

# Transit Time Ultrasonic Modelling in Gas/Liquid Intermittent Flow using Slug Existence Conditions and Void Fraction Analysis

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## Abstract

In this paper, the performance of the clamp-on transit time ultrasonic flowmeter is experimentally investigated in two-phase gas/liquid flow in straight pipes. Experiments on air-water horizontal slug flows in a 50 mm id pipe were conducted over operating conditions covering 0.3-4.0 m/s and 0.6-3.0 m/s gas and liquid superficial velocity ranges, respectively. The mathematical model presented in this paper is an improvement on the previous closure method which was developed by Al-lababidi & Sanderson. The algorithm of the new mathematical model is based on both the analysis of the slug existence conditions and the statistical signals analysis of the conductivity probes measurements. Minimum and average liquid heights were evaluated using the PDF (Probability Density Function) analysis of conductance probe measurements. Using this approach it is demonstrated that the ultrasonic clamp-on flowmeter provides good agreement with mathematical correlations for predicting the slug body velocity with  $\pm 5\%$ .

## 1. Introduction

The accurate prediction of multiphase flow characteristics is essential for flowmeter design and safe operation of oil and gas pipelines <sup>(1)</sup>.

Multiphase flow measurement is usually undertaken by methods which employ either partial separation or homogenization <sup>(1)</sup>. These are generally difficult to achieve in the slug regime which is one which commonly occurs in multiphase flows. There are other measurement techniques which can be employed such as neural networks. Closure methods such as that proposed by Stewart <sup>(2)</sup> are based on correlations to calculate the slug characteristics such as velocities in the slug zone, velocities in film zone, lengths for the slug and film zones, and the average velocities and hence the liquid and gas flowrates. However, when applied, this closure model gives a very large error in the measurement of the gas and liquid phases.

The mathematical model which is presented in this paper represents a new methodology of incorporating transit-time ultrasonic techniques in two-phase gas/liquid flows under different conditions of the existence of slugs, stable or unstable. The mathematical model is based on a model developed by Al-lababidi & Sanderson <sup>(3)</sup> to validate the estimated transit-time ultrasonic velocity in two-phase gas/water flows under slug flow conditions.

The new model considers the front of a slug as a one-stage sudden expansion (or as a hydraulic jump) and the back as an inviscid bubble of the type described by Benjamin <sup>(4)</sup>. The occluded air in the front part of the slug moves at the same velocity as the liquid in the slug and behaves as if it were uniformly distributed. Void fraction, translation velocities, the length of individual slugs, and the liquid heights (in front, body and behind the slugs) are measured using conductivity probes.

## 2. Transit-time Ultrasonic Flowmeter Principle

The transit-time ultrasonic method is based on the difference of the sound velocity in the flow direction and the opposite direction. This method gives a flow velocity averaged along a particular acoustical path. For a single beam device, to convert this path velocity to a velocity averaged over the entire-section of the flowing medium, the knowledge of the flow velocity profile is essential <sup>(5)</sup>. Ultrasonic flowmeters are affected by such distortions in velocity flow profile which often results in erroneous measurements. The velocity profile distribution is not usually flat and can vary significantly depending on the properties of the fluid and the pipe configuration in which it flows. The flow profile depends on the fluid viscosity, the Reynolds number, the relative roughness and the shape of the conduit, upstream and down stream disturbances, and whether the pipe is fully charged <sup>(5)</sup>.

Knowledge of the flow profile is critical in converting a flow reading along a particular beam to the velocity averaged over the entire cross-section of the flowing medium. The previous closure method removes the velocity profile correction factor introduced automatically by the flowmeter on the assumption of a fully developed flow in a fully charged pipe and substitutes it with an appropriate meter factor for a partially filled pipe. A correction factor of the cross sectional area of the flow is also made. As long as the average height of the liquid is above the 50% of the cross-section area of the pipe, the clamp-on transit-time ultrasonic flowmeter will continue to function. The closure method equation is:

$$Q_{\text{Estimated}} = Q_{\text{Indicated}} * \frac{A_{\text{partial}}}{A_{\text{full}}} * \frac{K_1(h)}{K_2(Re)} \quad (1)$$

where:  $Q_{\text{(Estimated)}}$  is the estimated ultrasonic liquid flowrate, which is the output from the closure method;  $Q_{\text{(Indicated)}}$  is the indicated ultrasonic liquid flowrate, which is the output from the clamp-on transit-time ultrasonic flowmeter, test output reading;  $A_{\text{partial}}$  is the partial-filled area of the pipe, which depends on the height of the water film;  $A_{\text{full}}$  is the cross-sectional area of the pipe;  $K_1(h)$ : is the correction factor for the height of the water film;  $K_2(Re)$ : is the velocity profile correction factor and it is calculated by firstly estimating a nominal Reynolds number from the experiment data and specific correlation<sup>(6)</sup>.

### 3. Calculation of the Algorithms of Slugs Existence Conditions

The parameters characterizing a slug are given in Figure 1. The tail, station 4, moves at the bubble velocity  $V_{tB}$ . Station 2 denotes the front, which moves at velocity  $V_{tF}$ . The bubbles dispersed in the slugs move with an average velocity  $U_{G3}$ . The void fraction within the slug at station 3 is  $\alpha$  and  $H_{LS}$  is the liquid height in slug body region. The slower moving liquid in front of the slug is accelerated to the average liquid velocity  $U_{L3}$  within the slug. The liquid shed at the back decelerates under the influence of wall shear and forms a stratified layer behind the slug with height  $H_{LF}$ . The stratified flow between slugs consists of a large gas bubble, moving with an average velocity  $U_{G1}$ , and a liquid layer moving with an average velocity  $U_{L1}$ .

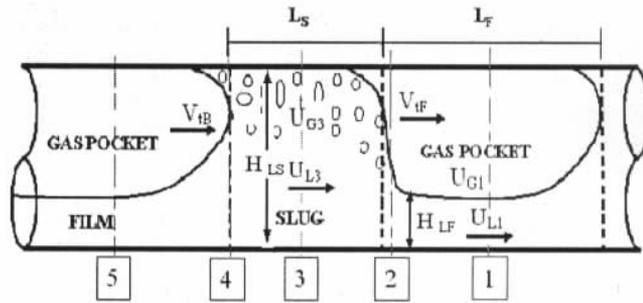


Figure 1: A profile of a Typical Slug in Two-phase Gas/Liquid Flows

### 3.1 Calculation of the Algorithms of Stable Slugs

A considerable simplification to the transmission ultrasonic measurement techniques in two-phase gas liquid can be made by assuming that every successive slug unit has an identical structure. This assumption results in the stable slug flow model. The pick up rates and shedding rates for each successive slug unit must be balanced. Consider a frame of reference moving with velocity  $V_{tF}$ . The stability requires that the volumetric flow of the liquid entering the slug at station 2 equals the rate at which liquid is shed at station 4. Therefore, the mass conservation of the liquid between stations 2 and 4 is derived:

$$(V_{tF} - U_{L1}) * A_{L1} = (V_{tB} - U_{L3}) * (1 - \alpha) * A \quad (2)$$

Where:  $V_{tF}$  is the front slug velocity;  $V_{tB}$  is the back or tail velocity;  $U_{L1}$  is the liquid velocity in the film zone;  $U_{L3}$  is the liquid velocity in the film zone;  $A_{L1}$  is the liquid area in the film region;  $A$  is the cross sectional area of the pipe and  $\alpha$  is the void fraction in the slug body. Hanratty et al<sup>(7)</sup> calculated the volumetric flow rate of liquid shedding from the tail of the slug  $X_L$  at station 4 as a function of slug velocities as given:

$$X_L = (V_{tB} - U_{L3}) * (1 - \alpha) * A \quad (3)$$

Choosing an inviscid solution given by Benjamin<sup>(4)</sup> which assumes negligible effect of aeration ( $\alpha = 0$ ):

$$X_L = 0.542 * A * \sqrt{gd} \quad (4)$$

From Equation (2), the liquid hold up in the film zone is derived:

$$H_{LF} = \frac{0.542 * \sqrt{gd}}{(V_{IF} - U_{L1})} \quad (5)$$

where  $H_{LF}$  is the liquid hold up in the film zone;  $g$  is gravitational acceleration; and  $d$  is the pipe diameter.

The liquid film velocity  $U_{L1}$  is given from Equation (5):

$$U_{L1} = V_{IF} - \frac{0.542 * \sqrt{gd}}{H_{LF}} \quad (6)$$

By substituting  $U_{L1}$  from Equation (6) in Equation (2), the liquid velocity  $U_{L3}$  in the slug body is given by:

$$U_{L3} = V_{IF} - \frac{H_{LF}}{H_{LS}} * (V_{IF} - U_{L1}) \quad (7)$$

Where  $H_{LS}$ : is the liquid height in the slug body zone.

## 4. Experimental Set-Up

### 4.1 Piping Arrangement & Flowmeter Instruments

The clamp-on transit-time ultrasonic validation mathematical model was tested on the 50mm diameter air/water facility over a range of gas flows, at constant liquid flowrate, where the injected rates of the liquid are accurately known and maintained as shown in Figure 2. Water is pumped to the test section using a positive displacement pump which has a maximum capacity of 35 m<sup>3</sup>/hr and a maximum discharge pressure 6 barg. The water flows from the pump is controlled by means of a by-pass line. The water flow is metered using a reference electromagnetic flowmeter and a GE Panametrics clamp-on transit-time ultrasonic flowmeter (Model DF868) in the test section. Compressed air is injected to the two-phase test through a special designed loop. This loop consists of a pressure regulator unit Instrument loading pressure and control valve, air filter, and mass flow controller. The air injection point is

located 1.5 m from the water inlet. The test section is 50 mm, i.d., and 875 mm long perspex pipe. The four pairs of flush-mounted conductivity probes and GE Panametrics clamp-on transit-time ultrasonic (DF868) were installed and located 17 m from the air/water mixing point. Data from two-phase air/water facility was acquired by a dedicated PC-based Data Acquisition System (DAS). This System consists of a Signal Conditioning Extensions for Instrumentation (SCXI) unit supplied by National Instruments and a series of custom-built signal conditioning units. Data was collected over a set of 12 channels, with a range of 0 to 5 V d.c. The incoming data was received by the 32 channel multiplexer and converted to an appropriate digital signal and this was then transferred to the PC via the parallel port multiplexer.

### 4.2 Conductivity Probes Spool Piece

The conductivity probes spool piece consists of four pairs of flush-mounted ring electrodes (A, B, C, and D). The probes were distributed along the perspex pipe of the test section with separation distance  $L_{AB} = 54$  mm,  $L_{BC} = 175$  mm, and  $L_{CD} = 275$  mm respectively.

### 4.3 Clamp-on Ultrasonic Flowmeter

The non-intrusive clamp-on transit-time ultrasonic flowmeter (DF868 Model) is mounted to the exterior of the spool. The clamp-on transit-time ultrasonic system consists of an electronics console, clamp-on ultrasonic transducers, connecting cables, and a clamping fixture to hold the transducers solidly in place on the pipe. A couplant is applied to the transducer faces to couple them acoustically to the outside pipe wall. The DF868 ultrasonic liquid flowmeter is operated in a single traverse mode where the transducers are mounted diametrically opposite each other, at approximately a 30° angle, and 32 mm axial distance between the transducers, and the ultrasonic signal is transmitted directly from one transducer to the other across the pipe.

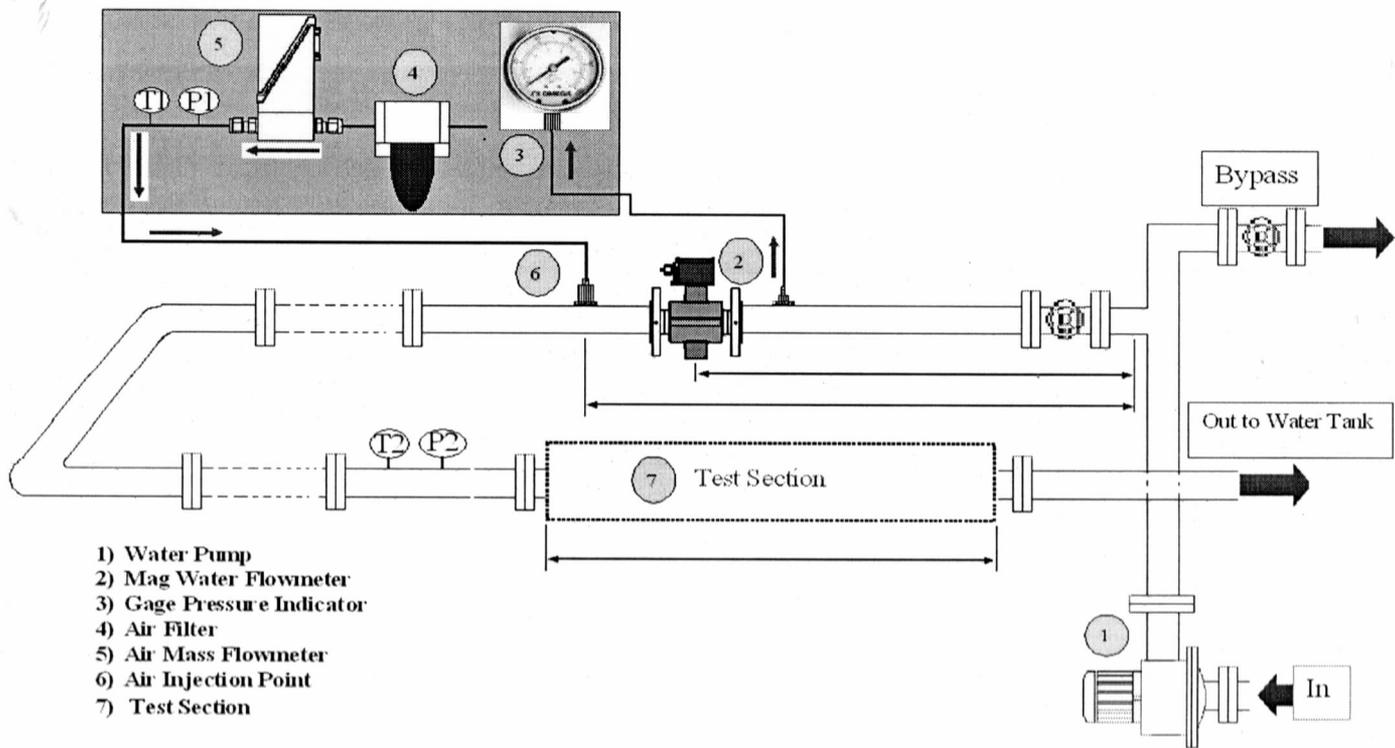


Figure 2: Schematic Diagram of the Two-Phase Air/Water Facility

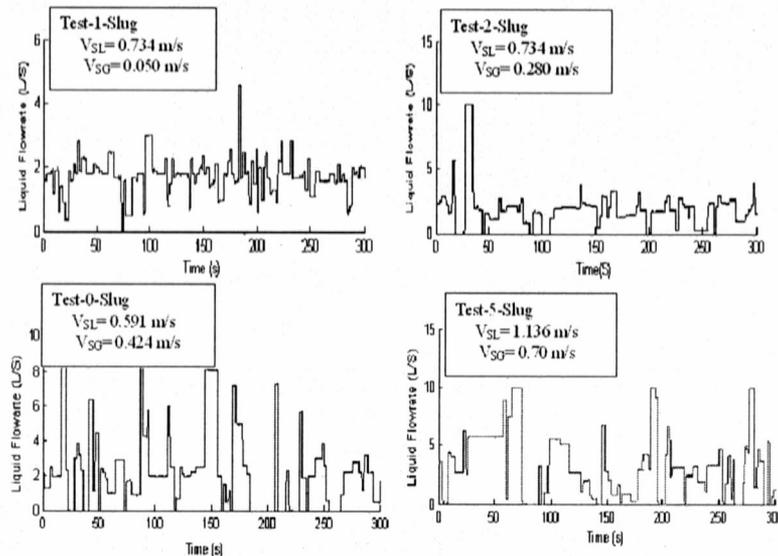


Figure 3: Clamp-on Ultrasonic Flowmeter Performance under Slug Flow Conditions

## 5. Test Results

A series of experiments was undertaken to investigate the behaviour and the performance of a clamp-on transit-time ultrasonic flowmeter in two-phase air/water flow.

The results show the performance of the liquid ultrasonic meter to be seriously affected by the presence of free gas in a

manner that is dependent on the actual flowrate of the gas and the flow regime. The performance of the clamp-on ultrasonic flowmeter under slug regime at different gas and liquid superficial velocities is shown in Figure 3. The number of the successful period and failure periods is dependent on the GVF in the system. By increasing the gas flowrate the number of the failure partition increases and the period of time of the successful partition is decreased.

## 5.1 Signal Analysis for Conductivity Probes Spool Piece (CPSP) Data

The distribution of the conductivity probes along the Perspex spool piece was used to calculate the translational velocity of the slug using signals cross-correlation technique. Figure 4 shows the PDF plot for slug flow at a  $U_{SL} = 0.591$  m/s and  $U_{SG} = 0.424$  m/s. In the PDF, Intermittent flow is associated with twin-peaks <sup>(8)</sup>, where the low liquid hold up (high void fraction) peak is pertinent to the stratified phase region and high liquid hold up (low void fraction) is associated with slug passage. From the analysis of the PDF, the following parameters can be determined:  $H_{LF}$  correspond to the low liquid hold up in stratified region,  $H_{LS}$  at which the maximum of the right peak occurs and  $H_{LS (MAX)}$ , where the PDF goes to zero.

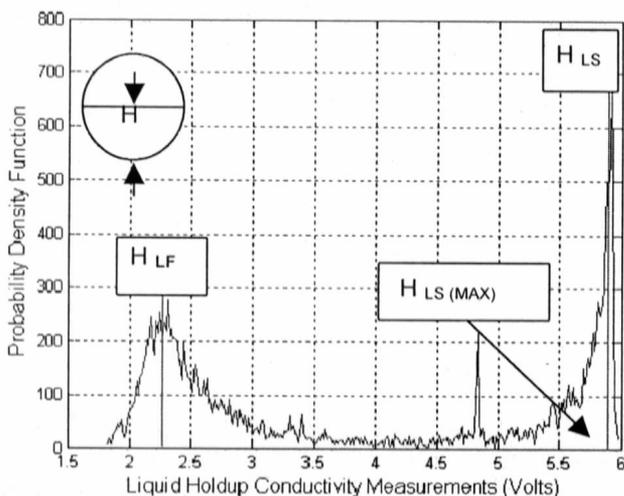


Figure 4: Liquid Hold up PDF Evaluation

In the determination of the time lag between signals a cross-correlation algorithm was used. The derived time was then used to calculate the translation velocity of the slug from the distance between the conductivities probes Equation (8): analysis of the conductivity probes data ( $C_{(A)}$ ,  $C_{(B)}$ ,  $C_{(C)}$ , and  $C_{(D)}$ ), Figure 5, the most straightforward technique for the

$$V_{t(XCORR)} = \frac{L(C_{(A)}C_{(D)})}{\Delta t} \quad (8)$$

Where  $L(C_{(A)}C_{(D)})$  is the distance between probes A and D.

The slug translation velocities calculated using this technique were compared with values derived from the theoretical correlations Table 1. The agreement is good for some cases, particularly at low velocity, but more erratic at higher mixture velocity.

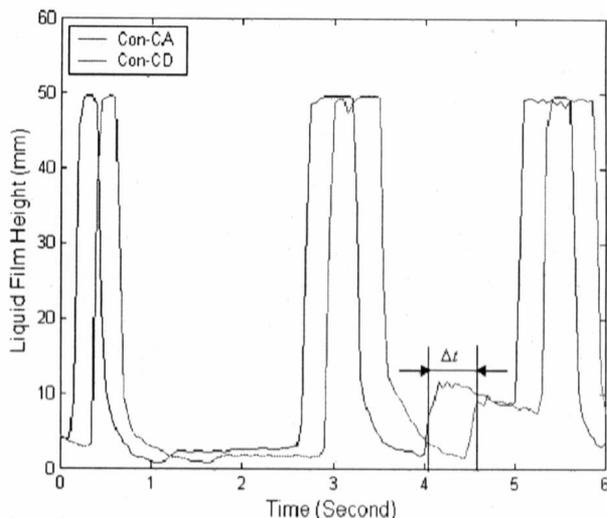


Figure 5: Holdup vs time from Conductivity Sensor Signal

## 5.2 Mathematical Correlations and $V_{(Estimated)}$ Validation

The aim of this work was to assess experience the performance of the clamp-on ultrasonic flow meter in two-phase air/liquid medium under slug flow conditions (low frequency slugs), and validate the estimated velocity  $V_{(Estimated)}$  with the slug body liquid velocity ( $U_{L3}$ ) which is derived from the mathematical correlations. The comparison of clamp-on ultrasonic estimated velocity  $V_{(Estimated)}$  and the slug body water velocity is shown in Table 2. At low slug frequency and low mixture velocity, the average estimated liquid slug velocity  $V_{(Estimated)}$  shows a good agreement with the slug body velocity ( $U_{L3}$ ) with an estimated error  $\pm 5\%$ .

				Signals Cross correlations	Nickline et al (1975)	Bendiksen (1984)
Test Conditions	$V_{(SL)}$	$V_{(SG)}$	$V_{(M)}$	$V_t$ (A&D) [XCORR]	$V_{(t)}$ [Calculated]	$V_{(t)}$ [Calculated]
	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
Test-0-Slug	0.591	0.424	1.015	1.268	1.217	1.394
Test-1-Slug	0.734	0.050	0.784	0.965	0.941	1.164
Test-2-Slug	0.733	0.280	1.013	1.014	1.216	1.393
Test-3-Slug	0.734	0.460	1.194	1.208	1.254	1.574
Test-4-Slug	1.143	0.440	1.583	1.508	1.662	1.963
Test-5-Slug	1.136	0.700	1.836	2.017	2.020	2.216

**Table 1: Two-Phase air/liquid Velocities**

Test Conditions	$V_{(SL)}$	$V_{(SG)}$	Clamp-on Ultrasonic Flowmeter	Mathematical Correlations Method	Error
			$V$ (Estimated)	UL3	
	(m/s)	(m/s)	m/s	m/s	%
Test-0-Slug	0.591	0.424	0.931	0.923	-0.914
Test-1-Slug	0.734	0.050	0.765	0.780	1.947
Test-2-Slug	0.733	0.280	0.850	0.806	-5.494
Test-3-Slug	0.734	0.460	0.943	0.946	0.402
Test-4-Slug	1.143	0.440	1.577	1.585	0.515
Test-5-Slug	1.136	0.700	1.689	1.677	-0.678

**Table 2: Comparison between  $V_{(Estimated)}$  and  $U_{L3}$**

## 6. Conclusion

The clamp-on transit-time ultrasonic flowmeter measurement was obviously and seriously affected by the presence of the second phase. As a result, a large deviation from the reference electromagnetic flowmeter was recorded. However, the closure method presented previously <sup>(3)</sup> offered a good improvement of the estimated slug body velocity  $V_{(Estimated)}$ . An algorithm was developed from the analytical structure of the slug flow with the assistance of the conductivity probes spool piece analysis. The algorithm was found to give a validation of the measured slug body velocity  $V_{(Estimated)}$  using the clamp-on ultrasonic technique and then compare it with slug body velocity derived from the algorithm. Bench tests have shown that under slug flow conditions with low mixture velocity,  $V_{(Estimated)}$  measured by clamp-on ultrasonic flowmeter shows  $\pm 5\%$  agreement with mathematical correlations.

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