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HORIZONTAL SLUG FLOW IN A LARGE-SIZE PIPELINE: EXPERIMENTATION AND MODELLING

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Abstract. *The knowledge of the slug flow characteristics is very important when designing pipelines and process equipment. When the intermittences typical in slug flow occur, the fluctuations of the flow variables bring additional concern to the designer. Focusing on this subject, the present work discloses the experimental data on slug flow characteristics occurring in a large-size, large-scale facility. The results were compared with data provided by mechanistic slug flow models in order to verify their reliability when modelling actual flow conditions. Experiments were done with natural gas and oil or water as the liquid phase. To compute the frequency and velocity of the slug cell and to calculate the length of the elongated bubble and liquid slug two pressure transducers were used to measure the pressure drop across the pipe diameter at different axial locations. A third pressure transducer measured the pressure drop between two axial locations 200 m apart from each other. The experimental data were compared with results of Camargo's[1] algorithm (1991, 1993), which uses the basics of Dukler & Hubbard's (1975) slug flow model, and those calculated by the transient two-phase flow simulator OLGA.*

Keywords: *Slug Flow, Gas-Liquid Intermittent Flow, Two-Phase Flow Instrumentation*

1. INTRODUCTION

The most used mechanistic representation of the slug flow is the unit cell model: the flow unit is composed of an aerated liquid slug and an elongated bubble. These singular structures succeed each other in the test section in an intermittent fashion, causing a fluctuation in the flow variables: velocities, flow rates, pressure gradients. Hence, the knowledge of the characteristics of the slug flow pattern, i.e., the frequency and velocity of the unit cell and the length of the liquid slug and elongated bubble, among other variables, is very important when sizing pipelines and designing receiving vessels and pre-processing equipment. The velocity of the unit cell, for example, determines the instantaneous gas and liquid flow rate delivered to a receiving vessel; the length of the liquid slug correlates strongly with the pressure drop.

The large amount of published papers presenting measurements and discussing the modelling of slug flows reflects the fact that this is the flow pattern that most frequently occurs in petroleum pipelines. The slug flow models based on the unit cell concept (Dukler and Hubbard, 1975 and Nicholson et al., 1978) are quite usual nowadays, composing some of the commercially available codes used by the oil industry to calculate two-phase flow facilities. These semi-empirical models rely, for development and comparison, on data bases generated by experimentation. However, the great majority of published data on the slug flow characteristics were taken in small-scale laboratory facilities, running with mixtures of air and water. Only a few data were collected in large-scale facilities (Gregory et al., 1978 and Gonçalves et al., 1996).

The objective of this work was directed toward this lack: one presented a set of measurements carried on a 6 inches horizontal pipeline, 200 m long, which is part of the test rig of Atalaia, operated by Petrobras. To identify and measure the structure of the slug flow, i.e., frequency and velocity of the unit cell, the length of the liquid slug and elongated bubble and the pressure drop, the signals delivered by pressure transducers were registered and processed. Two transducers measured the differential pressure across the pipe diameter at two distinct axial positions and a third transducer measured the pressure drop between two sections 200 meters apart. A complete set of data on the structure of gas-liquid slug flows was acquired. Limited results for gas-oil mixtures are also presented. To verify the adequacy of the mechanistic models based on the unit cell approach in modelling two-phase intermittent flows, the experimental data were compared with those calculated by Camargo's (1991, 1993) algorithm, which uses the basics of Dukler & Hubbard's (1975) slug flow model, and those calculated by a two-phase flow code. In this former case, simulation results delivered by OLGA version 3.3, a dynamic two-phase flow code, extensively used by the oil industry, were used as references.

2. TEST FACILITY, INSTRUMENTATION AND DATA PROCESSING

The experimental work was accomplished at the PETROBRAS Atalaia Test Site, located in northern region of Brazil. The test facility comprises pipelines and the auxiliary equipment, such as pumps, separators and stocking vessels. The flow diagram is depicted in Figure 1. The test section was a horizontal pipeline, 6 in (0.15 m) internal diameter and 200 m long. Two branchs of 100 m, approximately, connected by a long radius (10 meters) curved pipe, formed the total length of the test section. Due to such a long radius curve the test section was considered a straight pipeline for the calculation of pressure drop.

The instrumentation available in the test site included orifice plates for measuring the gas flow rate and a Coriolis mass meter for the liquid (water or oil) phase. These industrial size instruments were calibrated before the tests. The measurements consisted of 10 blocks of data, covering the range of superficial velocities (j_G ; j_L) equal to (0.49 m/s ~ 1.5 m/s ; 0.51 m/s ~1.6 m/s) for the water – gas mixture, and 13 blocks of data covering the range of (j_G ; j_L) equal to (0.38 m/s ~ 1.3 m/s ; 0.45 m/s ~1.5 m/s) for the oil – gas mixture. The oil and gas actual flow rate was reduced to the test section conditions taking its PVT properties.

To measure the frequency and velocity of the unit cell, ν_s and V_t, respectively, and to calculate the length of the liquid slug and elongated bubble, l_u and l_s, one acquired and processed the signal delivered by two pressure transducers.

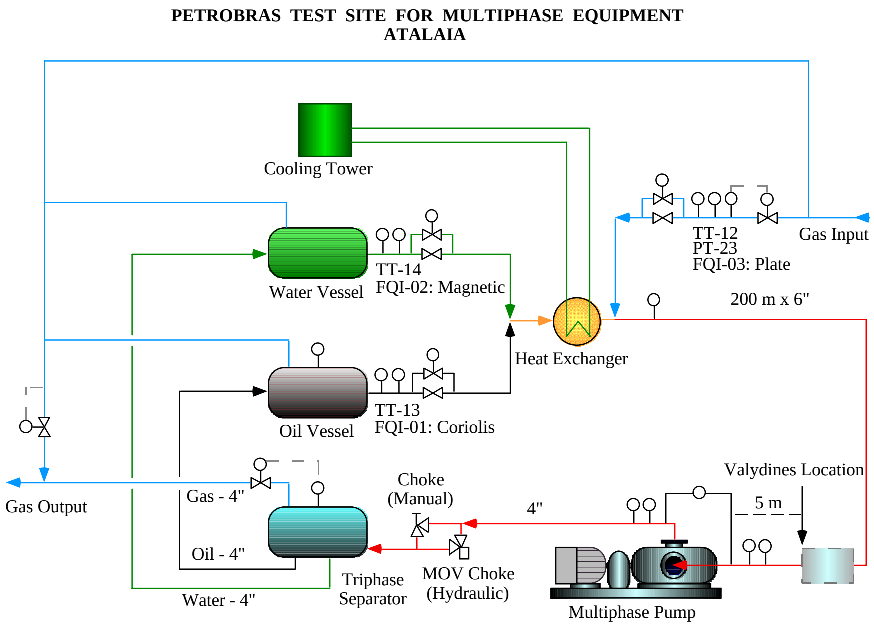

Figure 1- Flow diagram of the test facility.

These transducers measured the pressure difference across the pipe diameter, along the vertical axis, at two different axial position 0.7 meters apart. As the two structures composing the slug unit cell have distinct liquid hold-up, the measurement of the differential hydrostatic pressure across the pipe diameter must reveal this fact. Figure 2 depicts the unit cell, the variables defining the structures and the arrangement of pressure transducers. A third pressure transducer was used to measure the pressure drop in the test section.

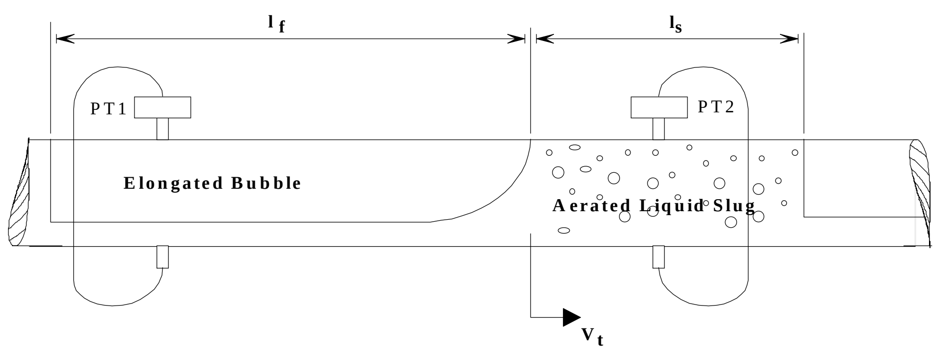

Figure 2- Slug flow unit cell, characteristic variables and instrumentation arrangement

The signals generated by the three transducers were conditioned and acquired in a Macintosh computer by a National Instruments MIO-16 A/D bus board. The software for data acquisition and processing was written in “G”, the graphical language used by National Instruments’ LabView®. The frequency of data acquisition was 100 Hz. A total of 16384 points pertaining to the twin signals generated by the differential hydrostatic pressure measurement were acquired in every run. In the corresponding time interval, there were various long-term fluctuations of the slug flow pattern. Figure 3 (a) shows a 40 seconds sample of the twin signals, the red line representing the relative output of the upstream sensor, and the blue line, the downstream sensor.

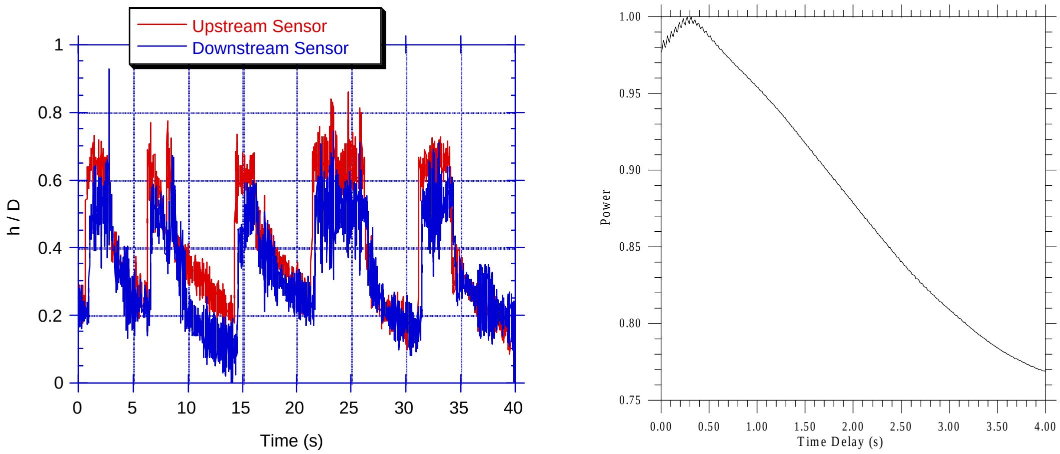

Figure 3 – (a) Twin signals delivered by the differential hydrostatic transducers (j_G = 0,61 m/s, j_L = 0,89 m/s); (b) typical cross-correlation and time shift of twin signals, j_G = 0,61 m/s and j_L = 0,89 m/s.

The frequency of the unit cell resulted from the power spectra of either one of the twin signals. The velocity of the unit cell is the distance between the hydrostatic probes, 0.7 m, divided by time shift between their respective signals. The cross-correlation of the twin signals delivered this time shift. Figure 3 (b) is a typical cross-correlation of the twin signals; the peak in the curve indicating the most likely time shift, 0.27 seconds. In this case the unit cell velocity is 2,59 m/s ± 2%.

To calculate the length of the liquid slug and elongated bubble, one had to set a threshold level to identify and separate the portion of the pressure signal pertaining to each structure. The elongated bubble flows like a separated two-phase pattern: the gas is adjacent to the upper pipe wall and an accelerating liquid film flows on the bottom of the pipe. Contrasting, the liquid slug can be thought as a dispersed flow pattern, with a dominant liquid volume surrounding small gas bubbles. Thus, the higher pressure corresponded to the liquid slug. The reducing pressure reflected the liquid film profile under the gas bubble. After inspection, a threshold level is set and the time interval corresponding to both structures is obtained. The length of the elongated bubble, l_f, and liquid slug, l_s, were calculated dividing the velocity of the unit cell by the associated time interval.

The pressure gradient along the test section was calculated dividing the time averaged pressure drop signal by the total length of the test section. Due to the high-pressure (up to 20 Kgf/cm^2) in test section and the use of flaming fluids (oil and gas), direct visualization was not performed.

Table 1 - Fluid Properties

Fluid	Temperature (°C)	ρ_L (Kg/m^3)	μ_L (Kg/m.s)	σ (N/m)
water	21	1000	$0,95 \times 10^{-3}$	0,073
oil	21	860	15×10^{-3}	0,0157
gas	21	$\rho_G = \rho_G$ (P,T)	$0,015 \times 10^{-3}$	-

3. RESULTS

To verify the adequacy of mechanistic models in disclosing the characteristics of the slug flow structures a special strategy was adopted, in this work. Horizontal slug flow models based upon the unit cell approach use, as a closure condition, a constitutive equation for the unit-cell (or slug) frequency or a correlation giving the length of the liquid slug or elongated bubble. OLGA requires the input of a ‘user supplied value’ for the slug frequency. Camargo’s (1991) algorithm has embedded correlations for the slug frequency, as Hill & Wood’s (1990), or slug length, like Nicholson et al. (1978) and Barnea & Brauner’s (1985). Besides, it accepts ‘user supplied values’’ for the slug frequency. With such degree of freedom, one calculated, with both codes, the variables characterizing the structures of the slug flow. Values for the slug frequency, as calculated by Hill & Wood’s correlation, were input into Olga. The measured values of the slug frequency were the ‘user supplied value’ into Camargo’s algorithm. Doing this, one was able to compare the results delivered by both codes and access the performance of a mechanistic model, comparing the results against measured data and values calculated by a commercial code.

3.1 Results for the gas-water mixtures

In Table 2 there are the 10 measured and calculated data points for the gas-water mixture. In the first two columns appear the *in situ* liquid and gas superficial velocities. The velocity of the unit cell is in the third column. The frequencies, as calculated by the OLGA code and the measured ones, follow. The three columns corresponding to each one of the following variables: length of the liquid slug, length of the elongated bubble and pressure drop are: the values calculated by OLGA, the values calculated by the Camargo’s code and the measured values. It is important to emphasize, once again, that the input frequencies in Camargo’s code were the measured ones.

If the velocity of the unit cell was correlated as a ‘drift flux like’ linear relationship,

$$V_t = C \cdot j + V_{dj} \tag{1}$$

where j is the total superficial velocity, (j_G+j_L), C is the angular coefficient and V_{dj} is a ‘drift velocity’, the result would be: C = 0,94 and V_{dj} = 1,07 m/s. These are reasonable values, validating the measured data in terms of averaged input quantities. Camargo’s code used the values suggested by Bendiksen (1984): C = 1,06 and V_{dj} = 0,73 m/s. The values suggested by Alves (1991) for a 10° inclination pipeline, are C = 1,06 and V_{dj} = 0,65 m/s.

Table 2. Results for gas-water mixtures. Calculated and measured values

Superficial Velocities		Vb (m/s)	Frequency (Hz)		Ls (m)			Lb (m)			Pressure drop (Pa/m)		
J_L (m/s)	J_G (m/s)	Measured	Olga's	Measured	Olga's	Camargo's	Measured	Olga's	Camargo's	Measured	Olga's	Camargo's	Measured
0,49	0,59	1,94	0,060	0,061	12,0	10,0	7,8	18,6	22,2	24,0	24,5	25,6	25,2
0,49	0,99	2,92	0,048	0,049	13,0	11,2	12,8	34,0	38,4	46,9	29,4	34,3	34,4
0,90	0,61	2,59	0,117	0,098	10,9	12,5	10,9	8,3	12,6	15,7	58,8	63,2	64,6
0,90	0,61	2,26	0,117	0,122	10,8	12,5	7,6	8,4	12,6	10,9	58,8	63,2	65,3
0,94	0,89	2,59	0,104	0,128	12,0	9,1	7,3	12,5	13,2	12,9	73,5	79,5	83,9
1,21	0,78	3,04	0,144	0,177	11,9	9,0	7,2	7,4	8,2	10,0	103,0	108,5	112,0
1,37	0,97	3,04	0,162	0,238	11,4	7,3	5,5	7,1	7,3	7,2	132,4	142,0	144,4
1,39	1,16	3,68	0,150	0,269	12,8	6,3	5,3	9,3	7,5	8,4	142,2	157,3	152,4
1,52	1,37	3,68	0,145	0,287	13,9	6,6	3,4	11,0	7,8	9,4	171,6	193,0	167,7
0,93	1,59	3,68	0,084	0,214	14,6	4,2	3,0	29,2	13,1	14,2	116,5	111,2	113,8

The first conclusion that arouse from the analysis of the data in Table 2 was that the frequency calculated by Hill & Woods’ correlation only agreed with the measured one for low and medium gas and liquid (water) superficial velocities, up to 1,0 m/s. For higher superficial velocities, the difference between measured and calculated values increased progressively and goes beyond 100% for the highest gas flow rate, j_G = 1,59 m/s. Figure 4 compares the frequency, measured against calculated data. The dotted lines encompass a deviation of ±30%. The highest frequencies, corresponding to the highest superficial velocities, presented the largest deviation. The comparison between the other variables must take into account these differences, as the measured frequencies were input values in Camargo's code.

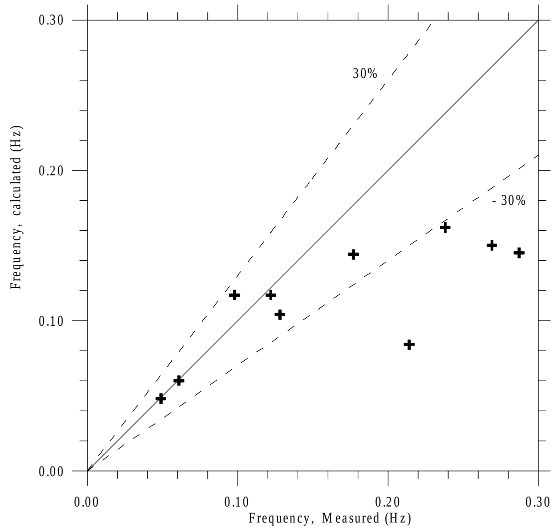

Figure 4 – Unit cell frequency: measured versus calculated (Hill & Wood's)

Figure 5 depicts the length of the liquid as calculated by OLGA (cross) and Camargo's (open circle) code plotted against measured data. The values calculated by Olga suggest a

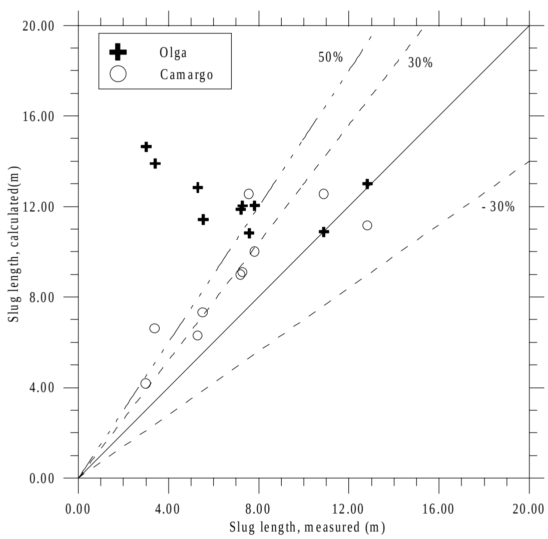

Figure 5 - Slug length: measured versus calculated data

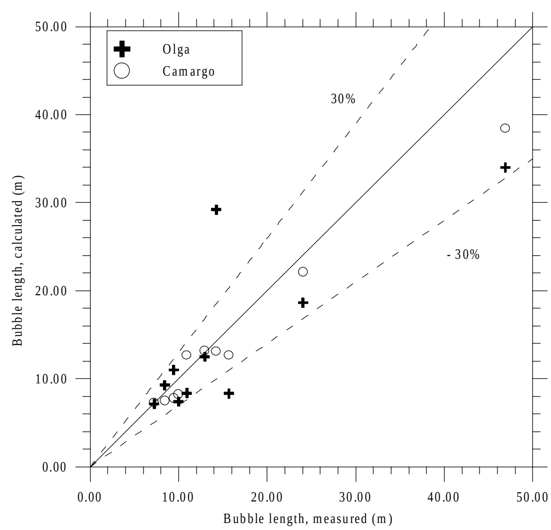

Figure 6 - Bubble length: measured versus calculated data

somewhat constant slug length, from 10,8 m to 14,6 m, within the full range of superficial velocities applied in the experiments. The measured values were within the range of 3,0 m ~ 12,5 m, the lowest values corresponding to the highest superficial velocities for both the gas and the water. The deviation between calculated and measured for 7 out of 10 data was greater than +50%. Camargo's code calculated the slug length much closer to the measured value. Most of the values were within the ±30% limiting lines, in the full range of superficial velocities applied.

The data in Table 2 revealed that very long bubbles (46 meters) existed for the lowest total superficial velocities. As both the gas and water superficial velocities increased, the elongated bubble became shorter. The codes were able to disclose this phenomenon. The values calculated by OLGA and Camargo's code were in reasonable agreement, as well as the measured and calculated data. The full set of data was within the range of ±30%, as showed in Figure 6. The values calculated by Camargo's code, however, were closer to the measured ones.

In Figure 7 appears the comparison between the measured and calculated pressure drop. Both codes calculated values that compared well with the measured ones, within ±20%, in the full range of superficial velocities applied in the experiments. Once more, the values calculated by Camargo's code were closer to the measured ones, with the exception of the value connected with the highest water superficial velocity. At this point is important to turn back to the mechanistic representation of the slug flow, in regard to the pressure drop calculation. Camargo's code used the proposition of (Taitel & Barnea, 1990), which added three terms to calculate the pressure drop along the unit cell: the frictional in the liquid slug, the frictional in the elongated bubble and the gravitational in the unit cell:

$$\Delta P_u = \frac{\tau_s \pi D}{A} l_s + \int_0^{l_f} \frac{\tau_f S_f + \tau_G S_G}{A} dx_f + \rho_u g \sin\beta l_u \qquad (2)$$

In Equation 2, β is the pipe inclination regarding the horizontal, l_u is the length of the unit cell, (l_s+l_f), g is the acceleration of gravity, ρ_u is the mean density of the unit cell, τ is the shear stress, S is the wet perimeter, A is the cross-sectional area, D is the pipe diameter, x is the axial direction and the subscripts $_s$ and $_f$ refer to the elongated bubble and the liquid slug, respectively. In a horizontal pipeline the gravitational term vanishes. The friction in the liquid slug exceeds, by far, the friction in the elongated bubble. Thus, if the code relied on the unit cell concept to calculate the characteristics of the unit cell, it must estimate the slug length correctly in order to calculate accurate pressure drops for different mixtures, flow properties and range of superficial velocities encountered in actual flows. The OLGA code, in spite of measuring slug lengths that did not agree with the measured ones in the full range of superficial velocities, calculated quite well the pressure drop.

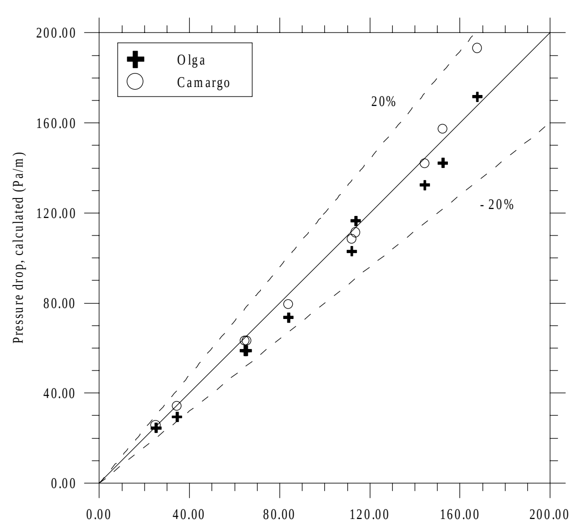

Figure 7 - Pressure drop in gas-water mixtures: measured versus calculated data.

3.2 Results for the gas-oil mixtures

There were limited results in this case: only the unit cell frequency, the relative length of the elongated bubble and the pressure drop could be measured due to a lack of correlation between the signals caused by a transducer malfunction. The relative length of the elongated bubble, ξ, is defined as the bubble length over the length of the unit cell:

$$\zeta = \frac{l_f}{l_f + l_s} \tag{3}$$

Table 3. Results for gas-oil mixtures. Calculated and measured values

Superficial Velocities		Frequency (Hz)		Relative length (β)			Pressure drop (Pa/m)		
J_L (m/s)	J_G (m/s)	Olga's	Measured	Olga's	Camargo's	Measured	Olga's	Camargo's	Measured
0,38	0,48	0,071	0,061	0,71	0,65	0,64	12,3	29,7	21,8
0,38	0,84	0,047	0,067	0,79	0,77	0,73	16,7	40,0	30,0
0,41	1,13	0,060	0,104	0,80	0,83	0,74	110,3	54,3	34,2
0,39	1,55	0,127	0,067	0,84	0,85	0,71	26,0	63,9	46,3
0,81	0,45	0,185	0,134	0,43	0,43	0,53	37,8	86,6	61,9
0,72	0,76	0,134	0,177	0,59	0,61	0,62	38,2	85,7	76,8
0,70	1,12	0,110	0,165	0,68	0,70	0,68	45,1	104,8	90,1
0,69	1,53	0,098	0,165	0,74	0,75	0,71	52,0	125,6	104,4
0,99	0,47	0,229	0,287	0,38	0,42	0,49	51,5	116,7	112,4
1,02	0,82	0,194	0,232	0,50	0,53	0,55	66,2	147,7	135,2
0,97	1,14	0,165	0,159	0,58	0,58	0,63	71,1	162,2	145,9
1,01	1,53	0,146	0,269	0,63	0,67	0,66	83,4	200,2	176,1
1,30	0,46	0,335	0,330	0,31	0,31	0,48	79,4	178,4	174,0

Similarly with what has happened for the gas-water mixtures, the difference between the frequencies calculated by Hill & Wood's correlation and the measured ones increased for the highest gas superficial velocities. However, as Figure 8 depicts, the data spread over the expected value - the straight line in the plot - indicates that correlation was able to trace the data trend.

The plot of the measured versus calculated bubble relative length is in Figure 9, as calculated by OLGA and Camargo's code. The agreement was reasonably good, most of the data were within ±20%, if one considers the full range of superficial velocities applied. The agreement between the data delivered by the two codes was even better.

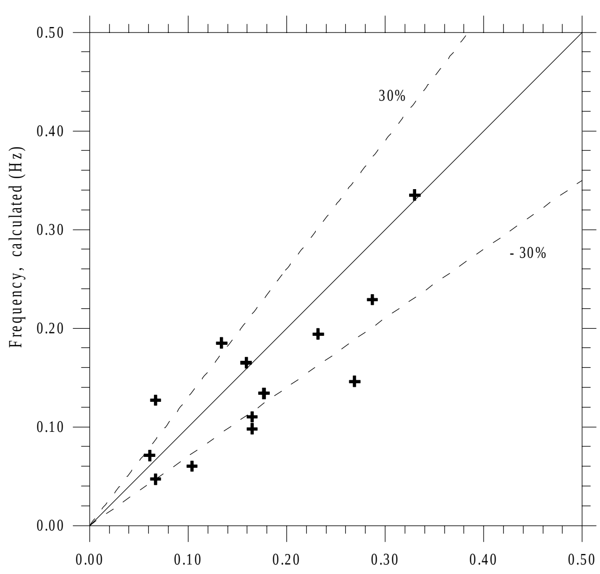

Figure 8 – Unit cell frequency: measured versus calculated (Hill & Wood's)

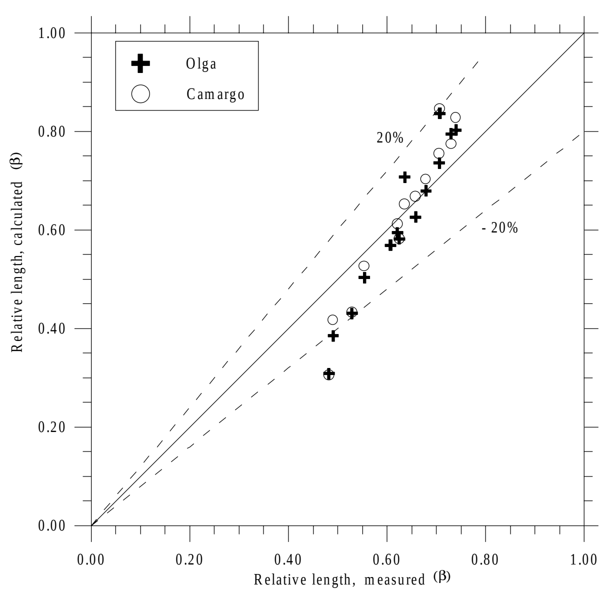

Figure 9 – Bubble relative length: measured versus calculated

Considering the fact that the Olga code used better adjusted values for the frequency of the unit cell in gas-oil mixtures, and the good results it delivered for the bubble relative length, surprised the values it calculated for the pressure drop. Figure 10 compares the data calculated by OLGA and Camargo's code with the measured ones. While the values delivered by Camargo's code, which used the measured frequencies as input data, were, in the full range of superficial velocities applied in the experiments, upper-bounding the measured data with an average deviation of less than + 20%, the values calculated by OLGA were consistently lower. The deviation augmented as the pressure drop increased, reaching –60% of the measured value.

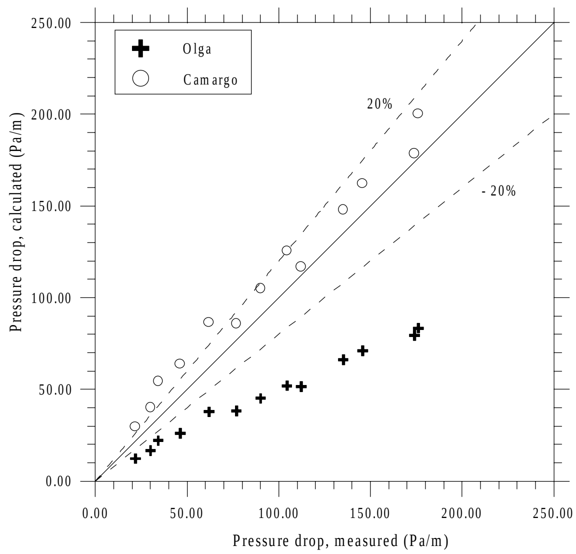

Figure 10 - Pressure drop in gas-oil mixtures: measured versus calculated

CONCLUSIONS

This work disclosed experimental data on slug flow characteristics occurring in a large-size, large-scale facility. These data, which included the frequency and velocity of the unit cell, the length of the liquid slug and elongated bubble, the relative length of the elongated bubble and the pressure drop, were performed for mixtures of distinct properties, natural gas + water and natural gas + oil. The measured data were compared with calculated values provided by OLGA, a commercially available transient two-phase flow simulator, and Camargo's (1991) algorithm, which is based upon the unit cell concept. The comparison between the measured and calculated data revealed that the use of proper closure conditions are essential for the adequate calculation of the characteristics of the slug flow structures over a full range of actual flow rates and fluid properties. Moreover, the comparison revealed that even when the codes used the same frequency input value, the calculated data do not necessarily agree among them. The results delivered by the "unit cell code" code were sistematically closer to the measured ones.

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