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Multiphase Gas Liquid Slug Flow Measurements Using Ultrasonic Doppler

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Abstract: *The accurate measurement of multiphase flows of oil/water/gas is a critical element of oil exploration and production. Thus, over the last three decades; the development and deployment of in-line multiphase flow metering systems has been a major focus worldwide. In this paper, an ultrasonic slug flow-metering concept has been proposed and investigated. Itaims to measure the flow rates of the liquid and gas phases from ultrasonic measurements made in slug flow regime to obtain good measurement accuracy. This employs ultrasonic raw signal Doppler (with in house signal processing) method combined with a flash-mounted conductivity ring. This approach has been tested on water/air flows in a 50mm pipe diameter facility in the School of Engineering in Cranfield University. The water and gas flowrate measurements using the proposed technique were compared with a reference measurement and a good agreement between these two measurements was obtained with an error ±15 % compared to a reference flowmeter. The gas measurement was within ±10 % of the measurement made using a reference flowmeter.*

Keywords:*ultrasonic Doppler flowmeter, Doppler raw signal, multiphase flow, signal analysis.*

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I. Introduction

Liquid gas slug flow in a pipeline is a common flow in oil and gas industry, chemical, nuclear plants. It is defined as an intermittent flow where long gas bubbles and liquid slug occur to block the pipe cross section.In term of accurately measurement of the two-phase (liquid, gas) slug flow, there are several attempts to accurately obtain slug flow using different methods and techniques in combination with T junctions[1], however, online measurement of two phase slug flow are still a challenge for oil and gas industry engineers[2]. Ultrasonic Doppler is thetechnique that has been implemented in two-phaseslug flow measurement clamped-on base. In this work ultrasonic Doppler transducer (500 KHz) was clamped on 10 metres away from reference points (turbine and electromagnetic flowmeter) on a 50mm horizontal pipe diameter two phase flow (gas-liquid) in the PASE laboratory in Cranfield University to online measure the liquid and gas flowrates in slug flow with a conductivity ring for fraction measurement.

II. Experimental Setup

2.1 Test rig overview

The test rig on which the experiments were undertaken consists of a closed loop of identical pipe diameters. The pipe geometry is 50mm of internal diameter, 20 metres in length. The loop is about 1 metre high from the ground to allow any future better visualization of the fluid and easy to access and control the liquid and gas valves and it is required for the return mixture pipe to the water tank to be entered from the inlet above the water level, which is 90cm.

2.1.1 Liquid supply system

Obviously, the liquid used in this test rig is water. It is supplied by a storage tank which is 2000 litres in capacity at atmospheric pressure and 1 m high, which is the same level as the experimental pipes and containing the amount of water required for the experiments. The water is pumped into the 50mm diameter pipe to the test rig by a centrifugal pump with a maximum capacity of $40m^3$/hr and amaximum discharge pressure of 500kPa (gauge). This pump is installed at the bottom of the water storage tank.

The pumped water passes through an electromagnetic flowmeter for volumetric flow measurement and then a pressure gauge before it mixes with air and flows to the measuring area[3].

2.1.2 Air supply system

The laboratory compressor takes air from outside at atmospheric pressure. The compressed air is then stored in a high-pressure tank. The air then passes through a pressure regulator to minimize fluctuation in pressure. Air is divided into two branches, the high pressure line where the volumetric flowrate is measured using a gas turbine flowmeter and the low pressure line where also the volumetric flowrate is measured using the same technique using different turbine flowmeter sizes which can deliver different flow-rates that are required for the experiments.

III. Device Installation and Set-Up

The ultrasonic Doppler transducer of Doppler flowmeter was proposed to install next to a conductivity ring, located around the pipe.The transducer has been clamped-on at 6 o'clock position (at the bottom) of the pipe where liquid is always present whether liquid in film or in slug, however, the challenge at this position is how can slug liquid and film liquid velocities be identified by the transducer. Figures1 and 2 illustratethe installation and the reading of ultrasonic Doppler transducer clamped-on at the bottom of the pipe beside a conductivity ring. However, normally, the near transducer wall section is the only section monitored. The zone of reflection is in a region of variable velocity.[4]

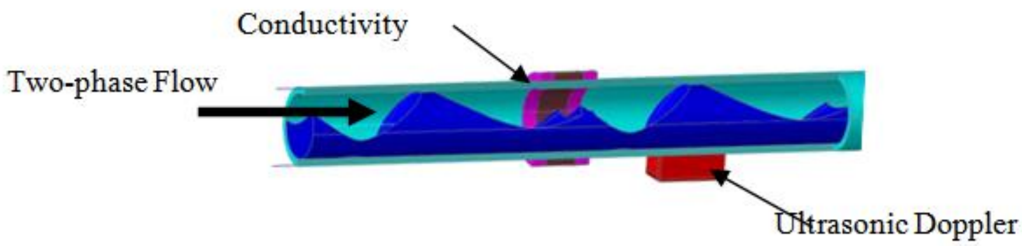

Figure 1: Ultrasonic Doppler installation in slug flow

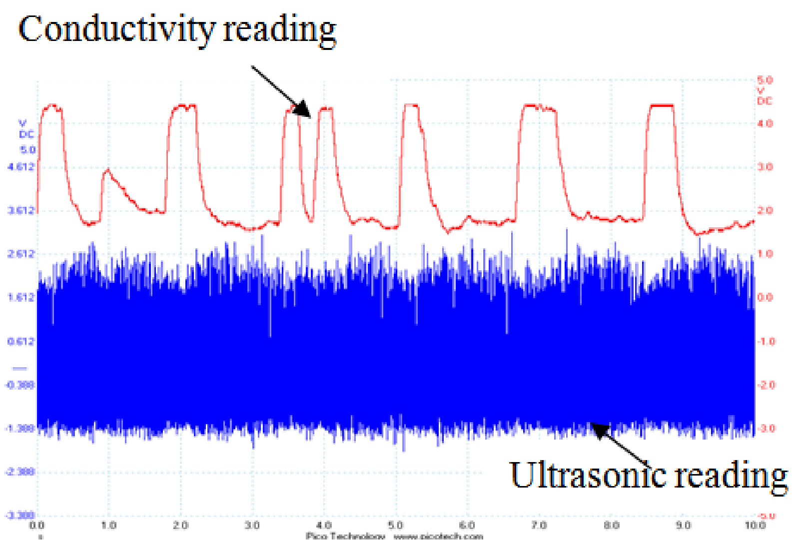

Figure 2: Ultrasonic Doppler at 6 o'clock position.

Using PICOscope two channels box is to instantly record signals from conductivity ring and ultrasonic Doppler at fixed sampling rate. These data is then analysed using mainly two commercial software such as Sigview and Autosignal.

3.1 Signal analysis using Sigview and Autosignal

The previous signals illustrated in figures 2 and 3 have two clear intensities in recoded signal from Doppler which can represent frequency shift from slug body and film which is in another way to be referred to slug velocity and film velocity in the pipe.

Analysing these signals, using Sigview is to identify the frequency shift from high and low intensity signals.

3.1.1 Analysing high and low intensity signal (slug body and film)

The slug body and film that are illustrating in figure 3, can easily extract their frequency shifts using Sigview and Autosignal as signal analysis software.

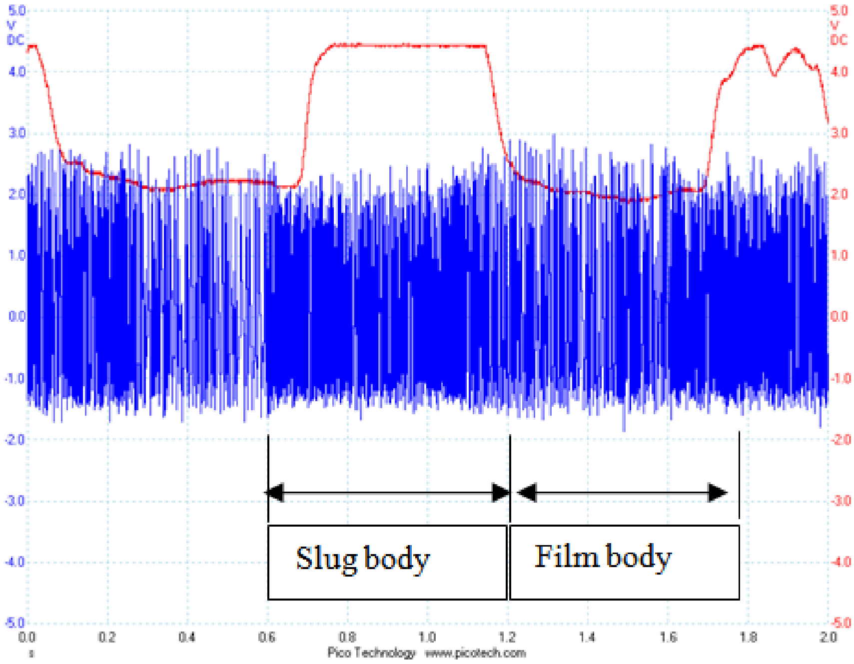

Figure 3: High and low intensity of slug flow

The slug body has a clear frequency shift that represents its velocity, using Autosignal wavelet spectrum can show the frequency change when slug liquid and film liquid pass, figure 4, shows this changes.

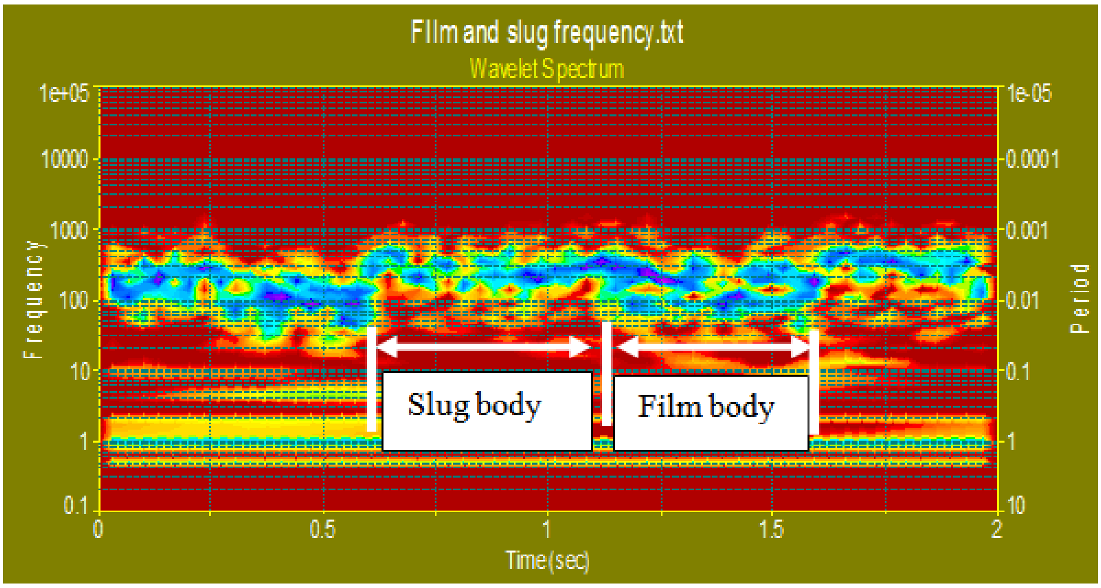

Figure 4: Slug liquid and film liquid frequency.

IV. Slug Film Liquid Velocity Measurements

To measure the instantaneous velocity of slug liquid and film liquid, their signals need to be FFT using either software they mentioned earlier.

- First, high intensity (slug body) signal is analysed using Sigview to extract its frequency shift at the peak which directly represents its velocity, as it can be seen from figure 5.

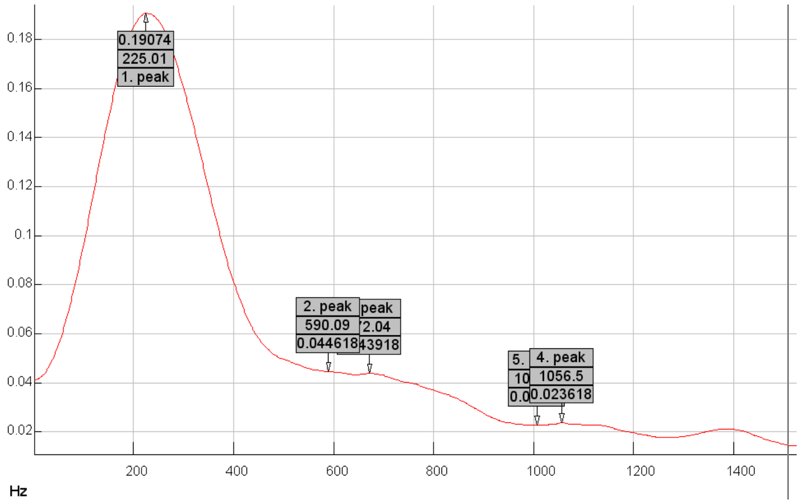

Figure 5, Slug body frequency peak shift

- Second, the low intensity (film body) signal is also extracted and using the same procedure for the high intensity signal therefore, the frequency shift can be determined. Figure 6 illustrates the frequency shift of the film liquid.

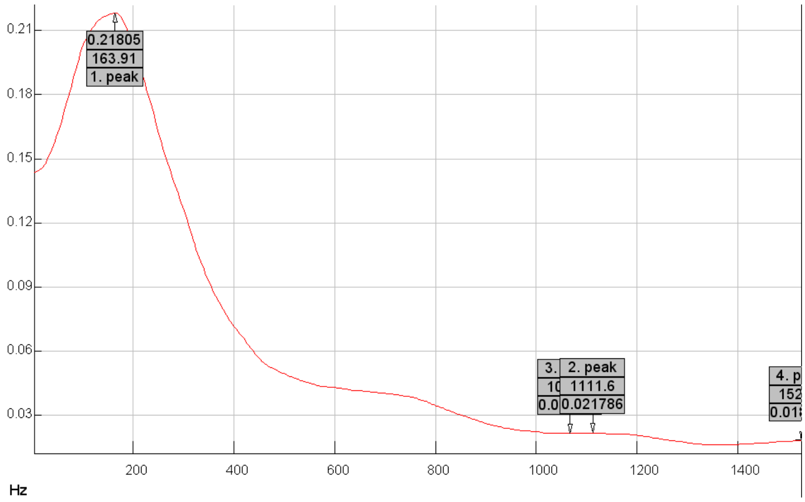

Figure 6: Film body frequency peak shift

Velocity measurements for each velocity can be determined form the Doppler equation which is as the following:

$$V_s = \frac{f_{ds} * C}{2 * f_t * \cos\theta} \text{ or } V_f = \frac{f_{df} * C}{2 * f_t * \cos\theta} \qquad (1)$$

Where, V_s, V_f , f_{ds} and f_{df} represent average slug liquid and film liquid velocities, slug liquid and film liquid frequencies , respectively.
C is the acoustic velocity in water.
f_t and $\cos\theta$ are the transmitted Doppler frequency and its angle, respectively.

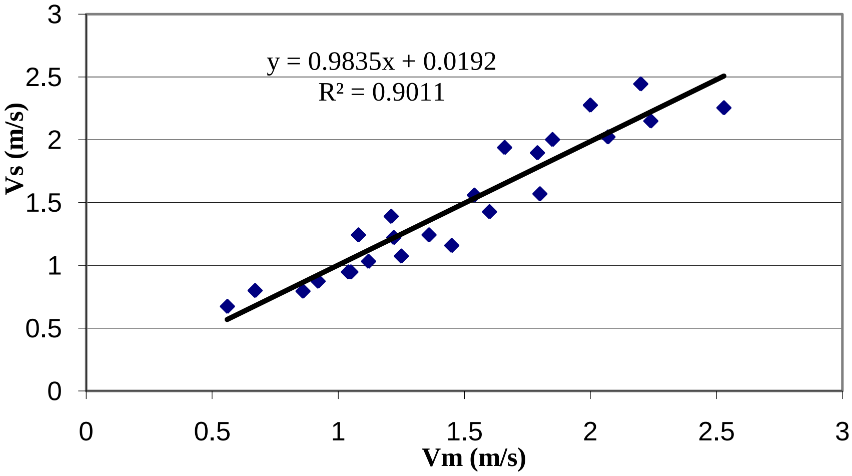

Figure 7: Slug velocity (Doppler) and mixture velocity (reference)

Linear relationship between Doppler slug velocity and mixture velocity at the reference as it can be seen from figure 7. Moreover, liquid film velocities in different slug velocities have inclined as the slug velocity increases as shown in figure 8.

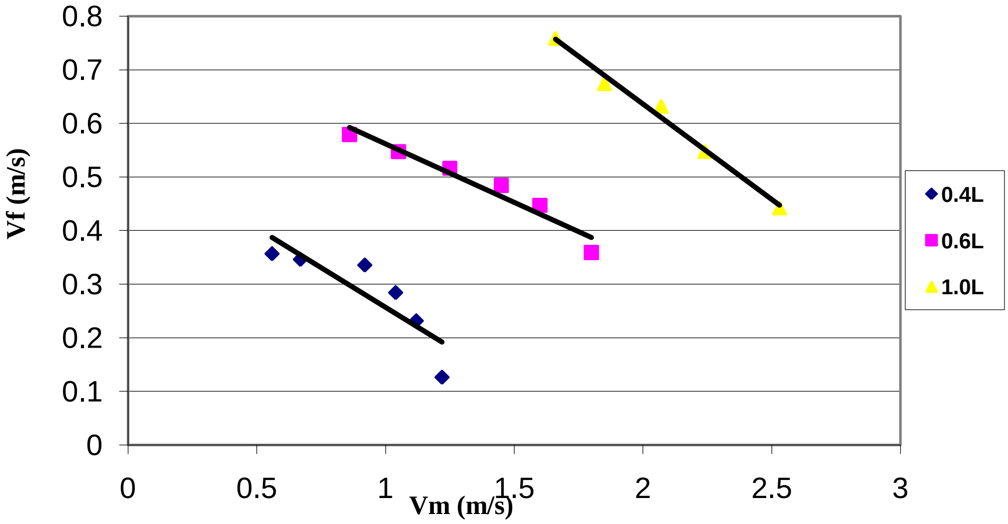

Figure 8: Film liquid velocity (Doppler) and mixture velocity

V. Liquid and Gas Flowrate Measurement within the Slug Flow

Since the velocities of the slug and the film are determined, the liquid and gas flowrate measurement can be obtained in combination with a conductivity ring which is installed to measure the fraction within the average slug body and film zone α_s and α_f , respectively.The flowrate of liquid and gas with the slug and film can be calculated from the following equations:

In these experiments, there were 4 fixed superficial liquid velocities (0.4, 0.6, 0.8 and 0.1m/s) associated with wide range of superficial gas velocities as it can be identified from the following figures.

- First, liquid flowrate measurement

Volumetric liquid flowrate in slug body and in film zone can be determined using the following equation:

$$Q_l = \frac{(t_s * \alpha_s * V_s + t_f * \alpha_f * V_f) * A}{(t_f + t_s)} \qquad (2)$$

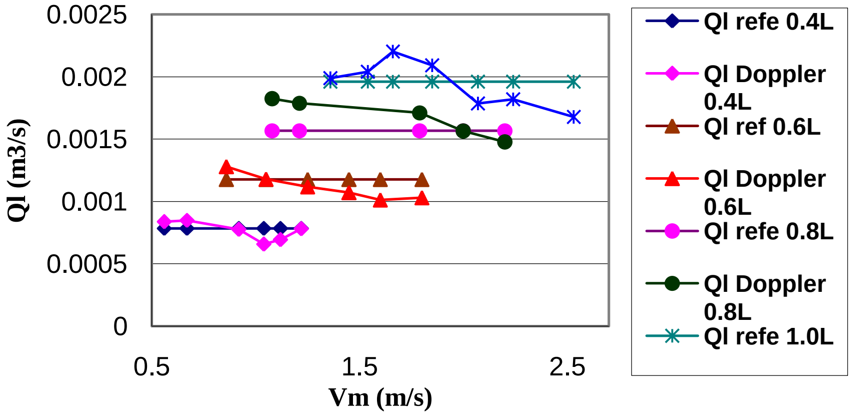

Figure 9: Volumetric liquid flowrate (Doppler) compared with the reference.

Figure 9 illustrates liquid ultrasonic Doppler flowrate performance in different gas flowrates starts from 0.2m/s to 1.2m/s to reach 66% GFV.

- Second, gas flowrate measurement

Assumingly, the slug velocity is the same as the gas velocity trapped between two slugs. The following equation can determine the volumetric gas flowrate:

$$Q_g = V_s * (1 - \alpha_f) * A \quad (3)$$

Where, Q_l and Q_g are volumetric flowrates of liquid and gas, respectively.

t_s and t_f are representing the average time when the slug and film body appears, this time can be obtain from the conductivity ring slug/film time measurement.

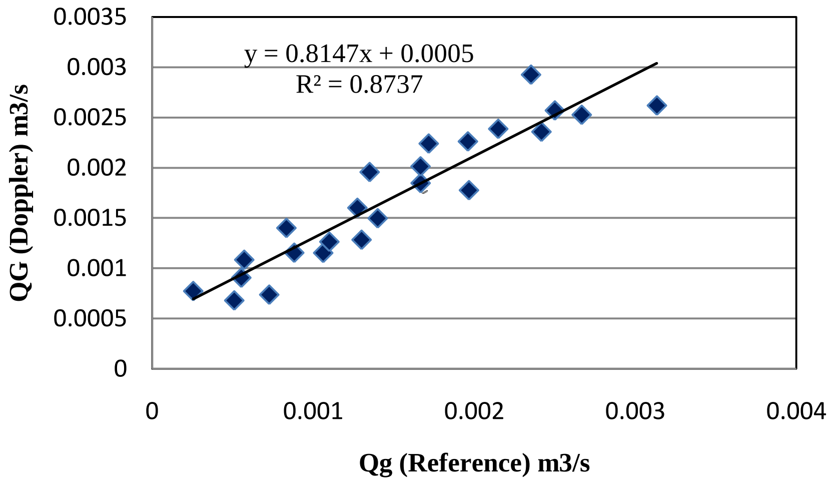

Figure 10: Volumetric gas flowrate (Doppler) compared with reference.

Comparing the gas flowrate measured via ultrasonic Doppler and the reference point, which measured via electromagnetic flowmeter. As a result, a good agreement was obtained, Figure 10 illustrates this agreement.

VI. Ultrasonic Doppler Measurements Validation

- First, slug flow measurement validation

Slug flow measurement using ultrasonic Doppler transducer has not been widely implemented to be able to compare slug velocity measurement. However, 'Al-lababidi and Sanderson (2006)' have used ultrasonic cross correlation method as slug velocity measurement; they reported that the slug velocity could be extracted from mixture velocity and some constants, as the follows[5]:

$$V_s = C_o * V_m + V_d \qquad (4)$$

To extract the coefficients C_o and V_d from slug velocity, they grouped their data as listed as the following:

Table 1: Slug flow coefficients and drift velocity

Group	Froude Number Values Range (Fr)
Group 1	Fr<2
Group 2	2<Fr<4
Group 3	Fr>4

Based on mixture Froude number the V_d and C_o can be obtained for each group.

$V_s = C_o * V_m + V_d$.

Group 1 : $V_s = 1.141 * V_m + 0.2017$ (5)

Group 2: $V_s = 1.1891 * V_m + 0.0285$ (6)

Group 3: $V_s = 1.20644 * V_m$ (7)

Figure 11, illustrates the comparison between slug velocity measurement using ultrasonic Doppler and slug velocity correlated.

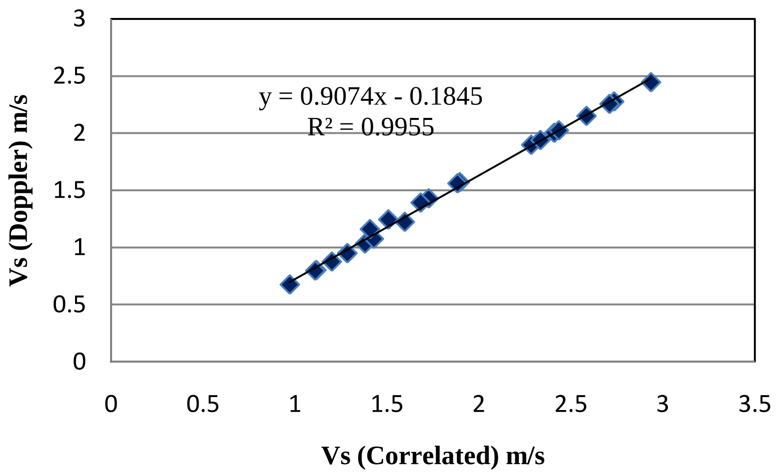

Figure 11: Slug velocity (Doppler) and slug velocity correlated.

- Second, film liquid measurement validation

Liquid film velocity measurement V_f was obtained by using ultrasonic Doppler installed at the bottom of the pipe where liquid is always existed whether it is as a result of slug or film flow.However, the film velocity measurement which was presented earlier needed to be validated with an available two phase flow liquid film velocity model.

Duckler and Hubbard developed a model where they assumed that there is no gas entrainment in the liquid film and no liquid droplet entrainment in the gas bubble.

By using standard turbulent velocity distribution in the slug, it was found out that:

$$C = 0.021 * \ln(\mathrm{Re}_s) + 0.022 \qquad (8)$$

Where, C is standard turbulent velocity distribution in slug and Re_s is Reynolds number in slug.

Where Reynolds number in mixture can be obtained using the following:

$$\mathrm{Re}_s = \frac{V_m * \rho_m * D}{\mu_m} \tag{9}$$

$$\rho_m = \rho_l * \alpha_s + \rho_g * \alpha_g \tag{10}$$

$$\mu_m = \mu_l * \alpha_s + \mu_g * \alpha_g \tag{11}$$

$$\alpha_g = (1 - \alpha_f) \tag{12}$$

Where, D pipe diameter, V_m mixture velocity. ρ_m and μ_m are mixture density and viscosity. ρ_l, ρ_g, μ_s, and μ_g are liquid and gas density, and liquid and gas viscosity, respectively.

So, film liquid velocity can be obtained from the following equation:

$$V_f\,calculated = V_m * (1 - C * \frac{\alpha_s - \alpha_f}{\alpha_f}) * \alpha_f \tag{13}$$

Figure12 shows some data for the comparison between liquid film velocity measured by Doppler and a correlated liquid film velocity.

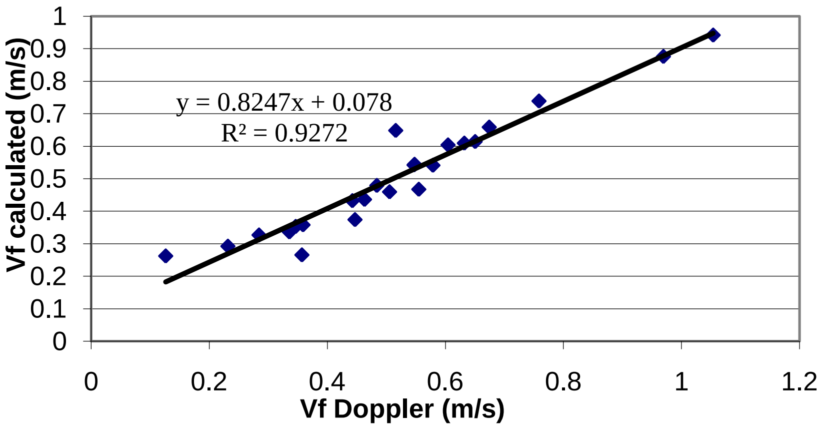

Figure 12: Film liquid velocity by Doppler and correlated

VII. Conclusion

By installing the ultrasonic Doppler (500 KHz) transducer at the bottom of the pipe (6 O'clock position), two phase (liquid/gas) slug flow has been investigated in term of accurately measuring slug body and liquid film velocities. In combination with a conductivity ring as a fraction measurement, slug liquid and film liquid flowrate as well as gas flowrate measurements have been successfully achieved. Ultrasonic Doppler measurement for liquid and gas flow-rates as well as the film velocity has been validated using different correlations available in the literature and a good agreement has been obtained.

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