DEVELOPMENT AND APPLICATION OF MULTI-WAVE UVP AND PIV MEASUREMENT METHODS TO MEASUREMENTS OF SINGLE-PHASE AND BUBBLY TWO-PHASE FLOWS IN A VERTICAL PIPE

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Summary

Two advanced measurement methods, i.e. multi-wave UVP (ultrasonic velocity profile) and PIV (particle image velocimetry) methods have been developed and applied to the measurement of single-phase and bubbly two-phase flows in a vertical pipe. These are non-intrusive measurement methods which are able to measure the instantaneous velocity profile and 2D velocity field. Thanks to the instantaneously measured velocity profile of single-phase and two-phase flows the characteristics and behaviour of single-phase and two-phase flows can be clarified. Relevant flow parameters can be obtained. The multi-wave UVP method, which is highly compact and able to work with opaque fluids and containers, is expected to be applied to the practical measurement of instantaneous velocity profiles, flow rate and local void fraction, etc., in industrial piping systems in operations such as oil and gas two-phase flows with the presence of deposition, crystalisation and corrosion. Therefore, it could be a very useful measurement tool in the oil and gas and power generating industries.

1. Introduction

Single-phase and two-phase flows play important roles in many industrial, technical and engineering systems. Some of the many examples are oil and gas flows in oil and gas and petroleum industry, water-steam flows in piping systems in heat removing systems, and in steam generators in energy systems. In such systems, the characteristics and structures of flows have direct correlations with many scientific and technical problems such as proper, optimised and safe operation and control of the whole system. Hence thorough understanding of single-phase and two-phase flows has very important practical implications. In addition to the single case of fully developed laminar flow in pipes, which has a beautiful analytical expression of parabolic radial velocity distribution, all of other cases are turbulent single-phase and two-phase flows whose behavior and structures vary a lot depending on the flow regime and flow geometry. There is no universal analytical expression for these flows. Therefore study of the characteristics and structures of single-phase and two-phase flows in pipes still attracts much attention [1, 2].

One of the most important parameters required for study of single-phase and two-phase flows in piping systems is instantaneous velocity distribution of liquid (in single-phase flow) and of liquid and gas (in two-phase flow). Methods for calculation of pipe flow velocity include numerical simulation and experimental measurement. Numerical simulation based on solution of mathematical models using PC has gradually improved due to enhanced models and computing power. It has advantages such as being possible for a wide range of flow parameters. However numerical models usually have to adopt various kinds of assumptions including approximations, averaging and model closures. Especially, two-phase flow models currently have to rely on experimental measurement data for many kinds of correlations between the liquid and gas phases. As a result, experimental measurement of single-phase and two-phase flows plays a tremendously important part. A major advantage of the experimental study of pipe flow is the possibility to confirm measured data directly. Exact flow parameters can be obtained using measurement techniques. The data can be used not only for study of flow, for calibration and validation of numerical models but also as data for boundary conditions of the models. Therefore properly measured data is highly important to build up knowledge and data banks for single-phase and two-phase flows, especially flows in industrial piping systems [1, 2].

Experimental methods for measurement of velocity of liquid flow can be classified into intrusive methods and non-intrusive methods. Intrusive methods all involve insertion of measuring probes into the flow field for measurement. Some typical examples are hot-wire and hot-film anemometries, wire mesh tomography and pitot tubes the intrusive effects of such methods disturb the flow field and cannot be neglected. In addition, experimental setup tends to be more complicated. Interuption of flow in operation may be required for the deployment of measuring probes. Therefore measurement of systems in operation is difficult. On the other hand, non-intrusive methods are always more attractive taking into account the avoidance of interference between the measuring probes and liquid flow. Popular examples of non-instrusive measurement methods are laser Doppler anemometry (LDA), ultrasonic velocity profiler, particle image velocimetry and nuclear magnetic resonance (NMR). The LDA method is a point-wise measurement method which needs an optical window for the operation of a laser beam. The UVP method is a velocity profile measurement method using ultrasound and signal processing. It is a non-intrusive and non-contact measurement method since ultrasound can penetrate many materials. Similar applications of ultrasound are very well known in the medical field. The PIV method is based on the statistical processing of particle images of the flow field. It can produce 2D and 3D velocity fields of flows with very high temporal and spatial resolutions. However it requires an optical windows for the exposure of the flow field into a laser sheet. NMR is also another non-intrusive and non-contact measurement method. It can obtain results in 2D and/or 3D. However the NMR method uses bulky hardware for safety protection and usually needs many operators for measurement. Therefore it is not suitable for measurement at small experimental sites, and in industrial on-site conditions. Taking into account the characteristics of the measurement methods listed above, the UVP and PIV methods would be superior to other methods for measurement of single-phase and two-phase flows in a vertical pipe.

The principle of the UVP method, which was originally developed for single-phase flow measurement, is extracting velocity information carried in ultrasound when it is reflected from moving objects. Therefore this method uses an ultrasonic transducer (TDX) to emit ultrasonic pulses into the flow field. In order to do that, a pulser/receiver (P/R) is used to generate electrical pulses to excite the piezoelectric element of the TDX. Ultrasound is reflected from particles seeded in the flow. Echo sound is then received and converted into a voltage signal by the same piezoelectric element of the TDX. The electrical signal is filtered and amplified by the P/R. An analog to digital converter (ADC) is used to digitise the voltage signal and transfer it to a PC. Signal processing techniques are applied to the received signal to extract flow velocity along the sound path. Since ultrasound can penetrate various materials and liquids, the UVP method can be used with opaque fluids and non-transparent containers. On the other hand, the PIV method is basically based on optical principles to obtain particle images of the flow field, and statistical methods for image processing. To capture particle images, the flow field is usually exposed to a laser (or light) sheet. Image processing techniques are applied to the recorded images to extract the velocity of the flow. Therefore the PIV method can provide detailed 2D or 3D velocity fields. However it must use an optical window for imaging the flow field. As a result, it can not be applied to opaque liquids and containers which are very often encountered in flows in industrial and engineering piping systems [3].

The UVP and PIV methods were originally developed for single-phase flow measurement. Application of these methods to two-phase flow measurement is not straightforward. In gas-liquid two-phase flows, which are very often encountered in reality, both ultrasound and light are scattered strongly at gas-liquid interfaces due to very high difference of acoustic impedance between liquid and gas. Received signals or data include information of both liquid and gas. That is also a problem with the LDA method when it is applied to two-phase flow measurement. In order to obtain instantaneous velocity of each phase, phase separation methods are required to select liquid data and gas data separately, either at an early stage to selectively collect data of each phase only or at a later stage to properly select the velocity of liquid phase only and gas phase only. A combination of both ways is also possible. A common solution to this problem is using multi-wave (ultrasound in UVP method or light in PIV method). The principle is using an appropriate wave for measurement of each phase. When two waves are used, measurement of two-phase flow is possible [4].

In this study, we have developed two methods for measurement of single-phase and two-phase flow velocity in a vertical pipe. The first method uses two ultrasounds with different centre frequencies and is called the multi-wave UVP method. This method can measure the instantaneous velocity profiles of each phase separately. For measurement of single-phase flow of liquid, this method works as the original UVP method in which only one frequency is used. The other method is a PIV method for only the gas phase in a two-phase flow. For single-phase flow measurement, the method works as normal PIV measurement. As part of the development of the measurement methods, test flow loops have been developed to confirm the validity of the two methods. For single-phase flow, instantaneous velocity profiles have been properly obtained for various Reynolds number (*Re*). For single-phase and bubbly two-phase flows, the multi-wave UVP method is confirmed using PIV data. Instantaneous velocity profiles of liquid and gas have been obtained for various liquid and gas superficial velocities. It is shown that multi-wave the UVP method exhibits robustness in two-phase flow measurement both in research and in engineering. The measured result is used for further analysis of relevant parameters (e.g. flow rate, local void fraction etc.) of single-phase and two-phase flows. In addition, measurements can be extended to other cases of single-phase and bubbly two-phase flow in a pipe.

2. Measurement methods for single-phase flow

2.1. UVP method

There are two signal processing methods for the calculation of velocity including the ultrasonic Doppler method (UDM) which exploits the Doppler effect, and the ultrasonic time-domain cross-correlation method (UTDC) which is a statistical method for analysis of time series data, i.e. echo waves. The first method was developed early, and is suitable for early electronics [5]. It has been widely applied in commercial UVP systems. The principle of the Doppler method will be introduced and exploited in this study. The other method, which is UTDC, has recently been developed. Due to the complexity of correlation algorithm, it tends to be computationally expensive. Early applications of UTDC were usually for offline measurement. Readers who are interested in the UTDC method can refer to [6]. At present, there is another method for measurement of fluid flow of very low velocity. The method is known as the phase difference method and is under development [7]. As a result, details of the principle of the ultrasonic Doppler method will be presented below.

In the Doppler method, the received digitised signal is analysed to obtain the Doppler shift frequency f_d, i.e. the change in frequency between emitted ultrasound and the reflected one (Doppler effect). The Doppler shift frequency has a direct relationship with flow velocity as shown below:

$$f_d = 2 f_0 \frac{v}{c} \quad (1)$$

Where:

v is the fluid velocity which has the direction in the sound path;

f_0 is the central frequency of the transmitted ultrasound;

c is the sound speed in the working liquid.

The principle of the Doppler method is explained in Fig.1.

As shown in Fig.1, the TDX emits an ultrasonic pulse into the flow field and switches to the receiving mode to receive echo signals. The reflected ultrasound from all depths in front of the TDX surface is received. The sound speed in the working liquid is known a priori. The measurement channels (the positions along the sound path where velocity is measured) are specified according to the time when the echo signal is sampled for the calculation of velocity. This is also known as the range-gated time system. For example, in Fig.1, the echo signal from the enlarged position is the signal that is sampled from the time series of echo signal after a time delay Δt (with the time origin being the time when the TDX emits an ultrasound pulse).

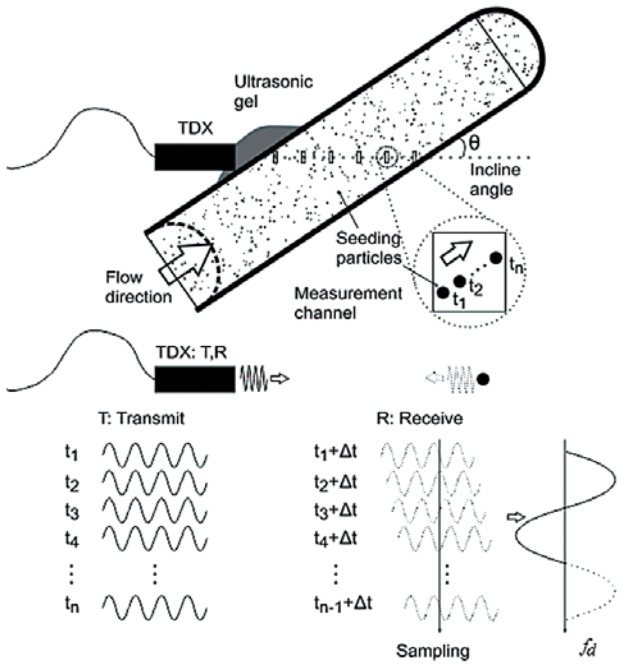


Fig.1. *Principle of the Doppler method*

The time delay is calculated according to Eq.(2) where Δx is assigned as desired in measurement setting:

$$\Delta t = 2\Delta x/c \quad (2)$$

Similarly for other measurement channels, signal processing of echoes from the channels provides Doppler shift frequencies at the channels and velocity of the channels are calculated straight forwards using Eq.(1). Since Doppler shift frequency is determined for the movement in the sound path direction, it can not be calculated for the movement in the direction perpendicular to that direction. As a result, in practical measurement, the TDX must be set inclined at an angle θ to the flow direction (Fig.1). Hence the flow velocity at a measurement channel is calculated using Eq.(3):

$$v = \frac{f_d}{f_0} \cdot \frac{c}{2\cos(\theta)} \quad (3)$$

Though each ultrasonic echo wave from a measurement channel does contain some information on the Doppler effect as a result of the movement of the fluid flow, it is currently impossible to extract Doppler shift frequency by using just only one echo wave which is corresponding to one emitted pulse. The reason is mainly due to the limitation of the speed of the digitiser. In a commercial UVP system, the numbers of echo waves from a measurement channel (corresponding to the number of emitted pulses) typically are 16, 32, 128, 256 and so on. These numbers are a power of 2 due to the fact that Fourier analysis is usually adopted in the signal processing to obtain Doppler shift frequency. Typical methods for the derivation of Doppler shift frequency are zero crossing method, Fourier analysis using FFT algorithm, auto-correlation etc. [4, 5, 8]. Due to its robustness, in this study, the auto-correlation technique is exploited.

In a typical UVP system, the ultrasonic pulses are emitted at a pulse repetition frequency F_{prf} and time duration $T_{prf} = 1/F_{prf}$. F_{prf} itself also implies the sampling frequency of the Doppler signal whose centre frequency is the Doppler shift f_d. These parameters set direct constrains on the maximum measurable velocity (v_{max}) and maximum measurable depth (P_{max}) of the UVP method due to the limitation expressed in the Nyquist sampling law (i.e. $f_d < F_{prf}/2$), and the limitation of the time duration set aside (between two emissions) for the TDX to hear echo signal (i.e. $T_{for\ receiving\ echo\ signal} < T_{prf}$). Such constraints are written in Eq.(4) and Eq.(5).

$$v_{\max} = \frac{F_{prf}}{2 f_0} \cdot \frac{c}{2\cos(\theta)} \quad (4)$$

$$P_{\max} < \frac{c \cos\theta}{2F_{prf}} \quad (5)$$

2.2. PIV method

A schematic diagram of the PIV method is briefly explained in Fig.2. Similar to the UVP method, the PIV method needs seeding particles as reflectors of light. It is usually assumed that seeding particles of approximately equal density with water are used. Therefore their effect on flow dynamics is negligible. The flow field is then exposed at least twice, in an appropriately short time interval, to a light sheet (which is usually a laser sheet). The image of the exposed area of the flow field is captured using a camera (recently using digital cameras). The captured images are image pairs or single images. The displacement of the particles between two adjacent exposures is estimated using statistical methods and image pairs. Based on the particle displacement, the velocity field of the flow is determined [9].

For the estimation of velocity using particle images, the images are divided into rectangular areas called interrogation windows (Fig.3). Statistical methods such as auto-correlation or cross-correlation are applied to the interrogation windows to determine particle displacement between two exposures.

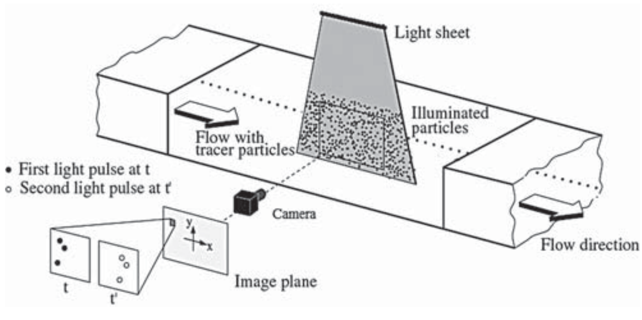


Fig.2. *Schematic diagram of the PIV method [9]*

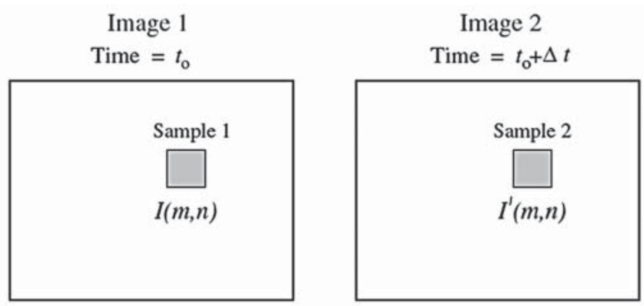


Fig.3. *Interrogation windows and single exposure images [8]*

Based on the displacement calculated for each interrogation window, spatially averaged (in the interrogation window) flow velocity of the windows is calculated [9]. Particle images are usually stored in gray scale images for the analysis of particle displacement. Currently, in a typical PIV system, the statistical method used is the estimation of the correlation coefficient of the time series data which are composed of two dimensional gray scale images. It is possible to calculate the correlation coefficient directly using particle images. However, very often, the correlation coefficient is calculated indirectly by adopting Fourier transform and Wiener-Khinchin theorem (Fig.4). The Wiener-Khinchin theorem states that Fourier transform of the auto-correlation function R_{II} and the power spectral function $|\hat{I}(r_x, r_y)|^2$ of the light intensity field $I(x, y)$ are Fourier transform of each other [9]. In more detail, in the case of single exposure/double frame images as shown in Fig.4, the correlation function is written as:

$$R_{II}(x,y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I(i,j) I'(i+x, j+y) \qquad (6)$$

Statistically, the correlation function provides essential information on the similarity of the distribution of the light intensity (i.e. the distribution of particles) in I and I' corresponding to each movement in *x* and *y*. Therefore the maximum of the correlation implies the real displacement of the particles between two adjacent images. As a result, flow velocity is inferred. Direct calculation of the correlation function is extremely time consuming. As a result, indirect calculation based on Fourier transform is used in most of the current commercial and scientific PIV systems. The algorithm of the displacement estimation, which is based on Fourier transform, is shown in Fig.5.

In addition to the application of Fourier transform, interpolation methods are exploited for the optimal estimation of the maximum of the correlation function of the particle displacement.

These methods are usually called sub-pixel estimation of particle displacement [9].

3. Development of measurement methods for two-phase flow

3.1. Multi-wave UVP method

When conventional TDX and UVP methods are applied to measurement of single-phase flow, ultrasound is reflected by only seeding particles in the flow field. Only one central ultrasonic frequency f_0 is used for measurement of liquid velocity. If the method is applied to two-phase flow measurements, ultrasound gets reflected from different reflectors including: seeding micro particles and interfaces between phases (e.g. liquid and gas interfaces). If only one TDX with one central frequency is used, it is difficult to classify the echo sounds reflected from different objects. Therefore it is very hard to tell which one is liquid data and which one is gas data. Moreover, if the interfaces between phases are large (compared with the cross sectional area of the ultrasonic beam), ultrasound can not go beyond the interface, i.e. it is blocked at the interface.

In the UVP method, measurement volume is a cylindrical shape specified by the ultrasonic beam diameter and the number of wave cycles in one emitted pulse. The thickness of the measurement volume is defined as *Nλ/2* where *N* is the number of wave cycle of one emitted pulse and *λ* is the wavelength. The measurement volume size has a relationship to the measured result. When different sizes are used, particular phase velocity in multi-phase flows can be measured. Experiments [11] showed that, if an ultrasonic beam of 2MHz centre frequency, 10mm diameter is used to measure bubbly flow whose bubble size is of an order of several millimeters, measured results mostly show bubble velocity. On the other hand, with the same flow conditions, if an ultrasonic beam of 8MHz centre frequency, 3mm beam diameter, is used, measured results exhibit mostly liquid velocity. As a result, the idea of using multi-wave ultrasounds for the measurement of two-phase flow has been proposed. If the TDX is possible to emit and receive two

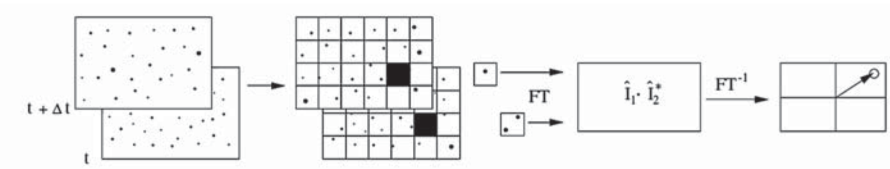


Fig.4. *Schematic diagram of the displacement estimation method using Fourier transform [9]*

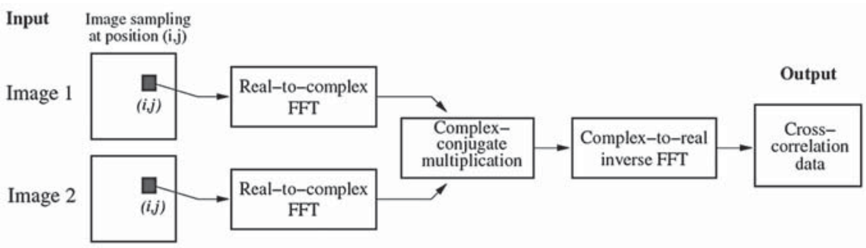


Fig.5. *Schematic diagram of the algorithm of the displacement estimation based on Fourier transform (figure from [9])*

ultrasounds of 2MHz and 8MHz frequencies simultaneously at the same position, phase velocities of bubbly flows can be measured. Based on this idea, the principle of multi-wave TDX and multi-wave UVP methods for the measurement of bubbly two-phase flows is devised and is shown below.

3.1.1. Multi-wave TDX

A multi-wave ultrasonic TDX is composed of two piezoelectric elements including 2MHz and 8MHz frequencies. Fig.6 shows a schematic configuration of a multi-wave TDX which can simultaneously emit and receive ultrasound of 2MHz and 8MHz frequencies independently at the same position for the measurement of bubbly two-phase flows.

The 8MHz frequency element is a cylindrical shape with diameter 3mm located at the centre and surrounded by the 2MHz frequency element which has an annular shape. Each element is controlled independently and simultaneously by two synchronised P/Rs. This uniquely designed multi-wave TDX enables the emission and reception of ultrasounds of 2MHz and 8MHz frequencies simultaneously and independently at the same position for bubbly flow measurement.

3.1.2. Pulser/receiver and data acquisition unit

Usually, the ultrasonic pulsed Doppler method is used with a tone burst P/R for the excitation of ultrasonic TDX and for reception of echo sound. However, we have proved that, by using low-cost, popular spike P/Rs in ultrasonic testing industry, measurement of instantaneous velocity profiles using a pulsed Doppler method is also possible [12]. Therefore, two spike P/Rs, which were synchronised, have been used to excite two piezoelectric elements of the multi-wave TDX simultaneously. After emission, reception of echo sound of both frequencies occurs at the same time. The captured signals of 2 and

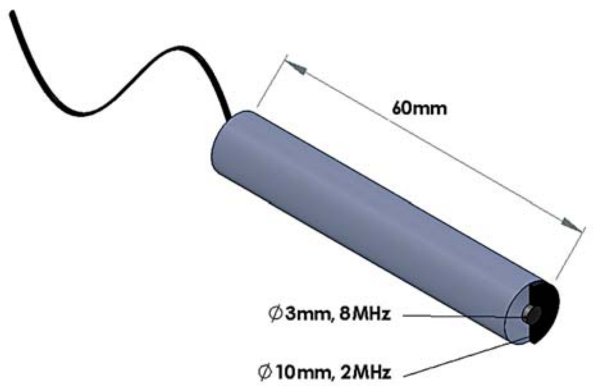


Fig.6. *A schematic configuration of multi-wave ultrasonic TDX*

8MHz frequencies are converted into voltage signals by the corresponding piezoelectric elements respectively. Voltage signals are then amplified and filtered by the P/Rs. For data digitisation and acquisition, a two channel, high speed ADC is used to connect with the two P/Rs. It is also synchronised with the P/Rs for data acquisition. Digitised signals of both channels are transferred into a PC for online signal processing to obtain instantaneous velocity profiles of two-phase flow.

3.1.3. Discrimination of gas phase from liquid phase

In two-phase flow, ultrasound is back scattered by both seeding particles and gas-liquid interfaces. Since the echo signal from gas-liquid interfaces is much stronger than that from seeding particles, with an appropriate small gain setting for the 2MHz TDX the 2MHz echo signal will contain only signal reflected from bubble surfaces. Therefore, it is assured that the 2MHz signal includes only bubble data. Though, it has been confirmed that measured data of 8MHz channel mostly includes liquid velocity, 8MHz frequency signal always includes bubble data if bubbles cross the 8MHz sound beam. Therefore, bubble data must be eliminated from liquid data to obtain velocity profiles of only liquid. For bubble data elimination, the relation between relative positions of bubbles and ultrasonic beams are all considered including the following cases (Fig.7):

- No bubble detected by both frequencies,
- One bubble crossing 2MHz beam,
- One bubble crossing 8MHz beam.

In pattern a), only liquid velocity profile is measured by 8MHz frequency. There is no bubble velocity (no bubble data) along the measurement line of 2MHz frequency. If one bubble crosses the 2MHz ultrasonic beam, case b), the bubble velocity is measured by 2MHz frequency; the liquid velocity is measured by 8MHz frequency at the same time (without bubble data since a bubble does not cross the 8MHz beam). When the bubble crosses the 8MHz beam, case c), both frequencies will measure bubble velocity. In this case, 8MHz frequency measures both liquid and bubble velocities. However, 8MHz ultrasound is obstructed by the bubble and the echo signal coming from the area behind the bubble must be considered as noise. As a result, the measured velocity behind the bubble needs to be deleted (Fig.7). With the proposed algorithm for phase velocity selection, instantaneous velocity profiles of both liquid and bubble can be measured

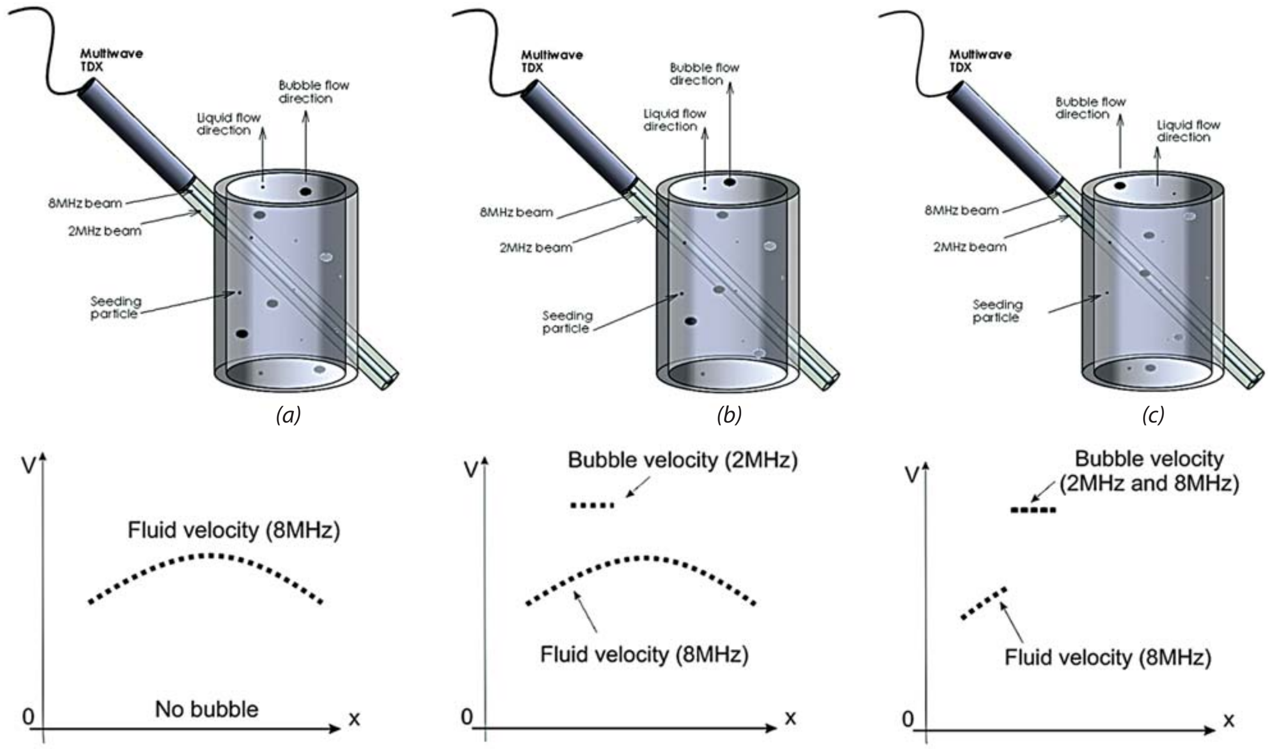


***Fig.7.** Relative positions of a bubble and ultrasound beams (up) and corresponding selection algorithms of valid liquid velocity (down)*

simultaneously along the measurement line. Using this method, relative velocity between bubble and liquid is no longer needed for the phase separation.

3.2. PIV method for bubbly flow

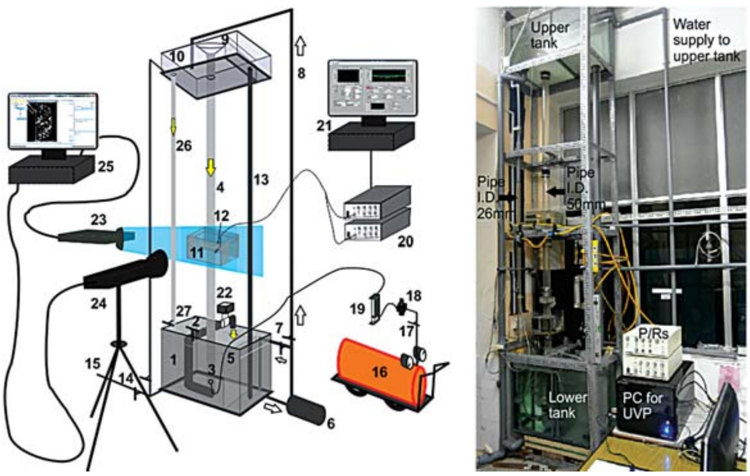
Similar to the application of the UVP method to measurements of bubbly two-phase flows, when PIV is applied to measurement of two-phase flows, light is reflected from both seeding micro particles and phase interfaces. Reflected light from phase interfaces is usually much stronger than that from seeding particles. Therefore the influence of reflected light from phase interfaces on that from seeding particles surrounding the interface is very considerable. This effect makes it extremely difficult to distinguish between areas of fluid and gas surrounding the interface. Generally, the solution to this problem is using fluorescence as seeding particles for fluid phase. Moreover, there are two cameras, each using a specific optical filter corresponding to lights of original wave length and of fluorescence emission. This means that one camera will capture only reflected light with original wave length from phase interfaces. The other camera will capture only light emitted from fluorescence with wavelength changed when fluorescence is exposed to a laser light sheet. As a result, signals from liquid and gas phases are separated completely. Then PIV analysis can be carried out for each phase separately [13].

Due to the limitation of the hardware including optical filters and fluorescence, in our method, we measure gas phase only. Images of bubbly two-phase flow without seeding particles are captured in the same way as in the conventional PIV method. The thickness of the laser light sheet is adjusted to be about the same as the average bubble diameter. This reduces excessive light reflected from gas-liquid interfaces on surrounding areas. By using an appropriate digital image processing algorithm and an appropriate size of interrogation windows, instantaneous velocity field of gas phase can be derived. Using this method, it is possible to confirm bubble velocity calculated by the PIV method directly using bubble images. Statistically, it is possible to confirm measured data of the multi-wave UVP method by using the PIV method for two-phase flow.

4. Single-phase and two-phase flow experimental apparatus

4.1. Experimental apparatus for measurement of single-phase and two-phase flows in vertical pipes

A schematic diagram of the experimental apparatus for measurement of single-phase and/or bubbly two-phase counter-current flows in vertical pipes is shown in Fig.8a. The apparatus is located in the Laboratory for Industrial and Environmental Fluid Dynamics, Institute of Mechanics, Vietnam Academy of Science and Technology (VAST) and is shown in Fig.8b. Where: 1: Floor tank; 2: Water flow rate controlling valve; 3: Bubble generator nozzle; 4: Measurement pipe of I.D. 50mm for single-phase and two-phase flow study; 5: Overflow weir of floor tank; 6: Water circulation pump; 7: Bypass valves; 8: Pipe for water supply to the upper tank; 9: Overflow weir of the upper tank; 10: Upper overflow tank; 11: Water box for housing ultrasonic TDX; 12: Multi-wave TDX (Japan Probe Co. Ltd.); 13: Drainage pipe for overflow water down to floor tank; 14: Water drainage valves; 15: Main water drainage pipe; 16: Air compressor; 17: Main air flow rate controlling valve; 18: Air flow rate regulator system (Cole Parmer Co. Ltd.); 19: Float valve for air flow rate measurement (Tokyo Keiso Co. Ltd.); 20: Pulser/Receiver of the UVP system (JSR Ultrasonics Co. Ltd.); 21: PC which houses ADC (National Instruments) and UVP software etc.; 22: Water flowmeter (Aichi Tokei Denki Co. Ltd.); 23: High power pulsed laser (Dantec Ltd.); 24: Camera (ordinary and high speed); 25: PC for controlling laser, camera, data logger and PIV software (Dantec DynamicStudio), etc; 26: Pipe for single-phase flow study (I.D. 26mm); 27: flow rate control valve of pipe 26.



(a) *(b)*

Fig.8. *Schematic diagram of the experimental apparatus*

(a) *(b)* *(c)*

Fig.9. *Typical two-phase flow regimes observed in the flow loop with 50mm I.D. pipe using a high speed camera (JVC Hybrid Camera GC-PX1, JVC Co. Ltd.) with frame rate 300Hz (a: bubbly flow; b: slug flow; c: annular flow)*

As shown in Fig.8a, there are two test pipes: test pipe 4 with I.D. 50mm, 3m long and test pipe 26 with I.D. 26mm, 2.4m long. Both are made of transparent acrylic that facilitates UVP measurement and optical flow visualisation for the PIV method. Because the ratio of pipe length to pipe I.D. of large test pipe 4 is not enough for fully developed laminar flow, it is used for measurement of fully developed turbulent single-phase flow and two-phase flow. The small test pipe 26 has a higher ratio of pipe length to pipe I.D., it is used for measurement of fully developed laminar and turbulent single-phase flow. Water flow rates in the measurement pipes are controlled using needle-type valves at the outlet of the pipes (Fig.8a). The water tanks have overflow weirs to ensure a constant pressure difference between the two tanks. This experimental apparatus is used for measurement and study of single-phase and bubbly two-phase flows. In the case of bubbly counter-current flow, bubbles generated at the bottom part of the measurement pipe flow upwards. Water flows down from the upper tank to the floor tank solely under the effect of gravity. As a result, a bubbly counter-current flow is formed in the measurement pipe. Moreover, other flow regimes can also be created in the measurement pipe such as slug flow, annular flow, and churn flow etc. as shown in Fig.9. These gas-liquid two-phase flow regimes depend on the correlation between water flow rate and that of gas supplied into the measurement pipe. The main parameters of the experimental apparatus are shown in Table 1.

Water flow rate in the measurement pipes is measured using a high precision turbine flowmeter located at the outlet of the pipe. The multi-wave TDX is attached to the outside of the measurement pipes, and inclined at 45 degree angle to the main flow direction (the vertical direction). For making the same acoustic impedance with that of working fluid in the measurement pipe, a water box is used for housing the TDX. The TDX surface is always submerged in water. Moreover the water box is also used to eliminate the distortion effect caused by the curved wall of the measurement pipe. This is important for optical visualisation, flow observation and for PIV method. For small test pipe 26, TDX can be submerged in the lower tank for measurement. In other parts of the pipe, ultrasonic gel is used instead.

In addition, it is possible to expand this experimental apparatus to cover also upward sin-

***Table 1.** Main parameters of the experimental apparatus of single-phase and bubbly counter-current two-phase flows in a vertical pipe*

Type of flow	Single phase downward (laminar/turbulent) Bubbly counter-current flow (turbulent)
Material of test pipes	Transparent acrylic
Inner/outer diameter of pipe 4	50mm/60mm
Inner/outer diameter of pipe 26	26mm/30mm
Lengths of pipe no. 4/pipe no. 26	3m/2.4m
Range of liquid flow rate/Re of pipe 4	0 - 39.5L/min/0 - 20,000
Air flow rate range (following the available range of the air flowmeter and the capacity of the air supply system)	0 - 6L/min
Measurement, observation location	Along the measurement pipes
Two-phase flow regimes	bubbly/slug/annular…

gle-phase and/or co-current two-phase flows for a wider study of pipe flow.

4.2. Configuration of the UVP and PIV systems

4.2.1. The multi-wave UVP system

Fig.10 shows a schematic diagram of the advanced multi-wave UVP system in the Laboratory for Industrial and Environmental Fluid Dynamics, Institute of Mechanics, VAST.

Main parameters of the multi-wave UVP system are:

- Central frequencies: 8MHz (for liquid); 2MHz (for gas);
- F_{prf} of the P/Rs: 100Hz - 5kHz;
- ADC: 2 channels, maximum sampling rate 100MHz.

UVP software.

4.2.2. The Dantec 3D-PIV system

An advanced Dantec 3D-PIV (stereo PIV) system has been adapted in the same laboratory for multi-purpose, fluid dynamics study. The system has the main features as shown below:

- High power, pulsed laser (Dantec Dynamics: Nd-YAG laser), synchronised with PC and camera;
- Maximum pulse power: 1,200mJ;
- Pulse emission time: 4ns;
- Laser wavelengths: 1,064 and 532nm;
- Cameras: high resolution 2,048 x 2,048, 8 bit grey scale;
- Maximum frame rate 15Hz;

Full, digital image processing software and 2D/3D-PIV softwares Dantec DynamicStudio.

4.3. Experimental conditions

Measurements were carried out in atmospheric pressure, at room temperature. The multi-wave TDX was fixed at an inclined angle of 45 degrees to the main flow direction using a TDX holder. The thickness of pipe wall at the measurement locations was 1mm. Nylon powder (WS-200P, Daicel-Evonic, Ltd.) with average diameter of 80μm and density of 1.02g/cm^3 was used as ultrasonic scatterers for measurement of liquid velocity and for PIV particle image. Measurement conditions are shown in Table 2 and 3.

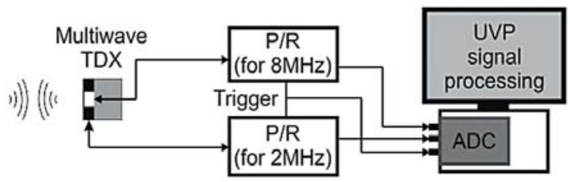


***Fig.10.** Schematic configuration of the multi-wave UVP system for measurement of single-phase and two-phase flows*

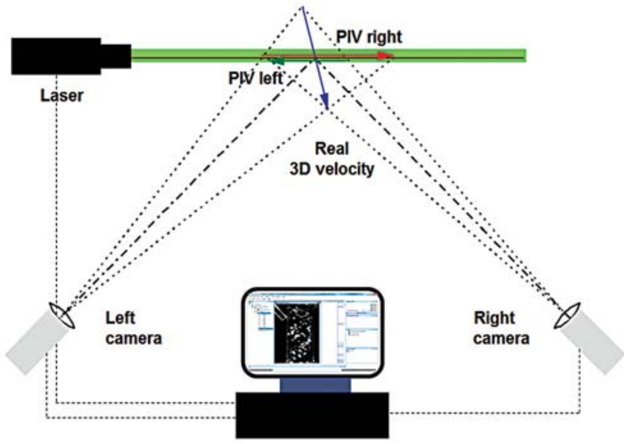


***Fig.11.** Schematic diagram of the Dantec 3D-PIV*

5. Measurement results

5.1. Measurements of single-phase flows

Fig.12 shows the arrangement of the multi-wave TDX and the pipe flow under measurement.

The TDX is inclined at a 45 degree angle to the flow direction. Only 8MHz ultrasonic frequency is used for the measurement of liquid velocity in the pipe. The spatial resolution in the sound path direction is 0.74mm which corresponds to a resolution of 0.523mm in the traverse direction which is perpendicular to the flow direction. For single-phase flow, only 8 MHz element of the multi-wave TDX is used. Measured results using only UVP method for fully developed laminar flow in the small diameter test pipe 26 are shown in Fig.13a.

Reynolds number in this case is around 1,400. As shown in Fig.13a, the measured result agrees well with the analytical solution of parabolic profile of laminar pipe flow. However, close to the wall, velocities at some measurement channels are lower estimated by the UVP method as compared with the parabolic velocity profile of the exact solution. The same situation happened with measurement of turbulent pipe flow using the UVP method (Fig.13b). This is due to the effect of the measurement volume size of the UVP method [14]. Close to the wall, some measurement volumes comes in contact with the pipe wall. They include fixed part of pipe wall and outside liquid. This decreases the measured velocity in such volumes.

For measurement of fully developed turbulent pipe flow, either pipe, pipe 4 or pipe 26 could be used. In this study, the larger diameter pipe 4 was used. Measurements have been carried out using both UVP and PIV methods. Measured results are shown in Fig.13b. It can be seen that the UVP result in this case also shows the wall effect while the PIV result is better close to the wall. In addition, a typical particle image and a velocity field calculated by the PIV method are shown in Fig.14.

Table 2. *Measurement conditions for single-phase flow*

Pipe I.D. Re number	Pipe 26 mm I.D.	Pipe 50 mm I.D.
Re = 1,400 (fully developed laminar flow)	*L/D* = 53 Measured results compared with analytical solution of parabolic velocity profile	
Re = 8,100 (fully developed turbulent flow)		*L/D* = 46 Measured results verified using PIV data

Table 3. *Measurement conditions for bubbly counter-current two-phase flow*

Liquid superficial velocity	129mm/s
Gas superficial velocity	0.68mm/s
Liquid inlet length/*D*; Gas inlet length/*D*	46; 15
Average bubble size	4 - 5mm
Results	Measured data confirmed by PIV method

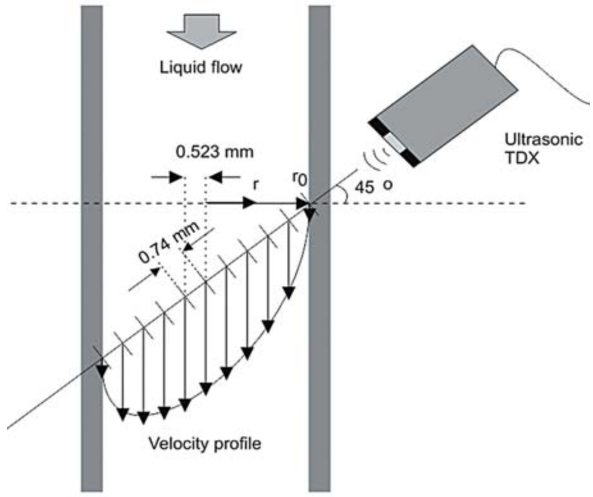


Fig.12. *Arrangement of the ultrasonic TDX and pipe flow under measurement*

5.2. Measurement of bubbly counter-current flow

In this case, liquid flows downward whereas bubbles rise upward (Fig.15). Two ultrasonic frequencies were used for the measurement. An 8MHz frequency (beam diameter 3mm) was used for liquid velocity measurement. 2 MHz frequency (beam diameter 10mm) was used for bubble measurement. The arrangement of the multi-wave TDX and the two-phase flow in the pipe is shown in Fig.15. A typical bubble image of the flow which has been measured is presented in Fig.16. The image was captured using a high speed camera (JVC Hybrid Camera GC-PX1, JVC Co. Ltd.) with frame rate 300Hz.

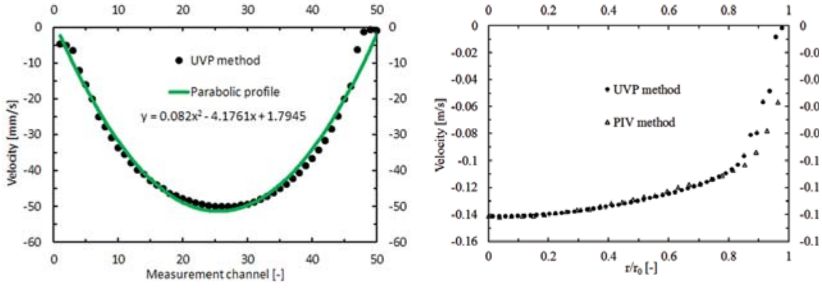
In this case, measurements have been carried out using both the UVP method (for both phases at the same time) and the PIV method (for the gas phase only, i.e. without seeding particles). Using the multi-wave UVP method, simultaneous measurements of both liquid velocity and gas velocity have been conducted. Instantaneous velocity profiles of both liquid phase and gas phase have been obtained. Using instantaneous values, average velocity profiles of separated liquid phase and gas phase are shown in Fig.17a. Measured results of the UVP method and the PIV method for the gas phase are shown in Fig.17b.

5.3. Accurate measurement of liquid flow rate, deposition, crystalisation and corrosion etc. in piping systems

In industrial piping systems, it is usually desirable to have highly accurate methods for flow rate measurement at various flow regimes (stationary state, transition state, non-fully developed etc.). Conventional measurement methods are either intrusive or need some assumption of the shape of velocity distribution, e.g. stationary and axisymmetric velocity profile etc. As a result, when the flow regime changes, the accuracy of the measurement cannot be confirmed. Using the measured velocity of the liquid phase in either single-phase flow or two-phase flow, it is possible to calculate the liquid flow rate with high accuracy by integration of liquid flux across the section of the pipe (Fig.18).

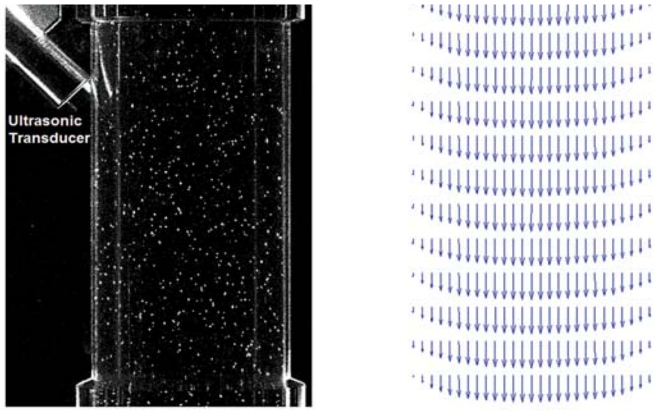
Using a measured velocity profile, the flow rate can be calculated using a simple equation $Q = \sum_{i=0}^{n} S_i V_i$ where S_n is the area of the measurement channel on the cross-section of the pipe; V_n is the time averaged velocity at the measurement channel. Using this method, there is no need of any assumptions concerning the shape of the velocity profile. Moreover, when more than one TDX are used for the measurement of the velocity profiles at a cross section, the effect of non-axisymmetric velocity distribution can be minimised. This is very helpful in measurement of the flow rate in piping systems with limited length of pipes. In such cases, junctions and bendings will make flows in pipes of short length highly unstable. Velocity profiles are highly non-axisymmetric. Other measurement methods of liquid flow rate will seriously suffer from such effects.

In addition, using the ultrasonic velocity profile method, measurement of deposition on the pipe wall is enabled. The echo signal captured during measurement clearly exhibits the part of the immobile pipe wall and the part of flowing liquid. Hence, the change in deposition on the pipe wall is monitored and measured directly. At the same time, corrosion of the pipe wall is measured. On the other hand,



(a) (b)

Fig.13. *Measurement of single-phase flow: (a) fully developed laminar flow (Re=1400); (b) fully developed turbulent flow (Re = 8100)*



(a) (b)

Fig.14. *A typical particle image of single-phase flow (a) and 2D velocity field calculated by PIV method (b)*

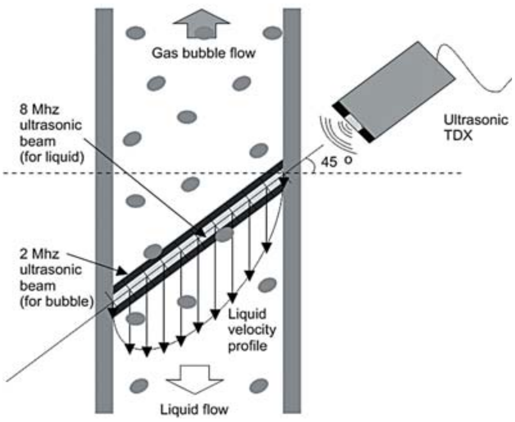


Fig.15. *Arrangement of the multi-wave TDX and the two-phase flow in the pipe*

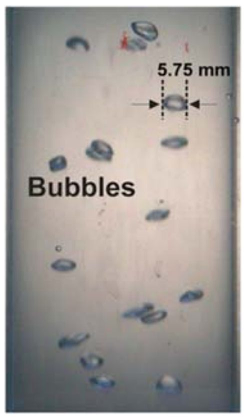
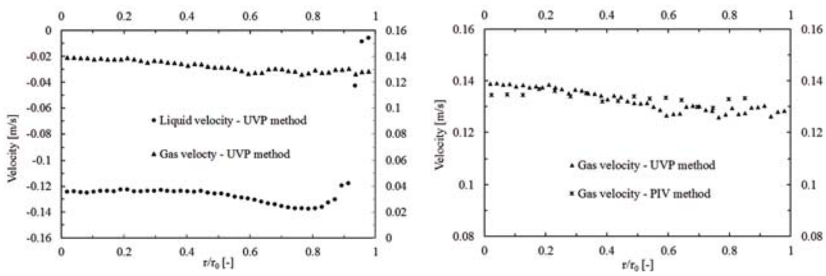


Fig.16. *A typical bubble image by high speed camera*



(a) (b)

Fig.17. *Measurement of two-phase flow: (a) liquid and gas velocity profile measured by UVP method; (b) gas velocity profile measured by UVP and PIV methods*

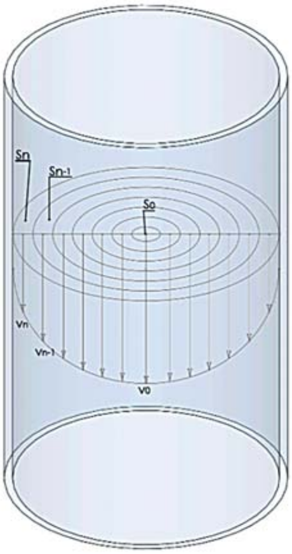


Fig.18. *Velocity distribution in pipe flow*

the intensity of echo sound is a function of the purity of the working liquid. Based on this idea, crystallisation of materials in flowing liquid can be measured.

6. Conclusions

The multi-wave UVP and PIV methods for measurement of single-phase and two-phase flow in a vertical pipe have been developed. Measured results using the multi-wave UVP method have been confirmed by the optical image processing method (PIV). It has been shown that this method has many advantages and robustness for single-phase and two-phase flow measurement.

Instantaneous velocity profiles of both single-phase and two-phase flows in a vertical pipe have been measured using the multi-wave UVP method. Measured results of single-phase flow agree well with mean velocity profiles of pipe flow. Based on measured velocity profiles of liquid phase and gas phase, other flow parameters can be derived. In addition, using instantaneous velocity profiles of the liquid phase, it is possible to calculate liquid flow rate with high accuracy.

Further research on various pipe flows in the oil and gas industry and in the energy industry using ultrasound will be carried out.

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