Measurement of Bubbly Two-Phase Flow in a Vertical Pipe Using Ultrasonic Velocity Profiler and Digital Optical Imaging

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ABSTRACT

In this study, a novel measurement framework for two-phase air-water bubbly flow has been developed. It consists of ultrasonic and digital optical imaging systems. The measured parameters include instantaneous velocity profiles of the two phases, void fraction and bubble size of the gas phase. The simultaneous velocity profiles of both phases are measured by the state-of-the-art multiwave Ultrasonic Velocity Profile method - multiwave UVP for short. The void fraction and bubble size are measured by a digital imaging system that exploits high-speed video imaging. Non-intrusive measurement of these instantaneous flow parameters is still a challenge in two-phase flow study. In the present investigation, two ultrasonic signal processing algorithms have been implemented and tested, namely Doppler signal processing and correlation one. Similarly, rigorous digital image processing algorithms implemented in ImageJ tool have been exploited and tested to obtain the average void fraction and bubble size distribution. Furthermore, measurements and analyses have been carried out for various flow conditions. For the particular flow configuration investigated, important experimental data of the two-phase counter-current bubbly flow have been successfully obtained for the first time. The measured data are useful for both experimental and numerical analyses, especially computational fluid dynamics - CFD analyses, of two-phase flows.

1. INTRODUCTION

Two-phase flow is encountered in many industrial and engineering processes. Some typical examples are nuclear power plants, chemical plants, oil-gas production systems etc. It typically plays a vital role in the operation of the systems since its existence critically alters the flow physics. Thus, for the optimal design of any particular component and/or the whole systems as well as for the proper and safe operation of such systems or processes, thoroughly understanding the behaviors of the two-phase flow is substantially required. Important parameters that govern the behaviors of two-phase flow include instantaneous velocity distribution of liquid and bubbles, bubble size distribution, distribution of local and average void fraction etc. Study on two-phase flow has been extensively carried out for the past several decades. However, due to the complex nature of two-phase flows, the behaviors of the flow parameters have not yet been fully understood. The demand for detailed experimental and numerical data of two-phase flows is tremendous [1].

In order to obtain local and average parameters of two-phase flow, numerical simulation and/or experimental measurement can be used. Numerical simulation is based on an approximate solution of the governing equations of two-phase mixtures or of each phase. Due to the limit of the present computational resources, it is still difficult to obtain high-resolution numerical simulations of two-phase flows. Thus, many approximations and simplifications must have been adopted in the solution method. Thus, the accuracy of the

numerical simulation must be carefully investigated. For exact observation of two-phase flow, experimental measurement is required. Moreover, measured data can also be used not only for the validation of the numerical simulation but also for the boundary data required in numerical models. As a result, measurement techniques have been developed in order to obtain the parameters of two-phase flow. Generally, measurement methods can be classified into two types which are intrusive methods and non-intrusive ones. Intrusive methods involve the insertion of the measuring probes into the flow field. Typical examples are the hot wire methods, the electrical conductivity methods etc. As mentioned before, the intrusive effects of these methods must be carefully considered. On the other hand, non-intrusive methods have also been devised for the measurement of two-phase flow. The X-ray or Gamma-ray methods, the laser Doppler method and the PIV method are some widely-used nonintrusive methods [2]. They are always desirable since intrusive effects can be eliminated.

Recently, an advanced measurement method that uses ultrasound to measure the instantaneous velocity profiles of fluid flow has been developed [3, 4]. The method is referred to as the ultrasonic velocity profiling method or the UVP method. It is a non-contact measurement method in which there is no need for the ultrasonic transducer or the TDX to touch the flow field. Using ultrasound, measurement can be carried out even with opaque fluid. There is no need for any optical windows. The measurement system is compact and portable, which can typically be designed to be clamp-on. Since the TDX does not come in contact with the flow field,

measurement can be carried out from outside of the flow. As a result, the aging problems caused by the direct contact between the TDX and the fluid flow can be eliminated. Measurement of flows working at extreme industrial conditions could be possible [5].

Using two ultrasonic frequencies, each works independently (but is synchronized with the other) based on its own signal processing of the UVP method, simultaneous measurement of the two phases in two-phase flows is enabled. Based on this idea, a multiwave UVP method has been developed [6]. In this method, 8 MHz ultrasonic frequency is used to measure liquid velocity profile; 2 MHz frequency is used to measure bubble velocity profiles. Measurement of liquid and bubble phases can be carried out at the same time and position along the measurement line which is the ultrasound path. The multiwave UVP method is used in this study to measure the bubbly counter-current two-phase flow in a vertical pipe of 50 mm inner diameter.

For the bubble phase, besides instantaneous velocity profiles of bubbles, other parameters such as void fraction (which is the fraction of the gas phase in the total flow volume), bubble size etc. play a critically important role both in theoretical study of two-phase flow and in state-of-the-art CFD-Computational Fluid Dynamics models. The local and average interfacial area concentration which is one of the most important parameters in the modelling of two-phase flows can be calculated by using void fraction and bubble size [7, 8]. In order to measure these parameters, optical visualization which is also a non-intrusive method is one of the widely used measurement methods besides other intrusive methods such as local optical probe, hotwire probe etc. In this study, a digital optical imaging system with a high-speed video camera (300 frames per second-fps) has been set up to capture high-quality bubble images. Noise has been removed from images and image quality is enhanced by image enhancement algorithms that have been extensively investigated, tested and selected for the images of the particular flow conditions and experimental conditions of this study. Then the size and shape of individual bubbles are calculated and tracked by segmentation algorithms. The suitable flow condition for this image analysis process should have as little as possible bubble overlapping in the flow images. Thus, based on those digital image processing algorithms, the bubble size distribution and averaged void fraction can be obtained.

Experimental measurement of instantaneous velocity profiles and of bubble data in two-phase flow study still encounters considerable difficulty. Particularly, for the specific flow conditions of this study, measured data are absent in the published literature. The objectives of this study are to set up and investigate a novel two-phase flow measurement framework; to test different signal/data processing algorithms (frequency-domain algorithms and time-domain ones), for particular flow conditions of bubbly counter-current vertical flow; to develop a robust measurement procedure for two-phase air-water bubbly flow in a vertical round tube; and to demonstrate measurement of instantaneous local parameters of two-phase air-water bubbly flow. The obtained results will give insights into the measurements of the particular two-phase flow configurations of this study. The received data can support numerical simulation using advanced two-phase flow CFD models.

The paper is structured as follows. Section 1 is the introduction to the present research. Section 2 outlines the principles of the measurement methods. Section 3 presents the experimental apparatus and the two-phase flow conditions. Section 4 shows the measured data and discussions. Section 5 lists the main conclusions obtained from this study.

2. MEASUREMENT METHODS

2.1 Principle of UVP and multiwave UVP methods

The principle of the conventional UVP method is shown in Figure 1 (a). The velocity of moving seeding particles in the flow field is calculated based on the Doppler effect. In the UVP method, the ultrasonic TDX emits a series of ultrasonic pulses into the flow field at a pulse repetition frequency F_{prf}. After the emission of each pulse, the TDX immediately switches to the receiving mode. Hence, the echo signal from all depths starting from the TDX surface forwards is captured. The maximum depth for the reception of the echo signal corresponds to the maximum time which is set for the receiving mode of the pulser/receiver (P/R) before the next pulse is emitted. As shown in Figure 1, when $t_{sample-n}$ varies, the positions where the fluid velocity is calculated along a velocity profile are specified. And, the echo signal corresponding to each position is acquired from the whole echo data. The Doppler shift frequency f_d of each position is obtained by processing the digital echo signal at each position. Thus, the fluid velocity at these positions is calculated. Hence velocity profiles of fluid flows are obtained.
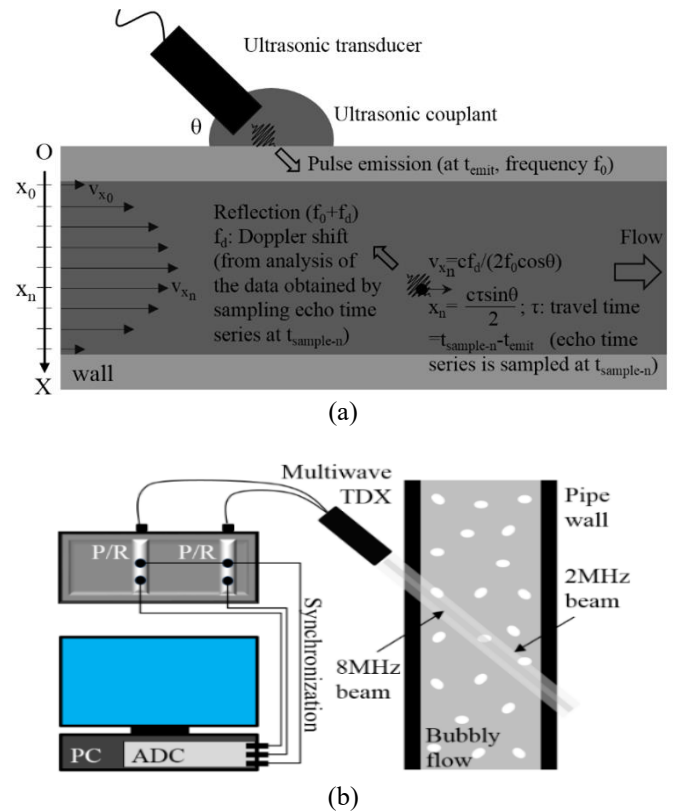

(a)

(b)

Figure 1. The principle of: (a) the UVP method; (b) the multiwave UVP method
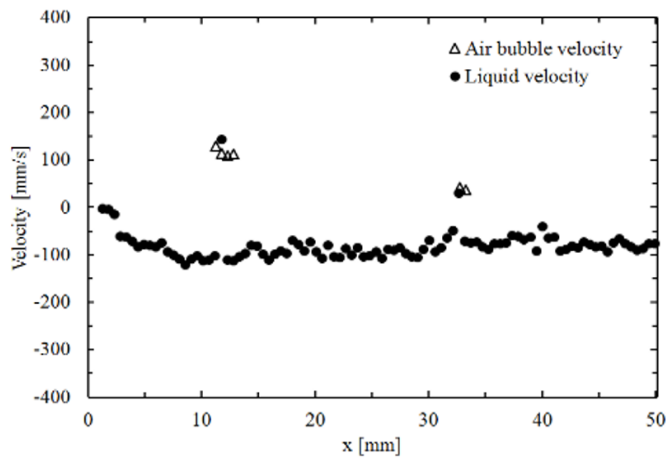
Two well-known signal processing algorithms are widely used to calculate f_d. These are Fourier transform-based signal processing that works in the frequency domain and correlation-based signal processing that works in the time domain. These algorithms are implemented in our multiwave

UVP system. The behavior of the two algorithms when they are applied to the measurement of two-phase air-water bubbly flow in this study is also evaluated.
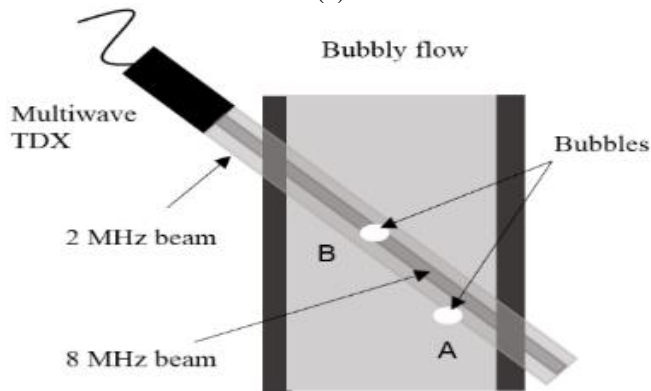
When the conventional UVP method for single phase flow measurement is applied to two-phase air-water bubbly flow, ultrasound is not only reflected from seeding particles-ultrasound reflectors but also gets reflected strongly from the bubble-liquid interface. Hence the measured velocity includes the velocity of bubbles as well when bubbles cross the ultrasonic beam. Thus, if we use two ultrasonic frequencies, it is possible to measure separately velocity profiles of each phase. There comes the idea of multiwave UVP method for two-phase flow measurement.

The multiwave UVP method exploits two ultrasonic frequencies [9]. In order to do so, a mutliwave TDX has been developed. The sensor is able to emit and receive two ultrasonic frequencies at the same time and position as shown in Figure 1 (b). The 2 MHz component has a diameter of 10 mm. It has a cylindrical and hollow shape. This sensor is used to measure the bubble phase. The sensor of the 8 MHz frequency has a diameter of 3 mm. This sensor fits in the hollow of the 2 MHz sensor and is exploited to measure the liquid phase. Each sensor is excited and controlled by one independent P/R to emit and receive the ultrasound. The P/Rs are connected with a two-channel data acquisition unit-ADC. The P/Rs and ADC are synchronized as depicted in Figure 1 (b). Received data of each channel is analyzed using the quadrature detection algorithm [6].

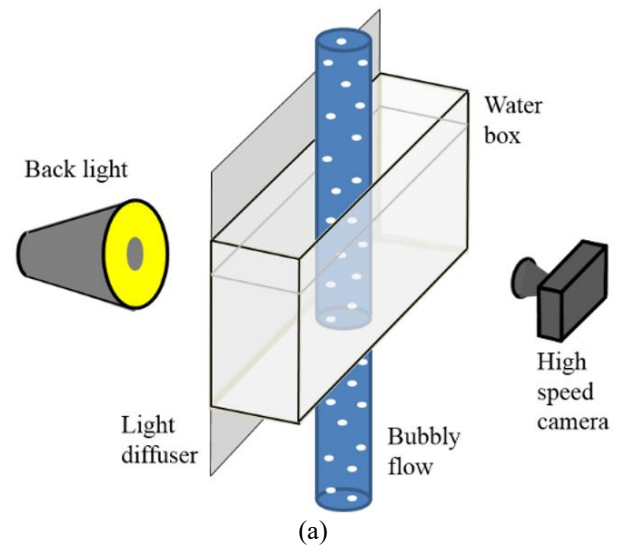## 2.2 Phase separation in multiwave UVP method

(a)

(b)

Figure 2. Instantaneous velocity profiles showing: (a) bubble data included in 8MHz data; (b) relative positions of bubbles and the ultrasonic beams
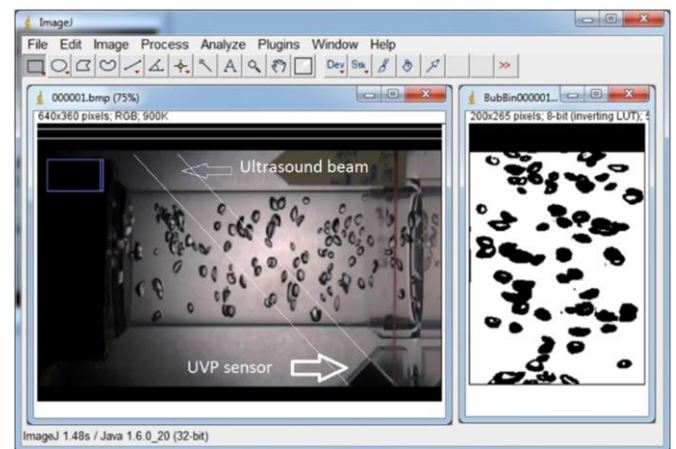
However, an inherent issue of phase separation in two-phase flow measurement must be considered. Similar to the applications of some other measurement methods, such as LDA-Laser Doppler Anemometry, PIV-Particle Imaging Velocimetry methods etc., to the measurement of two-phase flow, the measured data of the liquid phase includes some data of the bubble phase as well. In the multiwave UVP method, it is the inclusion of the velocity of some bubbles in the measured data of the liquid phase by the 8 MHz frequency. In the multiwave UVP method, the 2 MHz frequency can be set to measure only bubble velocity. Phase separation is not needed for the 2 MHz frequency. For the 8 MHz frequency, the problem is schematically shown in Figure 2 (a). A phase separation technique is required to eliminate the bubble velocity from the measured data, Figure 2 (b) [6].

As shown in Figure 2 (b), bubbles will be detected if they appear along the 2 MHz sound path. Using the detected information, the corresponding data of the bubbles included in the 8 MHz frequency is eliminated. Thus, instantaneous velocity profiles of each phase can be measured separately. It is worth noting that, presently, the phase separation is a post-processing procedure that is applied to the stored measured data of each frequency.

2.3 High-speed digital optical imaging and background subtraction

(a)

(b)

Figure 3. (a) high-speed optical imaging; (b) digital image processing implemented in ImageJ

Shadow images of the bubbly flow are obtained using a high-speed video camera JVC video camera (JVC Hybrid Camera GC-PX1, JVC Co. Ltd.), which is capable of filming the flow images at maximum frame rate 300 fps. At this speed, and with the flow configuration investigated, the effects of the bubble motion in the recorded flow images can be neglected. Visually, it means that negligible bubble streak can be assumed. The arrangement of the light source and the camera is schematically described in Figure 3 (a). A water box is used to eliminate the distortion of the bubble images which is caused by the round shape of the pipe wall. As shown in the bubble image on the left of Figure 3 (b), images with highly contrasted bubbles have been successfully obtained. Note that, for ease of presentation, the photo has been rotated 90 degrees clockwise. In addition, in Figure 3 (b), the position of the multiwave UVP sensor is noted. The location of UVP measurement and that of optical visualization is at the same position along the vertical direction of the flow. The results of optical visualization of the bubble phase in two-phase flow have been extensively investigated in detail previously and confirmed theoretically and experimentally [10, 11].

In each optical visualization, one image of the background flow, i.e., the single phase liquid flow without air bubbles, was taken. Before further digital image processing of the bubble images, preliminary processing of the flow images is carried out, such as background subtraction, region of interest-ROI extraction etc. The image on the right of Figure 3 (b) shows only bubbles in the ROI which is limited to the flow field. Note that the processed image on the right of Figure 3 (b) has been rotated back 90 degrees counter-clockwise to show the vertically upward flow of air bubbles. The macro feature of ImageJ facilitates automatic processing of a large number of images efficiently. During this process, the scale of the images which means the ratio of the number of the pixels (corresponding to the known size of some real object in the image) to the size of the object (usually in mm) is also set. The real size of the objects, i.e., bubbles in this study, detected in the following analyses is calculated using this scale.

2.4 Bubble image analysis algorithm

The objective of digital image processing algorithm in this section is to accurately detect or segment bubbles in bubble images. An example of the resulted image is shown in the right image of Figure 3 (b). For this purpose, widely-used straightforward yet robust thresholding algorithms implemented in the digital image processing tool ImageJ, NIH, USA have been used. The macro is in the form of function calls-scripts in ImageJ macro. To increase the accuracy of the bubble boundary recognition, the threshold for the separation between bubbles and background is carefully selected either based on the image of a known-size object submerged in the flow field or based on automatic thresholding algorithms. As the result, the accuracy of the detection of bubble boundary can be sufficiently high.

In addition, some other image processing algorithms are exploited to improve the quality of the bubble recognition such as hole filling, edge detection etc. [12]. One option is to use the Analyze Particles function of ImageJ which combines the above-mentioned algorithms with adjustable parameters. It is also possible to put a function call to Analyze Particles in an ImageJ macro to facilitate a batch processing of a large number of images. Consequently, individual bubbles are isolated from the bubble images and hence their parameters

are available and output to a text file for next analyses. Basically, this is just 2D information.

In the case of bubbly flow, based on theoretical and experimental analyses, the bubble shape can be adequately assumed to have some particular 3D shape, e.g., ellipsoid. Therefore, the bubble surface area which is directly related to the interfacial area concentration in two-phase flow can be obtained. In the same way, the bubble volume, and hence the void fraction of the flow field, can be well calculated accordingly. The surface area of bubbles and void fraction are instantaneous two-phase flow parameters which are of considerable importance in both theoretical and numerical analysis of two-phase flow.

It is worth noting that the limitation of optical visualization and of digital image processing algorithms is that the digital optical imaging method should only be suitable for two-phase flow configurations where we can avoid overlapping of bubbles in the recorded 2D images. Typically, these are low void-fraction bubbly flows, or flows with big isolated bubbles [13-15].

Below is the outline of the ImageJ macro used in this study:

Table 1. ImageJ macro for the digital optical imaging analysis

No.	ImageJ Script
1	dir1=getDirectory ("Choose source directory:");
2	dir2=getDirectory ("Choose background image directory:");
3	dirROI=getDirectory ("Choose ROI window directory:");
4	dir3=getDirectory ("Choose result directory:");
5	list1=getFileList (dir1);
6	list2=getFileList (dir2);
7	listROI=getFileList (dirROI);
8	setBatchMode (true);
9	for (i=0; i<list1.length; i ++) {
10	showProgress (i+1, list1.length);
11	open (dir2+list2[0]);
12	run ("Set Scale...", "distance=201 known=50 pixel=1 unit=mm");
13	open(dir1+list1 [i]);
14	run ("Set Scale...", "distance=201 known=50 pixel=1 unit=mm");
15	imageCalculator ("Difference", list1 [i], list2 [0]);
16	selectWindow (list2[0]);
17	close ();
18	selectWindow (list1 [i]);
19	open (dirROI+listROI [0]);
20	run ("Set Scale...", "distance=201 known=50 pixel=1 unit=mm");
21	run ("Crop");
22	run ("Invert");
23	run ("8-bit");
24	run ("Rotate 90 Degrees Left");
25	setAutoThreshold ("MaxEntropy");
26	setThreshold (0, 225);
27	setOption ("BlackBackground", false);
28	run ("Convert to Mask");
29	selectWindow (list1 [i]);
30	run ("Analyze Particles...", "size=6-30 circularity=0.6-1.0 show=Outlines display include summarize");
31	selectWindow (list1 [i]);
32	run ("Make Binary");
33	saveAs ("BMP", dir3+"BubBin"+list1 [i]);
34	close ();
35	selectWindow ("Drawing of "+list1 [i]);
36	saveAs ("BMP", dir3+"BubOutline"+list1 [i]);
37	close ();
38	if (i=list1.length-1) {
39	selectWindow ("Summary");

```
40        dotIndex=lastIndex Of (list1 [i], ".");
41        if (dotIndex!=-1)
42          path=substring (list1 [i], 0, dotIndex);
43        saveAs ("Results", dir3+"Summary"+path+".txt");
44        selectWindow ("Results");
45        saveAs ("Results", dir3+"Results"+path+".txt");
46      }
47   }
48   run ("Close");
```

As shown in Table 1, typical tasks in digital image processing process include:

Batch processing via a for loop-line 9

Background subtraction-line 15

Bubble detection-line 30

Interested readers can find details about these algorithms in ImageJ documentation [13-15].

2.5 Advantages and limitations of the measurement methods exploited

Main advantages of the two measurement methods used in this study can be outlined below. Both methods are non-intrusive, which is critically important in both theoretical study and practical applications. Non-intrusiveness eliminates any possible effects of the measuring probes on the two-phase flow field which is potentially highly affected by the existence of any inserted objects. In practical applications, it is of considerable difficulty to insert measuring probes in any working systems, especially in industrially extreme conditions. Furthermore, both methods can provide spatially-distributed data which is of significant importance in study of fluid flow in general, and of two-phase flow in particular.

Presently, major limitations of the UVP method can appear when the method is applied in practical situations, such as measurement of existing flow systems etc. The reason is that UVP method requires ultrasonic reflectors in the flow field. In working flow systems in practice, ultrasonic reflectors in the fluid flow might be lacking. This problem can be solved by generating cavitation bubbles with the use of a non-intrusive ultrasonic generator [16]. In this technique, careful investigation needs to be carried out regarding the effects of the appearance of cavitation bubbles on the flow characteristics/parameters. Besides, obviously, the digital optical imaging requires an optical window and transparent working fluid in order to capture the flow image. In some practical flow systems, satisfying this requirement might also be difficult.

3. EXPERIMENTAL APPARATUS AND TWO-PHASE FLOW CONFIGURATION

3.1 Experimental flow loop

A test flow loop has been set up as schematically shown in Figure 4 where 1: floor tank; 2: water flow-rate controlling valve; 3: bubble generator; 4: test pipe of 50 mm I.D. and made of transparent acrylic material; 5, 9: overflow weirs; 6: water pump; 7: bypass valves; 8: pipe for water supply to the upper tank; 10: upper tank; 11: water box; 12: multi-wave TDX (Japan Probe Co. Ltd.); 13, 15: drainage pipes; 14: water drainage valves; 16: air compressor; 17: air flow-rate controlling valve; 18: air flow-rate regulator (Cole Parmer Co. Ltd.); 19: float valve for air flow-rate measurement (Tokyo Keiso Co. Ltd.); 20: P/R (JSR Ultrasonics Co. Ltd.); 21: PC, ADC (National Instrument Co. Ltd.) and signal processing software etc.; 22: water flow-meter (Aichi Tokei Co. Ltd.); 24: High speed camera; 25: Light source; 26: PC for image acquisition and processing. Various two-phase flow regimes including bubbly flow, slug flow, annular flow etc. can be generated in the loop.

Though the bubbly counter-current flow that can be generated in the flow loop can be useful in theoretical study of two-phase flow, and can exist in some practical situations such as in one of the cooling modes in many power-generation facilities, bubbly co-current flow can be of highly significant importance as well. In these systems, the cooling water is pumped upward in cooling pipes/towers. At the same time, generated vapor bubbles also rise upward in the water flow. Hence a co-current bubbly flow usually exists in these flow systems. However, at present state, the flow loop has not yet been fully instrumented to be able to generate both bubbly counter-current and co-current flows in the test pipe. The extension of the flow loop has been fully planned but obviously needs further installation effort.
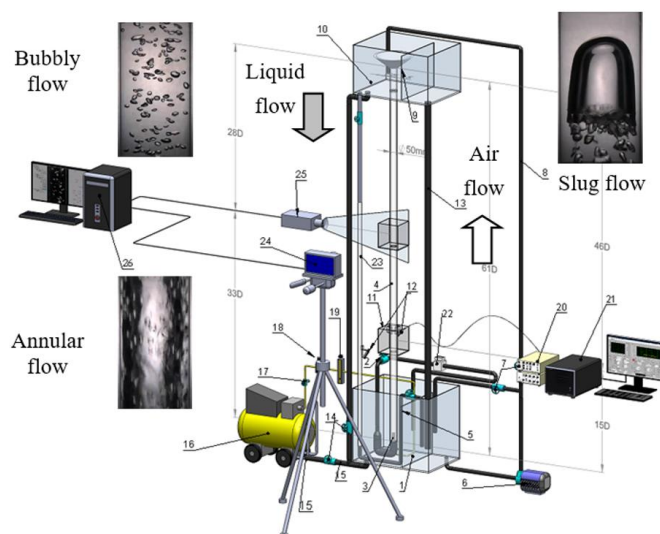

Figure 4. Experimental flow loop

3.2 Flow configuration and experimental settings

Bubbly counter-current flow in the test pipe (see Figure 4) has been measured at the fully developed regime and with varied liquid and gas superficial velocities. Liquid flows downward meanwhile bubbles rise upwards. Nylon power of 80 μm average diameter is used as ultrasonic reflectors for the UVP measurement of the liquid phase. Measurements are carried out for the flow conditions and measurement setups shown in Tables 2-4. For each measurement, 10,000 instantaneous velocity profiles of each phase are obtained. At the same time, the flow field is imaged and recorded.

Table 2. Experimental conditions

Flow Conditions	Value
System pressure	Atmosphere
Temperature	~30°C
Liquid superficial velocity	40-132 mm/s
Air superficial velocity	0.2-8 mm/s
Bubble size	3-5 mm

Table 3. UVP measurement settings

Setting Parameters	Value
Spatial resolution	0.74 mm
Temporal resolution	4 ms
Sound speed	1480 m/s
Number of profiles	10,000

Table 4. Digital optical imaging settings

Setting Parameters	Value
Image size	640×360
Image resolution	0.25 mm/pixel
Sampling speed	300 fps

3.3 Measurement calibration and measurement error

The components of the measurement systems have always been fully calibrated before measurements so they work properly as expected. This can be fully evaluated by checking the received data. Regarding the UVP system, the center frequencies of the multiwave UVP sensor are always confirmed to be 2 MHz and 8 MHz. As for the digital optical imaging system, the received digital images are always confirmed to be proper (i.e., no distortion) and of high quality in normal lighting condition. In order to evaluate the accuracy of the measured results, analysis of the measurement error has been carried out as follows.

Evaluation of the measurement error involves the calculations of the error of UVP measurement and that of digital optical imaging measurement. Though the two methods are applied at the same time and at the same measurement position, their non-intrusive nature helps ease the evaluation of measurement error because they do not interfere with each other and can be estimated independently.

When the measurement systems are properly setup and the measurement conditions are in the typical laboratory ambience, the error of the UVP measurement for both liquid and bubble phases should be the same as that of previous measurements using the same multiwave UVP system and should be typically in the range less than 1% for liquid phase and less than 10% for bubble phase [17].

As for the error of the digital optical imaging, measurement error depends on the image resolution and the size of the object, i.e., bubbles. It is a well-known fact that if the image resolution is low and the size of the object is small, the measurement error is large. Based on the image resolution and the average bubble size in this study, the maximum optical visualization error is estimated to be about 20% [17].

4. MEASURED RESULTS AND DISCUSSIONS

4.1 Multiwave UVP results

Using the multiwave UVP method, instantaneous velocity profiles of both liquid and bubbles have been measured along the measurement line, i.e., the ultrasound beam which is shown in Figure 3 (b). Two different signal processing algorithms which are the Fourier transform-based algorithm and the correlation-based one have been tested. Theoretically, the correlation-based techniques can be faster since the computation is not as demanding as the Fourier transform-based technique. This is absolutely confirmed by the results of our investigation in this study. Hence, only the results of the

correlation-based technique are presented here. It is worth noting that the Fourier transform-based techniques are of interest when we do analyses in the frequency domain.

Figure 5 (a) shows typical instantaneous velocity profiles of liquid and bubbles along the measurement line at a time instant. These profiles show velocity of both liquid and bubbles. Signal processing ensures that only bubble velocity is measured by 2 MHz frequency as shown in Figure 5 (a). Weak echo signal from seeding particles is eliminated from the received signal of the 2 MHz sensor. However, it is clear that, 8 MHz sensor measured velocity of both liquid and bubbles. Hence here is the area where the proposed phase separation technique plays its role.
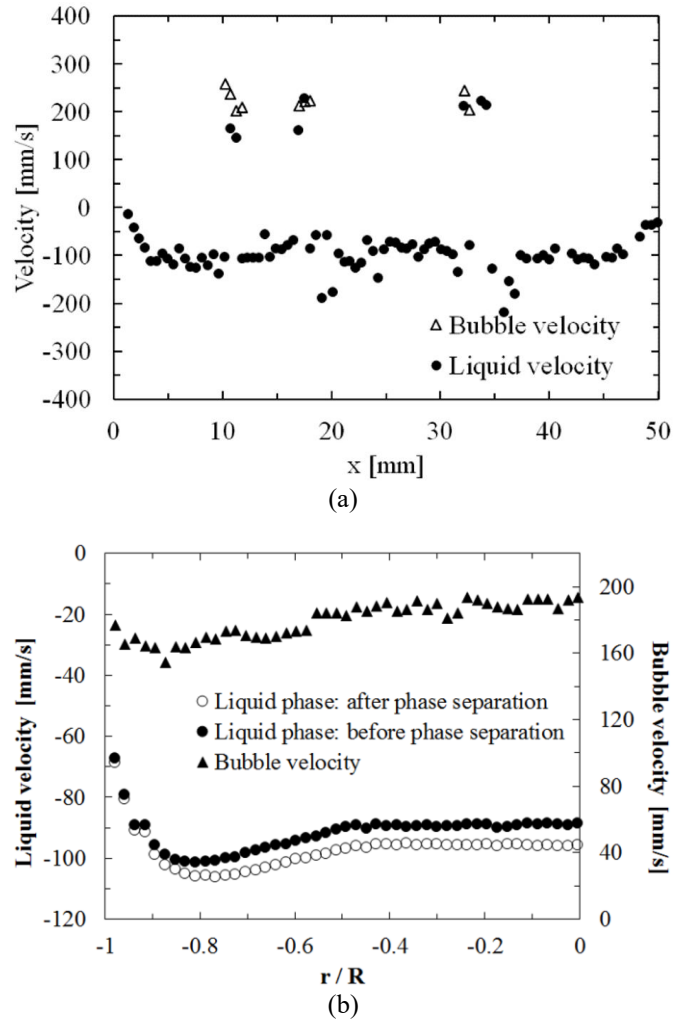

(a)

(b)

Figure 5. (a) instantaneous velocity profiles; (b) average profiles

During post-processing, the phase separation technique has been applied to the measured results of the 8 MHz frequency. to eliminate bubble data from measured data of liquid phase. After phase separation, the instantaneous velocity profiles of each phase are obtained. These data are important in both theoretical and experimental analyses of two-phase flow, e.g., for the calculation of the drift velocity which is the velocity difference between the two phases at a point in the flow field. The drift velocity plays an essential role in the Drift-flux CFD model [1, 3].

Besides instantaneous measured results, average velocity profiles of liquid phase (after phase separation) and bubble phase are shown in Figure 5 (b). Since, on average, the flow is

statistically axis-symmetric, Figure 5 (b) shows only one-half of the averaged profiles.

4.2 Digital optical imaging and image processing

Figure 3 shows typical images before and after processing using ImageJ. It is confirmed that all bubbles are detected after this processing.

As shown in Figure 6 (c), all bubbles in the bubble image can be detected and located. The instantaneous bubble shape can be well approximated as ellipses in 2D. As a result, instantaneous spatial-averaged void fraction can be estimated based on the number of bubbles and the bubble sizes detected. The time data of the estimated void fraction which is a highly important parameter of two-phase flow is shown in Figure 7 (a). Thus, the time-averaged void fraction of this flow condition can be calculated to be around 3.4%.
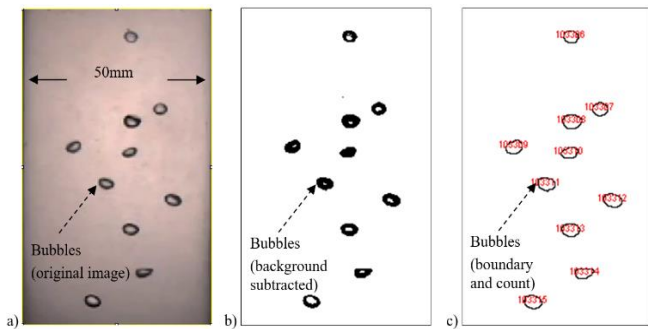

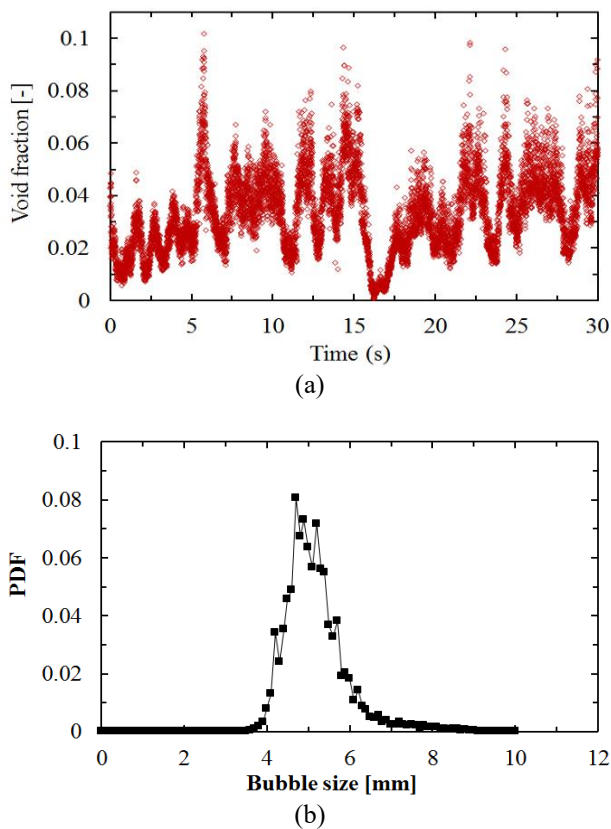**Figure 6.** Digital image processing with ImageJ

Figure 7. (a) spatial average of instantaneous void fraction at the measurement position; (b) PDF-probability density function of the bubble size

Based on the analyzed result of the bubble size, the probability density function-PDF of the bubble size distribution can be calculated. For this flow condition, the PDF of bubble size is shown in Figure 7 (b). The PDF exhibits that the bubble size of this flow condition is from about 4 to 7 mm. The average value is about 5 mm.

Such measured results by the optical visualization combined with those of the multiwave UVP method are highly useful for theoretical study of two-phase flows as well as for numerical simulations of two-phase flows using CFD codes.

It would be worth mentioning that the two measurement methods used in the above measurement would work well when the void fraction of the flow is relatively low. Regarding the UVP method, when the void fraction increases, there are a large number of air bubbles along the measurement line, i.e., the sound path. The bubbles might adversely obstruct the sound transmission or severely scatter the echo sound. As for the optical imaging method, obviously, at high void fraction, bubbles overlap in the bubble images. That causes large error in the image processing algorithms.

5. CONCLUSIONS

The experimental research on the measurement of counter-current bubbly two-phase flow in a vertical pipe using multiwave ultrasound and digital optical imaging has been designed and carried out. Research objectives have been worked out. Important two-phase flow parameters have been successfully obtained. A novel measurement framework of two-phase bubbly flows has been successfully established. The multiwave UVP and the digital optical imaging measurement methods have been proven to give satisfactory experimental data. Test measurements of the multiwave UVP method with Fourier-based signal processing and the correlation-based signal processing have been carried out. The latter would be more robust and more suitable. It gives better measured results for the flow conditions investigated in this study. This finding agrees well with the result of theoretical analysis of signal processing methods.

The results of this study are highly useful for both theoretical study of two-phase flows and numerical simulation of two-phase flow. The measured instantaneous/time-averaged velocity profiles of phase velocities play vital roles in drift-flux CFD model as well as in the derivation of other flow dynamics parameters such as the shear stress in the flow etc. The measured bubble size and void fraction, both instantaneous and/or spatial averaged values, are of immense importance in the calculation of the interfacial area concentration-IAC in two-fluid CFD models etc.

This study has been performed with counter-current bubbly flow in a vertical pipe. Future research will focus on the application of the two methods to the co-current bubbly two-phase flow which is commonly encountered in energy systems in industry. In addition, the detection of bubbles in the digital optical imaging method presently is limited to low void fraction flow condition only. Machine learning in general, or deep learning in particular, can be applied to bubble images to improve the bubble recognition when there is considerable overlap of bubbles. Our preliminary investigation has obtained initial prospective results. This result will be reported later on in our further study.

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NOMENCLATURE

TDX	Transduser
UVP	Ultrasonic Velocity Profiler
CFD	Computational Fluid Dynamics
PDF	Probability Density Function
IAC	Interfacial Area Concentration
fps	frame per second
f	ultrasonic basic frequency, s^{-1}
c	sound speed, $m.s^{-1}$
t	time, s

Greek symbols

τ	ultrasound travelling time, s

Subscripts

0	center (e.g., center frequency)
d	Doppler