TATIANA MASALA[1], GLENN D. HARVEL[1] JIAN SU[1,2*] and JEN-SHIH CHANG[1]

Determination of interfacial parameters of horizontal two-phase plug flow using a high speed pulse-echo ultrasonic technique

[1]*McMaster Institute of Applied Radiation Sciences and Department of Engineering Physics, McMaster University, Hamilton, Ontario, L8S 4M1, Canada*

[2]*Nuclear Engineering Program, COPPE, Universidade Federal do Rio de Janeiro, CP 68509, Rio de Janeiro, 21941-972, Brazil*

Abstract

This paper presents a high-speed, multiple-transducers, pulse-echo ultrasonic technique for the measurement of interfacial parameters of horizontal two-phase intermittent flow regimes. The ultrasonic system consisted of an ultrasonic driver, a multiplexer with 4 transducers, and a microcomputer equipped with a data acquisition card, a motion controller card and the Winspect Data Acquisition software. Two transducers were mounted on the top of a 2.1 cm inner diameter circular pipe, while the other two transducers were mounted on the bottom of the pipe. Using instantaneous liquid level measurements from multiple transducers, two-phase flow interfacial parameters in plug were determined, such as the lengths and the velocities of liquid plugs and bubbles, the shape of the gas-liquid interface, and hence instantaneous and cross sectional averaged void fraction and interfacial area. The results showed that the liquid plug velocities as well as the elongated bubble velocity increases with increasing superficial liquid and gas velocities. An experimental correlation for liquid plug velocity was proposed based on the present results. The results also showed that the time and cross-sectional averaged void fraction in the plug flow regime was only slightly influenced by the superficial gas velocity but was not influenced by the superficial liquid velocity.

*Corresponding author. E-mail address: sujian@nuclear.ufrj.br

Nomenclature

A	–	area, m^2
A_L	–	liquid cross-sectional area, m^2
a	–	empirical constant
b	–	empirical constant
h_L	–	liquid film thickness, m
L_p	–	plug length, m
R	–	radius of the circular pipe, m
r_1	–	semi-major axis, m
r_2	–	semi-minor axis, m
t	–	time, s
U_{gs}	–	gas superficial velocity, m/s
U_{ls}	–	liquid superficial velocity, m/s
U_p	–	plug velocity, m/s
x	–	transversal spatial coordinate, m
y	–	vertical spatial coordinate, m
z	–	longitudinal spatial coordinate, m

1   Introduction

The intermittent flow regimes are encountered commonly in gas-liquid two-phase flow for a wide range of gas and liquid superficial velocities which occurs commonly in many industrial applications such as nuclear and conventional power plants, crude oil/gas multiphase pipelines, and refrigeration equipment [1–9]. An intermittent flow occurs in a horizontal pipe when waves of a stratified liquid layer grow until they reach the top of the pipe. The plug flow regime is found at low gas superficial velocities, which is characterized by elongated bubbles moving along the top of the pipe and separated by plugs of liquid. At relatively high gas superficial velocities, a transition from plug to slug flow regime occurs. The slug flow regime is characterized by large elongated gas bubbles moving on top of a thin liquid layer, separated with aerated liquid slugs. Determination of interfacial parameters is essential for the understanding and modeling of horizontal two-phase intermittent flow as they directly influence the heat transfer and pressure drop characteristics.

Several experimental techniques have been developed for the measurement of interfacial parameters of intermittent two-phase horizontal flow, such as bubble velocity, bubble length, and liquid layer thickness. For example, the parallel wire technique has been used to measure the elongated bubble profile. Van Hout et al. [10] measured translational velocities of elongated bubbles in continuous slug flow by cross-correlating the output signals of consecutive optical fiber probes and by an image processing technique. Reis and Goldstein [11] presented recently a new non-intrusive technique for bubble profile and velocity measurement in horizontal slug flows, based on measuring the capacitance between two electrodes mounted around the external surface of a dielectric material tube.

Ultrasonic techniques have the advantages of being non-intrusive, easy to install, fast response, and can be used when other techniques are not applicable [12,13]. There are three main ultrasonic methods for two-phase flow diagnostics, namely the transmission [12,14], the pulse-echo [15–17], and the Doppler shift methods [12,18]. The Doppler shift method has the relative advantage when applied in a low void fraction liquid flow velocity measurements and gas bubble velocity measurements [12,18]. Morriss and Hill [18] developed a Doppler velocity method for two-phase pipe flow. With this method, representative images can be obtained in air-water flow for large values of water hold-up, however sharper focusing is needed to resolve millimeter scale bubbles accurately.

The ultrasonic pulse-echo method was intensely studied by numerous authors for two-phase flow measurement [15–17]. Chang et al. [16] developed a single transducer time averaging ultrasonic pulse-echo method (time averaging A-scan method) to determine flow regime, liquid level, and location of gas-liquid-solid interfaces in metal pipes and gas-liquid two-phase flow. Chang and Morala [17] developed a single transducer instantaneous ultrasonic pulse-echo and two transducer time averaged transmission methods. Using a polynomial regression method, it is possible to recognize the flow patterns such as stratified smooth, stratified wavy, plug flow and slug flow for an interval of 10 s, except the annular flow, using a two-transducer method [16,17]. This system can measure the bubble velocity of up to 0.7 cm/s. However, it is clear that this method cannot be applicable to bubbly flow or to any flow that contains a high degree of entrainment, and more transducers are necessary for more accurate results. Faccini et al. [19] presented a hybrid contra-propagating transmission ultrasonic technique (CPTU) for flow and time averaging ultrasonic transmission intensity void fraction measurements (TATIU) of air-water two-phase flow.

This paper presents a high-speed, multiple-transducers, pulse-echo ultrasonic technique for the measurement of interfacial parameters for horizontal two-phase intermittent flows. Interfacial parameters of two-phase plug flow such as the lengths and velocities of liquid plug were determined. The shape of the gas-liquid interface, and hence instantaneous and cross sectional averaged void fraction and interfacial area were also determined and discussed in detail.

2   Experimental setup

The experiments were performed in a horizontal two-phase flow rig, as shown schematically in Fig. 1. The two-phase flow test section consisted of a 5 meter long and 2.1 cm inner diameter circular pipe, which was made of glass for visualization of the flow patterns. Air and water at atmospheric conditions were injected into the entrance of the pipe through a mixing chamber that was used
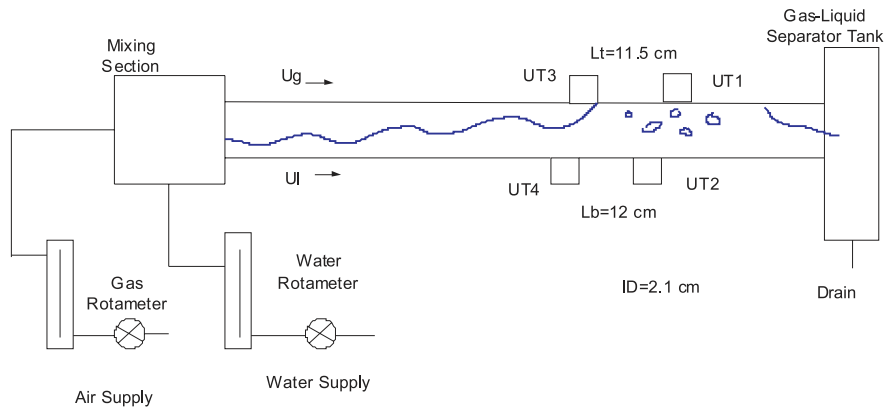
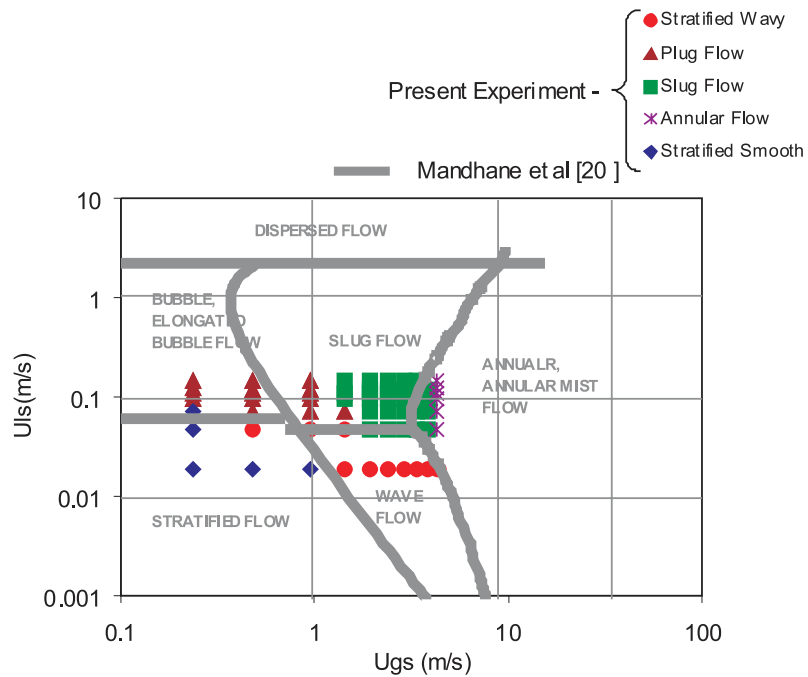Figure 1. Schematic of the horizontal air-water flow rig.

Figure 2. Two-phase flow regime map: comparison of the present results with the Mandhane et al. [20] flow map.

to enhance the onset of fully developed two-phase flow. Single-phase volumetric flow rates were measured with rotameters before the mixing section. All reported

superficial gas and liquid velocities are at standard conditions (1 bar, 20 ºC). The superficial velocity of the liquid was varied between 0.019 m/s and 0.144 m/s and the superficial velocity of the gas ranged from 0.24 m/s to 4.33 m/s. A flow regime map is created based on the superficial liquid and gas velocities. Over 70 data points were used to define the flow map that is shown in Fig. 2, compared with the flow regime map of Mandhane et al. [20].

3   Ultrasonic instrumentation

The ultrasonic system developed in this work for two-phase flow measurement consists of three physical parts: a Pentium IV microcomputer, a Staveley Sonic 260 Multiplexer, and four Panametrics 10 MHz $\frac{1}{4}$" (0.64 cm) ultrasonic transducers, as shown schematically in Fig. 3. The computer is equipped with a Data Acquisition Card (Digitizer – Compuscope12100), a Motion Controller Card (DMC1800), and a Winspect Data Acquisition Software [21]. The second element of the system is the multiplexer model Staveley Sonic 260 unit, which generates the excitation pulse sent to the transducers and receives the echo signal, which is amplified and sent to the computer/digitizer as the so-called RF (*Radio Frequency*) signal. The multiplexer is a multi-function device and can accommodate up to 16 transducers. The transducers themselves, mounted on the cylindrical pipe through cables, are the third element of the system. Four Panametrics Ultrasonic Transducers, Model A112S 10MHz $\frac{1}{4}$" (0.64 mm in diameter) contact transducers are used. Transducers 1 and 3 were mounted on the top surface of the pipe at a distance $L/D = 70$ from the inlet of pipe, with a separation distance of 11.5 cm between them. The other two transducers, Transducers 2 and 4, were mounted on the bottom surface of the pipe at roughly a distance $L/D = 65$ from the inlet, with a separation distance of 12 cm, as shown in Fig. 1.
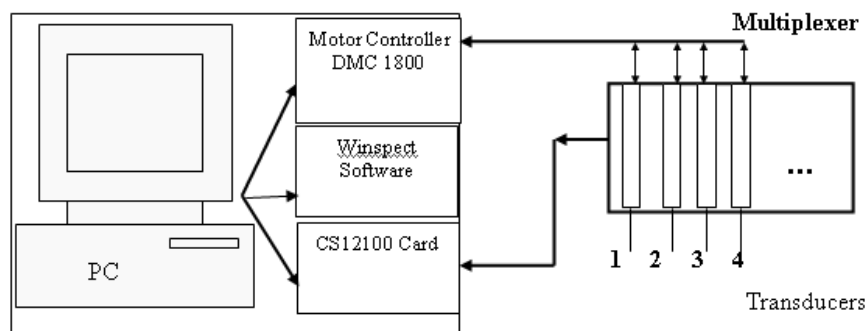

Figure 3. Schematic of the ultrasonic system.

The measurement system is controlled by the Winspect software [21], with the Compuscope 12100 digitizer used to acquire the ultrasonic data. In operation, the Winspect software initiates a data acquisition cycle by first setting the multiplexer to the correct channel via the DMC 1800 parallel connector unit and then sending a software trigger to the digitizer. The digitizer has the capability to send a synchronous external trigger pulse upon receiving the software trigger. This pulse is used to trigger the Pulser/Receiver unit of the multiplexer to generate a pulse to send to the four transducers. The echoes received by the transducers produce the RF signals, which travel back to the Pulser/Receiver unit of the multiplexer, and are amplified and passed on to the digitizer which then digitizes the data. The Winspect software then processes the RF data, and a liquid level estimate is generated and displayed on a C-scan representation or on an A-scan representation. The multiplexer is set to RUN automatically, which means that all four transducers receive an electrical pulse every 6 ms until the scanning time is completed. For the present experiments, the scanning time was chosen to be between 3 and 10 seconds.

The RF signal received by the digitizer from the transducer via the multiplexer consists of the desired signal, which can be post-processed to determine the liquid level, void fraction, plug velocity, and other two-phase flow parameters. However, not all the RF data received are useful, such as multiple echo repetitions, therefore a gate was used to allow only the acquisition of the signal that travels a distance equal to the diameter of the tube and to ignore all other repetition echoes. Some signal processing is required to improve the waveforms and the C-scan for a clearer interpretation of the results. The first step in the signal processing is to remove the unidentified points by filtering the signal; the second step is to rectify the waveform; and finally an enveloping function is applied which tapers the ends of the data array without affecting the center portion significantly. The filtering is done by using point-by-point multiplication with the center half of the signal being multiplied by unity while both the beginning and end quarters are multiplied by coefficients which taper from unity at the center of the segments to zero at the ends. The filter is used to cut down on noise in the next step of processing due to sudden drops at the ends of the data segment. Figure 4 represents a typical result in the A-scan plot, as it was detected by Transducer 1 placed on the top surface of the tube in the case of a plug flow regime, for pre-subtraction and post-subtraction signals.

The waveform resulting from the signal processing is further analyzed with a peak-detection program specifically devised to identify the amplitude peaks associated with the gas-liquid interface. The peak detection program, implemented in Visual Basic, automatically provides liquid level information inside the tube from the C-scan processor. The program first reads the time-of-flight data from
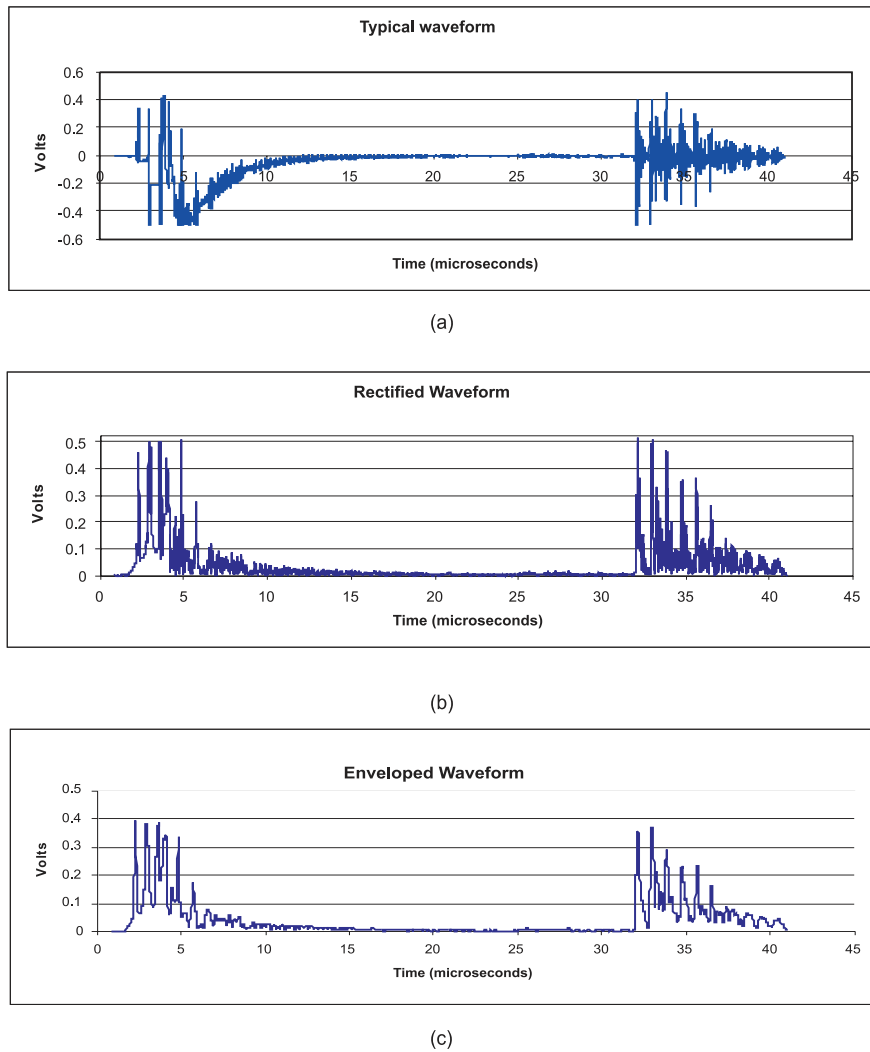
(a)

(b)

(c)

Figure 4. Typical A-Scan signal processing – Typical waveform (a), Rectified waveform (b), Enveloped waveform (c).

the C-scan files and stores them into variables. It then converts all the data into A-scans for each sample. The user has the option to set the algorithm to read the data starting with the signal that corresponds to the tube-wall/liquid interface or tube-wall/gas interface. The algorithm then detects from the A-scan all the other peaks that are greater than a set percentage of the amplitude of the highest peak and finds thus the second highest peak. Therefore, it identifies the signal coming from the reflection at the liquid/gas interface, or tube-wall/liquid interface, reads the time-of-flight of that signal, and calculates the instantaneous liquid level.

4   Experimental results

Figure 5 presents a typical C-scan representation of the ultrasonic signals for a plug flow, as was detected by Transducer 2 placed on the bottom surface of the pipe. As can be seen, the instantaneous location of the liquid/gas interface and liquid/tube-wall interface was recorded by the transducer. The liquid/tube-wall interface was encountered in the region between 1.0 and 1.7 s acquisition time by recognizing that the ultrasonic signal traveled through the water a distance equal to the diameter of the pipe.
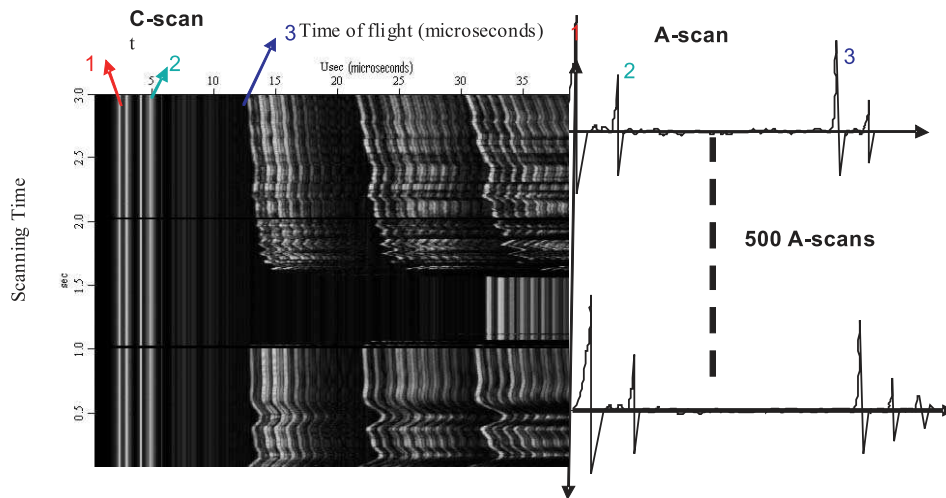

Figure 5. Typical C-Scan representation of the ultrasonic signal from transducer 2.

Once the waveform signal processing is completed, the C-Scan data as shown in Fig. 4 can be very easily interpreted. These C-scan images can be interpreted by extracting the A-scan waveforms that were described in the previous section which give the time of flight and implicitly the liquid level.

The instantaneous location of the liquid/gas interface was extracted from the C-scan data using the peak-detection program that converts the raw ultrasonic C-scan (or 20.000 A-scans) data provided by the four transducers during a 3 s acquisition period into liquid level measurements. Figure 6 shows typical liquid level measurements obtained from transducers 2 and 4 for plug flow. Similar measurements were obtained for the other two transducers.

For plug flow, the plug front and plug tail can be easily identified from the instantaneous change in liquid level. The plug front passes by the four transducers sequentially. The exact instant in which the plug front passes a particular
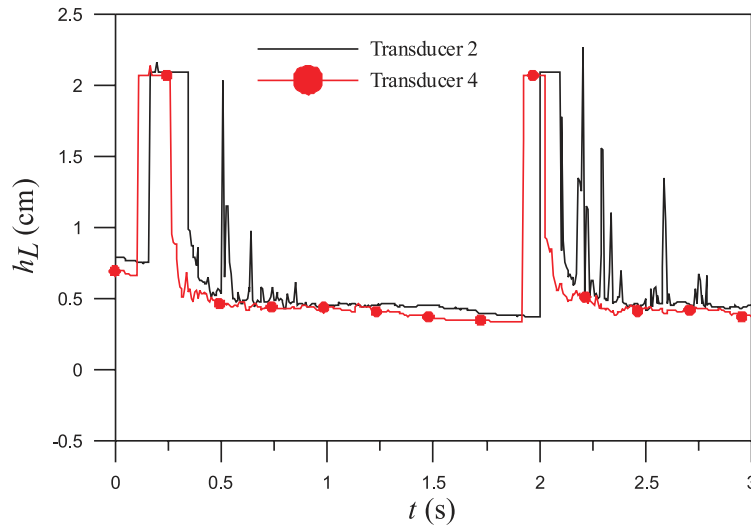
Figure 6. Typical instantaneous liquid level distribution for a plug flow from transducers 2 and 4. The shift in the spectrum is representative of the time of flight of the gas-liquid interface.

transducer is identified and plotted in time-position coordinates. The four points from all transducers are best-fitted into a straight line whose slope is the velocity of the plug front. The same procedure is used to determine the velocity of the plug tail.

Chang and Morala [17] suggested that two ultrasonic transducers mounted with a longitudinal distance S may be used to determine the bubble speed by dividing S by the time difference Δt detected by the two transducers. The procedure developed in this work is an extension of the procedure proposed by Chang and Morala [17] to include multiple transducers. It is expected that the velocity determined by best-fitting of a 4 transducer signal be better than that determined by two transducers. This idea may be extended to more transducers, thus determining acceleration of the plug front and plug tail.

Figure 7 shows the plug front and trail trajectories for $U_{ls} = 0.12$ m/s and $U_{gs} = 0.48$ m/s. The front and trail velocities are obtained by determining the slopes of the trajectories by a best-fitting procedure. The plug velocity is taken as the average of the velocities of the plug front and tail. The plug velocity data are shown in Fig. 8 as a function of the superficial liquid velocity, for superficial gas velocities of 0.48 and 0.96 m/s respectively. The experimental data are compared with the correlation of Wallis [22] for slug flow regime, as follows:
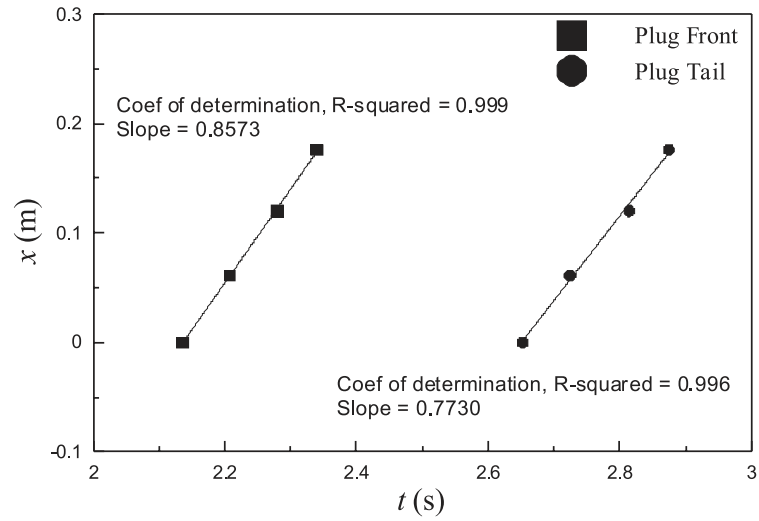
$$U_p = 1.2(U_{ls} + U_{gs}). \tag{1}$$

Figure 7. Plug front and tail trajectory for $U_{ls} = 0.12$ m/s and $U_{gs} = 0.48$ m/s.
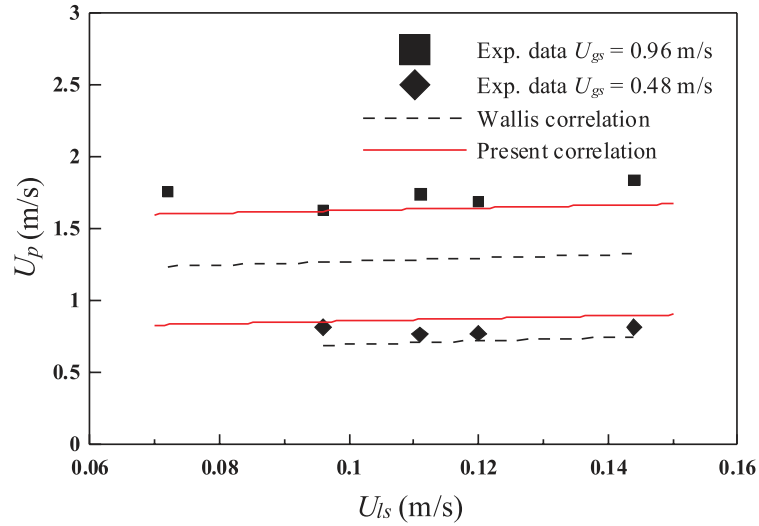

Figure 8. Plug velocities for $U_{gs} = 0.48$ and 0.96 m/s compared with Wallis's and present correlations.

It can be seen from Fig. 8 that the correlation of Wallis, also developed using slug flow experimental data, predicts reasonably the plug velocity for the lower gas superficial velocity, $U_{gs} = 0.48$ m/s, while underpredicts the plug velocity significantly for the higher gas superficial velocity, $U_{gs} = 0.96$ m/s. The best fit correlation for the plug velocity based on the present work is expressed as follows:

$$U_p = aU_{ls} + bU_{gs}. \tag{2}$$

In this work, the plug velocity is expressed as a linear combination of the superficial liquid and gas velocities. The present correlation is obviously dimensionally correct, with a and b both dimensionless coefficients. The Wallis correlation becomes a particular case of the present correlation when the coefficients are taken as $a = b = 1.2$. Based on present experimental data, $a = 0.9$ and $b = 1.6$ gave the best fit with the experimental data as the regression coefficient increases from 1.2 to 1.6, which implies that the superficial gas velocity has a stronger influence on the plug velocity than the superficial liquid velocity. Once the plug velocity is calculated, it is straightforward to determine the plug length by multiplying the plug velocity by the difference between the time instants when the plug front and the plug tail pass the same transducer, say, transducer 3:

$$L_p = U_p(t_{f3} - t_{t3}). \tag{3}$$

The plug length dependence on the liquid superficial velocity for the gas superficial velocities of 0.48 m/s and 0.96 m/s is shown in Fig. 9. Figure 9 shows that all the
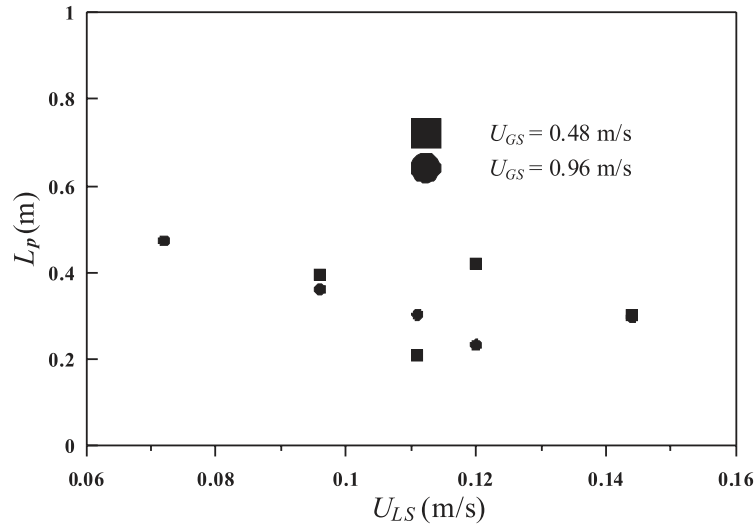

Figure 9. Plug length dependence on liquid superficial velocity.

experimental data of plug length lie between 0.2 and 0.5 m. The experimental data indicates the general tendency of a decreasing plug length with increasing superficial liquid velocity. However, the large dispersion of the data prevents us from obtaining a definite conclusion of the plug length dependence on the superficial liquid and gas velocities. The variation of plug length is expected, as it is well known that the plug length strongly depends on the inlet condition. The plug length may also depend upon fluid properties and the hydraulic diameter.

In order to calculate the void fraction for a plug flow regime, the cross-sectional shape of the elongated bubble is assumed to be elliptical. The area of the ellipse is $A = \pi \cdot r_1 \cdot r_2$, where r_1 is the semi-major axis of the ellipse, as shown in Fig. 10, and r_2 is the semi-minor axis. Then, the liquid cross-sectional area A_L of the gas-
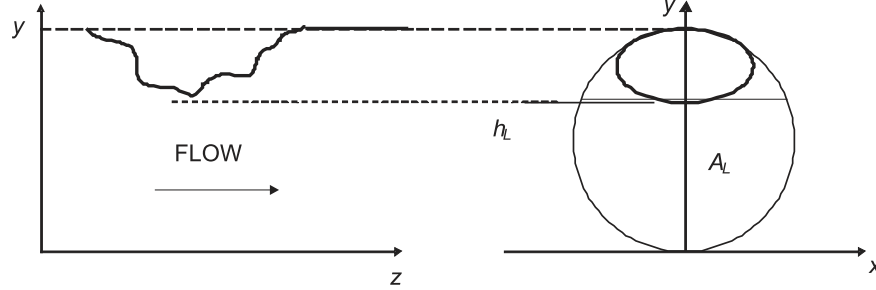

Figure 10. Estimation of cross section interfacial area in a plug flow.

liquid two-phase plug flow regime in a circular pipe is given by subtracting the cross-sectional area of the gas (ellipse of semi-major and semi-minor axes r_1, r_2) from the cross-sectional area of the pipe (circle of radius R):

$$A_L = \pi(R^2 - r_1 r_2). \tag{4}$$

The semi-minor axis of the ellipse is calculated as $r_2 = R - h_L/2$, where h_L is the instantaneous liquid level as measured by the instruments, and the semi-major axis can be calculated with a good approximation as:

$$r_1 \cong \sqrt{R^2 - (h_L/2)^2}. \tag{5}$$

Considering the liquid cross-sectional area A_L given by Eq. (4) the void fraction for plug flow can be calculated. The ellipse approximation works well for small diameter pipes where viscous forces are stronger. The ellipse-like shape of the elongated bubble in cross-section is due to the surface tension of the liquid, which tends to push the liquid up on the pipe walls. For larger diameters, this approximation does not hold anymore because the curvature of the liquid/gas interface at the contact with the walls will only be local. Therefore, in these situations, the shape will be a combination of an arc of a circle in the upper side of the elongated bubble, following the pipe wall shape, and a somehow linear shape at the bottom, at the liquid surface, with curvatures in the areas where the free surface of the liquid wets the pipe walls. For a better estimation of the cross-sectional shape of the elongated bubble, additional experimental work and analysis are necessary.

The time averaged void fraction as a function of superficial liquid velocity for different superficial gas velocities for plug flow regime is shown in Fig. 11.
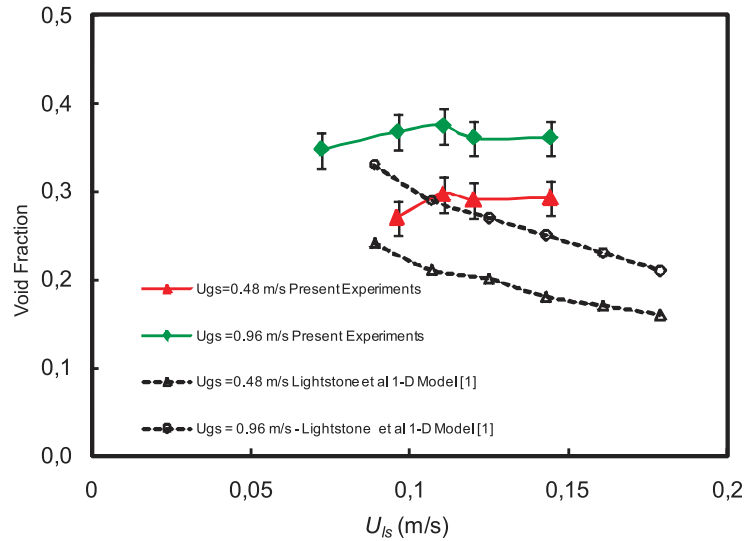
Figure 11. Time-mean void fraction in plug flow.

As shown in Fig. 11, for an increase in superficial gas velocity from 0.48 m/s to 0.96 m/s the void fraction increases which is in agreement with 1-D Model results obtained by Lightstone et al. [1]. This could be explained from the simple fact that for higher gas flow rates, the formation of the water bridge becomes a very effective method for pushing the liquid down the pipe resulting in the observed increase in void fraction. However in the region where the liquid superficial velocity is about 0.12 m/s the void fraction slightly decreases. One of the reasons for the decrease in void fraction in this situation could be due to the change in the shape of the liquid plugs or in the frequency of the liquid plugs that were captured by the system. Comparing the present results with those obtained by Lightstone et al. [1] it shows they are in satisfactory agreement, as shown in Fig. 11 for an increase in superficial gas velocity the void fraction decreases. The only discrepancy arises from the fact that in the present results the void fraction as a function of the liquid superficial velocity is observed first to increase slightly then it decreases where again it starts to increase while for a 1-D model it shows that the void fraction is decreasing linearly. This disagreement between the experimental data and the Lighstone's 1-D model should be investigated in future works.

5 Conclusions

In this paper, a high speed ultrasonic multi-transducer pulse-echo system for dynamic measurements of interfacial parameters in two-phase intermittent gas-

liquid flow is demonstrated. The instantaneous liquid film level was obtained by 4 ultrasonic transducers mounted in the top and bottom of a circular pipe (Four transducer instantaneous ultrasonic method), after signal processing of the C-Scan representation of the ultrasonic signals. From instantaneous liquid level measurements, interfacial parameters of two-phase plug flow were determined, such as the lengths and velocities of liquid plug, the shape of the gas-liquid interface, and hence instantaneous and cross sectional averaged void fraction and interfacial area. The results showed that the liquid plug velocities as well as the elongated bubble velocity increases with increasing superficial liquid and gas velocities. An experimental correlation for plug velocity was proposed based on the present results. The results also showed that the time and cross-sectional averaged void fraction in plug flow regime is only slightly influenced by the superficial gas velocity, but not significantly by the superficial liquid velocity.

References

[1] Lightstone L., Osamusali S.I.,. Chang J.S.: *Gas-liquid two-phase flow in symmetrically dividing horizontal flow.* AIChE J. **37**(1981), 111–122.

[2] Bertola V.: *Experimental characterization of gas-liquid intermittent subregimes by phase density function measurements.* Exp. Fluids **34**(2003), 122–129.

[3] Cook M., Behnia M.: *Slug length prediction in near horizontal gas-liquid intermittent flow.* Chemical Engineering Science **55**(2000), 2009–2018.

[4] Cook M., Behnia M.: *Pressure drop calculation and modelling of inclined intermittent gas-liquid flow.* Chemical Engineering Science **55**(2000), 4699–4708.

[5] Cook M., Behnia M.: *Bubble motion during inclined intermittent flow.* Int. J. Heat Fluid Flow **22**(2001), 543–551.

[6] Fossa M.: *Gas-liquid distribution in the developing region of horizontal intermittent flows.* ASME J. Fluids Eng. **123**(2001), 71–80.

[7] Lewis S., Fu W.L., Kojasoy G.: *Internal flow structure description of slug flow-pattern in a horizontal pipe.* Int. J. Heat Mass Transfer **45**(2002), 3897–3910.

[8] Sharma S., Lewis S., Kojasoy G.: *Local studies in horizontal gas-liquid slug flow.* Nuclear. Eng. Design **184**(1998), 305–318.

[9] Shemer L.: *Hydrodynamic and statistical parameters of slug flow.* Int. J. Heat Fluid Flow **24**(2003), 334–344.

[10] van Hout R., Barnea D., Shemer L.: *Translational velocities of elongated bubbles in continuous slug flow.* Int. J. Multiphase Flow **28**(2002), 1333–1350.

[11] dos Reis E.,Goldstein L. Jr.: *A non-intrusive probe for bubble profile and velocity measurement in horizontal slug flows.* Flow Measurement and Instrumentation **16**(2005), 229–239.

[12] Lynneworth L.C.: *Ultrasonic Flowmeters*, Physical Acoustics **14**, Academic Press, New York 1980.

[13] Banerjee S., Lahey R.T. Jr.: *Advances in two-phase flow instruments.* Adv. Nuclear Sci. & Tech. **13**(1981), 227–414.

[14] Chang J.S., Ichikawa Y., Irons G.A., Morala E.C., Wan P.T.: *Void fraction measurement by an ultrasonic transmission technique in bubbly gas-liquid two-phase flow.* In Measuring Techniques in Gas Liquid Two-Phase Flows (J.M. Delhaye, G. Cognet, eds.), 319–335, Springer, Berlin 1984.

[15] Chang J.S., Ichikawa Y., Irons G.A.: *Flow regime characterization and liquid film thickness measurement in horizontal gas-liquid two-phase flow by an ultrasonic method.* In Measurements in Polyphase Flow (T.R. Heidrick, B.R. Patel, eds.), 7–12, ASME Press, New York 1982.

[16] Matikainen L., Irons G.A., Morala E.C., Chang J.S.: *Ultrasonic system for detection of transient liquid-gas interfaces using the pulse-echo technique.* Rev. Sci. Instr. **57**(1986), 1661–1666.

[17] Chang J.S., Morala E.C.: *Determination of two-phase interfacial areas by an ultrasonic technique.* Nuclear Eng. Design **122**(1990), 143–156.

[18] Morriss S.L., Hill A.D.: *Ultrasonic imaging and velocimetry in two-phase pipe flow.* ASME J. Energy Resources Technology **115**(1993), 108–116.

[19] Faccini J.L.H., Su J., Harvel G.D., Chang J.S.: *An Advanced Ultrasonic Technique for Flow and Void Fraction Measurements of Two-Phase Flow.* Proc. 12th Int. Conf. Nuclear Eng., Virginia, Arlington 2004.

[20] Mandhane J.M., Gregory G.A., Aziz K.: *A flow pattern map for gas-liquid flow in horizontal pipes.* Int. J. Multiphase Flow **1**(1974), 537–553.

[21] *UTEX Scientific Instruments.* Winspect Reference Guide Ver. 6, 1–132, 2004.

[22] Wallis G.B.: *General correlations for the rise velocity of cylindrical bubbles in vertical tubes.* Report **62**, GL.130, General Electric Co., 1962.