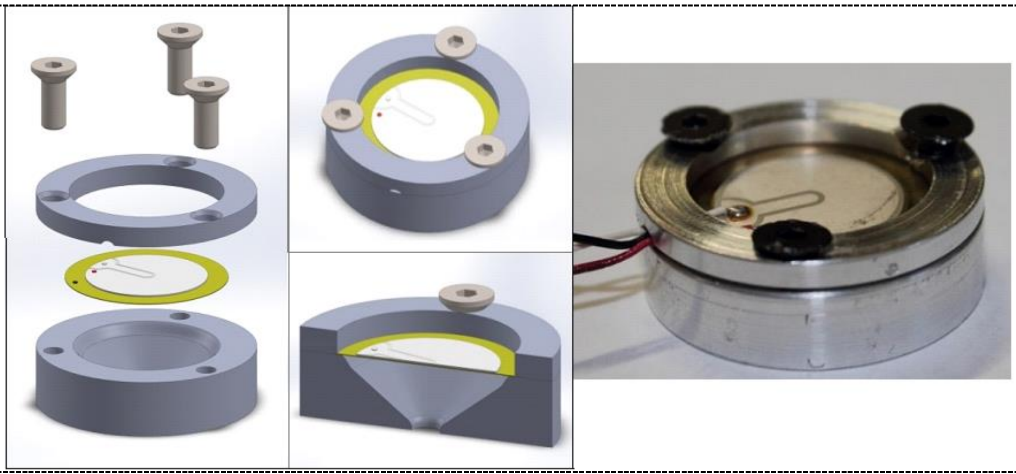

Figure 3. Device with piezoelectric actuator.

This actuator was able to produce a good synthetic jet by operating the piezoelectric actuator at a frequency of 4200 Hz. Although it had good results in terms of intensity and penetration of the jet, this device was quickly abandoned. Because, for the proposed activity, it was necessary to adopt a high number of single jets (80 as will be better described later). For this reason, the initial idea of developing a self-built actuator, designed according to the indications of the two equations reported above (1 and 2), has not proved to be us useful us we expect. The main reason for this was our difficulty to produce a high number of devices perfectly identical or capable of producing synthetic jets with substantially identical characteristics. Another reason lies in the fact that piezoelectric elements generally require high operating voltages (to within a magnitude of hundreds of volts) which is not really recommended for devices in contact with the human body. For this reason, it was decided to adopt commercial devices and modify them appropriately. The devices selected for our application were earphones for playful

applications such as listening to music from mobile devices (MP3 players, smartphones, etc.). The selected devices, visible in figure 4, have the advantage of being economical; already equipped with electrical wiring; with small dimensions. The main disadvantage, however, consists in the fact that they are not designed to generate synthetic jets but to spread pressure oscillations with frequency in the audible range. This condition required the realization of a relatively simple modification, consisting of the shielding of the protective grid of the vibrating membrane contained therein, shielding obtained simply by gluing a piece of the adhesive tape to the grid and making a single central hole (with a diameter of 1.5 mm in our application) to make the discharge channel for the synthetic jet generation. In figure 5 it is possible to see an example of a modified headset speaker.
In order to realize a mattress with a uniform distribution of the devices in a 0,05x0,05 m square grid, 80 of a so modified headset speakers have been realized, as it is possible to see in figure 6 and figure 7. In these two images, it is possible to observe also the cabling, the function generator, the amplifier an all the devices necessary to run the experiment.
Due to the adoption of commercially available devices, and after their manipulation, equations 1 and 2 have no longer been adopted, due to the difficulty of determining the constant and required parameters for the solution. An empirical procedure was therefore adopted to determine the presence of the synthetic jet and to optimize the driving frequency of the loudspeaker. The simple empirical procedure has been identified in the exposure of the jet to the flame of a candle. If the flame is deflected, the device correctly generated a synthetic jet. With this procedure was also possible to individuate the best resonance frequency of the jet equal to 380 Hz.

Figure 4. Headset speaker adopted.

Figure 5. Modified headset speaker.

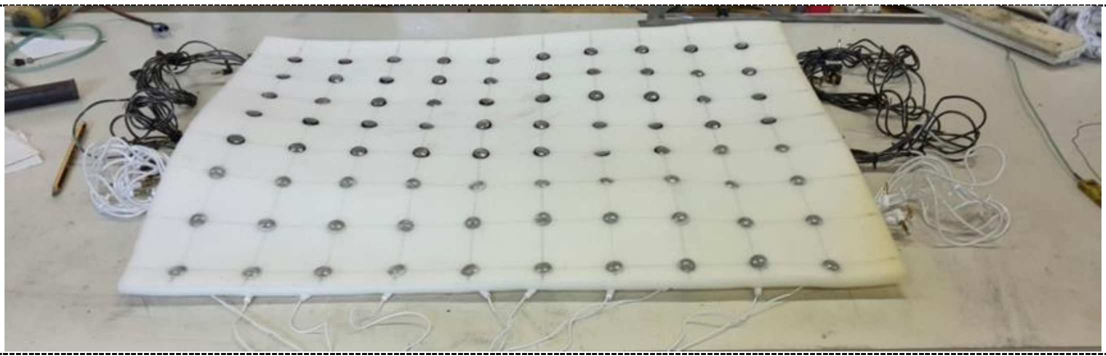

Figure 6. In this image 80 speakers are uniformly distributed along a blanket 0.35 x 0.45 m.

Figure 7. A view of the device equipped with the signal generator, the amplifier and an oscilloscope for monitoring the driving signal.

3. Experimental apparatus

The jets generated have been widely investigated essentially utilizing a classical PIV apparatus, reported in fig. 8, constituted by a double cavity Nd:YAG pulsed laser with 100 mJ/pulse, drove in second harmonic at a wavelength λ=532 nm; a TSI® PIVCAM cross-correlation CCD camera with a resolution of 1280 × 1024 pixel, equipped by an optical objective NIKON® 50 mm f/1.2; a TSI® Laser-Pulse 610034 synchronizer; a periscope optical arm. The collection and subsequent processing of the PIV images were carried out using the TSI® software Insight®. The adopted analysis software was capable of carrying out cross-correlation peak deviation analysis with a resolution lower than one pixel [23, 24], while the export and reconstruction of the results obtained were done using the Tecplot® software.
The PIV images have been collected adopting a liquid seeding constitute by olive oil dispersed, in the measurement field, through a low-velocity air-assisted atomizer. In practice, we generated a kind of fog around the investigation area. The nominal dimension of the oil droplets was of the order of magnitude of 2 µm.

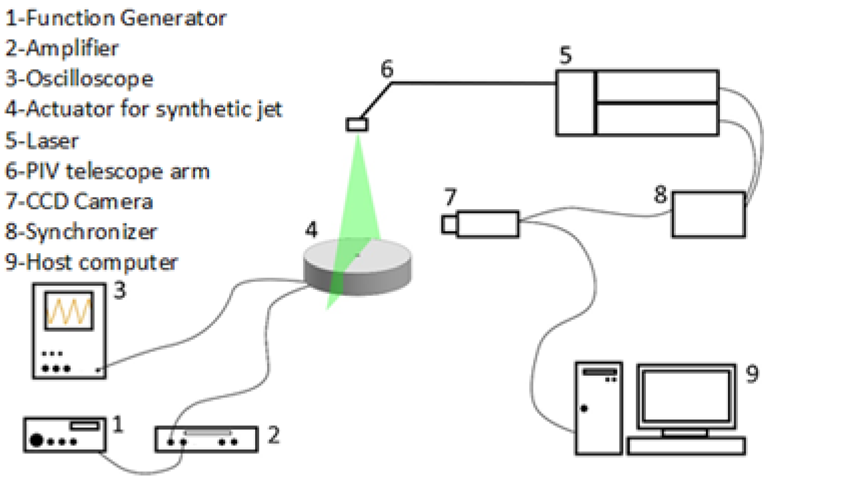

Figure 8. Schematic representation of the PIV setup adopted.

The PIV measurements were carried out both on the single jet and on a pair of jets, spaced as on the mat created, ie at a distance of 0.05 m, piloted in phase opposition. Driving pairs of speakers at the same

frequency but in phase opposition, was necessary to minimize the acoustic disturbance introduced into the environment. In fact, even if driving the loudspeakers with an average power (RMS) not exceeding 1 mW, having to drive 80 loudspeakers would have induced an acoustic disturbance which was however audible and, certainly annoying, for example in applications for bedridden patients. Phase opposition has substantially eliminated or greatly reduced this problem.
In addition to the PIV, the background-oriented schlieren visualization technique was adopted, the optical scheme, of which is shown in figure 9, was constituted using a 6 mW CW HeNe laser with λ=632 nm, a translucid screen, and a CCD Camera (the same camera adopted for the PIV setup). This optical scheme was adopted, according to [25, 26], to obtain speckle distributions on the screen, figure 10, to increase the sensibility of the devices. In practice, the optical scheme adopted is that of the laser speckle-based background-oriented schlieren. The adoption of this technique, although not having a quantitative answer, like the PIV, was necessary due to the extreme simplicity of collecting the images of the jets produced. This feature was very useful in the "in situ" verification of the presence or absence of the synthetic jets produced. It should be noted that the positioning of the 80 devices on the mattress and their relative wiring have created many practical difficulties due to lack of signal, positioning error, etc… The possibility of having a technique capable of quickly signaling the presence or absence of the jet, without the need to inseminate the surrounding air, made it possible to fine-tune the final artifact. The collection and subsequent analysis of the images were carried out by collecting a background image in the absence of perturbation, then a series of five consecutive images (acquisition frequency equal to 1 Hz) was collected and processed by cross-correlating them with the reference image. The software used was the same as the PIV, namely Insight® for the cross-correlation and Tecplot® for the subsequent reconstruction of the results obtained. Insight® provides the displacement of the cross-correlation peak as velocity vectors while in the Schlieren images this displacement is caused by variations in the refractive index of the air in the presence of the synthetic jet.

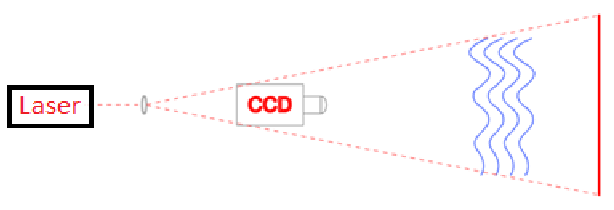

Figure 9. Optical setup of the laser speckle based background oriented schlieren.

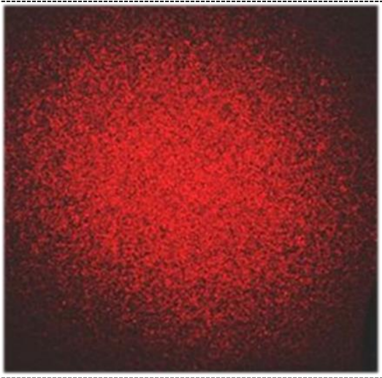

Figure 10. Speckle image formed on the target.

4. Results and discussion
The experimental investigations were first conducted on a single device by carrying out PIV measurements of the synthetic jet. This jet was obtained by driving the loudspeaker with a sinusoidal signal with a frequency of 380 Hz and an amplitude of 5 V. The single pairs of images, temporally separated by a Δt equal to 2 milliseconds were acquired with a frequency of about 1 Hz. As already mentioned above, the area affected by the synthetic jet was inseminated by means of an air atomizer capable of dispersing olive oil in a mist of drops with a nominal diameter equal to about 2 μm. The images were analyzed with a 32x32 pixel matrix. Figure 11 and figure 12 show the mediated images on 20 single acquisitions respectively of the velocity and vorticity distribution obtained.

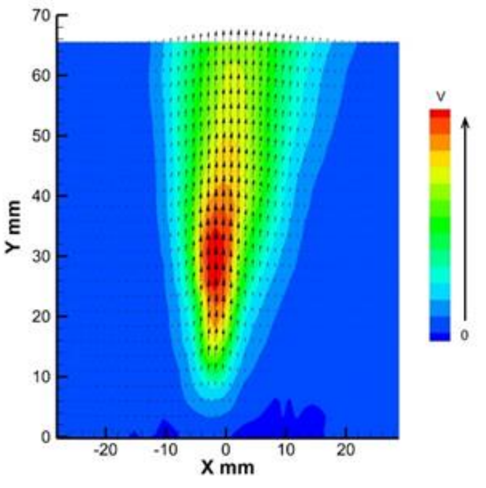

Figure 11. Average velocity distribution.

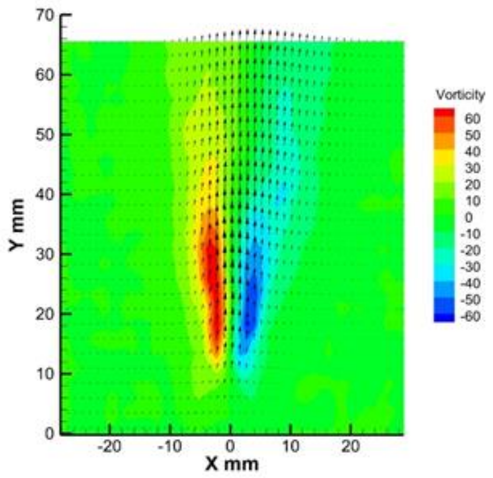

Figure 12. Average vorticity distribution.

The velocity distributions obtained show that the driving frequency of 380 Hz is able to generates a fairly intense jet, confirming the empirically results obtained observing the interaction of the jet with the flame of a candle. The interesting parameters detected are constituted by the distance of penetration of the jet which exceeds 60 mm or by comparing it to the diameter of the outlet duct, equal to 1.5 mm, the value of 40 l/d is exceeded. Furthermore, at a distance of about 60 mm, the jet extends its effects to a circular crown with radii greater than 20 mm. This last parameter is decisive for establishing the minimum positioning distance of two consecutive loudspeakers. This minimum distance was equal to 50 mm and was verified by coupling two devices, spaced 50 mm apart, and measuring the speed distribution shown in figure 13. In this image, the instantaneous velocity distribution demonstrates that the two jets begin to superimpose their effects already at a distance of 50 mm or at an l/d = 33. It should be noted briefly that the two velocity distributions shown in figure 13 represent an instantaneous flow field and since the two loudspeakers were driven in phase opposition, they differ slightly from each other having recorded different moments of the evolution of the jets.

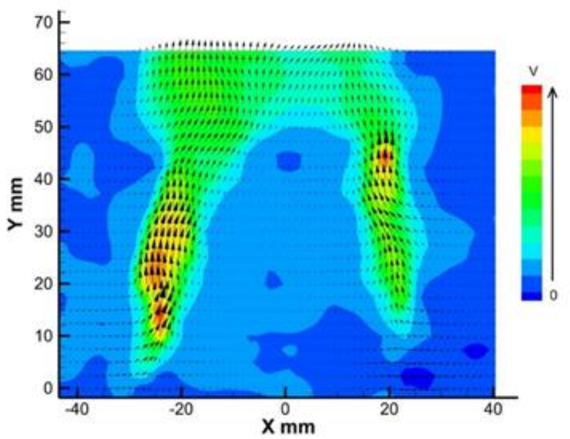

Figure 13. Instantaneous velocity distribution of two jets.

Although the PIV measurements have allowed the exhaustive description of the flow field produced, they can allow experimental measurements on a few synthetic jets at a time. Furthermore, the PIV measurements require a rather complex experimental setup, just think of the need to inseminate the investigation area. This situation turned out to be quite problematic when making the mat equipped with 80 synthetic jets which presented problems of positioning, wiring, etc... These problems did not guarantee that all the loudspeakers would work simultaneously and correctly. Understanding whether the single actuator was in operation proved to be particularly difficult due to the low momentum produced, remember that the discharge channel has a diameter of 1.5 mm and the levels of pressure generated are to within magnitude of less than one pascals (acoustic pressures). These circumstances required the use of the background-oriented schlieren visualization technique which, due to its simplicity of setup, made it possible to monitor the formation of the synthetic jets produced directly "in situ". It seems obvious that before adopting this visualization technique it was necessary to carry out comparative tests with the data provided by the PIV. In figure 14 a BOS image of the synthetic jet is visible. At a first analysis, it would seem that the result obtained is somewhat far from what was obtained with the PIV, but this is understandable by remembering how the Schlieren techniques record inhomogeneity of the refractive index present along the optical path. The variation of the refractive index, described by the well-known Gladstone-Dale relationship, is also a function of the gas pressure (ambient air in our case), therefore from the inhomogeneities of pressure induced by the synthetic jet. In fact, taking an instantaneous speed distribution PIV like the one shown in figure 15 it is possible to superimpose it on the image of figure 14 obtaining the image of figure 16. In this last image, it can be observed how the two results substantially overlap, demonstrating how the BOS technique, even if it describes the jet in the studio in an approximate manner, allows to determine its presence or not.

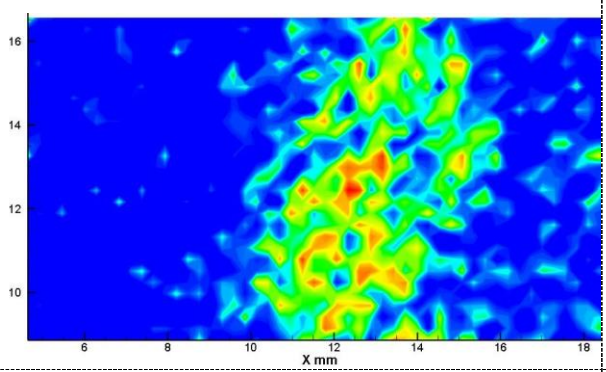

Figure 14. Distribution of inhomogeneities of diffraction index induced by synthetic jet (false colour representation).

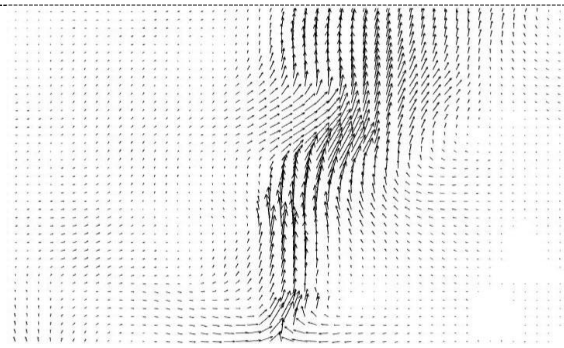

Figure 15. Velocity distribution of the same jet of the previous figure obtained with a traditional PIV technique.

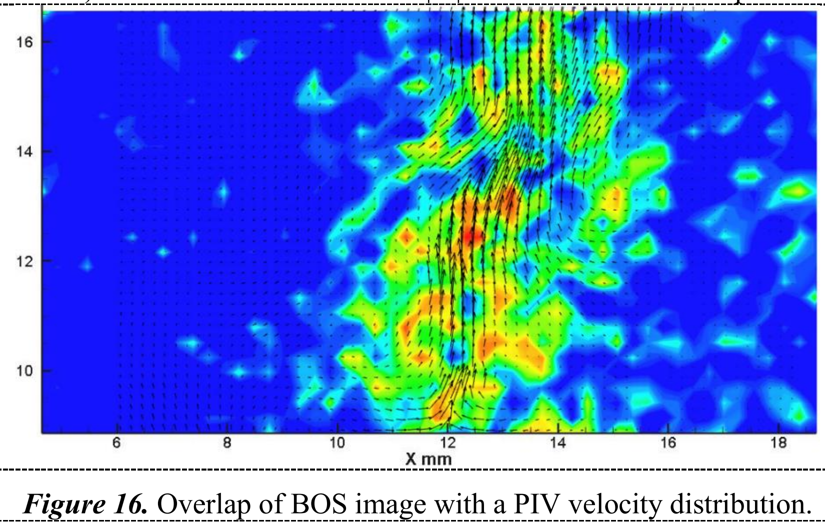

Figure 16. Overlap of BOS image with a PIV velocity distribution.

At the end of this work, it is appropriate to mention the first results achieved with the mat instrumented with synthetic jets, carried out by exposing a fabric soaked in distilled water to the action of the synthetic jet as visible in figure 17. Figure 18 shows a detail of the area of a piece of a fabric moistened with distilled water (the humidity halo is visible) with the central part, superimposed on a synthetic jet, visibly drier (circled) than the surrounding area. The obtained results, although preliminary and empirical, demonstrate the ability of the device to speed up the drying of the fabric.

Figure 17. Drying test of fabric with an area soaked in distilled water (darker area on the fabric lying on the instrumented mat).

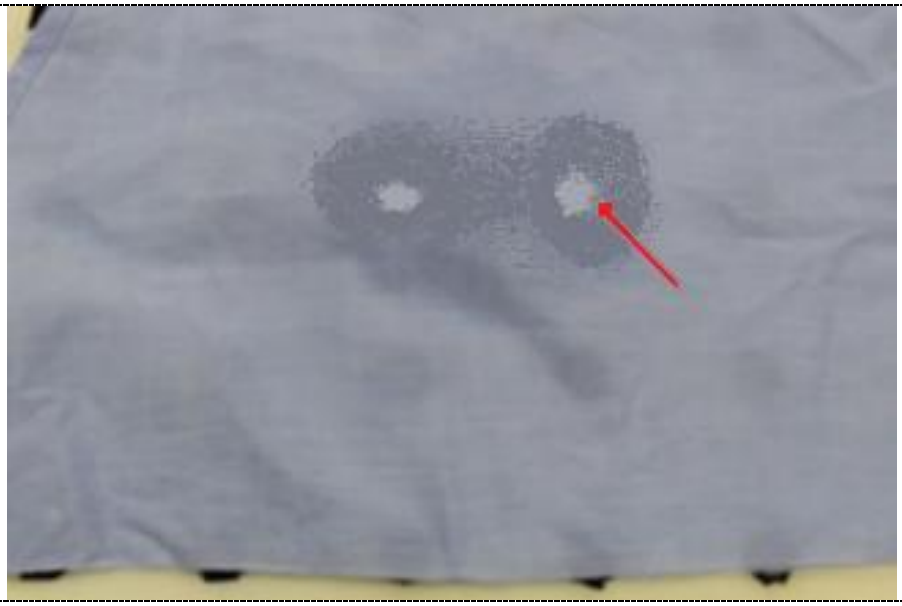

Figure 18. A detail of a dried zone evidenced by the arrow.

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5. Conclusions

In this work, an experimental investigation was presented on the use of synthetic jets in applications aimed at improving human comfort by improving skin transpiration conditions. The activity involved the construction of a mattress, instrumented with 80 synthetic jets, which will be used to improve comfort conditions in cases where there is prolonged contact of parts of the human body with fabric and/or padding such as, for example, in the case of professional drivers or in the case of patients immobilized in bed for long periods and who may develop sores from decubitus. The study started with the creation of synthetic jets by means of modified earphones for audio headphones and continued by extensively investigating the jets obtained using the optical technique of Particle Image Velocimetry. A second optical technique, consisting of the background-oriented schlieren, was adopted to visualize the presence of the jets directly on the manufactured article. Finally, the first series of empirical tests were carried out to verify the ability to remove moisture from a fabric, previously soaked in distilled water, exposed to the action of the synthetic jets made. The results of these latest tests, although encouraging, require further analyzes to be carried out quantitative information, like the moisture evaporation rate, under controlled environmental humidity and temperature.

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