A new Particle Tracking Velocimetry

A. Baldassarre[a], M. De Lucia[a], P. Nesi[b], F. Rossi[a]

[a]Department of Energy Engineering (DEF), University of Florence, Italy
mdl@gedeone.de.unifi.it; http://gedeone.de.unifi.it
[b]Department of Systems and Informatics (DSI), University of Florence, Italy
nesi@ingfi1.ing.unifi.it, nesi@dsi.unifi.it, http://www.dsi.unifi.it/~nesi

ABSTRACT

Particle Image Velocimetry (PIV) is a non-intrusive optical measurement method to capture flow velocity fields. It provides the simultaneous visualisation of the two-dimensional streamline pattern in unsteady flows and the quantification of the velocity field over a plane. To reveal the flow motion, the flow is seeded by small scattering particles. The instantaneous fluid velocities are evaluated by recording the images of tracers, suspended in the fluid and traversing a light sheet. A PIV system consists of seeding particles, illumination unit, image acquisition system, and a processing computer with appropriate software. For industrial applications a standard PIV system is not suitable, for its costs, sizes and needs of specialised users and work areas. In this paper, the realisation of a new PIV system is described and compared with the standard PIV. The solution proposed is a Continuous PIV, CPIV, system: with respect to a standard PIV, it is composed of a continuous laser light source, a low cost standard CCD camera. A specifically new image-processing algorithm has been developed. This studies the grey level distribution in the particle trace image, and indicates those particles moving with an out-of-plane velocity vector component and the measure with a limited error.

Keywords: PIV, velocity flow estimation, vision-based technique, motion analysis.

1. INTRODUCTION

During the last ten years, Particle Image Velocimetry (PIV) had received a rapid evolution. They are non-intrusive optical measurement methods to capture flow velocity fields[1, 2]. PIV provides the simultaneous visualisation of the two-dimensional streamline pattern in unsteady flows, as well as the quantification of the velocity field over an entire plane. With the improvement of image acquisition (optics and CCD technology) and light and processing systems, several kinds of PIV systems were studied and proposed [3]. Different techniques have been defined for studying fluids in different regimes. In the last few years, a particular PIV system has been widely used, for studying flows in many different conditions. Hereafter, this is called *standard PIV* system. In this case, a pulsed laser is used as a light source, while small seeding particles, and a CCD camera or a photographic film are used such as a recording system for the standard PIV system[4]. A common light source is a Q-switched Nd:Yag laser, frequency doubled, that is possible to have with a very short time lag between successive pulses. Using cylindrical lenses expands the highly collimated laser beam, thus producing an intense light sheet down to a thickness of tens of microns. In a PIV system, the illumination pulses need to be synchronised with the image exposition. This is usually achieved by programmable pulse delay generators that can be either stand alone or hosted by the computer performing the image acquisition and analysis. In the standard PIV measures, it is possible to record one or two successive images of the small particle tracers. With non-standard cameras, especially developed for PIV, it is possible to acquire two images, each of which is synchronised with one laser pulse. The duration of the Q-switched Nd:Yag pulse is of only a few nanoseconds (typically 10 ns or less). Thus, the images obtained show one illuminated spot, due to the scattering particle, in two different positions in the two successive images. Knowing the time lag between the two light pulses and measuring the distance between the two positions allow evaluating the velocity component in the illuminated plane.

The detection of the sign of particle velocity vectors is a classical problem of PIV analysis[5, 6]. In fact, most of the solutions proposed are capable of evaluating only the magnitude and direction of the velocity vector, without the sign. To solve this problem, many different solutions were proposed for the standard PIVs. One of the most largely used methods is based on the introduction of a known and fixed shift between the two images recorded corresponding to the two flashlights. This method is made with rotating mirrors[7], and was studied in several different conditions from many authors [8, 9]. This solution can be used with pre-existent systems, just recording with the camera the images coming from the mirror instead of directly from the measurement area. The disadvantages of this technique are due to the complexity of the system alignment and to the configuration. Other techniques that have been defined and implemented to solve the sign ambiguity problem[10] are: electro-optical image shifting[11], multi colour systems[12, 13], etc.

In a PIV system, the processing methods used to study the velocity vector are very important. These can be characterised on the basis of the seeding density and of the image acquisition method (single frame or multiple frames). Typically, on the bases of the seeding particle density three different partially overlapped categories can be identified: **(i)** low density; **(ii)** medium density; and **(iii)** high density/smokes.

In the first case, the techniques with direct analysis are mostly used. With these methods, a scanning analysis of the single frame is provided in order to find the single particle properties and then correlate two subsequent particle images[14]; thus the problem is reduced to find couples of points due to the two pulses -- e.g., algorithms for Particle Tracking. In these algorithms, it is usually required to remove erroneous vectors that can be due to insufficient particle pairs, or out-of-plane velocity (when the particles come/go from/out of the image plane). This is due to the fact that a velocity component in the orthogonal direction to the light sheet can bring the particles seeding away from the illuminated area, during one of the two flashes. It is impossible to study a misalignment of this kind in particle motion, only studying the intensity of the particle image. A variation of the light scattered from the single particle can be due to a different size of the particle, as the G. Mie scattering theory demonstrates.

In the second case, statistical methods are used such as those based on correlation of the image grey level matrix[15, 16]. The images are scanned with rectangular windows, and in each of these windows a uniform motion flow is supposed; it thus works on a local area of the flow image and produces a measure of the average local displacement of region particles. When one image showing the same scattering particle in two different positions is acquired, the autocorrelation is used. Studying the autocorrelation matrix it is possible to locate two symmetric peaks, corresponding to the shift vector in the single window. The symmetry does not allow knowing the sign of the shift. In a multiple frames acquisition system the cross-correlation is determined for two subsequent images. In this case, the same local areas located in two successive images are taken. It is possible to indicate only one peak, representing the whole shift (module, sign and direction). Correlation-based processing is a quite robust technique, but it is time-consuming and it is necessary to analyse the image by window, thus reducing the spatial resolution of the system.

In the third case, two images have typically to be considered. Thus, algorithms for optical flow estimation can be profitable applied[1, 2], such as the interference techniques[14]; these methods are based on optics systems producing interference patterns from a negative image of two equally spaced particle images. The separation between two adjacent fringes is proportional to the displacement of the single particle. With this techniques it is possible to estimate the velocity with a good precision, but the needing of a particular optic arrangement for visualising and analysing the interference pattern does not allow a real time analysis. Beside these techniques are the differential ones, that are useful for the flow motion analysis with very high density seeding or smokes. Differential techniques are based on several constraints, whose unknown quantities are prospectic projection components of motion field on the image plane. For example Optical Flow Constraint (OFC), whose coefficients are partial derivatives of brightness on the image plane[1].

The work described in this paper is mainly focussed on medium and low density seeding. The goal of work has been to develop a low-cost, easy to use, safe and flexible solution for the massive measuring of velocity flow in centrifugal compressors of Nuovo Pignone GE. They perform the measures by using a Laser-Doppler Velocimetry, LDV.

The paper is organised as follows. In Section 2, the solution proposed is presented. In Section 3, some experimental results are reported and discussed. Conclusions are drawn in Section 4.

2. THE SOLUTION PROPOSED

From previous works made with a LDV system on turbomachinery at Nuovo Pignone, it becomes clear the importance of a compact and low cost system for studying the gas flow velocimetry inside turbomachinery, even if with lower accuracy.

A modified PIV system, such as that developed in this research, can be the solution. It has a good data rate and small sizes, a *quasi* real time processing, and it is user friendly. The characteristics of this system have been chosen in order to use it in turbomachinery applications. The most important ones are bidimensional analysis, user friendly, high data rate, computerised acquisition procedures and measurements post-processing, economics. Other advantages of the used methodology, regarding the measurements at low velocity, are the availability of simple and rapid image processing algorithms; detecting of the out-of-plane condition for the particle seeding; determination of the velocity vector sign. In order to satisfy all these points, a standard PIV system has to be modified. In fact, in a standard system there is a Q-switched Nd:Yag laser as a light source, with high energy per pulse; a non-standard CCD camera and a PC interfaced processing unit. The principal limitations, on the adoption of these systems in an industrial applications (for the flow studies at velocity in the range of 100 m/s), is the use of high power pulsed laser (needing specialised and qualified staff in controlled areas). These have typically big dimensions and high costs. The solution proposed is composed by a cw low power laser, a standard high resolution bw CCD camera with a high-speed electronic shutter; a frame grabber for the acquisition and post-processing of the PIV images. A specific new algorithm for the processing of the images obtained with this acquisition system has been developed. The algorithm is very simple and computationally cheaper with respect to the cross or auto-correlation techniques.

The solution proposed is based on the fact that: it is possible to use (as light source) continuous wave laser instead of pulsed lasers. With this approach, the moving particles produce a continuous line on the image plane. The trace length depends on the exposition time of the CCD camera. This solution has been called **Continuous PIV**, **CPIV.** The solution proposed is showed in Fig.1. It should be noted that the early developed PIV systems were based on the analysis of images produced with continuous light sources (streak photography technique). In the past these techniques did not received a great success, because of their poor accuracy in the measurements based on an estimation of the length of the traces on the images[3]. Presently the image acquisition systems and the image analysis algorithms have been strongly improved as it is shown paper.

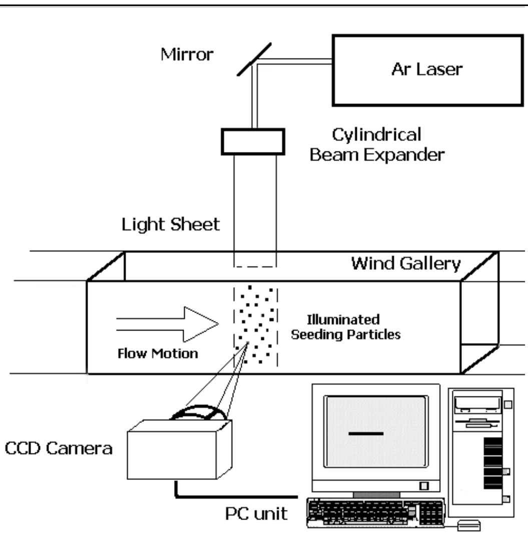

Figure 1.a: Experimental set-up of the CPIV solution

Figure 1.b: Particle trace negative image, as recorded with a CPIV system

The limit of this approach continues to be the maximum value of the velocity that can be measured. It is lower than that can be performed by using standard systems, such as those described above. In fact, with the increment of velocity, two facts limit the system performance. Firstly, at higher velocity the exposition time has to be shorter in order to maintain the particle inside the measurement area. The maximum length for single traces depends on the exposition time that is inversely proportional to the maximum measurable velocity. Moreover, at higher velocity, a lower brightness of the particle trace on the image is obtained. In fact, a particle moving at higher velocity remains in front of each CCD sensor element (i.e., confidentially the pixel) for a short time, scattering towards it less light. This can be balanced using a higher power laser, knowing that the adoption of a very high energy is possible only with pulsed laser.

With a simple CPIV system is not possible to solve the sign of the velocity vector. This is not due to the use of a cw light source, but to the particular image recording technique (single frame). In order to remove the directional ambiguity, two CCD cameras, with two different exposition times, have been used to simultaneously acquire the images of the tracing particles. With this solution, in the grabbed images, each particle produces a trace of different length for each image. They start at the same coordinates in both images, but they stop at two different co-ordinates of the image plane. The position of the trace end gives the sign of the velocity vector.

In order to analyse the continuous traces of the particles, particular post-processing software was developed and implemented. With a cw light source, it is possible to analyse the grey level distribution of the trace image, instead of studying the intensity of the single point particle image. The algorithm developed can be considered as a technique based on direct analysis of the images (see introduction). It works scanning the image in order to find single pixels belonging to a trace, and then to measure the trace length (in pixels). The most important difference between this technique and the others of direct analysis is that it is not necessary to find similar particle images to reconstruct the trace, as is due in the case of pulsed standard PIV. Beside this, the processing time can be reduced, scanning the traces on a grid.

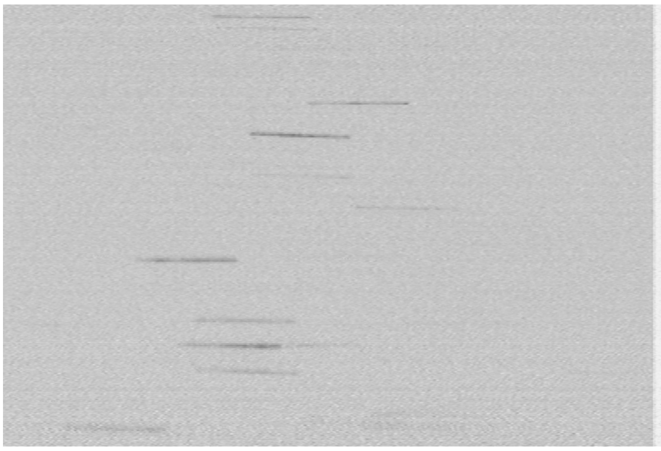

Figure 2: A negative CPIV image, that shows some particle traces

The algorithm is developed in three steps.

1) The detection of traces.
2) The extraction and the measure of the trace.
3) The classification of the trace in order to avoid erroneous measures.

2.1 Trace Detection

Consider a grid in the image, generally with a different density along *X* and *Y* axes. The grid is scanned in both directions, looking for the intersections between the grid and the traces. The grid line step is a fundamental parameter: if the grid is too dense, the elaboration process is too much time consuming, but if in the grid there are few lines it is impossible to intercept correctly the traces. The grid line step can then be chosen knowing the range of the velocity to be measured: the particle moving at the lowest velocity has to produce a trace whose length is longer than the grid rectangular diagonal. If Δx and Δy are the grid dimensions, the following condition has to be satisfied:

$$\sqrt{\Delta x^2 + \Delta y^2} < \frac{v_{\min} * \tau}{L_p}$$

where: V_{min} is the detectable minimum velocity, τ is the exposure time, and L_p is the length of the square in the measuring plane corresponding to the single pixel.

The scanning process compares every pixel image grey level with a given threshold value, T_{ld} (Threshold for line detection). Pixels having a grey level grater than T_{ld} provoke the passing to the next step in which the depth of the trace is considered in order to reduce the number of errors. Only traces having a width, *W*, included in a range (*Wmin*<*W*<*Wmax*) can be considered as valid. This is performed to avoid detection errors due to the acquisition noise and partially overlapped traces; both these cases can originate errors in the measurements. It is possible to find intersections between a grid line and a trace that larger than the expected width, this can be due to the presence of a small angle between the trace and the line grid. In this case, the intersection is neglected since it will be easily recognised during the scanning in the other direction. In order to simply the algorithm and to make it faster the estimation of the width has been performed only along the *X* and *Y* axes. The changes in width due to the angle between the trace and the grid are directly enforced in the detection parameters, *Wmin*, *Wmax*.

2.2 Trace Extraction and Measure

The trace extraction and the corresponding measure of its length is performed during a second scanning, starting from the point of intercepted trace. The scan is performed analysing adjacent pixels along the mean trace line, till the condition on the expected width is satisfied (thus the criteria reported above is used for deciding the start and the end of the trace). During the trace scan the grey level is compared with a lower threshold value, respect to the one used for the grid scan, in order to consider in the right way the reduced brightness at the trace end. Once the trace is completing analysed, the grid scan starts in that point in which it was suspended. The extracted trace is removed from the image in order to avoid multiple detection of the same line in different line grids. On the basis of the extracted trace the measure of velocity (expressed in m/s) can be performed as:

$$V = \frac{L 10^{-3}}{M\, t_{\mathrm{exp}}}$$

where *M* is the magnification (pixel/mm), *L* is the trace length (pixel) and t_{exp} (s) is the CCD exposure time.

On the other hand, before to make the measure it is mandatory to verify if the detected trace is a topologically correct measures or not on the basis of the reasoning reported in the next section.

2.3 Trace Classification

The algorithm is based on the analysis of the grey level of single particle image intensity. With this analysis, it is possible to know the real position of the seeding particle with respect to the light sheet (whose spatial intensity distribution is known). The distribution is close to be gaussian centred in the centre of illuminated area. By means of the analysis of the distribution of the grey level along the trace it is possible to identify those scattering particles moving with a velocity vector parallel to the illuminated plane, and those that have a component of the velocity vector orthogonal to the same plane. The algorithm proposed estimates the mean grey level along an orthogonal direction to the trace, in every point belonging to the trace itself. If it is considered the distribution of the single trace grey level, the motion of the particle respect to the light sheet can be classified. In Fig. 3, a schematisation of the possible configurations is reported. It is possible to see how the particle can traverse the light sheet and the corresponding trace mean grey level distribution.

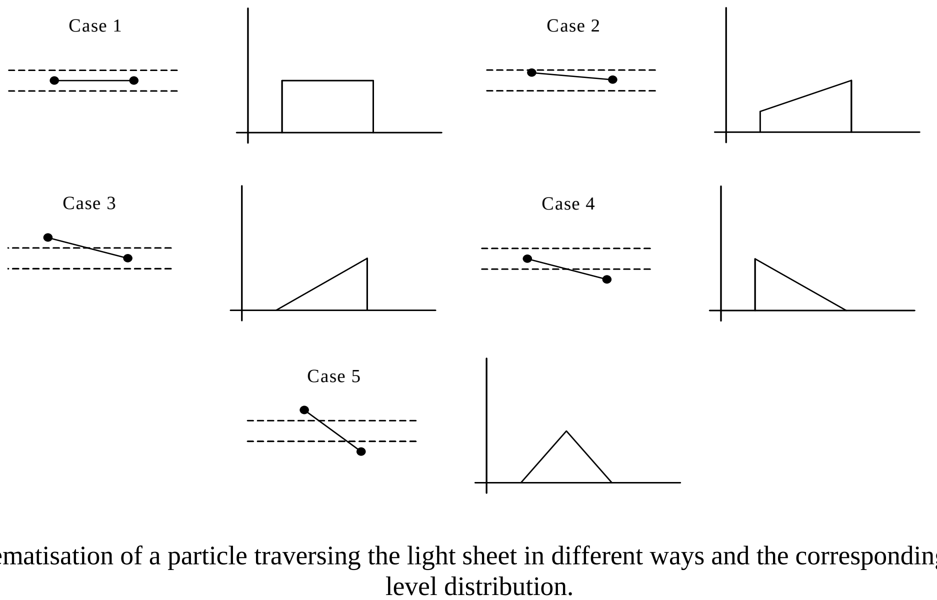

Figure 3 – Schematisation of a particle traversing the light sheet in different ways and the corresponding trace mean grey level distribution.

It is possible to indicate the following cases.

- *Case 1*. The particle is moving parallel to the light sheet plane during the whole exposure time. There is a sharp variation in the grey level distribution in the correspondence of the exposition time start and end. The grey level is uniform along the whole trace, and its value mainly depends on (i) the particle dimension and (ii) the distance form the central plane of the light sheet. The correct velocity vector module is measured by knowing the particle trace length.
- *Case 2*. The particle traverses the light sheet forming an angle different from zero between its velocity vector and the light sheet plane, but it is completely included in the illuminated area during the whole exposition time. The grey level has a sharp variation at the CCD exposition start and it presents an increment of the image brightness till a new sharp variation in correspondence of the exposition end. The increment is due to the arrival towards the centre of the light sheet plane in which a higher intensity is present. When the start and end time can be detected, the particle displacement and velocity are correctly measured (for example with a couple of images). In this case, it is also possible to coarsely estimate the orthogonal component of the velocity vector, because the derivative of the grey level distribution is proportional to it.
- *Case 3.* The particle passes across the light sheet and it is outside at the exposition starting time. The grey level distribution is similar to a triangle. It is not possible to exactly know the opening and/or closing time; the trace length is shorter than the real displacement of the particle in the exposure time. Thus, the velocity vector cannot be correctly measured.
- *Case 4*. The particle passes across the light sheet and it is outside at the exposition ending time. The grey level distribution is similar to a triangle. It is not possible to exactly know the opening and/or closing time; the trace length is shorter than the actual displacement of the particle in the exposure time. Thus, even in this case the velocity vector cannot be correctly measured.
- *Case 5*. The particle passes across the light sheet and it is outside at both the starting and ending time instants. The grey level distribution increases to a maximum value and then decreases. The distribution shown in the figure is only a schematisation since the actual distribution should be close to be a deformed gaussian. Moreover, the shape of the distribution also depends on the angle between of the particle direction and the light sheet. The trace is shorter than the real displacement in the chosen exposition time, thus the velocity vector cannot be correctly estimated.

Therefore, only traces of the form belonging to cases 1 and 2 are correct sources for measuring the velocity vector in the light sheet plane. In order to classify the above cases an algorithm is needed. It has be strongly fast since the number of traces per image may be high. To this end, a specific approximation has been performed.

The estimation of the grey level distribution and the subsequent trace classification is performed on the basis of the mean grey level of 3 segments whose length is the 10% of the total trace length. One of these segments is in the middle of the trace, and the other two are at the ends, at a fixed distance of 5% of the total length. Two half traces are considered: the first one starts at the first pixel of the traces and ends at the middle one; the second starts from the middle one and ends at the last pixel of the traces. If L_i is the mean value of the i-th segment level, the particle trace can be used to measure the velocity vector if the following classification index is lower then a fixed value:

$$I = \frac{(L_3 - L_2)^2}{M_2^2} + \frac{(L_2 - L_1)^2}{M_1^2}$$

where M_1 *and* M_2 are the mean grey level of the first and the second segment respectively. If the trace grey level distribution satisfies this condition, it belongs to the cases 1 or 2 and it can be used for the velocity vector measurements. The index had to be defined in this way, in order to give the right weight to the contribution of all the traces (even the one of case5).

The great advantage of this algorithm is the possibility of detecting the condition of out-of-plane in the particle motion. The importance of this is due to the fact that the particles traversing the light sheet plane with a velocity vector component orthogonal to that plane can give a wrong contribution to the velocity estimation. In fact, if a particle is outside the illuminated plane at the end and/or at the start of the exposition time, the trace representing its displacement is shorter than it should be, giving a lower value of the velocity vector.

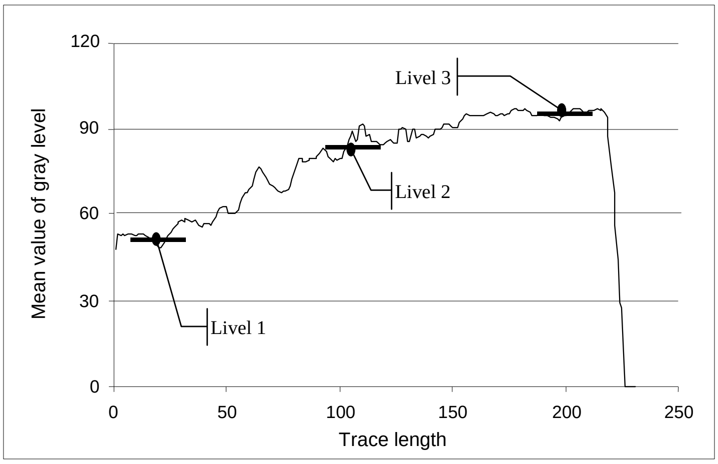

Figure 4– Mean grey level used by the classification index

2.4 Algorithm and System Implementation

The algorithm has been implemented by using C++ language. The whole software application for velocity estimation is comprised of three parts:

(i) the user interface, for choosing the parameter used in the algorithm (grid dimensions Δx and Δy, maximum and minimum expected value for the trace length, threshold value for the grey level in the grid scanning, threshold value for the grey level in the trace scanning, fixed value for the trace classification index, CCD exposure time, magnification factor);

(ii) frame grabber control for image acquisition (a MATRIX Vision GmbH PCgrab-G1)

(iii) analysis and measurements algorithm, as above described.

When the measurements starts, the program initialises a measurement loop: every recorded image is processed and the information of each identified and measured trace is saved in a report file. The measurement loop stops when the user wants or after a fixed number of identified and measured traces. The estimated velocity field can be visualised starting from the recording file.

3. EXPERIMENTAL RESULTS

In order to validate the above described algorithm and solutions a set of experiments have been performed in a free channel wind channel (i.e. without obstacle). Some testing conditions were assumed: velocity constant in time and uniform in the measuring area. This measuring area was previously used for the wind channel calibration. Thus, it has been possible to use the information on the calibration curve to know the exact flow velocity in that area (called the "real" velocity of the flow) and then to estimate the system and measuring error. The flow velocity used during the experimental test was changed in the range from 10m/s to 40 m/s.

As a first step, a brief description of the wind channel, the calibration method used for its characterisation, and the other items used in the CPIV system proposed, is reported.

At the entrance of the wind channel, a convergent nozzle has been places. It guides the flow entering the channel; thus, avoiding the problems of separation of fluid flow. Then, the flow passes through a honey comb and then goes in a horizontal square section part of the channel (140x140x900 mm), where the measurements are performed. Three of the four channel walls are made in optical worked glass, with antireflection coating. The laser beam passes through the upper horizontal wall, so that the laser light sheet intercepts the channel in the direction of its axes and along its mean line. The light, scattered from the seeding particles, is collected through the front vertical glass. The fourth wall (the back one) is made by aluminium, and it has two little holes: one of these was used for measuring the inside static pressure, and the other one can be used for a Pitot tube (for reference measures). Inside the channel, a centrifugal fan sucks up the airflow. The fan is located at one side of the channel and it is moved with a 15 kW electric motor. This is connected to a mod. FR-A 240 Mitsubishi inverter, controlling the power frequency in the range 0 - 400 Hz, with 1/100 Hz precision. In this way, it is possible to control the flow velocity inside the channel with high precision. For the channel calibration there were measured the static and dynamic pressures with a mod. K-FB Asea Brown Boveri probe. The signal from the probe has been read by an acquisition system mod. HP 34970A, with a 20 channels multiplexer HP 34901A (57 readings per second with precision of 5 ½ digit). The signal was then analysed with the software developed at the department. Fig. 5 shows the calibration curve that was performed with this instrument. V_{adim} and ΔP_{adim} are defined as following: if p_0 is the total pressure at the channel inlet, p_1 is the static pressure inside the channel, v_1 is the flow velocity inside the channel, ρ_0 the air density, two adimensional variables are defined:

$$p_{adim} = \frac{p_1}{p_0};$$

$$v_{adim} = \frac{v_1}{\sqrt{\frac{p_0}{\rho_0}}}$$

ΔP_{adim} is the adimensional pressure difference between room pressure and the measurement point pressure inside the gallery. During a PIV test measurement it is possible to know the real velocity (called in the following V_{rif}) of the flow inside the gallery just measuring the static pressure at the channel wall and the room pressure, and using the calibration curve plotted in fig.5.

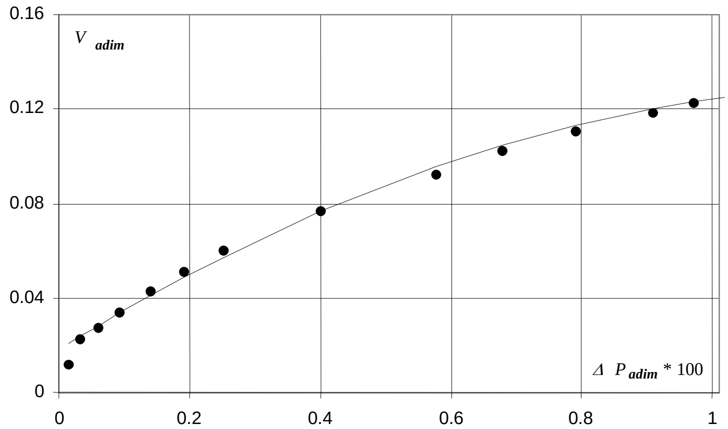

Figure 5 - Wind channel calibration curve

The CPIV system proposed and developed at the Department of Energy Engineering is composed of an image recording system, a cw laser as a light source, and a producer of seeding particles, as briefly described in the following.

The scattering particle images were acquired by a standard low cost Sony CCD camera (mod. XC 77RR-CE), with this characteristics: image dimensions 756x580 pixels; BW standard composite video output signal; exposure time till 1/2.364.583 s; image acquisition can be triggered by an external signal; auto gain and white balance. It was used a Sigma photographic lens (f 90 mm). The composite video output signal is collected from a MATRIX Vision GmbH PCgrab-G1 frame grabber. The light sheet has been generated by using a NEC cw Argon laser (mod. GLS3102), having 150 mW output power, 800 μm beam diameter and 3 mrad divergence. The beam laser is first deflected from a mirror and then passes through a cylindrical beam expander.

The most important seeding types used in PIV and LDV systems are smokes and polystyrene particles. The latter has some worthy characteristics, such as monodispersion, presence at the same time several particle diameters, and well-known scattering and mechanical properties. On the other hand, the polystyrene particles sold by the industries is very expensive; thus, resulting unsuitable for PIV or LDV industrial applications. For this reason, we have developed, at the Department of Energy Engineering, a system to produce polystyrene particles, thus reducing the experimental costs in PIV and LDV applications. The seeding injection inside the channel (or whatever it is the measurement area) is a very critical procedure, because the quality and repeatability of a PIV measurement depend on it. The seeding particles have not to significantly influence the flow field and the tracers' distribution has to be uniform in the channel. There are several methods for injecting the seeding inside the test volume, depending on the flow under studying and on the seeding itself. In the experimental conditions described in the present work, the polystyrene particles are created in a water solution. Thus, they have to be heated in order to vaporise the water content before their insertion into the channel. This is necessary because the water drops do not have a fixed size and several polystyrene particles could remain inside the drops. The temperature used to dry the seeding has to be limited to avoid the damaging of the particles. It was so used a convergent/divergent nozzle, inside which compressed air is blown (at 1.5 bar); the air is then heated at 70°C. Inside the nozzle the accelerated air sucks the seeding up form a tin. The distance of the nozzle from the channel entrance has to be big in order to vaporise all the seeding water, and at the same time it has to be little, so as all the seeding particles enter the channel, with a uniform spatial distribution.

In each experiment, before recording the CPIV images, the system has been calibrated for determining the magnification factor (pixel/mm). This operation has been performed during the experiments to validate the results but it is completely unuseful during the final employment of the tool. For the calibration, a specific glass with a very fine grid has been used. The line grid was equally spaced (1 mm). The position of this glass can be varied, because it stays on a sledge with two micrometric screws; the glass is thus positioned in the light sheet.

When the test experiments were made, the temperature and static pressure in the measurement volume have been taken, in order to know the real velocity inside the channel $\boldsymbol{V_{rif}}$. These parameters are used to evaluate adimensional parameter to extract velocity from wind channel characteristic curve[17]. For each experiment, the $\boldsymbol{V_{rif}}$ has been compared with the velocity measured with the CPIV system, and then was calculated the relative error (with sign):

$$E_{\%} = 100 * \frac{V_{rif} - V_{piv}}{V_{rif}}$$

There were performed 6 measurement sessions, with increasing velocity. The velocity range has been between 10m/s and 35m/s. For each test session, several frames were recorded and processed, so as it was possible to manage data corresponding to about 100 traces.

In Tab. 1 and Figs. 6, 7 the test conditions and the results of the CPIV system measurements are reported. V_{rif} is the flow velocity measured by the wind channel calibration curve; V_{piv} is the same velocity measured by the CPIV system; t_{exp} is the CCD camera exposure time; M is the magnification factor; there are then the standard deviation and the percentage error (E% as defined earlier) on the V_{piv} measured.

Test session	**T °C**	**V_{rif} (m/s)**	**V_{piv} (m/s)**	**variance (m/s)**	**t_{exp} (ms)**	**M (pixel/mm)**	**E% (%)**
1	22	11,1	10,60	0,07	0,384	30	4,52
2	24,1	14,8	14,18	0,08	0,384	30	4,18
3	24	20,8	19,89	0,13	0,240	30	4,39
4	24,1	25,3	24,27	0,16	0,240	30	4,08
5	24	29,8	28,57	0,21	0,167	30	4,13
6	23,5	34,1	33,01	0,19	0,167	30	3,20

Table 1 – CPIV experimental conditions and results.

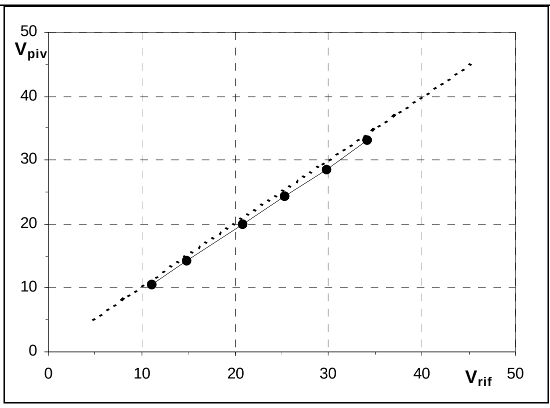

Figure 6 – Measured and reference velocity

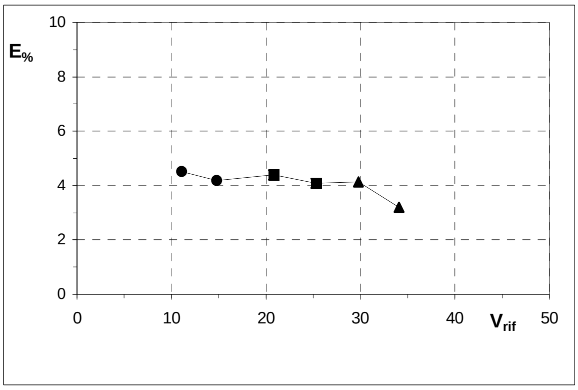

Figure 7 – Percentage relative error. Data represented with different symbols are recorded with different exposure time

Observing Figs. 6 and 7, it is possible to see that with the proposed approach (in the velocity range considered) the percentage error is lower than 5%. Data error represented with different symbols are recorded with different exposure time (in order to avoid trace image length too long respect to the area recorded). The sign of the error is always positive. This can be due to the fact that the technique used tends to underestimate the velocity. Even if V_{rif} can have a systematic bias error, it has to be studied the possible causes of a bias error in the CPIV system proposed. One error source can be due to the seeding, that cannot exactly follow the flow. This fact is difficult to be proven and however it is common to all measurement techniques based on the use of particle tracers (such as LDV and standard PIV). Also the algorithm can contributes to the production of errors: the particle traces intensity is less bright at the ends. Using a simple binarization algorithm with a threshold value can give an error of one pixel or more in the localisation of the trace end. In this way the algorithm developed can give an underestimate of the trace length. The number of pixels, corresponding to the absolute error value in the trace length determination, is independent on the trace length. If we consider having 2 pixels absolute error in the localisation of the trace ends, and a trace expected length between 120 and 90 pixel, there is a relative error between 2,1% and 3,3%. This fact partially justifies the systematic error made in the test measurements. The error can be compensated using some statistical considerations. Beside this, the percentage error seems to decrease with increasing velocity. This is due to the fact that the absolute error on the trace length measuring is quite always the same, but the traces are different in length and are recorded with different exposure times.

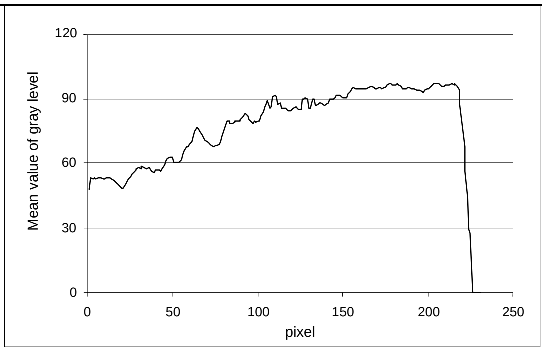

Figure 8- Mean grey level distribution of a particle with an out-of-plane velocity component

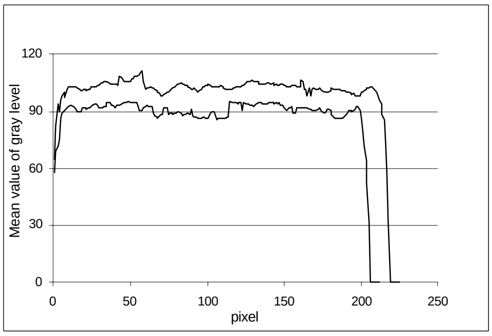

Figure 9 – Mean gray level distribution of a particle moving parallel to the light sheet plane

In the previous section, it has been stated that the new algorithm developed can indicate those seeding particles moving with an out-of-plane velocity component. This is done by analysing the mean grey level distribution of the trace image. In figures 8, 9 there are the mean grey level distribution of three particles: as it can be seen, one is moving with an out-of-plane velocity component (fig. 8); the other two are moving with the velocity vector parallel to the light sheet. The mean grey level distribution has two different mean values, because one is in a plane with higher brightness of the laser light (the spatial distribution of the laser light is no uniform).

4. CONCLUSIONS

In this paper, the development and the experimental validation of a new flow measurement system based on PIV technique has been described. The proposed solution comes from the standard PIV systems, but it presents some modifications in order to adapt a PIV system to an industrial application (low cost, small sizes, high security).

The experimental validation of the system was made on a test rig, after a preliminary period of study and project. The test measurements were made at velocities lower than 40 m/s, because there were difficulties due to the test rig (if greater velocities were used) and to the instrumentation. For what concern the instrumentation, the problems were mostly due to the maximum power obtainable from the light source. In fact fixed the light source power, the time for which a particle stays in front of a pixel decreases at increasing velocities, thus reducing the traces image brightness. A few experimental tests were made at velocities greater than 50 m/s, but the images recorded in this condition had very low brightness, not sufficient for a good image processing. It is possible to have brighter images using a light source with higher power, for example just duplicating the power used for the experiments described in this work. The system could however remain at low cost, using a light source power of about 1W.

The accuracy of the system is satisfactory and it can be improved studying deeply some correction factors to introduce in the algorithm developed at DEF laboratories. The work described in this paper can also be improved if flows with velocity gradients are tested.

The direction ambiguity of the system can be solved using a two cameras system, as previously said. The two cameras have to be triggerable with external signal, so as they can acquire an image starting at the same time. If the two cameras record the same measurement area (even if with different prospective) and are triggered from the same synchronism signals, they can sample the particle passing the interested area in a synchronous way. For this system a frame grabber with a double electronic circuitry to sample the images from the two cameras is necessary (and the sampling has to be simultaneous). The sign of the velocity vector is known if the synchronised cameras have different exposure time. The two cameras system is thus used in a different way with respect to the standard of two cameras PIV technique (using the two cameras to measure the third velocity component). The CPIV cost is low even using two cameras and a particular frame grabber, if compared to the standard multiple-frame PIV systems costs.

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