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EXPERIMENTAL ANALYSIS OF PRESSURE DROP OF HORIZONTAL TWO-PHASE SLUG FLOW IN CORRUGATED PIPELINES

Lucas Y. Kashiwakura, lucaskashiwakura@gmail.com
Carlos E.R.S.C. Mendoza, mendoza.cadu@gmail.com
Carlos L. Bassani, langebassani@gmail.com
Henrique Stel, henriqueazevedo@utfpr.edu.br
Fernando C. Vicencio, fernando_castillo_@outlook.com
Rigoberto E.M. Morales, rmorales@utfpr.edu.br
Multiphase Flow Center (NUEM), Postgraduated Program in Mechanical and Materials Engineering (PPGEM), Federal University of Technology – Paraná (UTFPR) – Av. Sete de Setembro, 3165 - Rebouças CEP 80230-901 - Curitiba - PR - Brasil

Abstract. *Slug flow is a common flow pattern found in oil and gas production in offshore applications. The pressure drop estimation for this flow pattern has been largely studied over the last decades due to its importance in facilities' designs. Most part of those studies considered the pipe roughness, but not its inner corrugated geometry, which is a project constraint due to duct flexibility needs. This geometry affects the pressure drop due to turbulence and drag induced by the discrete cavities on the wall, and then it shall be contemplated on the models. For these purposes, an experimental loop has been designed for pressure drop measurements of air-water slug flow on corrugated pipes for three different groove geometries. The measurements were compared to the results obtained from Lockhart-Martinelli's methodology, which proposes a correction factor over the single-phase pressure drop prediction. The methodology showed accordance for corrugated pipelines and the new coefficients of the curve fitting are presented in this work. The pressure drop estimation using this new curve fitting is within a ±20% accuracy range.*

Keywords: *multiphase flow, slug flow, corrugated pipes, pressure drop.*

1. INTRODUCTION

Multiphase flows can assume several spatial configurations depending of the flow characteristics, as superficial velocities, phase fractions, fluid properties, and pipeline diameter and inclination. These spatial configurations are known as flow patterns. Among them stands out the intermittent pattern, also known as slug flow pattern, which is frequently found in nuclear and oil industries. Slug flows are characterized by the successive intermittent passage of the so called unit cells, composed by a liquid slug, which might contain small dispersed bubbles, and an elongated bubble, which slips over a liquid film.

In the oil extraction process, knowledge of flow characteristics such as the pressure drop or the friction factor is important for facilities' design. The pressure drop is related to the drag due to the pipe wall and to the phase's interface. It is also highly dependent on the mixture velocity and the phases' properties, interaction and spatial configuration. From a unit cell idealization, Dukler and Hubbard (1975) suggest that horizontal slug flow pressure drop occurs due to the drag on the pipe wall and to the liquid film acceleration necessary to reach the slug velocity during the scooping phenomena. Taitel and Barnea (1990) extended this study for flow in any pipe inclination, adding terms related to weight/buoyancy forces (gravitational term), to drag on liquid-gas interface and to the elongated bubble shape. Finally, Cook and Behnia (2000) highlight the importance of head loss on the elongated bubble rear due to a fluid recirculation resulted from the hydraulic jump.

Several experimental correlations and mechanistic models for pressure drop and friction factor prediction have been developed since the 1950's. Lockhart and Martinelli (1949) propose an association of the single-phase pressure drop with a correction factor. Chisholm (1967) presents a simple correlation to determine this correction factor as a function of the ratio of liquid and gas single-phase flow pressure drops. Beggs and Brill (1973) suggested correction factors for two-phase flow drag based on a single-phase friction factor, the mean phase fraction and the pipeline inclination. García *et al*. (2007) developed a correlation for the two-phase flow friction factor as a function of the liquid Reynolds number, validating their correlation with a large data base.

The previously cited correlations were obtained for pipes without inner discrete cavities. However, in offshore oil production scenarios the ducts are corrugated, which provides flexibility to the pipelines and, therefore, resistance to the oscillations in the seabed. Moreover, it simplifies their transportation and installation processes, due to its kilometric extension. The discrete cavities, originated during the pipe manufacturing process, are periodically spaced inside the pipelines. As a negative characteristic, these cavities increase drag globally, which have to be considered during the production line design.

However, estimating the friction factor in geometries with corrugated walls is not an easy task, even for single-phase flows. The influence of the cavities on the flow pattern largely depends on its aspect ratio (Perry *et al*., 1969), width and pitch (Jimenez, 2004). In addition, they can increase the turbulence intensities close to the wall, increasing the global shear stress in accordance (Djenidi *et al*., 1994). The friction factor in corrugated pipes is also a complicated combination of form and friction drags (Vijiapurapu and Cui, 2007). Stel *et al*. (2012) developed a friction factor correlation for single-phase turbulent flow in corrugated ducts as a function of the groove geometric characteristics, which is valid for a range of flexible pipe geometries used by the petroleum industry. The authors affirm that the cavity width in the flow direction is the most sensitive parameter in head loss, but their correlation is not valid for two-phase slug flows.

Owing to this lack of studies, the goal of this paper is to study the pressure drop for two-phase slug flow in horizontal corrugated pipes used by the petroleum industry. Experimental data for pressure drop in corrugated tubes were measured using pipes with different groove dimensions. These experimental measurements were fitted to the Lockhart and Martinelli's (1949) methodology and new correction factors were obtained and presented in this paper.

2. PRESSURE DROP MODEL

The present work extends the Lockhart and Martinelli's (1949) pressure drop calculation methodology for horizontal corrugated pipes. The Lockhart and Martinelli's (1949) model, also known as separated model, adjusts the two-phase pressure drop using a correction factor over a single-phase pressure drop in case of each phase flowing separately. This correction factor is a regression from experimental data. Thus, it already considers the interaction between the two phases, such as liquid-wall, gas-wall and phases' interface drags, including the mixture zone pressure drop phenomena. Lockhart and Martinelli's (1949) methodology presents a fair accuracy and remarkable simplicity when compared to others pressure drop models, hence it is often used in field applications.

The single-phase pressure drop is calculated assuming only single-phase flow in the pipeline, and can be calculated from superficial velocities. The pressure drop of a single-phase flow is given by:

$$\left.\frac{dP}{dL}\right|_{S\psi} = \frac{f_{S\psi}\rho_\psi j_\psi^2}{2D} \tag{1}$$

where $f_{S\psi}$ is the friction factor for single-phase flow, ρ_ψ is the phase density, j_ψ is the superficial velocity of the phase and *D* the pipe inner diameter. The subscript *S* indicates a hypothetical case of single-phase flow and the subscript ψ may refer to the liquid (*L*) or the gas (*G*) phase. The single-phase friction factor $f_{S\psi}$ is obtained from the Blasius correlation:

$$f_{S\psi} = C_\psi \,\mathrm{Re}_{S\psi}^n \tag{2}$$

$$\mathrm{Re}_{S\psi} = \frac{\rho_\psi j_\psi D}{\mu_\psi} \tag{3}$$

where C_ψ = 64 and *n* = -1 for $\mathrm{Re}_{S\psi}$ < 2300 (laminar flow) and C_ψ = 0.184 and *n* = -0.2 for $\mathrm{Re}_{S\psi}$ > 2300 (turbulent flow), being $\mathrm{Re}_{S\psi}$ the single-phase flow Reynolds number. The two-phase pressure drop can be extrapolated based on the single-phase pressure drop:

$$\left.\frac{dP}{dL}\right|_{TP} = \left.\frac{dP}{dL}\right|_{S\psi} \phi_\psi^2 \tag{4}$$

where the subscript *TP* represents two-phase flow and ϕ_ψ^2 is the correction factor regarding single-phase pressure drop of phase ψ. Lockhart and Martinelli (1949) affirmed that this correction factor is dependent on the ratio of liquid/gas single-phase flow pressure drops. The square root of this ratio is known as the Lockhart-Martinelli's parameter:

$$X = \sqrt{\frac{\left.\frac{dP}{dL}\right|_{SL}}{\left.\frac{dP}{dL}\right|_{SG}}} = \sqrt{\frac{f_{SL}\rho_L j_L^2}{f_{SG}\rho_G j_G^2}} \tag{5}$$

The Lockhart-Martinelli's parameter can be easily predicted since it is dependent only on superficial velocities, single-phase friction factors and phases' densities. With the Lockhart-Martinelli's parameter, one just simply calculates the correction factor and multiplies it by the single-phase pressure drop to find the two-phase flow pressure drop. In order to obtain the correction factor, Chisholm (1967) suggests the following expressions:

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{6}$$

$$\phi_G^2 = \frac{\phi_L^2}{X^2} \tag{7}$$

where C is a coefficient obtained from data regression which depends on each phase flow regime, i.e., laminar or turbulent. Table 1 presents the values of C as suggested by Chisholm (1967) for liquid-gas flow in any flow pattern for pipes without inner discrete cavities, i.e., non-corrugated pipes or just simply "smooth pipes".

Table 1. Values of C for smooth pipes (Chisholm, 1967).

Liquid phase	*Gas phase*	*C*
Turbulent	Turbulent	20
Laminar	Turbulent	12
Turbulent	Laminar	10
Laminar	Laminar	5

3. EXPERIMENTAL METHODOLOGY

To obtain the pressure drop of a liquid-gas slug flow in horizontal corrugated pipelines, an experimental setup was assembled in the NUEM/PPGEM/UTFPR facilities. Figure 1 shows a schematic representation of the experimental circuit.

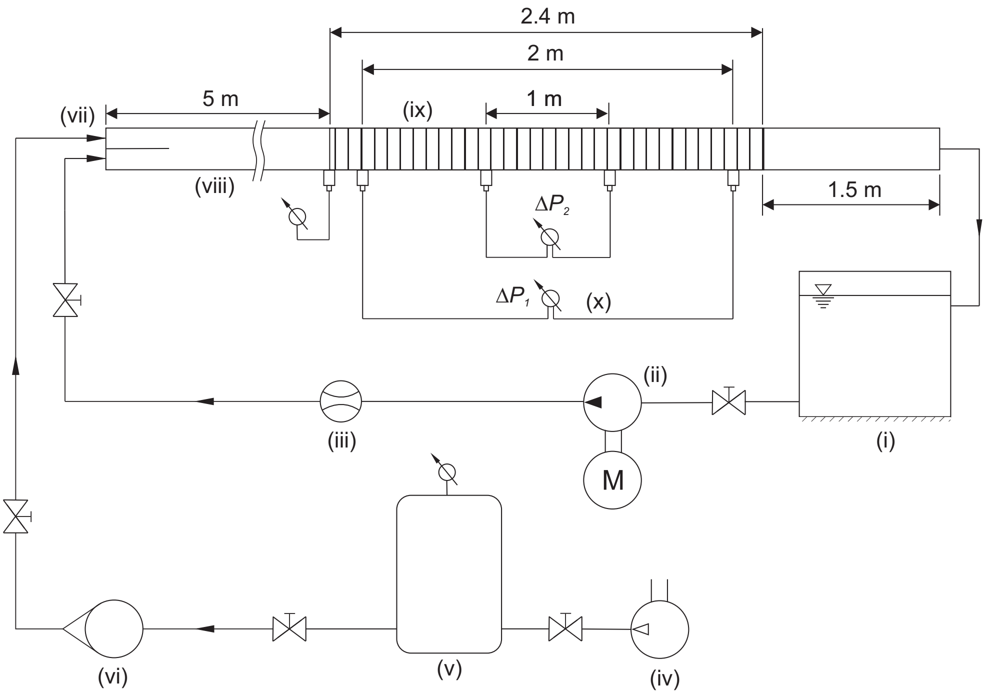

Figure 1. Experimental loop for two-phase flow measurements at the NUEM/PPGEM/UTFPR.

Water is stored at ambient conditions at a reservoir (i) and is pumped (ii) to a 19mm ID smooth pipe, where a Coriolis flow meter (iii) is positioned. On the other hand, air is boosted through a compressor (iv) and is sent to a compressed air storage tank (v). The gas volumetric flow rate is measured by a rotameter (vi) before mixing with water (vii). The mixture flows along a 5m (L/D ≈ 190) development section (viii). The test section (ix) is composed by a corrugated pipe with 26mm ID and 2m length (L/D ≈ 75). One pair of differential pressure meters (x) were used (distance of 1 and 2m). The mixture returns through a pipeline to the water tank, where the phases separate by gravity. Pressure drop and phases superficial velocities were acquired with a National Instruments board. The LabVIEW 2010 (National Instruments) program was used to capture captured signal.

The test section is made of plexiglas and is a corrugated pipe. Along the duct internal wall, the small cavities are periodically distributed in shape of rings, which were machined on the pipe wall. The groove pitch (s), width (b) and height (h), illustrated in Fig. 2, where varied to create three different corrugated pipe configurations. Table 2 presents the groove dimensions of the three pipe geometries assumed (C1, C2, C3). Experimental data was also measured for smooth (non-corrugated) pipes. The experiments were executed for liquid and gas superficial velocities varying between 0.25 and 2 m/s. The mixture superficial velocities range from 1 to 3.25 m/s.

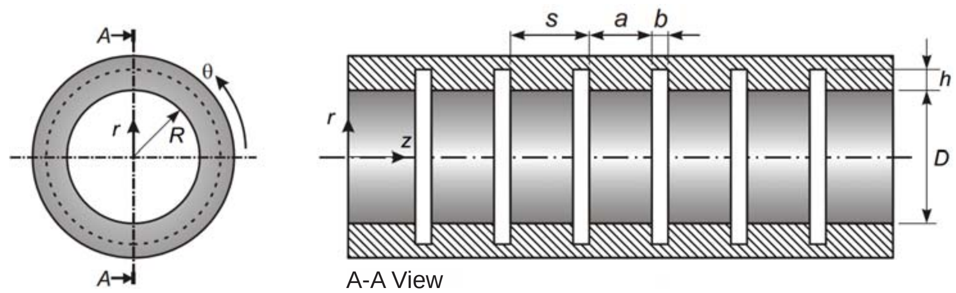

Figure 2. Representation of corrugated pipe geometric characteristics.

Table 2. Groove dimensions.

Configuration	*a/D*	*b/D*	*h/D*	*s/D*
C1	0.110	0.015	0.030	0.125
C2	0.110	0.040	0.030	0.150
C3	0.110	0.040	0.040	0.150

4. RESULTS AND DISCUSSION

The Chisholm's (1967) regression for the correction factor ϕ_L^2, Eq. (6), is dependent on each single-phase flow regime. For the chosen test grid, the liquid phase is always in turbulent regime, however the gas phase has changed between laminar and turbulent flow (considering $Re_{transition} \approx 2300$). Thereby, the pressure drop experimental results were analyzed separately for laminar gas and turbulent liquid (*LT*) and for turbulent gas and liquid (*TT*).

Figure 3 presents the correction factor ϕ_L^2 as a function of the Lockhart-Martinelli's X parameter for the different pipelines. The experimental data is represented by the dots, were the black dots are the *LT* cases and the white dots are *TT* cases. The curve fitting for Eq. (6) using the Least Square Method is also showed on Fig. 3, where the continuous lines represent the *LT* cases and the dashed lines represent the *TT* cases. It is clear that the curve fitting represents the behavior of the experimental data.

Table 3 presents the curve fitting C coefficients and the coefficient of determinations R^2 for the different regimes and pipelines. The coefficient of determination stayed above 0.87, which shows a good agreement of the Chisholm's (1967) correlation for smooth and corrugated pipes. Thus, it is possible to affirm that the Lockhart and Martinelli's (1949) methodology is also valid for corrugated pipes. The C coefficient has different values when compared to the Chisholm's (1967) regressed ones for smooth pipelines, being $C = 12.4$ instead of 20 for *TT* (-38%) and $C = 16$ rather than 10 for *LT* (+60%). These differences are due to the following factors: (i) the experimental data for Eq. (6) curve fitting were not from the same data used by Chisholm (1967) and (ii) Chisholm (1967) estimated C for a range of $0.01 < X < 100$, which covers other two-phase flow patterns besides the slug flow one.

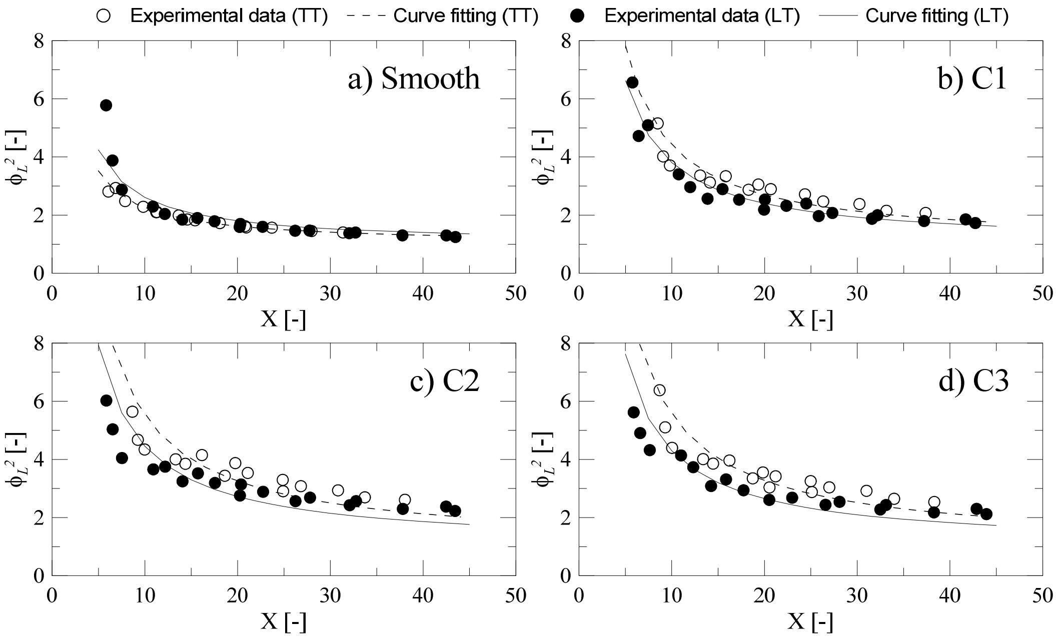

Figure 3. Correction factors ϕ_L^2 obtained by experimental data and their fitted curves for smooth pipes (a) and corrugated pipes for configurations C1 (b), C2 (c) and C3 (d).

Table 3. Obtained *C* values.

Gas	*Liquid*	*Geometry*	*Smooth*	*C1*	*C2*	*C3*
Turbulent	Turbulent	*C*	12.4	33.9	45.1	45.4
		R^2	0.977	0.898	0.889	0.900
Laminar	Turbulent	*C*	16.0	27.9	34.4	32.9
		R^2	0.874	0.947	0.941	0.970

Regarding that the major part of literature work for slug flow pressure drop estimation is for non-corrugated pipes, Figure 4 presents the increase factor due to the pipe corrugation. Thus, the Y-axis is the correction factor ϕ_L^2 ratio between the corrugated pipe and the smooth one. It is noticeable that pressure drop in corrugated pipes may be 25% to 200% larger than in smooth pipes (for the X range here analyzed), depending on the Lockhart-Martinelli's parameter, on the phases flowing regimes and on the grove dimensions. It can be stated that, for higher gas-liquid superficial velocities ratio j_G/j_L, i.e., lower X parameters, the corrugation induced drag on slug flows is higher for any groove dimension. Thus, interactions between the corrugated pipe wall and the mixture flow are dependent on the phases' flow rates and are proportional to the gas-liquid flow ratio. It is known by literature that the gas phase induces turbulence on the liquid one, mainly on the hydraulic jump of the elongated bubble rear, therefore increasing head loss (Cook and Behnia, 2000). With the present work, it can be concluded that the gas phase also induces drag between the corrugation and the mixture.

In the same way, one can analyze the influence of phases' properties on corrugation drag induction. The X parameter is proportional to the liquid-gas single-phase friction factor f_{SL}/f_{SG}, which by their way are related to the liquid-gas Reynolds number ratio Re_{SL}/Re_{SG}, which are directly proportional to the liquid-gas densities ratio ρ_L/ρ_G and inversely proportional to the liquid-gas viscosities ratio μ_L/μ_G. Thus, for a higher ρ_L/ρ_G ratio, the X parameter tends also to be higher and the corrugation induced drag is lower. In the other hand, for a higher μ_L/μ_G ratio, the X parameter is lower and the corrugation induced drag tends to be higher. This analysis is made by Fig. 4, which was constructed by Eq. (6) using the C coefficients of Tab. 3, curve fitted for air-water slug flow. Since X is a dimensionless parameter, the behavior for changes on phases' properties can be stated, but one cannot affirm that the increase or decrease on pressure drop is the same showed in Fig. 4. For this, it is necessary to verify the C coefficients for experimental measurements with other fluids.

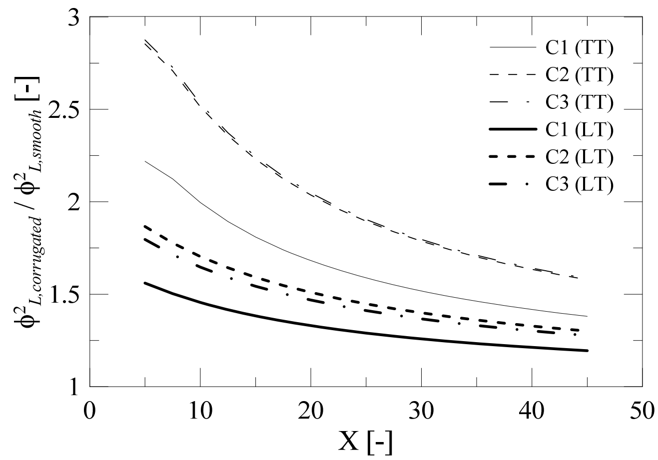

Figure 4. Increase factor on slug flow pressure drop due to the pipe corrugation.

At last, some discussion can be made for the different groove dimensions on drag induction. By Tab. 2, the configurations *C1-C2* show a main change on the groove width *b*, and a minor change on its pitch *s*. In the other hand, configurations *C2-C3* show changes only on the groove height *h*. By Fig. 4, it is noticeable the high vertical displacement between configurations *C1-C2* and a minimal displacement between *C2-C3*. Thus, one can state that the groove width is the most sensitive dimension on corrugation drag induction, in accordance with literature for single-phase flow (Stel *et al.*, 2012).

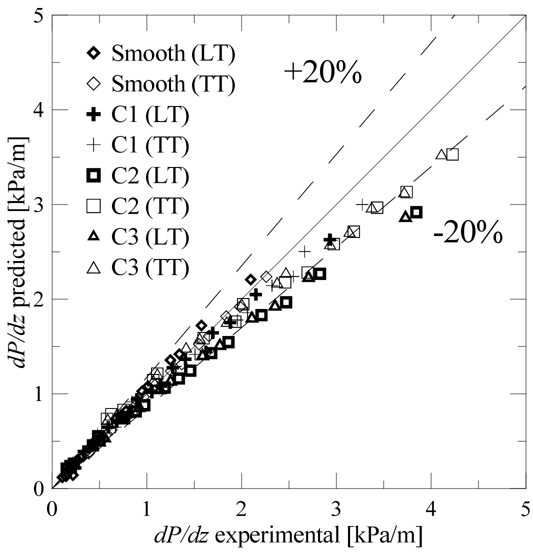

Figure 5. Estimated pressure drop comparison with experimental data.

Table 4. Statistical analysis.

Error [%]	*Turbulent-Turbulent*				*Laminar-Turbulent*			
	Smooth	*C1*	*C2*	*C3*	*Smooth*	*C1*	*C2*	*C3*
Average	-0.37	-1.86	-3.10	-2.12	4.53	-0.32	-4.95	-4.42
Standard Deviation	3.09	9.73	13.36	10.74	10.94	7.95	15.03	12.78
Maximum	8.25	16.95	21.40	20.46	13.78	14.92	27.44	18.81
Minimum	-3.96	-11.99	-16.46	-15.63	-34.66	-10.90	-24.03	-23.28

Finally, the pressure drop was recalculated using the Lockhart and Martinelli's (1949) methodology using the new *C* coefficients fitted in the present work. Figure 5 shows the comparison of the estimated pressure drop and the experimental one. One can notice that almost all results are within a ±20% accuracy range. Table 4 show some statitics of this distribution, presenting the averages, standard deviations, maximum and minimum values of the percentage error between the predicted pressure drop and the experimental data. The average percentage errors remained under 5%, while the standard deviations stand between 3 and 15%. The limit percentage error values (maximum and minimum) are +27,4%, for *LT* in the *C2* corrugated pipe, and -34.7%, for *LT* in smooth pipe. From the statistical analysis made, it can be concluded that the obtained regression provides coherent and satisfactory results.

5. CONCLUSION

In the present work, Lockhart and Martinelli's (1949) methodology was applied to calculate the pressure drop for two-phase slug flow in horizontal corrugated pipes. Pressure drop was measured in an experimental loop for three different corrugated pipe configurations. Chisholm's (1967) correlation was curve fitted to experimental measurements in order to adjust the correlation for each groove dimensions set. The pressure drop was recalculated using this new curve fitted coefficients, and results fall within a ±20% accuracy range with respect to experimental data. Thus, the Lockhart and Martinelli's (1949) methodology for pressure drop prediction is valid for corrugated pipes. This work proposes new coefficients for the Chisholm's (1967) correlation, valid within the three different groove geometries assumed for the corrugated pipes analyzed (ID = 26mm) in a $5 < X < 45$ range. However, further experimental measurements with other pipe diameters, inclinations, corrugated pipe configurations, fluid properties and other variables could be performed to enhance the validity of the procedure developed in this paper.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE