The Technique of PIV and Its Applications

HASSAN ABDULMOUTI¹, TAMER MOHAMED MANSOUR²

¹ Dr. Eng. Damascus University (e-mail: hassanabujihad@hotmail.com)  
² Ph. D. Student, Tohoku University, Japan

ABSTRACT  
Particle Imaging Velocimetry (PIV) has been recognized as an essential and very useful technique for analyzing two- or three-dimensional complex flow fields and two-phase fluid flows. PIV techniques promise to give improved results because they provide a visual solution taking the total field into account. In addition, PIV offers many advantages for the study of fluid flow. PIV is a measuring technique that allows us to capture the flow velocity of whole flow fields in a fraction of a second. Hence, PIV has become more and more popular and it has rapidly spread in the world being recognized as the most advanced flow velocimetry because of its strong merits. Its application ranges have been expanding to measure turbulent flow, multiphase flow, internal flow of fluid machines, bioengineering, medical engineering, environmental engineering, energy engineering, development of new materials, sports science, life science, mechatronics, robotics and so on. Furthermore, PIV has been recognized as a powerful new measuring tool in thermal and fluid engineering fields including multiphase flows. Thus, PIV is a very promising powerful tool in the study of the structure of flows. In this paper, the principles and the typically used methods of PIV measurement are summarized. The classification of PIV methods is also explained. The flow structure of bubble-induced convection in a stratified liquid is investigated by using particle imaging velocimetry (PIV) measurement and pathline measurements.

Key words: Particle Imaging Velocimetry (PIV), Particle tracking Velocimetry (PTV), Computational Fluid Dynamics (CFD), Flow Visualization, Multiphase Flow, Image Processing, Bubbly Flow, Surface Flow and Stratified Liquid

1. INTRODUCTION

Particle imaging velocimetry (acronym PIV) is particularly promising, because it can instantaneously provide comprehensive and quantitative information about the whole flow field. Owing to remarkable recently progress, PIV is now developing into a very powerful tool, which may even be applied to 3-dimensional flow field.

The rapid development of Particle Imaging Velocimetry (PIV) and other new fluid measurement techniques is going hand in hand with multimedia techniques and their corresponding image processing techniques. However, the PIV technique has especially been developed with the noticeable development of modern computer techniques.

PIV is generally based on fluid visualization and image processing techniques. It is well known that fluid flow can be visualized by seeded particles or dye materials. The movement distances of all particles or ensembles of particle images (particle image patterns) in a whole flow field can be measured from a series of consecutive images to derive the velocity vector field. With this simple concept, an advanced tool for automated measurement of fluid flow; the velocity vector map obtained by PIV enables further extraction of physical information such as the pressure field and the vorticity field, by CFD (Computational Fluid Dynamics). A survey on PIV [1] confirmed that PIV has rapidly advanced in developing its fundamentals and widened its applications to multiphase flows, thermal flows and turbulence structures.

Many researchers have carried out extensive model experiments by focusing on flow field structures and many kinds of visualized images using PIV technique because it is a very powerful tool, very popular and has wide applications. In addition, the development of this technique is required. Hence, the motivation of the present work is the demand to summarize and demonstrate the principle of PIV technique. Beyond that, the present work is concerned with proposing the classification of PIV technique and its application, since it can contribute to various improvements.

Although PIV technique has previously been described in many literatures (references), previous research projects hardly elucidated the all principles of PIV technique, the classification of PIV technique and its applications. However, in the past detailed information about these points has not been acquired. On the other hand, there are very few and limited reports on research concerning these points. Hence there is still room for more improvement to get a good reference about PIV technique. However, more exact and detailed information is required in order to understand the basics and the classification and the principle of PIV technique. In this relation, information on PIV technique becomes more and more important.

Over the past decade particle image velocimetry (PIV) has undergone substantial improvements in measurement precision and reliability. Each new interrogation algorithm challenges the numerical precision and reliability of preceding ones.

It is also well known that PIV is now firmly established in the area of fluid mechanics as a powerful fluid dynamics tool to instantaneously measure the full-field flow velocity. Furthermore, PIV velocity measurement techniques are now well established and ready to be employed for industrial applications. A large part of recent investigations is devoted to the enhancement of the
quality and resolution of these techniques (improvements of image analysis methods) and to the extraction of useful information from large amounts of data provided (improvement in data extraction methods).

On the other hand, flow visualization is extremely important for the study of flow field structures and interactions. PIV is a natural extension of visualization techniques, where velocity vectors are measured simultaneously at thousands of points with high accuracy and resolution.

In addition, PIV is particularly useful in the measurement of unsteady flows. Latent turbulent structures can be unmasked with PIV, whereas averaging techniques (like LDV or PDPA) tend to wash out structures. In periodic flows, such as in internal combustion (IC) engines, turbines, and so on, the entire flow field information can be obtained for each phase angle. Furthermore, for steady flows with complex geometry where access may be difficult, PIV can be a useful tool. Time averaged velocity and turbulence values at each point in the flow field can be obtained with PIV when a sequence of frames is analyzed. In addition, PIV can be used to study turbulence structures if a sufficient amount of data can be acquired and analyzed [2, 3, 4, 5, 6 and 7].

Since the personal computer, laser light systems for visualization, image processing units, and video systems have pervaded every field of engineering, also without the exception of fluid and thermal engineering fields, the techniques of particle imaging velocimetry (PIV) have been advanced quickly and they offer many advantages for the study of fluid flow because of the following merits: 1. Instantaneous whole flow field measurement. 2. Contact-free measurement. 3. Easy extraction and processing of physical information through velocity information [8].

PIV enables fluid velocities across a whole flow region to be measured at a single instant in time in whole (global) volume of interest. This instantaneous velocity profile of a given flow field is determined by first digitally recording particle (microspheres or bubble) images within the flow over multiple successive video frames and then conducting flow pattern identification and analysis of the data. PIV is also useful for understanding the detailed structure of two-phase flows.

In addition, PIV is a non-intrusive measurement technique, which can be used to study the structure of various fluid flows. Therefore, it is a superior measurement technique for studying fluid flows, its primary advantage being the ability to capture spatial velocity distributions simultaneously and non-invasively [9, 10, 11 and 12].

On the other hand, PIV is used to measure the full time varying velocity field data of particle-seeded flow fields within either a two-dimensional plane or of a three-dimensional volume. Hence, PIV is used to determine the velocity fields in two and three-dimensions. It can also be used to study two-phase fluid flows if both phases can be distinguished. Thus, PIV is a very efficient measurement technique since it can simultaneously obtain both qualitative and quantitative spatial information about the flow field being studied. This information includes vorticity, path line, Reynolds stresses and kinetic turbulent energy, etc, while other flow measurement techniques (Laser Doppler Velocimetry, Hot Wire Anemometer...etc) only provide temporal quantitative information at a single point [13, 14, 15, 16, 17 and 18].

PIV relies on fast and accurate methods to instantaneously track numerous particles suspended in the flow. These particles can be seeded with micron size and with certain physical properties so that they accurately follow the flow path lines and respond to accelerations in the flow. PIV is a promising and powerful tool to study the structure of flows in general.

2. THE PRINCIPLE OF PIV:

Previously, the method for acquiring velocities at grid points using high-density distribution patterns of particle images was referred to particle imaging velocimetry (PIV), and the method used to track each particle for low particle number densities was referred to particle tracking velocimetry (acronym PTV). In this paper, PIV is used as a general term for velocimetry using particle images. However, it is necessary to review the present PIV techniques and examine their applicability to multiphase flow systems.

PIV, which combines the techniques of flow visualization and image processing to measure the flow field velocity, has developed very quickly in recent years. It has been developed rapidly with the remarkable development of computers and image processing techniques. The technique of PIV gives information on flow velocity, temperature and density through image analysis of visualized images of various types of flows [19].

The basic principle of PIV is to measure the field flow velocity indirectly by analyzing the motion of seeded particles in the flow. Usually the size of seeded particles is very small compared to the scale of the flow, thus the velocity of each seeded particle can be considered as the velocity of the fluid where it is located. The images of the movement distances of all particles or ensembles of particles (particle image pattern) in a whole flow field can be measured from a series of consecutive images to derive the velocity vector field. The main difficulty of PIV is particle identification. High accuracy of measurement requires a sufficient number of seeded particles in the measuring volume. If the movement of the fluid in the measuring volume is complex, such as in the cases of high velocity or strong rotation, it is very difficult to identify each particle in consecutive image frames. Since the end of last decade, many algorithms for analyzing the particles in frames have been developed, such as [9, 10, 11 and 20].

It is well known that there is no general-use type of standard PIV system. Each type of PIV needs fitting hardware and software to measure a flow field. Even though many types of PIV are applied today, they still include common processes. PIV measurements consist of four stages: 1) seeding, 2) illuminating, 3) photographing and 4) image processing. For accurate PIV measurements, each stage should be rigorously performed in whole experiment. The stages of a PIV measurement are detailed as follows: 1) Seeding: When particles have a good behavior of traceability to a fluid flow, the particle velocities usually represent the local fluid velocities. The small particles seeded in the fluid to trace its flow should (a) be distributed as homogeneous as possible in the fluid. (b) be well reflecting, (c) accurately follow the motion of the fluid, (d) not alter the properties of the fluid and its flow. Generally, the particles that satisfy the four conditions have diameters of 40 ~ 300 μm and a density that makes them almost neutrally buoyant in fluid. If the seeding concentration is appropriate, it corresponds to the density of velocity vectors desired. 2) Illuminating: In two-dimensional PIV measurement, the flow field of light scattering tracer particles is illuminated by a uniform light sheet. Usually,
the light source is a laser, whose beam is guided by a triangular prism and a cylindrical lens. The thickness of the light sheet is about 1 ~ 2 mm and the light intensity is adjusted to render the tracer particles clear enough to be photographed. 3).

Photographing: The images of particle motions following the fluid flow are recorded by various high-resolution cameras (CCD). In general, accurate velocity measurements require a short time interval $\Delta t$ between two consecutive images. The optical axis of the camera lens must be perpendicular to the plane of the light sheet. However, it is difficult to set up the camera precisely. Hence, the camera should be calibrated to determine its parameters before photographing. 4. Image Processing: Image processing is the most important stage in a PIV measurement. First, the images that record the motion of the particles are transmitted to an A/D converter to obtain digital images. Then, the digital images are processed. The processing includes removing noise, smoothing, converting the gray-scale images to binary images, labeling the particles, and calculating the center of gravity coordinates of the particles. Then, the coordinates of the particles are transferred from the image plane to the physical plane. Finally, the particle velocity vectors are calculated by various methods.

3. CLASSIFICATION OF PIV

The current PIV techniques are classified here by type according to the principles of flow velocity calculation after image processing. The techniques of PIV are classified and their principles of velocity measurement are explained and introduced as follows:

3.1. Path Line Method
The velocity of motion of a particle is determined from the exposure time, photographing time, and particle image positions on pictures, which are taken by a multiple exposure technique. A popular technique called “path line method” measures the velocity by dividing the particle path line length by the exposure time [21, 22 and 23]. Using such a simple path line technique, the start and the end points of the velocity vectors cannot be decided. In order to solve the problem of the flow direction, other techniques using velocity information [24], brightness difference at the start and the end points [25], color information [26], recorded lighting at a short interval [27], independent photography of the start and end points and the path line [28], etc, are introduced.

At its early stage, the path line method, which has a long history, was used to measure the length of a particle image path line and calculate the velocities of a visualized flow by hand. This method has been improved for automated measurement by introducing digital image processing but it is costly to determine the flow direction as shown in Fig. 1. Especially the direction ambiguity limits the application of this method to simple measurements of two-dimensional flows with low number densities of particles [29, 30 and 31].

3.2. Stroboscope Method:
Particle motions are photographed using pulse type lighting by a stroboscope, i.e. dotted lines of particle images are recorded on a picture. The velocity is determined by the distance between the dotted images and the lighting pulse interval. To get satisfactory measurement accuracy, the distance between dotted images should be longer than ten times the size of a particle image. This method can be applied to low particle number density flow because of the difficulty of particle identification.
LSV utilizes Young’s interference fringes formed by the scattered coherent light from particles in an interrogation spot [35] as shown in Fig. 2 and Fig. 3. Special high-concentration seeding is often needed to create speckle patterns [9].

A new dual beam sweep illumination technique has been developed and applied to measure flow velocities in an aerosol jet [33 and 34]. This dual-beam-sweep illumination is made by a beam splitter and a polygon mirror scanner for the measurement of a strongly unsteady high-speed flow with the LSV technique [36]. Additional procedures are usually necessary to determine the direction of particle motion. The laser speckle method has a great merit of good traceability of small particle motions in fluid flows and it is applicable to turbulent boundary layer flows, etc [29, 30 and 31].

3. 4. Brightness (or Concentration) Distribution Pattern Cross-Correlation Method (BDCC)

By tracking small local parts based on the highest similarity of spatial brightness (concentration) distribution patterns in two consecutive pictures visualized by small particles like smoke or dyestuff, velocities are calculated from the movement distances of the local parts and the time interval by using cross-correlation method [37, 38, 39 and 40]. The algorithm of particle brightness-distribution pattern tracking is the most popular one. As shown equation (3) or by the method of summation of brightness differences $E_g$ [42] defined by equation (4). In these equations, $f_{ij}$ and $g_{ij}$ are digital gray values of the pixels in the overlapping interrogation windows of size $MN$ pixels which consist of elements of particle clouds in the two consecutive frames, $\overline{f}$ and $\overline{g}$ are mean values of brightness in the interrogation windows (Fig. 4). The pair is considered to be identified when the maximum value of $C_{fg}$, or the minimum values of $D_{fg}$ or $E_{fg}$ found for a pair of interrogation windows. The velocity of the particle clouds is computed as $\overline{u}_i = \frac{B_{fg}}{\Delta t}$ by using the displacement $B_{fg}$ of the cloud center from the coordinate $P(x_i,y_i)$ to $Q(x_j,y_j)$ and the time interval $\Delta t$ between the two frames. BDCC is widely used and can be applied for high number density images [29, 30 and 31].

3. 5. Minimum Quadratic Difference (MQD)

MQD is a method for tracking ensembles of particle images of a digital PIV record by making use of the minimum quadratic difference (MQD) technique. This allows the application of the tracking principle to a much higher number of particle densities than single-particle tracking methods. This method is based on the principle of minimizing the (quadratic) differences between multi-component vectors or matrices in order to investigate the degree of similarity existing between such vectors or matrices. This principle is frequently used as a tool for analyzing or minimizing errors of numerical approximations or mathematical statistics equation (3). The MQD tracking method can be applied to both PIV double exposures and consecutive single exposures that are evaluated traditionally by auto- and cross-correlation, respectively. The MQD tracking method is more accurate than auto- or cross-correlation methods. This method has good tracking properties and allows reasonable computation [29].

3. 6. Absolute Gray Level Difference Method Using Successive Abandonment Algorithm

This method was proposed by [42]. The advantage of this method is that its computation is faster than the gray level cross-correlation method. In this method the summation of the absolute values of brightness differences is used to investigate the degree of similarity existing between patterns equation (4). The successive abandonment algorithm uses the F examination method (which is a statistical method) to eliminate the lower degrees of similarity under a certain threshold. This method has fair tracking and computation properties.

3. 7. Gray Level Auto-Correlation Method

The principle of this method is to calculate the auto-correlation coefficient in the image obtained by multiplex exposures. The displacement value can be obtained by the local maximum value of the auto-correlation coefficient. In the nth-times multiplex exposure image, $(2n-2)$ peak points appear symmetrically around the original point. When n increases, the value of the auto-correlation coefficient becomes lower. It is therefore difficult to detect the peak points. In this case a multiple (double) exposure method is used because it has a good performance. More than triple exposure methods cannot be used. The advantage of this method is that it is applicable to a rapid flow. By using this method, the maximum measurable velocity is limited by the time interval between the images. Therefore, it requires a high-speed camera and a recording device to measure rapid flows. The auto-

\[ C_{fg} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} f_{ij} g_{ij}}{\sqrt{\sum_{i=1}^{N} \sum_{j=1}^{M} f_{ij}^2 \cdot \sum_{i=1}^{N} \sum_{j=1}^{M} g_{ij}^2}} \]

\[ C_{fg} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} (f_{ij} - \overline{f})(g_{ij} - \overline{g})}{\sqrt{\sum_{i=1}^{N} \sum_{j=1}^{M} (f_{ij} - \overline{f})^2 \cdot \sum_{i=1}^{N} \sum_{j=1}^{M} (g_{ij} - \overline{g})^2}} \]

\[ D_{fg} = \frac{1}{NM} \sum_{i=1}^{N} \sum_{j=1}^{M} (f_{ij} - g_{ij})^2 \]

\[ E_{fg} = \sum_{i=1}^{N} \sum_{j=1}^{M} |f_{ij} - g_{ij}| \]
correlation method is in fact applicable to rapid flows because it is easy to get an exposure interval of a few nanoseconds \((10^{-12})\) by using a pulse generator. The disadvantage of this method is the inability in determining the direction of the displacement; therefore additional methods are needed like the image shift technique [9], or the triple exposure technique [43 and 44].

3. 8. Binary Image Cross-Correlation Method (BICC)

BICC is another kind of technique that employs an algorithm of particle distribution pattern tracking as shown in Fig 5. The motion of each particle is tracked based on the highest similarity of particle distribution patterns in two-consecutive binary pictures visualized by small particles. The particle velocity is calculated from the displacement (movement distances) of the particle center between the two consecutive frames and the time interval, by using a cross-correlation method (based on the pattern matching of particle clusters between two consecutive binarized images) [29 and 45]. This method is called binary image cross-correlation method (BICC), and uses binarized images of two consecutive frames for high-speed calculations. The computation of the cross-correlation value given by equation (1) can be simplified according to an exact mathematical discussion as follows:

\[
C_n = \frac{L}{\sqrt{mn}} \quad (5)
\]

where \(L\) is the summation of logical products of the image brightness binarized with the value of 1 or 0 at each pixel in two overlapping interrogation windows for two consecutive frames, \(m\) and \(n\) are the numbers of bright pixels in the first and the second window, respectively. The computation time of equation (5) is much shorter than that of equation (1) or equation (2). Therefore, the method of BICC is widely used and provides a real time measurement of the velocity field flow. This method has good tracking but it is limited to the case of low number densities of particles.

![Fig. 5: Principle of binary image cross-correlation method.](image)

Fig. 5: Principle of binary image cross-correlation method.
The images on the left show two separated patterns of particles, and the image in the right shows the two patterns overlapped. Here the radii of all particles are assumed to be the same [29 and 45].

3. 9. Delaunay Tessellation Technique (DT-PTV)

Another method of particle distribution pattern tracking is the so-called Delaunay tessellation technique [30, 31 and 46], which also uses two consecutive binarized images. An example of the Delaunay tessellation is shown in Fig. 6. The similarity of the two Delaunay triangles consisting of three centroids of particle images in each of the two pictures instead of interrogation windows is evaluated by the following equation:

\[
C_{fg} = \frac{\text{Area}(A \cap B)}{\sqrt{\text{Area}(A) \cdot \text{Area}(B)}} \quad (6)
\]

Where \(\text{Area}(A \cap B)\) stands for the overlapping area of the triangles \(A\) and \(B\). \(\text{Area}(A)\) is the area of triangle \(A\), and \(\text{Area}(B)\) is that of triangle \(B\). This technique has much higher speed performance than the method of BICC, and can obtain information of fluid rotation and translation velocities. Spurious vectors, which appear in the pattern tracking methods, can also be more effectively decreased by the technique of the Delaunay triangle. However, computation work for this method is extremely large when it is extended to the measurement of three-dimensional flows.

![Fig. 6: The triangular net is generated by Delaunay tessellation](image)

Particle tracking is performed by tracking each triangle [30, 31 and 46]

3. 10. Spring Model

Particle distribution patterns constructed by centroid locations of neighboring particles around a target particle are compared in two consecutive frames and their similarity is evaluated by calculating stresses in an imaginary spring system which connects the neighboring particles as shown in Fig 7. Information about fluid rotations can also be obtained by this technique and fewer spurious vectors are found. A three-dimensional technique of the spring model has already been developed. This method, which was developed by [47] has good tracking and fast computation properties and is also suitable for shear flows.

![Fig. 7: Spring Model](image)

3. 11. The Velocity Gradient Tensor Method (VGT)

The method of the velocity gradient tensor [48] is a new technique to analyze not only translations but also general fluid deformations such as rotation, shear, expansion and compression (Fig. 38). The minimum value of a sum of squared particle distances for two consecutive overlapping frames is used to identify particle pairs in the particle pattern tracking. The evaluating formula of particle distances is derived from Taylor series including the velocity gradient tensor reflecting shear, rotation and expansion in the fluid motion. This method is applicable to the case of low particle number density and has a
good tracking and fast computation properties.

$$E_{ik} = \sum_{j=1}^{n} d_{ij}^2 = \sum_{i=1}^{n} \left[ \|x_j - x_i\| - (x_{ij} - x_i) \right] + \delta u(x_i)(x_{ij} - x_i) \Delta t$$ (7)

Fig. 8: Schematic diagram of the velocity gradient tensor method [48].

3.12. Four Consecutive Time Step Particle Tracking Velocimetry (PTV)

This method is based on Particle Trajectory Tracking, which is frequently called Particle Tracking Velocimetry (acronym PTV) [49, 50, 51, and 52]. Using four consecutive pictures of flows visualized by tracer particles, which are photographed at short time intervals, each particle is tracked and identified and then the velocities of particles are calculated from the particle movement distances and the time interval. This method [25, 39 and 40] identifies each particle by investigating whether each trajectory of particle motion in the sequence is smooth or not. Therefore, the principle of the trajectory tracking algorithm is based on evaluating the smoothness of a particle trajectory. A method for evaluating the smoothness employs the change in the direction of a particle trajectory in two consecutive frames [49]. The other evaluates the deviation of combined changes in particle displacement and direction in four consecutive frames [50], as shown in Fig. 9. This method identifies particle pairs by calculating the evaluation function $t_s$ with the following equations:

$$\sigma_s = \sqrt{\frac{\sigma_t^2}{d_m^2} + \sigma_\theta^2}$$ (8)

where:

$$d_m = \frac{1}{3} (d_{ij} + d_{jk} + d_{kl})$$

$$\sigma_t = \frac{1}{3} \left( |d_{ij} - d_m|^2 + |d_{jk} - d_m|^2 + |d_{kl} - d_m|^2 \right)$$ (9)

$$\sigma_\theta = \frac{1}{2} \left( \frac{1}{3} \left( |\theta_{ij} - \theta_m|^2 + |\theta_{jk} - \theta_m|^2 + |\theta_{kl} - \theta_m|^2 \right) \right)$$ (10)

$$t_s = \frac{1}{3} \left( |x_{ij} - x_k|^2 + |x_{jk} - x_l|^2 + |x_{kl} - x_m|^2 \right)$$ (11)

With $x_i$, $x_j$, $x_k$, and $x_l$ regarded as the coordinates of the same particle in four consecutive frames when the value of $t_s$ is minimized. There is a third algorithm, which evaluates the changes in acceleration in four consecutive frames [49]. The other evaluates the deviation of combined changes in particle displacement and direction in four consecutive frames [50], as shown in Fig. 9. This method identifies particle pairs by calculating the evaluation function $t_s$, with the following equations:

$$t_s = \frac{1}{3} \left( |x_{ij} - x_k|^2 + |x_{jk} - x_l|^2 + |x_{kl} - x_m|^2 \right)$$ (12)

With $x_i$, $x_j$, $x_k$, and $x_l$ regarded as the coordinates of the same particle in four consecutive frames when the value of $t_s$ is minimized. There is a third algorithm, which evaluates the changes in acceleration in four consecutive frames [49]. When the particle number density is so low that the spacing between particles is large compared with the displacements of the particles between exposures, the pairs of images are easily recognized and any special algorithm for trajectory tracking is no longer necessary. This is the simplest case for particle identification in the PIV technique [52]. The method of PTV provides a possible technique for three-dimensional measurements and can decrease spurious velocity vectors.

Fig. 9: Schematic diagram of the 4-PTV algorithm [49 to 52].

Spurious vectors may appear in the velocity vector field of PIV measurements due to mis-matching of particle pairs. In this case, the measurement accuracy and reliability are decreased. Therefore, some proposals such as detection and removal of spurious vectors, and replacement of spurious vectors by correct ones have been made [55, 56, 57, 58 and 59]. In order to decrease and eliminate spurious vectors, first, noise signals should be excluded in the process of image recording by controlling illumination, seeding and recording devices carefully. Secondly, noise should be removed during the image processing of calculating brightness, coordinates, area and centroids of particle images. Finally, spurious vectors in the measured velocity vector field should be removed. A method for the removal of spurious vectors has been proposed by [29 and 46]. This method is based on the principle that spurious vectors do not satisfy the continuity equation of fluid flow.

3.13. VVH and Two-Frame Particle Tracking Velocimetry 2-PTV

This method uses the concept to match the probability between two consecutive image frames to obtain an instantaneous 2-dimensional velocity field. This method for correctly tracking particle paths from only two image frames is based on the iterative estimation of match probability and non-match probability as a measure of the matching degree [49].

Fig. 10: Schematic diagram of VVH and 2-PTV [49]

It is well known that in the case of the PTV method, the centroid of each particle image has to be determined in the image frame. Given such discrete points from each of two sequential images captured at different times, the next step is matching each particle image position in the first image with its corresponding position in the second image. This matching problem procedure is also known as the correspondence problem, which can be solved by analyzing the optical flow in the images. The optical flow is a distribution of apparent velocities of the brightness pattern in an image. The 2-PTV method is a form of disparity
4. EXPERIMENTAL APPARATUS AND FLOW VISUALIZATION EXPERIMENTS

An experimental apparatus for investigating the bubble convection pattern in immiscible two phase stratified liquid is constructed as shown in Fig. 11. The tank is 500 mm in length, 750 mm in height, and 24 mm wide. The stratified liquid in the tank, which consists of water and silicone oil, stands H=500 mm high. The experimental conditions of the two layers are summarized in Table 1. The bubble generator consists of 110 needles (each needle being 0.15 mm in diameter) installed at the bottom of the tank. The injector surface of the bubble generator is the area A= (55x22) mm². The gas flow rate is precisely controlled by a pressure regulator and a flowmeter. A lighting setup with a black background and metal halide lamps is used for taking pathline images and PIV measurements. The visualized flows are recorded by a digital video camera (Sony, DCR-VX1000) that captures 30 fps. The digital images are preprocessed through the NIH image software version 1.60 (produced by the National Institutes of Health of the United States of America). The preprocessing entails sharpening, binarizing and smoothing of the images. In this paper, the horizontal direction is considered to be the x axis, and the y axis is the vertical direction centered in the bubble plume. The point of origin of the x, y coordinate system is located at the center of the bubble generator, as shown in Fig. 11. The bubble injector conditions are shown in Table 2; the values in this table are calculated by using the time average of 120 consecutive frames in the image processing (4 seconds).

The averaged bubble diameter and the standard deviation have been calculated by measuring more than 1200 bubbles in the local VTR images in the bubble plume using image processing. These images are taken by recording local pictures of the injector region of the bubble generator. The measurement uncertainty for the bubble diameter is estimated to be around (0.01 mm) according to the pixel resolution. The void fraction (α) is calculated by using the equation \( \alpha=Q_b/AxV_b \), [16, 60, 61 and 62], where A is the area of calculation in the injector region, (injector surface of the bubble generator), A=(55x22) mm², \( V_b \) is the rising bubble velocity. The measurement uncertainty for the void fraction is estimated to be about 2%.

In order to clarify the flow pattern of the internal liquid flow (the flow field around the bubble plume) in immiscible two-phase stratified liquids, the spherical tracer particles (made of a high-porous polymer with diameters of 200 to 600 µm, and a density of 1010 kg/m³), are seeded in the entire tank as tracer particles for both the pathlines and the PIV measurements and then the flow is visualized. The recorded images are ported to a computer. The flows are measured in this section by using the PIV technique and the pathlines measurements for 3 cases of (\( \gamma=\frac{h_2}{H} \)), where \( \gamma \) is the ratio of the height of the second layer (oil) to that of the total liquid height. Figure 12 shows sample of the recorded images of the flow field for the cases: (a) \( \gamma=0 \) and for case-4 of the experimental conditions, (b) \( \gamma=0.1 \) and for case-3 of the experimental conditions and (c) \( \gamma=0.3 \) and for case-1 of the experimental conditions respectively. In these images the bubble plume is located in the middle of the image, while the particles are distributed around the bubble plume. The images are ported to a computer and the pathlines are calculated for 60 consecutive frames (2 seconds) averaging the movement of the particles after preprocessing the digital images through NIH software as shown in Fig. 13. Moreover, the time-averaged velocity vector maps of these cases are obtained by using the BDCC (Brightness Distribution Cross-Correlation) method [9, 37, 38, 39 and 40], as

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of water</td>
<td>( \rho_{L1}=1000 \text{ kg/m}^3 )</td>
</tr>
<tr>
<td>Kinematic viscosity of water</td>
<td>( \nu_{\text{water}}=10^{-6} \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>Initial water thickness</td>
<td>( h_1=350 \sim 500 \text{ mm} )</td>
</tr>
<tr>
<td>Density of silicone oil</td>
<td>( \rho_{L2}=900 \sim 935 \text{ kg/m}^3 )</td>
</tr>
<tr>
<td>Kinematic viscosity of oil</td>
<td>( \nu_{\text{oil}}=10^{-5} \sim 5 \times 10^{-4} \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>Initial oil thickness</td>
<td>( h_3=0 \sim 150 \text{ mm} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature of environment</th>
<th>12-20 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gas flow rate</td>
<td>( 20.0 \times 10^6 \text{ m}^3/\text{s} )</td>
</tr>
<tr>
<td>Density of air</td>
<td>1.25 kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Gas flow rate ( Q_b ) (m³/s)</th>
<th>Mean bubble diameter ( D ) (mm)</th>
<th>Standard deviation of ( D ) (mm)</th>
<th>Void fraction ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>( 0.28 \times 10^6 )</td>
<td>0.20</td>
<td>0.008</td>
<td>0.0020</td>
</tr>
<tr>
<td>Case 2</td>
<td>( 1.39 \times 10^6 )</td>
<td>0.30</td>
<td>0.012</td>
<td>0.0035</td>
</tr>
<tr>
<td>Case 3</td>
<td>( 2.78 \times 10^6 )</td>
<td>0.45</td>
<td>0.020</td>
<td>0.0050</td>
</tr>
<tr>
<td>Case 4</td>
<td>( 4.17 \times 10^6 )</td>
<td>0.60</td>
<td>0.028</td>
<td>0.0070</td>
</tr>
<tr>
<td>Case 5</td>
<td>( 5.56 \times 10^6 )</td>
<td>0.75</td>
<td>0.037</td>
<td>0.0090</td>
</tr>
<tr>
<td>Case 6</td>
<td>( 6.94 \times 10^6 )</td>
<td>0.80</td>
<td>0.045</td>
<td>0.0105</td>
</tr>
<tr>
<td>Case 7</td>
<td>( 8.33 \times 10^6 )</td>
<td>1.00</td>
<td>0.051</td>
<td>0.0115</td>
</tr>
<tr>
<td>Case 8</td>
<td>( 9.72 \times 10^6 )</td>
<td>1.15</td>
<td>0.058</td>
<td>0.0130</td>
</tr>
<tr>
<td>Case 9</td>
<td>( 11.11 \times 10^6 )</td>
<td>1.35</td>
<td>0.065</td>
<td>0.0145</td>
</tr>
<tr>
<td>Case 10</td>
<td>( 12.50 \times 10^6 )</td>
<td>1.55</td>
<td>0.072</td>
<td>0.0160</td>
</tr>
<tr>
<td>Case 11</td>
<td>( 13.89 \times 10^6 )</td>
<td>1.75</td>
<td>0.080</td>
<td>0.0180</td>
</tr>
<tr>
<td>Case 12</td>
<td>( 15.28 \times 10^6 )</td>
<td>1.90</td>
<td>0.089</td>
<td>0.0190</td>
</tr>
<tr>
<td>Case 13</td>
<td>( 16.67 \times 10^6 )</td>
<td>2.00</td>
<td>0.098</td>
<td>0.0200</td>
</tr>
</tbody>
</table>

Fig. 11 Schematic diagram of experimental apparatus

Table 1. Experimental and simulation conditions of the two layers
shown in Fig. 14. The grid averaging method is used in order to get grid-rearranged vector maps. These results are obtained by using more than 250000 velocity vectors for each case, which are captured during 120 frames (4 seconds).

According to these figures the detailed flow mechanism inside the two layers can be explained as follows. The resulting flow is steady and symmetric relative to the bubble plume center because a small gas flow rate is given, the main upward liquid flow in the water layer is driven along the bubble plume by the rising bubbles. The flow evolves as follows: The momentum of the upward flow attains a maximum near the oil-water interface. Just under the oil-water interface the upward flow changes its orientation into a horizontal flow. Then, a pair of liquid circulations is generated next to the bubble plume. After time passes by, the pair of circulations induces a whole scale circulation in the entire water layer. At the same time, some bubbles accumulate on the oil-water interface. Beyond that, a part of the bubble plume penetrates and passes through the oil stratum causing a secondary flow inside the oil layer by the buoyancy of the penetrating bubbles. The velocity of the bubbles inside the oil layer is less than that inside the water layer due to the high oil viscosity. Thus, the velocity of the bubbles decreases quickly when they enter the oil layer. Therefore, the void fraction inside the oil layer increases. The flow pattern inside the oil layer is still very weak and basically it is only rising bubbles and particles for the case (b). When the ratio reaches γ≥1/3 case (c), a different flow pattern results inside the second layer, while the first layer preserves almost the same flow pattern. When the ratio reaches γ≥1/2, the flow pattern becomes complicated because double convection occurs near the interface of the two layers. Also, inside the bubble motion strange behavior may occur. However, the detailed mechanism of generating the secondary flow inside the oil layer (which is similar to that induced in the water layer) for the case (c) can be explained as follows: The oil flow is driven by the bubble plume. The momentum of this flow becomes maximum near the free surface (but is still smaller than that induced in the vicinity of the oil-water interface). Just under the free surface the upward flow inside the oil layer changes its orientation into a horizontal flow. Then, a pair of liquid circulations is generated in the oil layer besides the bubble plume. Around this pair of circulations, the accumulated bubbles on the oil-water interface slowly rise through the oil layer to the free surface and float. However, the pair of circulations inside the oil layer is smaller than that induced inside the water layer due to the effect of the oil viscosity. Hence, the surface flow induced by the bubbles inside the oil layer at the free surface is weaker and smaller in scale than that induced inside the water layer in the vicinity of the oil-water interface.

In order to clarify the detailed structure of the flow in the two layers, the two-dimensional distribution of the kinetic energy is calculated from the measured averaged velocity vector map as shown in Fig. 15. This shows that the highest kinetic energy is generated at a long distance in the center of the bubble plume and in the vicinity of the oil-water interface.

5. SUMMARY AND CONCLUSION

PIV has been developed rapidly with the recently noticeable development of computers and image processing techniques. The technique of PIV gives information on flow velocity, temperature and density through image analysis of visualized images of various types of flows. Unlike the traditional point-measurement methods, it can measure the simultaneous whole flow field at fairly good accuracy. PIV including image processing method is recognized as a powerful new techniques to measure and elucidate thermal and fluid engineering fields including multiphase flows, and it expands to measure complex flow structures like bubbly two-phase flow. And also an accurate computer prediction for the bubbly flow has become possible using recent quick advanced techniques for CFD research. By further development of these new research methods, a large improvement of conventional system using bubbly two-phase flow and a creation of new techniques for industrial and environmental devices are expected.

Due to the complexity of fluid motion phenomena and the difficulties involved in applying equations of motion to even the
simplest of realistic situations, fluid dynamics relies heavily on experiment. Of course the Computational Fluid Dynamics (CFD) techniques provide a competitive solution to solve many kinds of flows, but the models and various schemes need extensive investigations to verify even now. PIV techniques based on image processing have important advantages over more conventional techniques both for industrial and laboratory applications. Although the field is still developing, the most important techniques have been developed successfully to measure many kinds of flows, including the multi-phase flow. Because of its strong merits, the technique of PIV has been recognized as the most advanced flow velocimetry, and has rapidly become more and more popular in the whole world. The areas of application have been expanding, for example, to the measurement of turbulent flows, multiphase flows, internal flows of fluid machines, bioengineering, medical engineering, environmental engineering, energy engineering, development of new materials, sports science, life science, mechatronics, robotics and so on. Furthermore, PIV has been recognized as a powerful new measuring tool in thermal and fluid engineering fields including multiphase flows. In addition, the use of PIV has extended to determine the velocity fields in two and three-dimensional, two-phase fluid flows. PIV is therefore a promising and powerful tool to study the structure of flows. As a result it is made clear that the PIV technique can contribute to various improvements.

Flow visualization of the bubble plume in two immiscible stratified fluids are carried out in order to improve the applicability of the bubble plume as an oil fence. The covering effect of the oil layer on the free surface and the convection due to the bubble plume are investigated by using image processing. PIV measurements and pathlines measurements. The main experimental results can be summarized as follows:

1. The flow structure is sensitively modulated by the gas flow rate and bubble size.
2. The velocity of the surface flow induced by the bubble plume in the vicinity of the oil-water interface is larger and stronger than that inside the oil layer. Moreover, the surface flow is particularly rapidly generated in the vicinity of the oil-water interface.
3. The highest kinetic energy is generated at a far distance inside the bubble plume and in the vicinity of the oil-water interface. This observation confirms the idea that the bubble plume can indeed generate a strong and wide surface flow over the bubble generation system.

6. REFERENCES

Visualization Pictures—Measurement of Two-Dimensional Vortex
Visualization, Proc. of the 11th Images Processing Conference,
9, pp. 12-16
Processing System for Path Line Picture, Trans. of JSME (B),
Particle Streak Velocity Field Measurements in a Two-Dimensional
Mixing Layer, Physics of Fluids, 24-6, pp. 995-999.
Development of a Real-Time Velocimeter Measurement System for
Two-Dimensional Flow Field Using a Digital Image Processing
Technique, Trans. of JSME (B), 55-509, pp. 107-115.
Visualization Photography and Digital Image Processing Techniques,
Trans. of JSME (B), 53-493, pp. 2762-2770.
Engine Using Flow Visualization and Particles Tracking
System Using a Digital Image Processing technique, Report of
Grant 1986-3 for Scientific Research by the Japan Ministry of
Education.
Discussion of the Cross-Correlation Methods for PIV. J. Flow
30. Song X.. (1999). The Development of HT Technique and Its
Application to the Investigation of Flow Structure in Bubbly Flow,
3-D PTV Measurement of Bubble Rising Flow in Cylindrical
Vessel. ISIJ Int., vol. 36, pp. 54-57.
Visualization Society of Japan, 7-25, pp. 84-89.
Beam Scanning Technique. Proc. of the 1st Int. Workshop on
PIV95-Fukui, pp. 155-158.
PIV'95-Fukui, pp. 155-158.
(1991), Two-Dimensional and Time Series Measurement of
Thermally Stratified Shear Flow Using Correlation Technique, J. Of
The Visualization Society of Japan, 11-Suppl. No. 1, pp. 157-160.
Development of a Real-Time Velocity Measurement System for
High Reynolds Fluid Flow Using a Digital Image Processing
Time Series Measurement of Turbulent Flow Field Sing Image
43. Song X., Yamamoto F., Murai Y., Iguchi M.. (1997). Cross-
Correlation Algorithm for PIV by Delaunay Tessellation Proc. of
the 2nd Int. Workshop on PIV97-Fukui, pp. 109-115.
Algorithm Vector Histogram and Spring Model. Proc. of the
1st Int. Workshop on PIV95-Fukui, pp. 21-32.
Proc. of the 2nd Int. Workshop on PIV97-Fukui, pp. 51-56.
Measurement System for Particle Tracking Velocimetry, Using Binary J. of the
Algorithm for Particle Tracking Velocimetry, Using Binary J. Of the
51. Song X., Yamamoto F., Murai Y., Iguchi M.. (1997). Cross-
Correlation Algorithm for PIV by Delaunay Tessellation Proc. of
the 2nd Int. Workshop on PIV97-Fukui, pp. 109-115.
Algorithm Vector Histogram and Spring Model. Proc. of the
1st Int. Workshop on PIV95-Fukui, pp. 21-32.
Proc. of the 2nd Int. Workshop on PIV97-Fukui, pp. 51-56.
Particle Tracking Velocimetry Based on Automated Digital Image
384-391.
Tracking Velocimetry in Three-Dimensional Flow. Exp. Fluids 15,
pp. 279-294.
by M. C. Roco, Butterworth-Heinemann, pp. 33.
Real-Time Measurement System for High Reynolds Fluid Flow
Using a Digital Image Processing Technique, J. of the Visualization
Measurement of Bubble Plume Generated Surface Flow Using
2. Pp. 31-37.
Immiscible Stratified Liquids Induced by Bubble Plume. The
Patterns in Two Immiscible Stratified Liquids Due to Bubble
Plume. The 10th International Symposium on Flow