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AIR-WATER SLUG FLOW PRESSURE DROP ANALYSIS IN CORRUGATED PIPES

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Abstract. *Corrugated pipes have periodic cavities on inner wall that provide dynamic changes in the flow. Oil and gas offshore production lines consist of corrugated pipes and the most observed flow pattern in these lines is slug flow. The pressure drop is an important project requirement for facilities design, safe operations and must be predicted quickly and reliably. Some studies proposed correlations to predict the pressure drop for slug flow in smooth pipes. However, limited research has evaluated the slug flow pressure drop in corrugated pipes. This work carried out an experimental analysis of horizontal air-water slug flow pressure drop in three different inner diameters (26, 40 and 50 mm ID) with three distinct cavities width (1,2, 1,6 and 2 mm). The effects of inner diameter and cavity width on slug flow pressure drop were analyzed. The results demonstrated that increasing the cavities width in corrugated pipe increases the pressure drop. The experimental data were fitted and a pressure drop multiplier correlation was proposed. Comparison between predictions and experimental data showed 10% accuracy.*

Keywords: *two-phase pressure drop, corrugated pipes, slug flow, cavities width, pressure drop Lockhart-Martinelli multiplier.*

1. INTRODUCTION

Pressure drop is an important parameter for design, operation, production and transport systems. For horizontal flows, the pressure gradient is due to frictional losses that cause a pressure drop in the downstream direction. Two-phase flows can assume different geometrical configurations in the pipe, named as flow pattern. The flow pattern depends on the pipe geometrical variables (diameter and inclination), operational parameters (phase flow rates) and physical properties of the two phases (densities and viscosities).

The main approach used for prediction of two-phase pressure drop in smooth pipes is the model proposed by Lockhart and Martinelli (1949). This model assumes that each phase flows separated in the cross-sectional area of the pipe. The authors proposed that the liquid-gas flow pressure drop ($dP/dL|_{LG}$) can be calculated by a factor ($\phi^2|_L$) that multiplies the liquid single-flow pressure drop ($dP/dL|_{SL}$), as shown in Eq. (1). The $dP/dL|_{LG}$ can also be predicted by a factor ($\phi^2|_G$) and single-flow pressure drop ($dP/dL|_{SG}$) dependent on the gas phase.

$$\left.\frac{dP}{dL}\right|_{LG} = \phi^2\Big|_L \left.\frac{dP}{dL}\right|_{SL} \tag{1}$$

Lockhart and Martinelli (1949) showed that the factor (ϕ^2), named in literature as pressure drop multiplier factor of Lockhart-Martinelli, is dependent of the square root of the ratio between the liquid and the gas single-phase flow pressure drops (X), known as Lockhart-Martinelli parameter X, Eq. (2).

$$X = \left(\frac{dP/dL\,|_{SL}}{dP/dL\,|_{SG}}\right)^{1/2} = \left(\frac{f_L \rho_L J_L^2}{f_G \rho_G J_G^2}\right)^{1/2} \tag{2}$$

where f_L and f_G, ρ_L and ρ_G, and J_L and J_G are the liquid and gas friction factor, density, and superficial velocity, respectively.

Some previous studies proposed correlations for the pressure drop multiplier ($\phi^2|_L$) in smooth pipes. Chisholm (1967) expressed the pressure drop multiplier as the function of Lockhart-Martinelli parameter X and an empirical coefficient C, as show in Eq. (3).

$$\phi^2 |_L = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (3)$$

where C is dependent of phase flow laminar or turbulent regime.

Vaze and Banerjje (2013) proposed that the coefficient *C* can be calculated in terms of the liquid and gas Reynolds number, as shown in Eq. (4).

$$C = C_1 \, \mathrm{Re}_{SL}^{p} \, \mathrm{Re}_{SG}^{q} \quad (4)$$

where C_1, p, and q are coefficients that are obtained by curve fitting of the experimental results and Re_{SL} and Re_{SG} are the liquid and gas Reynolds number, respectively.

Naidek et al. (2017) proposed an experimental correlation for estimating the pressure drop multiplier in corrugated pipes that consists of two kinds of multipliers factor, Eq. (5). The first is due to the effects of the insertion of the corrugated cavities and the second one is due to the interaction between liquid and gas phases as proposed by Chisholm (1967) using the coefficient C proposed by Vaze and Banerjje (2013). Naidek et al. (2017) empirical correlation has some limitations for cavity width (0.4 $\leq$ *w* $\leq$ 1.0 mm) and inner diameter pipe (26 mm ID).

$$\left.\frac{dP}{dL}\right|_{LG}^{c} = \overbrace{\underbrace{\max\left[0.18\ln\left(\frac{w}{D}\right)+1.88\ ;\ 1\right]}_{\text{Corrugated caivities effect}} \phi^2\big|_L}^{\text{Pressure drop multiplier}} \left.\frac{dP}{dL}\right|_{SL}^{s} \quad (5)$$

The purpose of this work is to present an experimental analysis of horizontal air-water slug flow pressure drop in three inner diameters of corrugated pipes (*D* = 26, 40 and 50 mm) with different geometric configurations of cavities width (*w* = 1.2, 1.6 and 2.0 mm). Based on the experimental results a new pressure drop multiplier correlation will be proposed for estimating the liquid-gas slug flow in corrugated pipes.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

An experimental apparatus was designed to measure the slug flow pressure drop in corrugated pipes made of transparent Plexiglas with inner diameters of *D* = 26, 40 and 50 mm. A schematic representation of the experimental apparatus is illustrated in Fig 1. Water is pumped from the tank (1) and passes through a Coriolis-type flowmeter (3) which returns the water density and temperature. The water kinematic viscosity was calculated by an empirical correlation using the measured temperature (FOX et al. 2011). Air is compressed and stored in a pressure vessel and a manual valve (8) were used to controls the flow rate. A gauge pressure transducer (13) was used to estimate the local gas superficial velocity. Liquid (4) and gas (8) valves were used to set the desired diameter circuit. A differential pressure transducer (14), with a measurement range of 0-10 kPa and accuracy of ±0.04%, evaluates the pressure drop in the corrugated pipe test section.

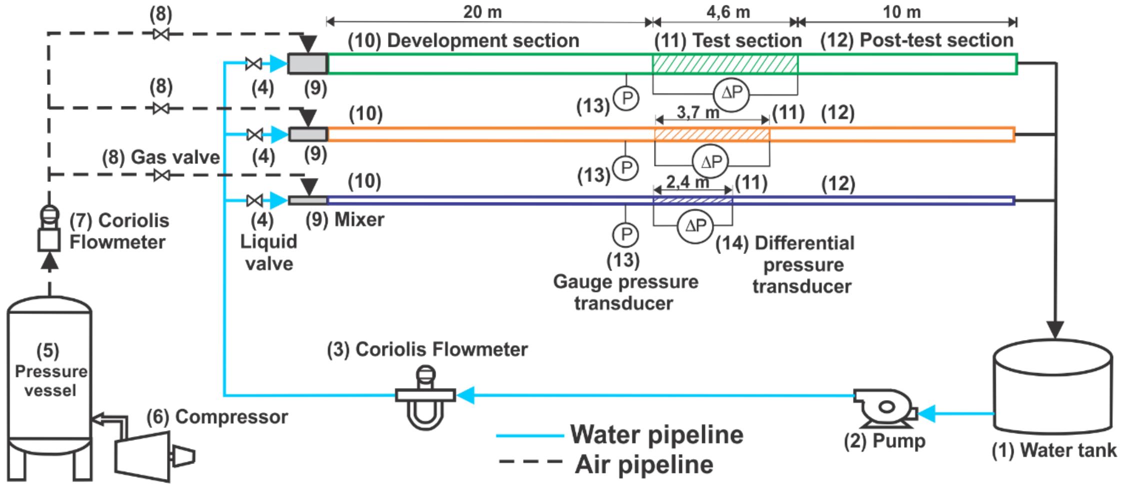

Figure 1: Schematic of the experimental apparatus.

The corrugated pipes have rectangular cavities helically distributed along the pipe wall, as shown in Fig. 2. Different geometric configurations of corrugated pipes were analyzed using three distinct cavities width of w = 1.2, 1.6 and 2.0 mm. The cavity pitch and height were fixed at p = 3.9 mm and h = 1 mm, respectively. The distance between cavities (d) is dependent on cavities width variation (w). Air and water at ambient pressure and temperature (100 kPa and 298 K) were used as working fluids. A total of 26 liquid-gas superficial velocities combination were used in the experimental tests with a liquid and gas superficial velocities ranges from 0.5 to 2.5 m/s and 0.75 to 2.5 m/s, respectively, as shown in Fig. 3.

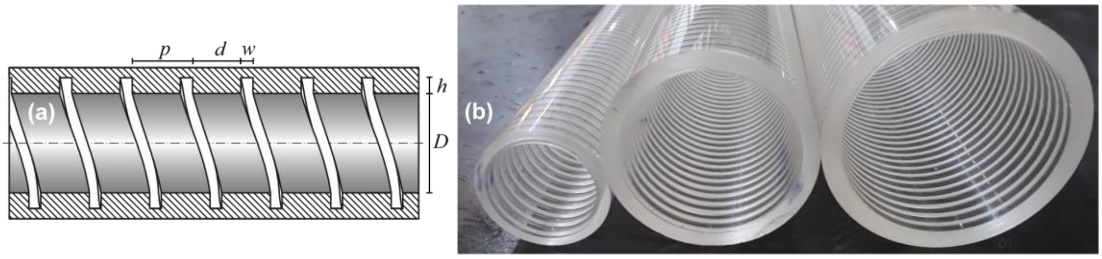

Figure 2. Corrugated pipe with cavities helically distributed on inner wall. (a) Schematic representation and (b) Experimental test section.

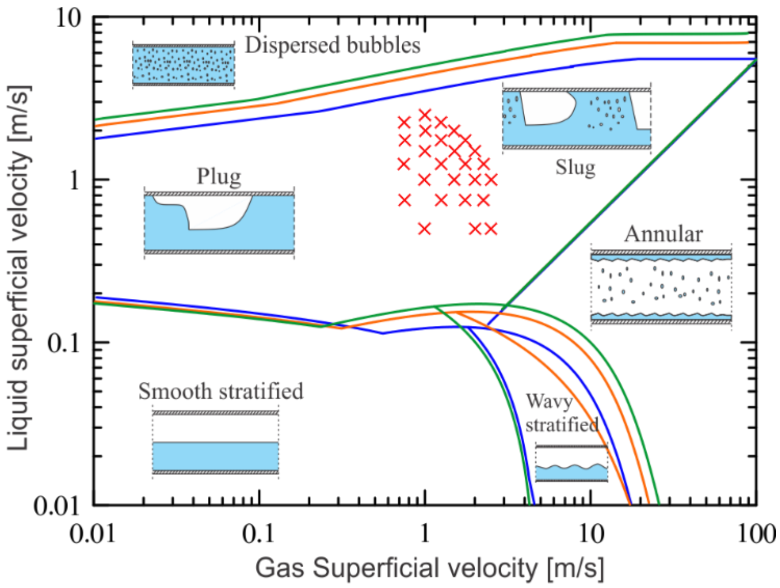

Figure 3. Experimental combinations of superficial phase velocities plotted on the flow map proposed by Taitel and Dukler (1976) for air-water flow at 26 mm-ID (blue line), 40 mm-ID (orange line) and 50 mm-ID (green line) pipe.

Measurements for the water single-flow pressure drop for Reynolds number ranging from 10,000 to 80,000 in smooth pipe with different inner diameters were used to calculate the friction factor and the experimental results were compared with the predicted by Blasius' correlation, $f = 0.316Re^{-0.25}$. The comparison showed a maximum percentage deviation of 1.7%, 4% and 2.7% between experimental results and prediction for the different inner diameters of 26, 40 and 50 mm, respectively. These results assured accuracy from the experimental tests.

3. RESULTS

Figure 4 (a) shows the experimental results for two-phase pressure drop ($dP/dL|_{LG}$) in corrugated pipes with different geometric configurations (CPD-w) as a function of the liquid Reynolds number (Re_L). The liquid-gas slug flow pressure drop increases with the increase of the liquid Reynolds number and decreases with the increase of the corrugated pipe inner diameter. Analyzing the effect due to the cavity width variation it can be observed that the liquid-gas pressure drop increases with the increase of cavities width. Figure 4 (b) presents the pressure drop multiplier ($\phi^2|_L$) versus Lockhart-Martinelli parameter X. The pressure drop multiplier also increases with the increases of cavities width and tends to decay with X.

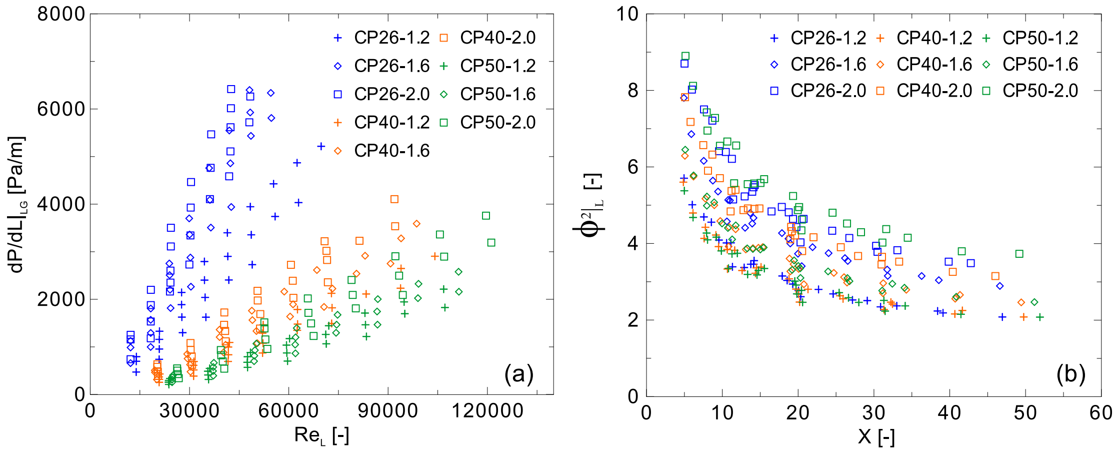

Figure 4. Experimental results for air-water slug flow pressure drop in corrugated pipes (CP) for three different inner diameters (*D*) and cavities width (*w*). (a) Pressure drop ($dP/dL|_{LG}$) and (b) Pressure drop Lockhart Martinelli multiplier ($\phi^2|_L$).

Figure 5 shows a comparison between the experimental air-water slug flow pressure drop in corrugated pipes with the estimated by Naidek's correlation, Eq. (5). Figure 5 (a) presents the results for the different inner diameters of corrugated pipes with the smaller cavity width (w = 1.2 mm). It can be observed an agreement of ±7% for the different inner diameters of corrugated pipe. However, the comparison for the air-water pressure drop in corrugated pipes with larger cavity width (w = 1.6 and 2.0 mm), Fig. 4 (b), shows an underestimation with a maximum percentage deviation of -40%.

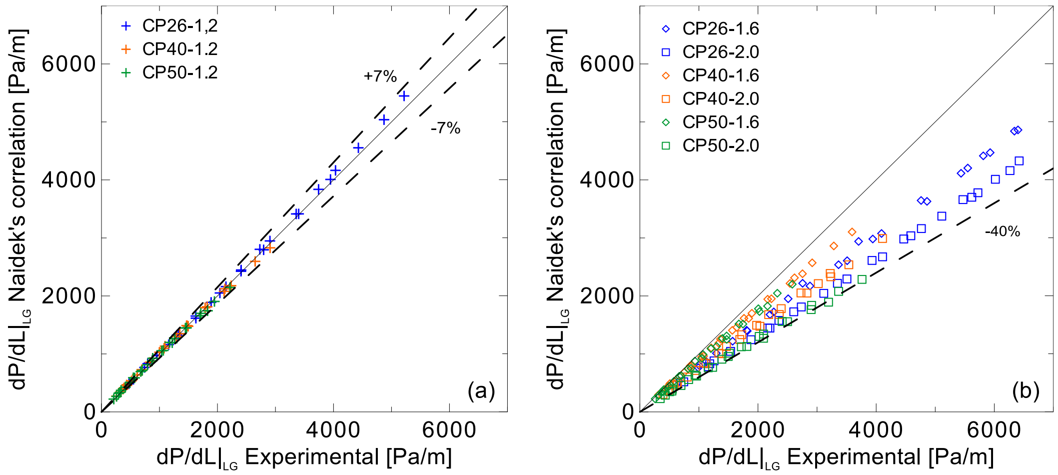

Figure 5. Comparison between the experimental pressure drop data in different corrugated pipes with the prediction using Naidek's correlation. (a) Smaller cavity width (w = 1.2 mm) and (b) Larger cavities width (w = 1.6 and 2.0 mm).

These comparisons suggest that Naidek's correlation has a satisfactory agreement if the range of cavity width used was closer to range recommended by the authors ($0.4 \leq w \leq 1.0$ mm). An analysis of the factor due to the insertion of the corrugated cavities, named in this work as corrugated factor ($\phi^2|_c$), was carried out as a function of the corrugated pipes geometrical configurations. The $\phi^2|_c$ is calculated by the ratio between the experimental pressure drop multiplier data, showed in Fig. 3 (b), and the $\phi^2|_L$ calculated from Eq. (3) using the coefficient C proposed by Vaze and Banerjje (2013), Eq. (4).

The corrugated factors are approximately constant with respect to the Lockhart-Martinelli parameter X for the different corrugated pipes configuration, behavior also observed by Naidek et al. (2017). Due to this behavior, a mean of the corrugated multiplier factor data will be used for the next analysis. As the corrugated pipes used in the present work have a variation on cavity width (w) that provides a variation on the distance between cavities (d), which occurs due to the constant value adopted for the cavity pitch (p = 3.9 mm), the corrugated factor was evaluated as a function of cavity width and distance between cavities. The corrugated factor ($\phi^2|_c$) tends to increase with the increase of the ratio w/D and to decrease with the increase of the ratio d/D.

Based on the experimental results, the corrugated factor was regressed as a function of cavity width and distance between cavities and a new correlation was proposed, as shown in Equation 6. The coefficient of determination of this correlation is $R^2 = 0.914$.

$$\phi^2 |_c = 0.96 \ \ln\left(\frac{w}{D}\right) + 3.14 \left(\frac{d}{D}\right)^{-0.14} \tag{6}$$

Thus, the air-water slug flow pressure drop in corrugated pipe can be predicted by the Eq. (7).

$$\left.\frac{dP}{dL}\right|_{LG} = \left(0.96 \ \ln\left(\frac{w}{D}\right) + 3.14 \left(\frac{d}{D}\right)^{-0.14}\right)\left(1 + \frac{1,6\,\text{Re}_L^{0.31}\,\text{Re}_G^{-0.07}}{X} + \frac{1}{X^2}\right)\left.\frac{dP}{dL}\right|_{SL} \tag{7}$$

Figure 6 compares the pressure drop predicted by the correlation proposed, Eq. (7), with the experimental data. An average deviation of ±10% was observed. The correlation presented in this study was analyzed and proposed to predict the two-phase slug flow pressure drop in horizontal corrugated pipes with different cavity width (1.2, 1.6 and 2.0 mm) and inner diameter (26, 40 and 50 mm). The accuracy of the proposed correlation need be evaluated in corrugated pipes with larger cavity width and different inner diameters.

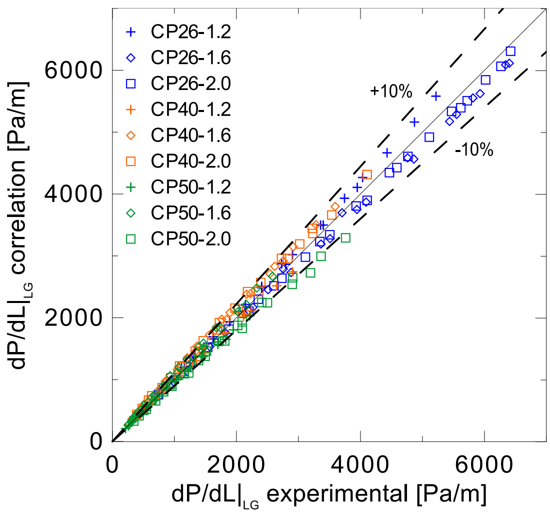

Figure 6. Comparison between the pressure drop estimated by the proposed correlation and the experimental data.

4. CONCLUSIONS

In this study, an experimental analysis of air-water slug flow pressure drop in different corrugated pipes configurations were carried out. An experimental apparatus was designed to provide two-phase pressure drop measurements in three different cavity width and three different inner diameters of corrugated pipes. It was observed that the geometrical configuration of corrugated pipes (cavity width and distance between cavities) affects the two-phase pressure drop. As a result, the two-phase slug flow pressure drop in corrugated pipes tends to increase with increasing the cavity width. The experimental data were curve fitted and a new correlation for the pressure drop multiplier factor was proposed. The correlation proposed agreed within ±10% accuracy with the available experimental data.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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