Development of a multiphase flow meter by means of multiple ultrasonic velocity profile measurements

S. Roberto Gonzalez A.[1*], Yuichi Murai[1], Yuji Tasaka[1], Yasushi Takeda[1]
[1] Division of Energy & Environmental Systems, School of Engineering, Hokkaido University, N13W8, Sapporo 060-8628, Japan (*Corresponding author, e-mail: sroberto@eng.hokudai.ac.jp).

In this paper the liquid phase velocity and gas-liquid interface information are obtained from Ultrasonic Velocity Profile (UVP) measurements. They are used to estimate the liquid phase flow rate of a gas-liquid two phase flow. Three ultrasonic transducers are used simultaneously at different azimuthal locations in the pipe. The gas-liquid interface can be detected with one UVP transducer. However, the curvature of the interface in the cross sectional area of the pipe can not be inferred. By using three ultrasonic transducers the estimation of the gas-liquid interface curvature can be improved. The liquid flow rates in these experiments ranged from 0.6 m^3/h to 7.2 m^3/h. The gas void fraction ranged from 0 % (pure liquid) to 50 %. Only liquid flow rate calculations are performed, no gas phase calculations are shown in this paper. The estimated liquid flow rate values show good agreement with the actual liquid flow rate values.

Keywords: Multi phase flow, flow meter, Doppler, interface detection

1 INTRODUCTION

Gas-liquid two phase flows are a common occurrence in engineering applications; these types of flow can be encountered in the food industry, oil industry, and power generation processes among others. This paper deals with the liquid flow rate measurement of a gas-liquid two phase flow in a horizontal pipe; although the flow rate measurement in a vertical configuration is more commonly performed [1], the flow rate measurement of a two phase mixture in a horizontal orientation occurs in the transport of oil-gas mixtures from the wells to the reservoirs [1,2,3]. As noted by Oddie and Pearson [1], several devices are available to measure multiphase flows. However, they mostly lack a mechanical understanding of the flow itself. A noninvasive, reliable method to estimate the liquid flow rate of a gas-liquid two phase mixture accurately and in real time is the driving motivation of the present research work; the instantaneous liquid velocity measurements from three ultrasonic transducers are used in the liquid flow rate calculation; no gas flow rate estimations are performed.

With regard to multiphase flow measurement, two of the most commonly used flow meter devices in industry are the Coriolis type and the electromagnetic flow meter. The Coriolis flow meter, although an accurate device, has implicit some assumptions of the actual flow [1], i.e. the phases do not slip with respect to each other when oscillated and the phases are incompressible. Due to these assumptions the Coriolis flow meter is suitable for a liquid-liquid application but not for a solid-gas or gas-liquid application.

On the other hand the electromagnetic flow meters process signals that depend on the electromagnetic conductivity of the phase of the flow. It is non intrusive and it has no moving parts; but it may need a separate measurement of the liquid phase density to perform the mass flow rate measurements [1]. Approaching the gas-liquid flow metering problem by means of ultrasound offers similar advantages. It is also a non intrusive method and it has no moving parts, therefore maintenance free. In a recent study, Wada et al [4] demonstrated the use of the echo intensity as a way to obtain pattern recognition of a two phase flow. Using the idea presented by Wada et al [4] a method is presented here to calculate the liquid flow rate of a gas-liquid two phase flow by using three simultaneous UVP measurements.

2 EXPERIMENTAL SETUP AND METHOD

2.1 Experimental setup

A schematic diagram of the experimental setup can be seen in Figure 1. It mainly consists of the gas–liquid two phase flow loop and three UVP–DUO systems. Water and air are used as the liquid and gas phase respectively. The water is fed into the pump by the water reservoir. It flows through the pipe loop and returns in a horizontal path. At the beginning of the horizontal path the gas phase is added. Before the gas is added to the liquid phase both the gas phase and the liquid phase volumetric flow rates are measured. In this way the desired void fraction for every test is set. The test section that houses the three ultrasonic transducers is located 2.4 m from the entrance of the gas phase. It is a cylinder of 40 mm in inner diameter and 90 mm in length made of an ultrasonic absorbent material. The ultrasonic absorbent material of the test section is selected to avoid interference among the UVP transducers due to the proximity to each other. A schematic diagram of the test section can be seen in Figures 2a and 2b.

The transmitting frequency of the UVP-DUO systems is 4MHz in all the tests performed. The ultrasound wavelength, λ, is 370 μm. 100 μm ion exchange (Diaion) particles are added to the flow. Due to theoretical considerations the size of the flow tracers must be larger than one quarter of the emitted ultrasonic burst [5].

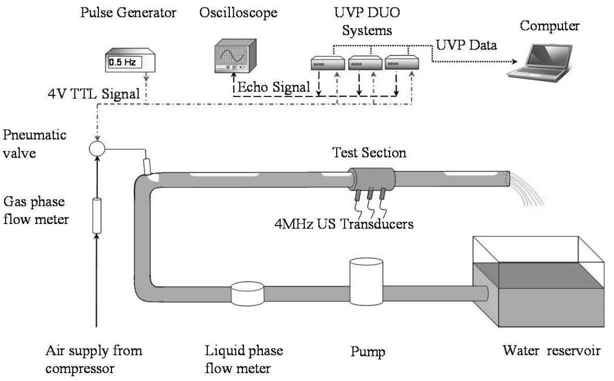

Figure 1. Experimental setup

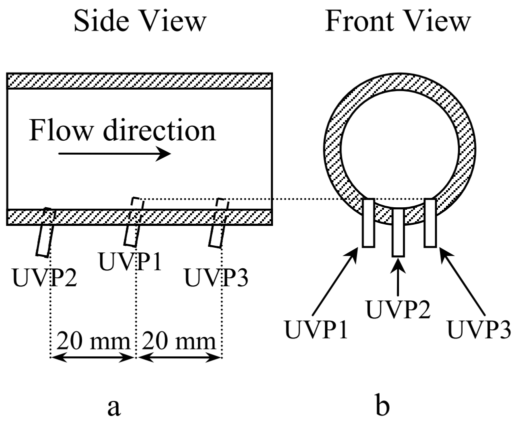

Figure 2. US transducer arrangement in the test section a) Side view b) Front view

2.2 Experimental method

For every UVP file captured one gas-liquid interface height time series, $ht_n(t)$, is obtained; n = 1,2,3 (one gas-liquid interface height time series for each transducer). The gas-liquid interface height is obtained as follows: each UVP file contains velocity and echo intensity information; from every echo intensity profile the maximum absolute echo intensity value is located and labeled as the location where the gas-liquid interface is found. Due to the location of the transducers the gas-liquid interface height is detected at a different time. This mismatch in the interface height series can be adjusted by finding the maximum correlation coefficient between the series. Then the interface height can be placed as if they are in the same plane, as seen in Figure 3a. After that, the portion of the cross sectional area of the pipe occupied by the liquid phase can be estimated. Consider a square area as that shown in Figure 3a. This area is divided into 200 elements in both the horizontal and the vertical direction. The locations of transducers 1, 2 and 3 and the location of the gas-liquid interface height are x_1, x_2 and x_3 and $s_1(x_1, y_1)$, $s_2(x_2, y_2)$ and $s_3(x_3, y_3)$ respectively. In the range $x_1 \le x \le x_3$ the free surface is calculated by a cubic polynomial function (spline interpolation), [6]. In the ranges $0 \le x \le x_1$ and $x_3 \le x \le x_f$ the gas-liquid interface is calculated by a linear extrapolation. The slope of the line in these ranges is the slope of the curve at $x = x_1$ and $x = x_3$ respectively.

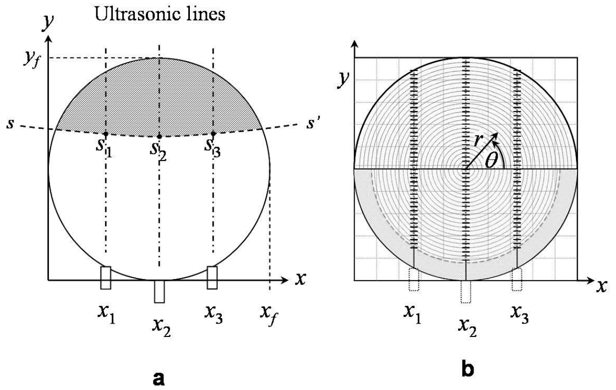

Figure 3. a) Gas-liquid interface height position b) Channel distribution

The velocity values obtained from the three UVP transducers are located as shown on Figure 3b. Next they are distributed radially. At the bottom of the pipe, there are no UVP velocity values (grey shaded region); the first measuring channel (Channel 0) is located at y = 3.6 mm from the bottom of the pipe. This is because it takes several microseconds to the UVP DUO system to switch from transmitting to receiving mode, so the echo from the particles closest to the transducer will be lost during the switching time. Consequently, the first measurement is located 3.6 mm away from the bottom of the pipe. In the region 0≤y<3.6 mm the following liquid velocity values apply.

$$180 \le \theta < 250 \quad V(r,\theta) = 0.7\overline{V}_{UVP1} \tag{2.1}$$

$$250 \le \theta < 290 \quad V(r,\theta) = 0.7\overline{V}_{UVP2} \tag{2.2}$$

$$290 \le \theta \le 360 \quad V(r,\theta) = 0.7\overline{V}_{UVP3} \tag{2.3}$$

The values $\overline{V}_{UVP1}$, $\overline{V}_{UVP2}$ and $\overline{V}_{UVP3}$ are the average liquid velocity values of transducers 1, 2 and 3 respectively from channel 0 to the channel where the gas-liquid interface is located. The constant 0.7 is the value obtained in the region $0 \le y < 3.6$ mm from the power law equation [7]; this equation is used in single phase turbulent flow; the assumption is that the gas phase is located in the upper part of the pipe, then the liquid velocity, not disturbed by the gas phase, develops in the lower part of the pipe as it does in single phase turbulent flow. The position of the velocity values, so far distributed in cylindrical coordinates, are converted to Cartesian coordinates. With both the liquid velocity distribution and the cross sectional area of the pipe occupied by the liquid phase known, the volume swept out in time *dt* can be obtained from equation 2.4.

$$vol = \iiint V(x,y,t)\,dA\,dt \tag{2.4}$$

Finally, from the instantaneous volumes the time average liquid phase flow rate is calculated from equation 2.5.

$$Q_e = \frac{\iiint V(x,y,t)\,dA\,dt}{\int dt} \tag{2.5}$$

3. RESULTS

Experiments were conducted at eight different liquid flow rates: 0.6, 1.8, 2.8, 3.4, 4.5, 5.2, 6.2 and 7.5 m^3/h. The void fraction, α, in the flow is 0 % (liquid phase only), 10 %, 20 %, 30 %, 40 % and 50 %. The void fraction, α, is defined as:

$$\alpha = \frac{Q_g}{Q_a + Q_g} \tag{3.1}$$

Q_g is the actual gas flow rate and Q_a is the actual liquid flow rate. The difference between the actual liquid flow rate, Q_a and the estimated liquid flow rate, Q_e is expressed by δ_e

$$\delta_e = \frac{Q_e - Q_a}{Q_a} \tag{3.2}$$

Before every test is performed both the gas phase and the liquid phase are set to the desired values; then the flow rate is measured pouring the mixture in a bucket for a specific amount of time. The volumetric flow rate of the liquid phase is then calculated and recorded; this is the actual flow rate, Q_a. Next, the UVP measurements are performed.

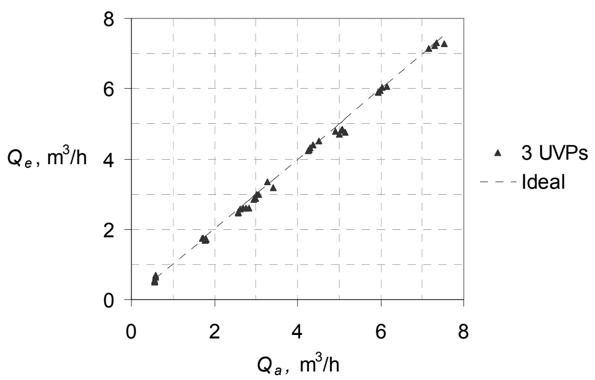

Figure 4. Estimated liquid flow rate, Q_e versus actual liquid flow rate, Q_a

Figure 4 shows the estimated liquid flow rate versus the actual liquid flow rate. The tests of Q_a = 0.6 m^3/h are of the stratified flow type. The tests of 1.8 ≤ Q_a ≤ 7.5 m^3/h are of the elongated bubble and slug flow type (depending on the void fraction of the flow) [8]. This figure shows a good agreement between the estimated and the actual liquid flow rate values in the range of liquid flow rates tested. Figure 5 shows the difference between the estimated liquid flow rate and the actual liquid flow rate. The experiments conducted in the range 0.6 ≤ Q_a ≤ 7.5 m^3/h have an average and standard deviation value of -1.9 and 5.1% respectively. The high standard deviation value is mainly due to the tests of lowest flow rate, Q_a = 0.6 m^3/h. In the range 1.8 ≤ Q_a ≤ 7.5 m^3/h, the average and standard deviation values are -2.6 and 2.6 % respectively. Although the average of these tests decreases, more importantly, the standard deviation of these tests decreases by 49 %.

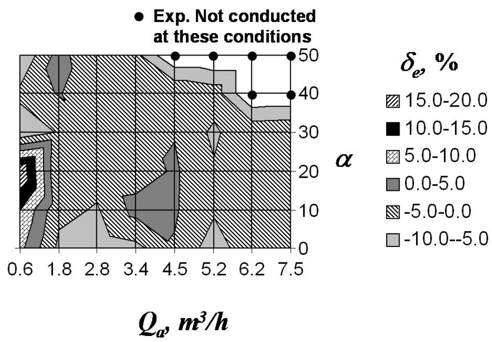

Figure 5. δ_e values of the tests performed

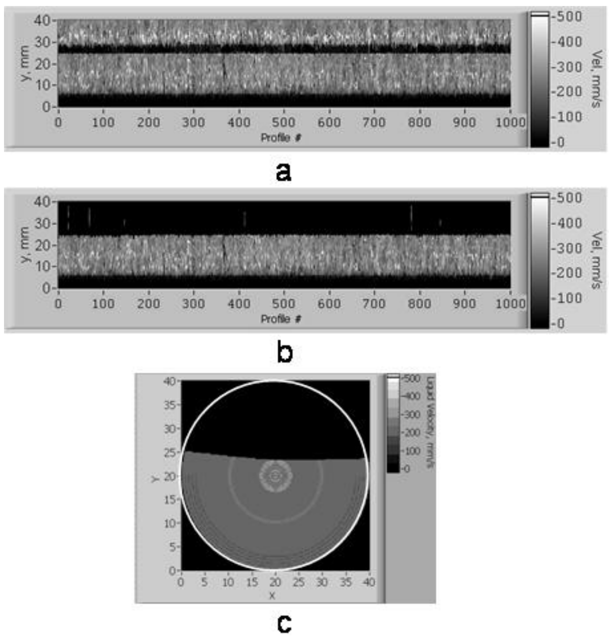

Figure 6. Q_a=0.6; α =10% a) Raw data b) Processed data c) liquid phase velocity distribution, profile #50

Figure 6 shows the test of Q_a = 0.6 m^3/h and α = 0%; the superficial liquid velocity is 0.13 m/s; only the first 1000 velocity profiles (or 24 %) of the 4096 profiles captured are shown. If all of velocity profiles are displayed important details of the flow may be lost; the upper part of the pipe is occupied by the gas phase. After the UVP file is processed and the gas-liquid interface detected the data is plotted as in Figure 6b; there are no liquid velocity values in $0 \leq y \leq 3.6$ mm; the liquid velocity values in this region are the liquid velocity values obtained from the power law equation as mentioned in section 2.2. Figure 6c shows a flow map (velocity profile # 50) of the cross sectional area of the pipe. The upper part of the pipe is occupied by the gas phase. The gas–liquid interface height detected by each one of the three transducers has a very similar value; due to it the gas-liquid interface is not flat as expected but instead it shows a small curvature. Liquid velocity values are higher near the center of the pipe. The darker color lines in the lower part of the pipe and near the wall are the values due to the power law equation.

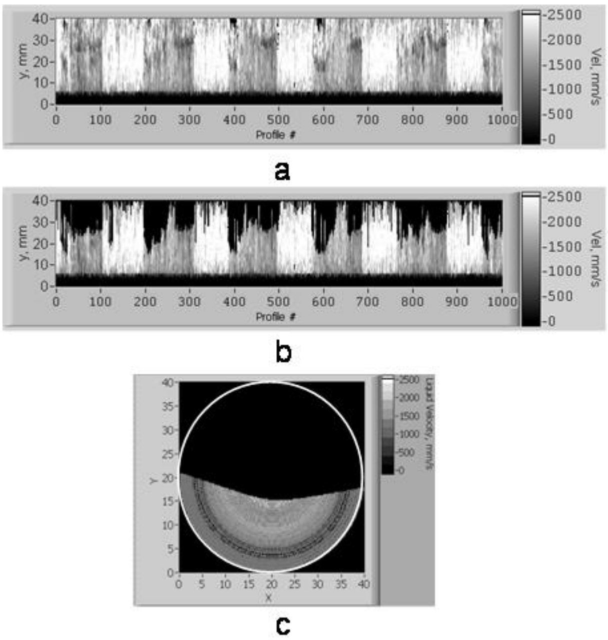

Figure 7. Q_a=6.2; α =30% a) Raw data b) Processed data c) liquid phase velocity distribution, profile #221

Figure 7a shows the raw data of the test of Q_a = 6.2 m^3/h and α = 30%, the highest void fraction tested for this liquid flow rate. Figure 7b shows the UVP data processed; at this void fraction the gas-liquid interface can be seen below the middle of the pipe. Figure 7c shows a sample flow map of liquid velocity profile # 221. The gas phase occupies more than 50% of the cross sectional area of the pipe and it is not symmetrically distributed in the upper part of the pipe. This figure also shows higher liquid velocity values near the center of the pipe that decrease radially. The dark (low velocity) values correspond to the near field effect where the transducers output lower liquid velocity values than the actual liquid velocity values. If only one UVP transducer is used, the gas-liquid interface must be assumed to be flat. By using three ultrasonic transducers a more accurate gas-liquid interface shape is obtained.

4. CONCLUSIONS

In this study the liquid flow is assumed to be one dimensional; however, it is acknowledged that this is not true in the vicinity of the bubbles (especially in their leading and trailing edge) where the relative velocity between the bubbles and the liquid phase creates complex liquid motion that is far from one dimensional. Nonetheless, the estimated liquid flow rate values results show good agreement with the actual liquid flow rates. The following conclusions can be inferred from the present study:

- The maximum echo intensity value can be used to estimate the location of the gas-liquid interface. It can be applied to pure liquids as well as gas–liquid two phase flows where the void fraction is as high as 50%.
- The expected average and standard deviation δ_e values are -1.9 and 5.1% respectively in the range $0.6 \leq Q_a \leq 7.5$ m^3/h. The tests of Q_a= 0.6 m^3/h show a larger variation than the rest of the tests.
- In the range $1.8 \leq Q_a \leq 7.5$ m^3/h the expected average and standard deviation δ_e values are -2.6 and 2.6 % respectively.

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