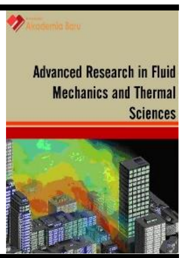
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



A Review in Particle Image Velocimetry Techniques (Developments and Applications)

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ARTICLE INFO

Article history:
Received 28 August 2019
Received in revised form 23 October 2019
Accepted 20 November 2019
Available online 4 February 2020

Keywords:
Particle image velocimetry; 3D fluid flow; PIV; flow measurements; HPIV; SPIV

ABSTRACT

The latest entrant into the fluid flow measurement field is the particle image velocimetry (PIV) which offers velocity field immediately in flow domains. Referring to the definition, the placement is recorded by PIV over time pertaining to small tracer particles that were released in the flow for local fluid velocity extraction. Thus, PIV can be regarded as a quantitative extension pertaining to visualisation techniques for qualitative flow being practiced for a number of decades. This review provides a detailed background pertaining to evolution of PIV, principle of operation, basic elements, key features, uncertainty, errors in PIV as well as few applications of PIV. Recent advances pertaining to the PIV technique have been aimed at procuring all three components with regards to fluid velocity vectors simultaneously in a volume or in a plane that enables wider applications with the PIV technique for investigating more complex flow phenomena. In recent years, developing of various advanced PIV techniques have been successfully achieved, including three-dimensional (3D) particle-tracking velocimetry (3D-PTV), tomographic PIV, holographic PIV (HPIV) technique and stereo PIV (SPIV). A comparison has been done between the main PIV techniques.

1. Introduction

Particle image velocimetry (PIV) can be defined as an imaging-based flow diagnostic technique that depends on seeding fluid flows that possess tiny tracer particles as well as spotting the motions pertaining to the tracer particles for derivation of fluid velocities. For measuring PIV, employing of a sheet of laser light is done for illuminating the targeted region. The tracer particles lead to scattering of the passing laser light. The positions of the tracer particles are recorded with photographic film or digital cameras at two separate time points in a defined time interval. A well-developed computer intensive PIV image processing procedure is employed to determine the displacements pertaining to

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each tracer particles or, usually, groups of tracer particles. The particle velocity vectors are provided based on displacements over a defined time interval. It is assumed that the tracer particles move with identical velocity as local working fluids when deducing the working fluid's velocity [1].

PIV has already been established as an effective tool for studying complex flows as well as offering both qualitative and quantitative details. In such a scenario, PIV is employed as a complimentary technique in tandem with the LDV to offer data as well as insight into the flow field that can cover even a large spatial area pertaining to the regions of interest. As already mentioned above, employing a conventional PIV system proved to be successful in one of the risk reduction experiments. In such application, mounting of the cameras and laser was done outside the tunnel, which was at a distance of 3.66–3.96 meters away from the model. Though it was easy to carry out the installation process, this arrangement was found to suffer from various disadvantages. First, it is not deemed as being efficient with regards to test operations. Since the system cannot be pitched along with the model, calibration and reconfiguration of the system is required before obtaining data at various angles of attack. Second, the long working distance results in amplification of small changes at the model's vertical position pertaining to the PIV images. This leads to variation in the wing surface's location from one image to the other. Such variations would likely need conditionally averaged PIV images so as to accurately indicate the spatial expanse of key off-body flow characteristics [2].

For velocity field measurements pertaining to fluid flows, PIV is now regarded as a key experimental technique. The technique helps to produce quantitative visualizations pertaining to the instantaneous flow patterns, which are usually employed for supporting the validation of numerical simulations or the development of phenomenological models pertaining to complex flows. However, because of the complex relationship existing between experimental parameters and measurement errors, the quantification pertaining to the PIV uncertainty is not considered as a trivial task, which usually depends on subjective considerations. As these methodologies pertaining to the objective and reliable uncertainty quantification (UQ) for experimental data are deemed significant, numerous types of PIV-UQ approaches have been put forward in the last years, which are aimed at determining the objective uncertainty bounds in PIV measurements [3].

PIV as a technique enables simultaneous measurement of the fluid velocity for all the regions that were illuminated based on a two-dimensional light sheet, as shown in Figure 1. Introduction of particles in the seeding flow with regards to their motion is employed for estimating the local fluid kinematics. The particles are selected for being near neutrally buoyant as well as to effectively scatter light. The multiple exposure photographic methods are employed to record particle motion, from the information about the time between the recording positions pertaining to consecutive image in tandem with camera magnification to obtain the particle velocity. The selection of recording parameters is done to obtain good spatial separation pertaining to the image, ensuring reliable velocity measurement as well as ensuring accuracy [4].

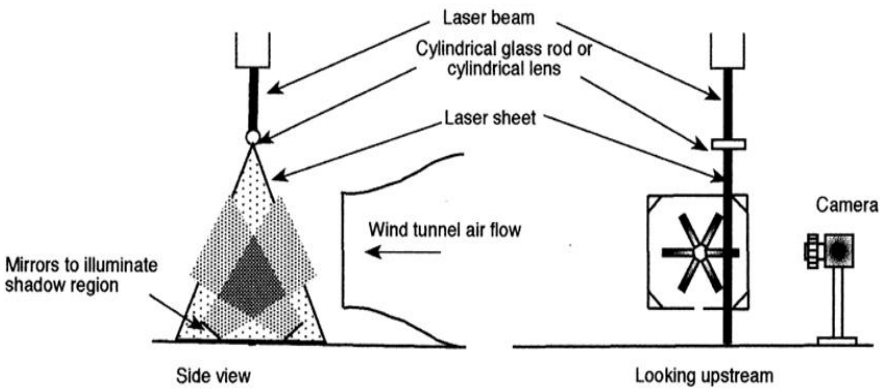

Fig. 1. Typical PIV experimental arrangement used in wind tunnel [4]

Pitot-static tubes were employed to obtain few of the earliest quantitative velocity measurements pertaining to fluid flows. In the 1920s, hot-wire anemometers were introduced [5], which led to considerable advancement, particularly with regards to frequency response, probe miniaturisation as well as the ability to determine multiple velocity components. However, insertion of a physical probe is needed for both these techniques to be applicable, which also allows intrusion of the flow itself. In the 1960s, laser was invented that subsequently resulted in the development of the laser- Doppler anemometer employs a laser probe that allows measuring non-intrusive velocity. Even though there has been rapid advancement in the design of such systems as well as increase in sophistication of the associated electronics, one should acknowledge these methods are at preferable 'spot-sage', i.e. obtaining of the speed data can be done solitary at that spot where the sensor has occupied. Whereas these methods are still regarded prominent in the tentative armour, the capacity to measure 'secular' speed has made (PIV) more particular in the fluid flow area. (PIDV), also commonly referred as (PIV), comprise a flow measuring category methods which allow recording the pertaining distance to tiny particles that are introduced in a flow zone. Even though these methods are yet in the developmental stage, numerous papers with excellent review have been published already, including Adrian [1,27], Grant [4] and Prasad [5], all of which talk about the measurement technique, historical development as well as applications pertaining to PIV. A simple principle is followed by a PIV system: A strong light source illuminates the flow, and imaging is carried out to record particle positions for the light that has been dispersed from particles path into the flow region like a detector matrix as well as a photographic film [6].

2. Principle of Operation

A PIV system' experimental setup usually includes various subsystems. For most of the applications, tracer particles need to be introduced the flow (as shown in Figure 2). Illumination is needed for these particles in a plane of the flow, which should be done at least twice in a short interval of time. Recording is done for the light that has been scattered by the particles either on a sequence of multiple frames or on a single frame. The PIV recordings are assessed to determine the displacement pertaining to the particle images amongst light pulses. Sophisticated post-processing is needed for dealing with massive volumes of data, which is gathered by employing the PIV technique.

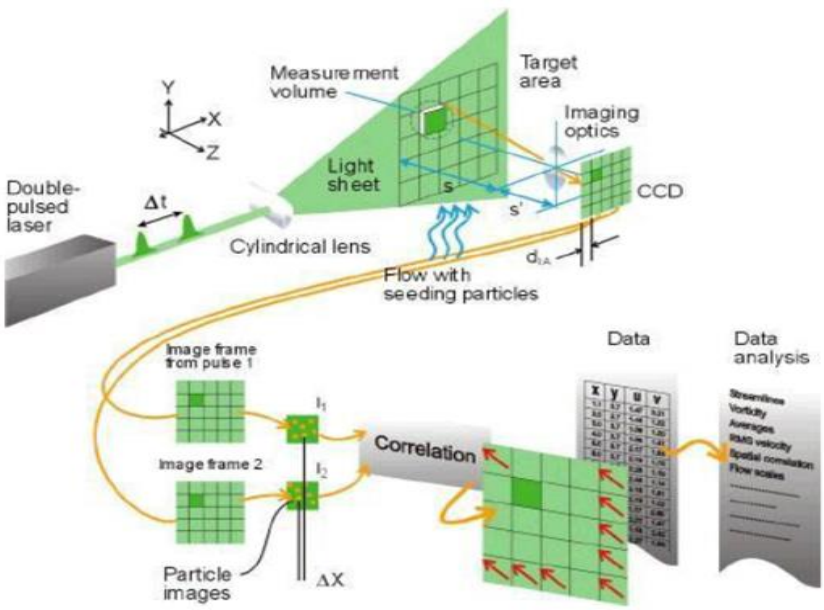

Fig. 2. Experimental arrangement for particle image velocimetery [6]

To the flow, small tracer particles are introduced. Through a laser (the time delay between pulses, based on the mean flow velocity as well as the magnification during imaging), illumination is carried out for a flow light sheet twice. It is believed that the movement of tracer particles is based on local flow velocity between two illuminations. A high quality lens either on two separate frames or on an elementary structure (film or digital camera of high resolution) put together on a special cross-correlation digital camera is employed to record the light that has been scattered by the tracer particles. Post development, a scanner is employed to digitise the photographical PIV recording. The digital sensor's output is directly transferred to a computer's memory. For appraisal, the PIV of digital segmentation recording is done into subdomains known as 'examination region.' For each region statistical methods are employed to determine the local displacement vector pertaining to the tracer particles' images for the first as well as second illumination. It is presumed that within one interrogation area, all of the particles homogeneously move between the two illuminations. The time delays between both illuminations as well as the magnification at imaging are considered for the calculation of the vector projection for the local flow of velocity into the plane pertaining to the light sheet (two-component velocity vector). For all interrogation areas pertaining to the PIV recording, repetition of the process of interrogation is done. Capturing of more than 100 PIV recordings per minute can be achieved with the help of (CCD) cameras (elements sensor of 1,000×1,000 and more). Performing high-speed recording with the help of (CMOS) sensors permit recording in the kHz range [22]. Assessing a single digital PIV recording by considering several thousand instantaneous velocity vectors (based on the interrogation area, recording size and processing algorithm) is in the order of a second when standard computers are employed. Should there be a requirement for data at faster rates to monitor the flow online, there are dedicated software algorithms commercially available to conduct assessment of reduced precision in fractions of a second [6].

3. Evolution of Particle Image Velocimetry

The rapid evolution pertaining to PIV occurred in tandem with developments in image processing, optical measurements techniques, speckle metrology and flow visualisation [7]. The speckle metrology method is employed to measure solid surface [8]. When a diffuse laser beam is targeted on an optically rough surface, multiple light scattering occurs that forms a speckle interference pattern pertaining to the observation optics' image plane. The speckle pattern or characteristic highlights are regarded to be closely connected with the illuminated surface roughness and these can follow any movement. The motion of flows was measured pertaining to a high concentration of seed particles, which are regarded as an extension to speckle metrology [9]. For quantification of the seeding density, defining of a resolution cell is done for the fluid by keeping the diameter identical to the particle image projection back into the flow. The PIV development has introducing into the standard of laboratories activities for the twenty years ago. It's dangerous to portend the future particularly when the improvement of PIV depends on the technology evolution of the component outside the filed such as computers, cameras and lasers.

4. Categories of PIV

As presented in Figure 3, the classical PIV technique can be defined as a two-dimensional (2D) measuring technique and can only measure two components in the plane of the illuminating laser sheet pertaining to flow velocity vectors. Due to the perspective transformation, velocity vectors' out of-plane component gets lost, while an unrecoverable error impacts the in-plane components [10].

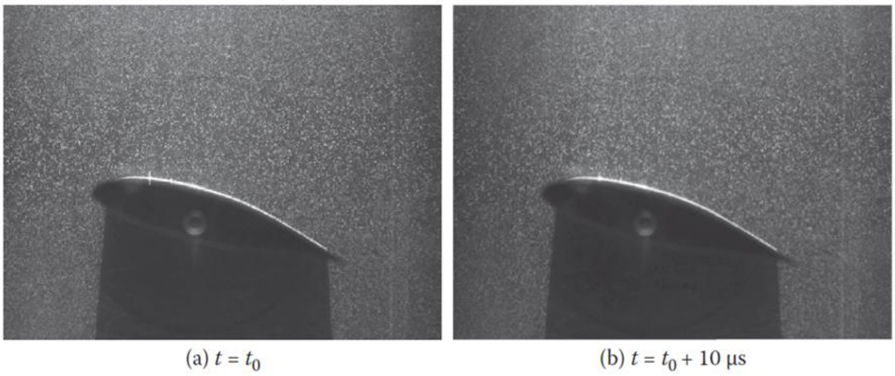

Fig. 3. A pair of PIV Images and the corresponding velocity distribution [10]

Recent advances pertaining to the PIV technique have been aimed at procuring all three components with regards to fluid velocity vectors simultaneously in a volume or in a plane that enables wider applications with the PIV technique for investigating more complex flow phenomena. In recent years, developing of various advanced PIV techniques have been successfully achieved, including three-dimensional (3D) particle-tracking velocimetry (3D-PTV) [11], tomographic PIV [12], holographic PIV (HPIV) technique [13] and stereo PIV (SPIV). Holographic PIV [13] (as shown in Figure 4) employs holography techniques to record image, which allows determining all three components associated with velocity vectors for the entire volume of fluid flow. Amongst the current PIV techniques, HPIV gives the highest measurement precision as well as spatial resolution [14].

However, HPIV is also regarded as being one of the most complex PIV techniques, which needs considerable investment for optical alignments and equipment as well as requires developing advanced data processing techniques. Much efforts are still needed to practically apply HPIV as a PIV technique for different complex engineering applications [15].

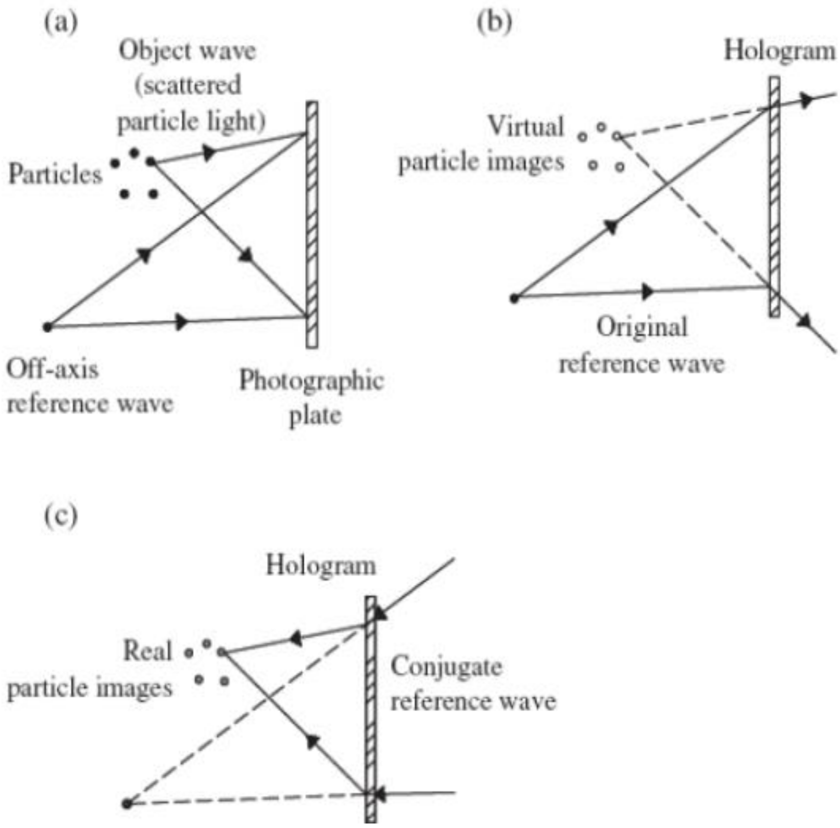

Fig. 4. Structure of optical off-axis set-ups in particle holography [15]

Usually, tomographic PIV [12] as well as three-dimensional PTV [11] techniques employ three or more cameras to record tracer particles' positions pertaining to the measurement volume from various observation directions. Determination of the locations pertaining to the tracer particles is done for the measurement volume based on 3D image reconstruction. Determination of the 3D displacements pertaining to the tracer particles in the measurement volume is done by employing particle-tracking (for 3D-PTV) or 3D correction-based image processing algorithms. For 3D-PTV or tomographic PIV measurements, there is a need to record the positions of almost all the tracer particles pertaining to the measurement volume via each of the image recording camera. Thus, differentiating the positions pertaining to the tracer particles becomes very challenging, if the tracer particle's image density becomes exceedingly high in the measurement volume. Thus, the measurement results pertaining to tomographic PIV and 3D-PTV systems are typically associated with poor spatial resolution when elucidating the flow structures as well as small scale vortex in the fluid flows.

In the laser illuminating plane, to simultaneously measure all the three components pertaining to velocity vectors, the stereo PIV technique is regarded as a method that can be easily accomplished and as being the most straightforward. To perform stereoscopic image recording (as shown in Figure 5), it makes use of two cameras at various view axes or by considering an offset distance. With regards to the view reconstruction, matching of the corresponding image segments pertaining to the two cameras' image planes allows reconstructing all of the three components associated with the velocity vectors in the measurement plane. Compared to the tomographic PIV and 3D-PTV methods, much higher in-plane spatial resolution can be achieved with stereo PIV measurements. Thousands of flow velocity vectors can be offered with regards to the measurement plane [16].

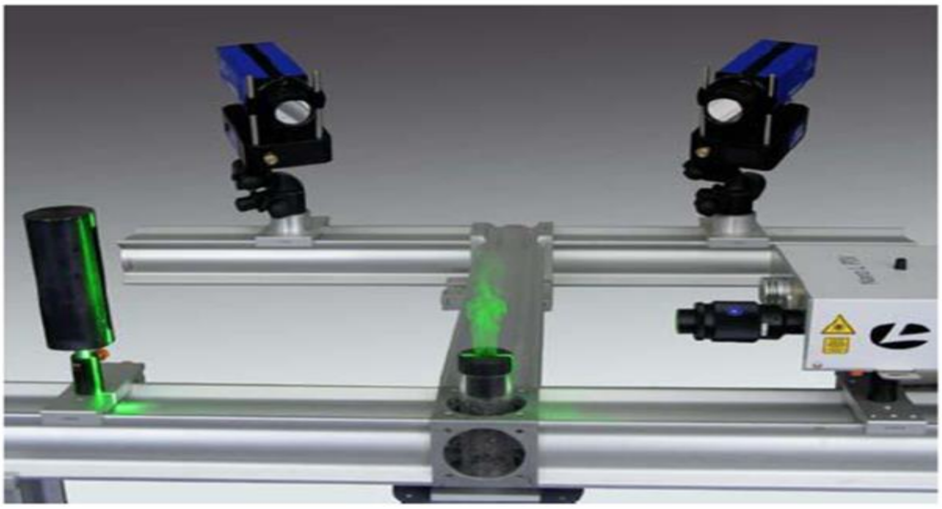

Fig. 5. 3D stereoscopic PIV based on the principle of stereoscopic imaging [16]

5. Main features of PIV

The key features of PIV are as follows.

5.1 Non-intrusive Velocity Measurement

The PIV technique, an optical technique, functions non-intrusively, which is different versus the techniques measuring the flow velocities using probes like hot wires or pressure tubes. This enables applying PIV even for high-speed flows possessing shocks or for boundary layers that are in proximity to the wall, where the presence of the probes could disturb the flow [17].

5.2 Indirect Velocity Measurement

In an identical manner as with laser Doppler velocimetry, the fluid flow velocity can be measured indirectly using PIV technique via measurement of the tracer particles' velocity within the flow, which – for majority of introduced to the flow before doing the test. The flow already includes particles pertaining to two phase flows. In such a scenario, the velocity of the particles themselves can be measured and even the fluid's velocity (that can be seeded additionally with tiny particles tracer) [17].

5.3 Techniques Area

The PIV area enables recording images pertaining to large parts defining flow fields for several applications in liquid and gaseous media as well as velocity information extraction from these images. This characteristic is regarded as being exclusive to the PIV technique. However, for a majority of the cases pertaining to a high temporal resolution, large spatial resolution is associated with PIV; limitation exists for the temporal resolution (frame rate with regard to recording PIV images) because of the current technological restrictions. When making a comparison of the results obtained via PIV and those achieved by traditional techniques, these features need to be considered. Spatial structures can be detected for instantaneous image capture as well as high spatial resolution pertaining to PIV even for unsteady flow fields [17].

5.4 Velocity Lag

To use tracer particles in measuring the flow velocity, it is important to cautiously evaluate each experiment to check if the particles will dedicatedly follow the fluid elements' motion, at least to the level needed by the investigations' objectives. The flow is followed more diligently by the small particles [17].

5.5 Illumination

For applications associated with gas flows, a high power light source is needed to illuminate tiny tracer particles so as to allow the scattered light to effectively detect the video sensor and photographic film. But the using of huge particles due to scattering efficiency with better lightning contradicts the demand to maintain particles as small as possible to enable the flow to follow smoothly. In majority of the applications, there is a need to find a compromise. For liquid flows, larger particles that scatter more light are typically accepted. Thus, we can employ light sources that have considerably lower peak power [17].

5.6 Density of Tracer Particle Images

Qualitatively, image density can be differentiated into three distinct types [1] as shown in Figure 6. With regards to low image density (Figure 6(a)), identification of the images can be done not only for individual particles but also images that correspond to the same particle that have originated from various illuminations. Tracking methods are needed to assess low image density. Thus, such type of situation is also called as 'Particle Tracking Velocimetry (PTV)'. The images pertaining to individual particles can be identified for medium image density (Figure 6(b)).

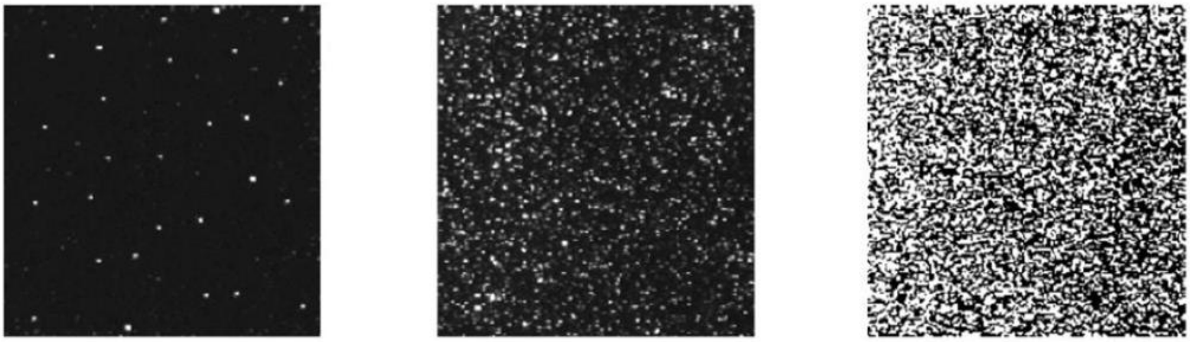

Fig. 6. The three modes of particle image density: (a) low (PTV), (b) medium (PIV), and (c) high image density (LSV) [1]

However, identifying image pairs via inspection of the recording visually is not possible. To enable employing standard statistical PIV evaluation techniques, there is a need for medium image density. For high image density (Figure 6(c)), detecting individual images is not possible as these frequently overlap and form speckles. Such type of situation is also referred as 'Laser Speckle Velocimetry (LSV)', a term that has been employed at the start of 1980s even for the medium image density case, since the evaluation techniques (optical) shared similarity with regards to both situations [6].

6. Basic Elements in PIV Technique

The primary elements which should be considered in the PIV technique are as follows.

6.1 Seeding

For imaging the flow field, it is important to seed the flow pertaining to light reflecting particles. The size of the particles need to be small so as to follow the flow but large enough to allow reflecting each of the measured velocity vector.

Different particles that can be employed for flow visualisation, PIV and LDV for liquid flow are displayed in Table 1 and those for gas flow in Table 2 [17].

Table 1
Seeding materials for liquid flow [17]

Type	Material	Mean diameter in µm
Solid	Polystyrene	10-100
	Aluminum flakes	2-7
	Hollow glass spheres	10-100
	Granules for synthetic coatings	10-500
Liquid	Different oils	50-500
Gaseous	Oxygen bubbles	50-1000

Table 2
Seeding materials for gas flow [17]

Type	Material	Mean diameter in µm
Solid	Polystyrene	0.5-10
	Alumina Al_2O_3	0.2-5
	Titania TiO_2	0.1-5
	Glass micro-spheres	0.2-3
	Glass micro-balloons	30-100
	Granules for systhetic coatings	10-50
	Dioctylphathalate	1-10
	Smoke	<1
Liquid	Different oils	0.5-10
	Di-ethyl-hexy-sebacate (DEHS)	0.5-1.5
	Helium-fiiled soap bubbles	1000-3000

The handling of commonly employed particles is not easy since most of the liquid droplets get evaporated quickly. Dispersion of solid particles is difficult since these are likely to get agglomerated. The particles need to be frequently flow injected once prior the entry of gas region into the division test. The injection process needs to execute without flow disturbing, however a manner as well as at a site that guarantees identical allocation pertaining to the sensor. As most of the current disturbance pertaining to numerous experiments framework is not strong enough to adequately blind the particles with the liquid, the particles need to be fed via many openings. Distributors, such as rakes that possess numerous small pipes with multiple tiny holes, are frequently employed. Thus, there is a need for particles that could be easily transported inside small pipes.

6.2 Capturing Image

The PIV modes recording can be classified to: (1) approaches that offer a single illuminated image pertaining to every illumination pulse and (2) approaches that allow capturing the illuminated flow pertaining to a single frame. These divisions are also known as 'multi-frame/single exposure PIV' and 'single frame/multi- exposure PIV,' respectively [1].

7. Micro PIV

Most of the measurements pertaining to microfluidic devices have been restricted to the flow's bulk characteristics, like bulk velocity, wall pressure and specific impulse (for micro-nozzles). PIV methods are preferred for nano-scale and micro-scale fluid mechanics as these allow avoiding Brownian motion along with high seeding density [18].

For micro-PIV, the size of the seed particle needs to be small so as to diligently follow the flow without impacting the flow field, generating unnecessarily large images and clogging the device. In tandem, the size of the particles also need to be large enough so as to allow imaging effectively and diminish the impact of Brownian motion [19].

The micro-particle image velocimetry (µPIV) approach was first presented by Santiago *et al.,* [20]. Conventional microscopy, as well as digital imaging methods, is employed as optical velocimetry technique to quantitatively determine the double-component velocity information pertaining to a plane measurement two-dimensional. Based on the selected microscope, regions objectives pertaining to implementing ranged of 50×50 μm^2 with regards to a 100×magnification lens to 1×1 mm^2 with regards to a 5×magnification. Within the interest region, velocity information spacing was found to lie in the order of 1 µm. Also, this can allow achieving locative resolution reach to 100 nm [21].

To obtain a high image quality, camera's sensitivity/quantum efficiency should also be the highest. For unsatisfactory signal quality, intensified CCD cameras can be used as an alternative but poor image quality is associated with intensifiers. Double-shutter cameras help to decrease the time interval to 1 µs for two consecutive recordings, which enables measuring high velocities with high magnification. Fluorescence imaging considerably increases a µPIV recording's quality. To the flow, introduction of fluorescent tracer particles is done. Illumination with monochrome laser light results in exciting of the fluorescence and the light emitted by the tracer shifted to a longer wavelength, while the light was reflected and scattered by all other obstacles, such as the microchannel's walls, at the original wavelength. In the microscope, an optical filter is positioned between the digital camera and the light collecting objective. At the illumination wavelength, light is reflected by the optical filter, while the fluorescent light with a longer wavelength is transmitted. With the help of this optical setup, the camera sensor collects the light that originates from the fluorescent tracer particles, while the optical filter blocks other non-fluorescent disturbances as well as the light that originates from the channel walls.

Figure 7 shows a µPIV framework [21]. Presently, after deploying the advanced techniques, the highest spatial resolution of this approach is around 1µm. By utilising smaller seed particles which illuminate at small wavelengths, this constraint can be decreased to a factor of 2 to 4 [17]. Introducing a step particle tracking post the PIV based correlation still results in higher spatial resolutions. Thus, spatial resolutions could also be reasonably achieved in the order of smaller magnitude.

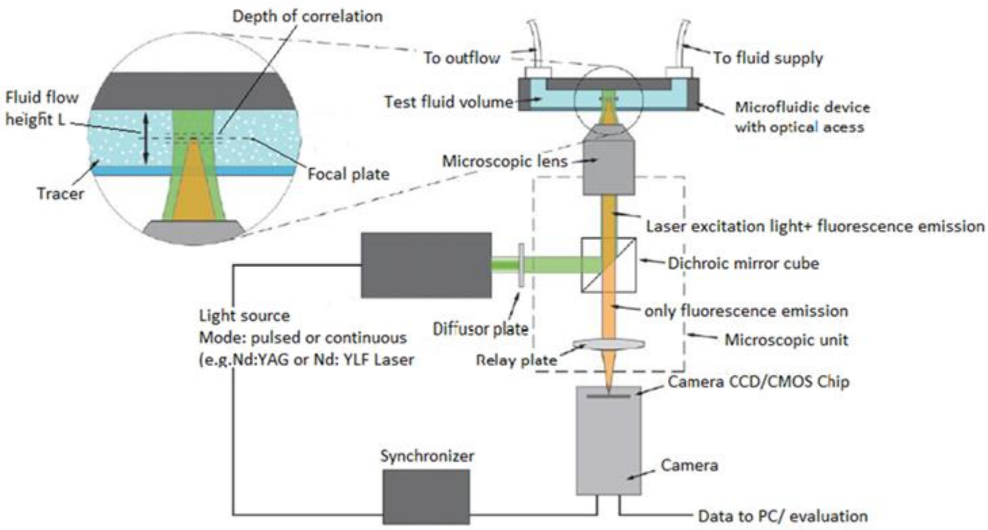

Fig. 7. Schematic of a µPIV [21]

8. PIV Applications

The PIV technique has several uses in various domains of research. Some of these uses are mentioned below to depict how this approach has been deployed [6].

8.1 Boundary Layer Flows

Measuring of three component velocity field instantaneously pertaining to the flow inside the pipes with circular cross-section can be done via stereoscopic particle image velocimetry (SPIV) Figure

8. The light sheet is orthogonal to the flow direction for this reason the flow construction advected through measurement by the mean flow.

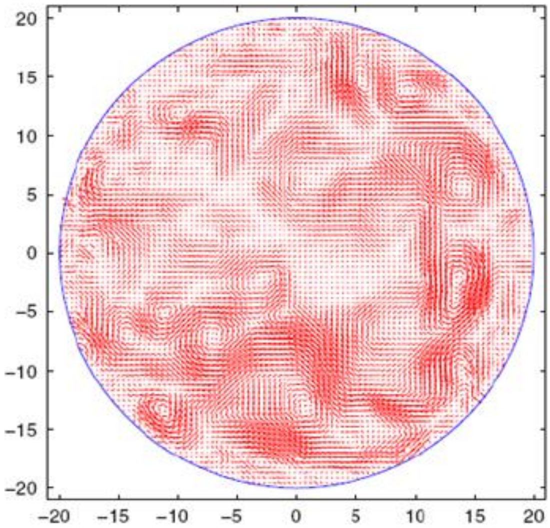

Fig. 8. Example of the instantaneous turbulent flow field in a cross-section of the pipe. Displayed resolution is 8× 8 px, or 0.5×0.5 mm2 [22]

8.2 Supersonic Flows

The tomographic results are more suitable for 3D immediate structure of interaction .The 3-D instantaneous flow organisation pertaining to a shock turbulent shock wave incident boundary layer interaction at Mach number could also be evaluated based on proper orthogonal decomposition [22] and tomographic particle image velocimetry [21]. Figure 9 reveals the volumes containing uncorrelated measurement of immediate streamwise velocity. The domain range is 0.1–0.6δ

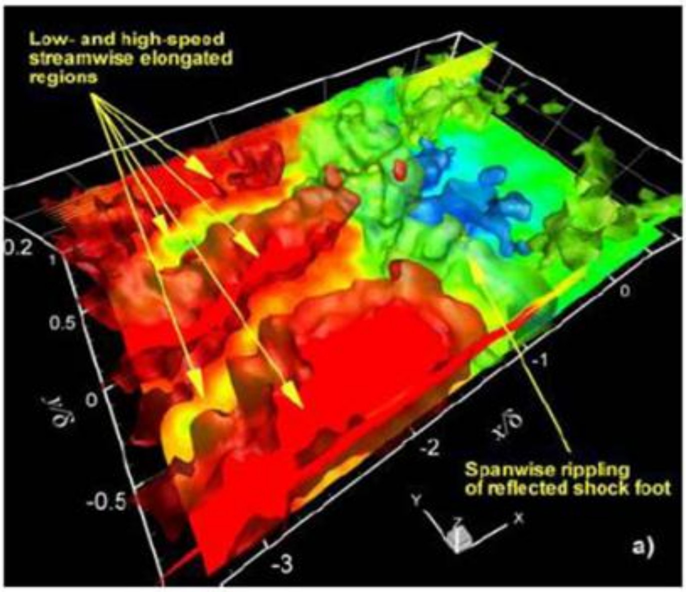

Fig. 9. Instantaneous flow organization of the interaction

8.3 Shock Tubes and Shock Tunnels in PIV

Shock tubes and shock tunnels give rise to compressibility which can be signified by big tendency as well as short time durations. Thus, such currents are a strenuous for all types of mechanisms measurement. Furthermore, density information is necessary for every test. Contemporary, (PIV) was widely put to test and effectively applied to various flow configurations in the shock tunnels and tubes.

The experimental arrangement with the shock tube and the PIV system [23] is depicted in Figure 10. A smoke generator burning incense resin was employed to introduce particle seeding, which provides a smoke particle diameter of roughly (1) µm. The open-end tube, as well as the around air air close to the opening, was seeded prior to every test. A pressure transducer placed near to the shock-tube opening was found to trigger the PIV system.

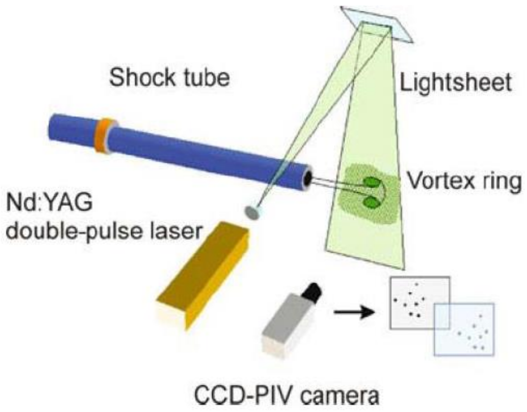

Fig. 10. PIV setup [23]

8.4 Tomographic Particle Image Velocimetry

Tomographic particle image velocimetry (T-PIV) is a contemporary three-dimensional, three-component (3D3C) velocimetry. With the help of this method, illumination of a tracer-particle field is achieved volumetrically, which is also concurrently imaged from different viewing angles, while inferring of the 3D Mie-scattering field is done through tomographic reconstruction based on the simultaneous particle images. The subsequent tomogram pairs are split into interrogation boxes (IBs), and the average particle displacement is projected through cross-correlation. Thus, T-PIV renders rapid 3D3C measurements of the fluid velocity field [24].

8.5 X-ray Particle Tracking Velocimetry (XPTV)

Non-spherical particles' fluidisation has come under significant focus as it is a common occurrence in the thermochemical disposal of municipal solid waste (MSW) and biomass in fluidised beds, like pyrolysis, combustion, and gasification. In comparison to spherical particles, the non-spherical particles' hydrodynamic characteristic is deemed as being anisotropic, which brings about considerable changes in the drag force with varying particle orientation [25].

9. Errors in PIV

There are errors present in PIV measurements that arise due to the different sources. Some of these errors are as follows [4].

i. Tracking errors occur due to the incapability of a particle to follow the flow without slipping.
ii. Gradient errors are caused from the deformation and rotation of the flow within an interrogation spot resulting in loss of correlation.
iii. Bias errors arise during the estimating process of the peak signal location to sub-pixel accuracy.
iv. Random errors occur because of the noise in the recorded images.
v. Acceleration errors are caused due to the approximation of the Eulerian local velocity of the Lagrangian flow of tracer particles.

Through meticulous selection of experimental environments or conditions (for instance, assessing and tracking errors), some minimisation of errors can be achieved. Then again, the other sources of error are intrinsic to the quality of correlation in PIV, and hence cannot be eradicated. For instance, even though there is no presence of noise in the recorded images, the position of the correlation peak can be affected due to arbitrary correlations between particle images that do not belong to the same pair. Moreover, alignment errors occur because of a phenomenon known as pixel locking, in which the location of the peak signal is biased towards the nearest pixel and it applies centroiding schemes or a curve fit to trace the discretised signal with sub-pixel accuracy. In a similar manner, gradient errors will arise in turbulent flow. Also, acceleration errors will occur due to the very principle of PIV that uses the Lagrangian motion of particles in order to attain approximation of the instantaneous Eulerian flow velocity [5].

10. Uncertainty in PIV

The following parameters are functional in the uncertainty that is present in PIV measurements [26].

10.1 Particle Image Diameter

The particle diameter (in pixel units) as it occurs in the recording medium is referred to as the particle image diameter, d_T. The diameter is proportional to the width of the correlation peak [27]. The correlation peak can be created by applying an autocorrelation or a cross-correlation. An autocorrelation consists of correlating a single image with itself, while a cross-correlation involves correlating two distinct images together. Several different values have been recommended for optimum particle image diameter that ranges from under 2 pixel units [20] to over 6 pixel units [28]. The optimum particle image diameter usually is in the range of 2 to 4 pixel units [29].
Peak locking leads to biased displacements towards integer pixel values [26]. The uncertainty can increase as a result of peak locking or pixel locking, when particle images become too small (≤ 1 pixel).

Another condition under which the uncertainty increases is when the particles become too large (for a 3-point sub-pixel estimation method and fixed camera resolution). With an increase in the particle image diameter, it becomes difficult to locate the centre of the correlation peak (used to assess sub-pixel displacement) as the correlation peak becomes wider [29].

10.2 Displacement Gradient

The amplitude of the correlation peak gets diminished and a broadening of width takes place due to flow velocity gradients or displacement gradients. The peak becomes less detectable with the reduction and expansion of the correlation peak, which eventually leads to greater uncertainty. Figure 11 depicts the impact of the displacement gradient on the correlation peak, where Figure 11(a) and Figure 11(b) represent cross-correlation maps that are derived from synthetic images. Figure 11(a) shows no displacement gradient, while Figure 11(b) indicates a (0.2) pixel/pixel displacement gradient. Different techniques [30] can be used to obtain the displacement gradient, which include the radial basis functions [31, 32], the finite difference techniques [33], and the biquadratic polynomial with least-squares interpolation [34].

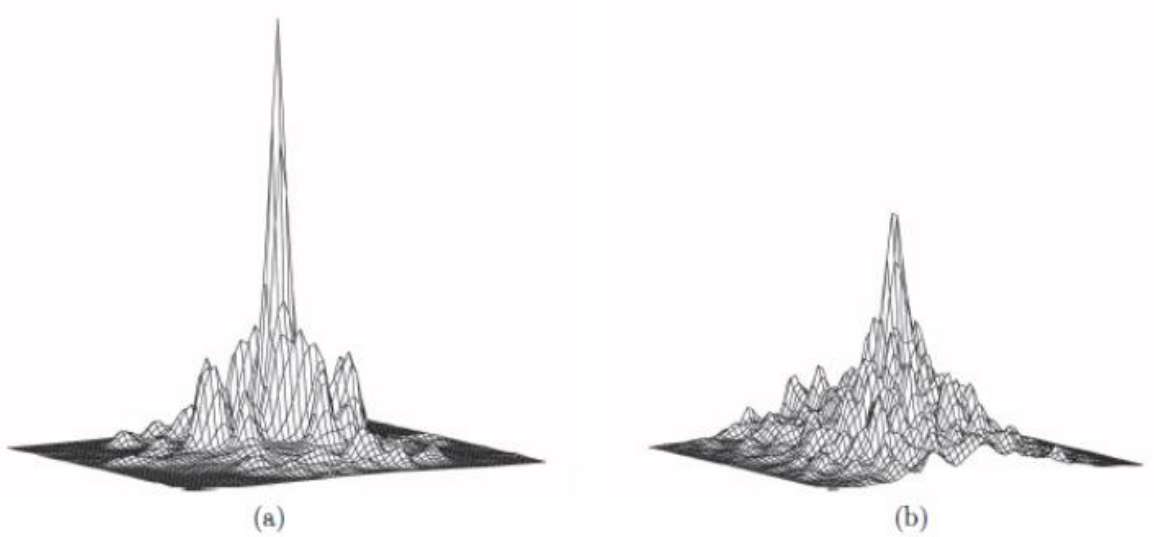

Fig. 11. A demonstration of the effects of displacement gradients on the correlation peak. The correlation of synthetic images with constant parameters show the difference between applying (a) no gradient and (b) a 0.2 pixels/pixel gradient [38]

10.3 Sub-Pixel Interpolation

In its original state, the PIV resolution measurements was restricted to integer pixel values. Sub-pixel interpolation methods are used in PIV to enhance the accuracy and resolution. These techniques identify the location of the correlation peak and fit a curve to the correlation peak profile. Some of the methodologies that exist for assessing the sub-pixel displacement include the Gaussian interpolation [35], the polynomial interpolation [36], the peak centroid technique [37], and the sin interpolation [38]. According to the recommendation, the optimal sub-pixel fit technique has the probability to be a function of the particle image diameter [39]. The interpolation technique that is used and how appropriately it fits the correlation peak profile determines the uncertainty of the sub-pixel displacement [40].

10.4 Particle Image Density

The density of particle image, N_I, is another significant parameter that impacts the PIV measurement uncertainty. The mean number of particles per interrogation region is known as the particle image density. It is suggested to have the value of N_I greater than 10 particles [41]. There are two ways in which the PIV measurement uncertainty is affected by N_I.

i. The probability of a valid displacement vector [41] increases, while the measurement uncertainty [26, 42] decreases with an increase in the number of particle image pairs within an interrogation window.
ii. A small value of NI in regions of shear can lead to an increased random uncertainty [43].

Hence, it is essential to know the local instantaneous particle image density as it has a considerable influence on uncertainty. The particle image density can exhibit variation with respect to time and space due to illumination issues or different seeding levels. The particle image density estimation can render the ability to promptly scan a PIV dataset for the various issues, ascertain the quality of a PIV dataset, and remove bad images before vector computation [40].

To estimate the value of N_I, some methods are available. In the case of adequately low N_I, one can easily attempt to count the number of particle images manually. But the task is subject to user bias and is quite time-consuming. Moreover, to account for overlapping and dim particles within an interrogation domain is also substantially difficult [40].

In another method of finding the value of N_I, a local maximum routine is used to find particles. A threshold is required to separate the low level peaks that are created by actual particles and those that are created by noise. This method is also incapable of determining the overlapping particles and inclines to underestimate N_I with an increase in the particle image density [40].

In a previous method for determining the instantaneous local uncertainty, the particle image density N_I was estimated by employing a binary threshold to an interrogation domain, finding the sum of the binary values of the image, and then dividing the derived value by the approximate pixel area of a single particle [43].

This method was used for computer created PIV images known as "synthetic images". This density estimation cannot be regarded as robust because it requires a threshold value unique to each image set and a correction factor, and it also is incapable of accounting for overlapping particles.

11. Conclusions

The PIV method is discussed in this review in terms of its evolution, applications, types, uncertainty and errors.

In the field of fluid flow measurement, PIV is an emerging technique. It has greater reliability and convenience, particularly for micro sized applications, than other conventional methodologies that have been applied traditionally in this field of researches such as hot wire anemometer and pitot tube that require probes to be present inside the flow to measure. On the other hand, PIV is non-intrusive measurement technique, which applies laser and light technique to find the trace of flow of particles inside the tubes or ducts. Therefore, in this technique, the flow is not likely to be impacted or deformed, enabling increased possibility for accurate measurements.

Significant amounts of efforts are still being made in order to improve the processing speed of PIV images through the application of complicated hardware and ingenious software. In the interim, complementary progress on experimental methods, such as HPIV and stereogrammetry, is contributing in enhancing the complexity of the images that need to be analysed. Over the coming years, this is a segment that will see sustained development.

In the plane of the illuminating laser sheet, PIV (2D) has the capability to measure just two components of the flow velocity vectors, while the out-of-plane component of velocity vectors is lost.

Some modifications have been made to PIV that enables it to measure three components of fluid velocity vectors in a volume or in a plane simultaneously, which further enables the PIV technique to have wider applications for studying more complex flow phenomena.

Compared to the 3D-PTV and tomographic PIV methods, stereo PIV measurements can have much higher in-plane spatial resolution. It has the capability to provide thousands of flow velocity vectors in the measurement plane.

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