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# EXPERIMENTAL ANALYSIS OF HORIZONTAL AIR-WATER SLUG FLOW PRESSURE DROP IN CORRUGATED PIPES

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***Abstract.*** *Oil and gas companies use corrugated pipes in offshore production riser lines where the most common flow pattern is slug flow. The cavities of the corrugated pipes are responsible for piping flexibility and can lead to dynamic changes in the flow, for example pressure drop variation. Pressure drop estimation is an essential project requirement for facilities design and this estimation must be quickly and reliably. Lockhart-Martinelli correlation consists in a factor (also known as multiplier of Lockhart-Martinelli) that multiplies the liquid single-phase pressure drop. This correlation is widely used to calculate two-phase pressure drop in smooth pipes. Naidek et al. (2017) proposed a correlation to calculate the pressure drop in d-type corrugated pipes valid for some recommendations and only for 26mm ID pipes. In this experimental study, a flow loop was designed to measure the pressure drop of horizontal air-water slug flow in three different inner diameters (26 mm, 40 mm and 50 mm) of d-type corrugated pipes. The experimental results was compared with predicted pressure gradient using Naidek's correlation. The comparison showed that only the experimental results for the 26 mm-ID agrees with the accuracy of 7% proposed by Naidek et al. (2017). Pressure drop multiplier' coefficients were regressed by experimental data and a better accuracy for the three inner diameters was observed.*

***Keywords:*** *Pressure drop, d-type corrugated pipes, slug flow, multiplier of Lockhart-Martinelli*

## 1. INTRODUCTION

Corrugated pipes have cavities in the inner wall that are spaced apart by a constant distance. Cavities' width and height are geometric characteristics that define the type of corrugated pipes. Perry *et al.* (1969) suggested a classification for corrugated surfaces as d-type and k-type where the first term is used to describe surfaces with square cavities and the second term describes surfaces with flat cavities. Several studies showed that the cavities on surfaces can modify the behavior of the flow and increase or reduce some flow properties (Chang *et al*., 2006; Chen *et al*., 1986; Djenidi *et al.*; 1994; Leonadi *et al.* 2007; Stel, 2010; Sutardi, 2003).

Prediction of the two-phase pressure drop in pipes is a significant design parameter of several equipment in many industries such chemical, nuclear, oil and gas and others. Two-phase flow has different spatial configurations, also known as flow patterns, that is dependent on the flow characteristics such fluid properties, operational parameters and geometrical variables. The slug flow is a very complex, unsteady and turbulent two-phase flow that is characterized by alternating flow of liquid slug and gas pockets that flow over a liquid film. The liquid plug has high acceleration and decelerations, which causes pressure drop changes (Tong and Tang, 1967).

Two general models have been used in the development of two-phase flow pressure drop: homogenous and the separated models. In the homogenous model, the two-phase flow is treated like a pseudo-fluid with an average velocity, average fluid properties and assuming no-slip condition. The separated flow model assumes that the gas-phase and the liquid-phase flow separately and each phase flows in part of the cross-sectional area of the pipe (Shoham, 2008).

Numerous works proposed, evaluated and surveyed correlations that predicted the two-phase flow pressure drop in smooth pipes (Hamad *et al*., 2017; Sun and Mishima, 2009, Xu *et al*., 2012 and Xu and Fang, 2013). However, there is a lack of studies for general accurate correlation for estimating the two-phase flow pressure drop in corrugated pipes. Naidek *et al.* (2017) proposed an experimental correlation for estimating the pressure drop of horizontal liquid-gas slug flows in a d-type corrugated pipes however, the correlation is limited only for inner diameter of 26 mm.

The purpose of this work is experimentally analyze analysis pressure drop for three different inner diameters of d-type corrugated pipes and compare the results with the pressure drop predicted by Naidek's correlation.

## 2. METHODOLOGY

## 2.1 Pressure Drop

Lockhart and Martinelli (1949) proposed a correlation, Eq. (1), to calculate the two-phase pressure drop based in the separated model.

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

where the index LG indicates liquid-gas two-phase flow, index SL indicates the liquid single phase and the $\phi$ represents the correction factor also known as multiplier of Lockhart-Martinelli.

The multiplier factor of Lockhart-Martinelli was correlated by Chisholm (1967), defined as

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

where $C$ is an empirical coefficient related with the phase flow laminar or turbulent regimes and $X$ is Lockhart-Martinelli parameter.

Vaze and Barnerjee (2013) proposed that the coefficient $C$ can be calculated in terms of the Reynolds number as

$$C = C_1 \operatorname{Re}_{SL}^{C2} \operatorname{Re}_{SG}^{C3} \tag{3}$$

where $C_1, C_2$ and $C_3$ are coefficients that are obtained by curve fitting of the experimental results, *Re* is the Reynolds number and the index SG indicates the gas single phase.

The Reynolds number is defined as

$$\operatorname{Re}_\zeta = \frac{\rho_\zeta j_\zeta D}{\mu_\zeta} \tag{4}$$

where the index $\zeta$ can represent the liquid or gas phase ( $\zeta = L$ or $\zeta = G$ ), $\rho_\zeta$ is the density phase, $D$ is the pipe inner diameter, $j_\zeta$ is the phase superficial velocity and $\mu_\zeta$ is the phase dynamic viscosity.

The Lockhart-Martinelli parameter is defined as

$$X = \left( \frac{dP/dL|_{SL}}{dP/dL|_{SG}} \right)^{1/2} = \left( \frac{f_L \rho_L j_L^2}{f_G \rho_G j_G^2} \right)^{1/2} \tag{5}$$

where $f_\zeta$ is single-phase flow friction factor that can be estimated by the Blasius correlation (Shoham, 2008), Eq. (6)

$$f_\zeta = a \operatorname{Re}_\zeta^{-b} \tag{6}$$

where the coefficients $a$ and $b$ are related with the phase laminar flow or turbulent flow. For laminar flow $a = 64$ and $b = 0,25$. For turbulent flow $a = 0,316$ and $b = 0,25$.

Naidek *et al.* (2017) proposed an experimental correlation, Eq (7), for estimating the pressure drop of horizontal liquid-gas slug flows in d-type corrugated pipes. The authors suggested that the multiplier factor of Lockhart-Martinelli can be divided in two kinds of pressure drop multipliers. The first is due to the introduction of the gaseous phase in a liquid single-phase flow, which is represented by the Reynolds numbers of phases and Lockhart-Martinelli parameter. The second is due to the consideration of the corrugated cavities that was represented by cavity width and inner diameter pipe ratio.

$$\left.\frac{dP}{dL}\right|_{LG}^{c} = \underbrace{\max\left[ 0.18 \ln\left(\frac{w}{D}\right) + 1.88 \; ; 1 \right]}_{\text{Corrugated cavities effect}} \underbrace{\left[ 1 + \frac{1,6 \operatorname{Re}_L^{0.31} \operatorname{Re}_G^{-0.07}}{X} + \frac{1}{X^2} \right]}_{\text{Gaseous phase insertion effect}} \left.\frac{dP}{dL}\right|_{SL}^{s} \tag{7}$$

where the index $c$ indicates corrugated pipe, the index $s$ indicates smooth pipe, $w$ is the cavity width. The authors suggested some recommendation for the correlation usage: slug flow pattern, helical d-type corrugated pipes, $D$ = 26 mm, cavity width and inner diameter ratio between $0.015 \leq w/D \leq 0.040$, Reynolds number range $12000 \leq \mathrm{Re}_L \leq 63500$ and $1200 \leq \mathrm{Re}_G \leq 4500$ and phases superficial velocities $0.5 \leq j_L \leq 2.25$ m/s and $0.75 \leq j_G \leq 2.5$ m/s.

## 2.2 Experimental Flowloop

The experimental flow loop shown in Fig (1) was designed to measure the pressure drop in three different inner diameters of d-type corrugated pipes. Plexiglas was used for smooth pipe section and corrugated pipe test section. Air and water at ambient pressure and temperature (100 kPa and 298 K) are the fluids used in the experimental tests. The fluids are mixed by a parallel plate mixer (5) which initially creates a stratified flow pattern that quickly modify to slug flow due the combination of phase superficial velocities. The corrugated pipes test section (9) was placed between smooth pipes sections. A development section (8) of 20-m length before the corrugated pipes test section was used to assure slug flow in the test section and a post-test section (10) of approximately 10-m length after the corrugated pipes test section was used to avoid reverse effects. Aspect ratio inner diameter/length (D/L) determined the length of each corrugated pipe test section. Water is pumped from the tank (1) and passes through a Coriolis-type (3) flowmeter that returns the liquid phase density and temperature. Air is compressed and stored in a pressure vessel and the air flow rate is controlled by a manual valve (14). A gauge pressure transducer (6) is used to estimate the local gas superficial velocity. Simple liquid valves (4) and gas valves (14) are used to set the desired diameter circuit. A differential pressure transducer (7) with a measurement range of 0-10 kPa evaluates the pressure drop in the corrugated pipe test section.

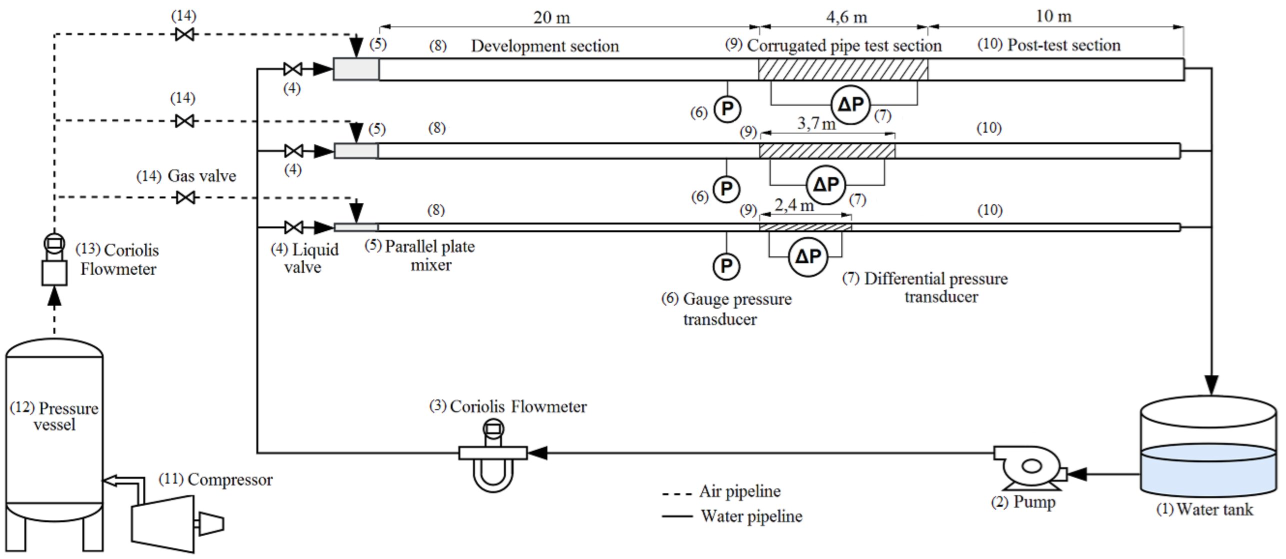


Figure 1: Schematic of the experimental flow loop.

The corrugated pipes were made with rectangular d-type cavities helically distributed along the pipe wall, as show in Fig (2). The cavities dimensions of the corrugated pipes are: $w$ = 1.20 mm (cavity width), $h$ = 1 mm (cavity height), $d$ = 2.9 mm (distance between cavities), $p$ = 3.9 mm (cavity pitch) and three different inner diameter of pipe ($D$ = 26 mm, $D$ = 40 mm and $D$ = 50 mm).

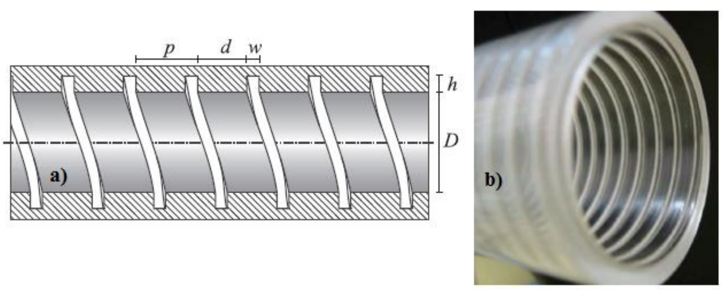


Figure 2: d-type corrugated pipe with cavities helically distributed along the pipe wall. (a) Schematic representation and (b) Experimental section test d-type.

### 2.3 Experimental procedures

Some steps will be taken in this work to assure accuracy from the experimental tests. (1) Friction factor of water single-phase flow measurements using Reynolds number range $14000 \leq \mathrm{Re}_L \leq 205000$ in smooth pipes were compared with the Blasius correlation (Fox *et al*. 2010). The friction factor was calculated as

$$f = \frac{(\Delta P / L) D^5 \pi^2}{8 \rho Q^2} \tag{8}$$

where $\Delta P$ is the measurement pressure drop, $L$ is the measurement length, $D$ is the inner diameter of pipe, $\rho$ is the fluid density and $Q$ is the volumetric flow rate. (2) Pressure drop of air-water slug flow measurements in smooth pipes were compared with the correlation proposed by Lockhart and Martinelli (1949) using the multiplier factor proposed by Chisholm (1967). (3) Pressure drop air-water slug flow measurements in corrugated pipe were compared with the correlation proposed by Naidek *et al.* (2017). Each step will be accomplished in the three different diameters.

Figure 3 shows 26 experimental combinations of superficial velocities that will be used in this experimental work plotted on the flow map for air-water flow at 26mm-ID pipe.

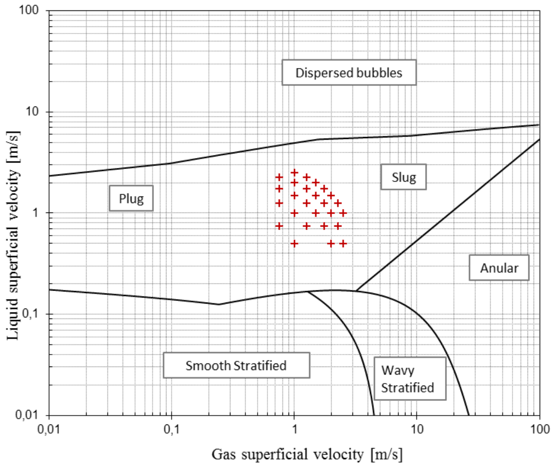


Figure 3: Experimental combinations of superficial velocities plotted on the flow map for air-water flow at 26mm-ID pipe proposed by Taitel and Dukler (1976).

## 3. RESULTS

Figure 4 presents the experimental friction factor of water single-phase flow in smooth pipe for the three different inner diameters.

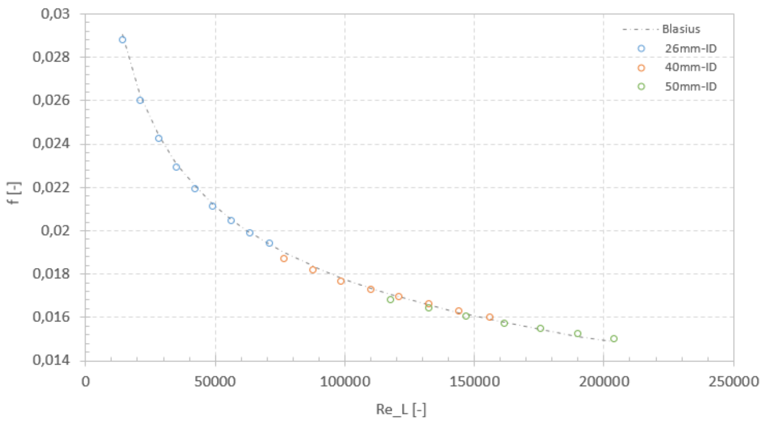


Figure 4: Experimental friction factor of water single-phase flow in smooth pipe for the three different inner diameters compared with Blasius' correlation.

Comparing these measurements with Blasius' correlation resulted in an absolute average percentage deviation of 0.61 % and a maximum percentage deviation of 1.4%. These results assure accuracy from the experimental flow loop measurements and setup.

Figure 5 shows the pressure drop of air-water slug flow in smooth and corrugated pipes for the three inner diameters. The pressure drop in corrugated pipes is bigger than in smooth pipes for all three inner diameters. Analyzing the inner diameter pipe effect, it was observed that the pressure drop descreases with the increase of the inner diameter pipe for both smooth and corrugated pipes. The same behavior also was obseved by Hamad *et al*. (2017) and Lu *et al.* (2018). Comparing the pressure drop in smooth pipes with the predicted with Lockhart Martinelli's correlation, absolute average percentage deviations of 4 %, 5% and 5.5 % and maximum deviations percentage of 9.3 %, 14.5 % and 10.2 % for the inner diameters of 26 mm, 40 mm and 50 mm were observed, respectively.

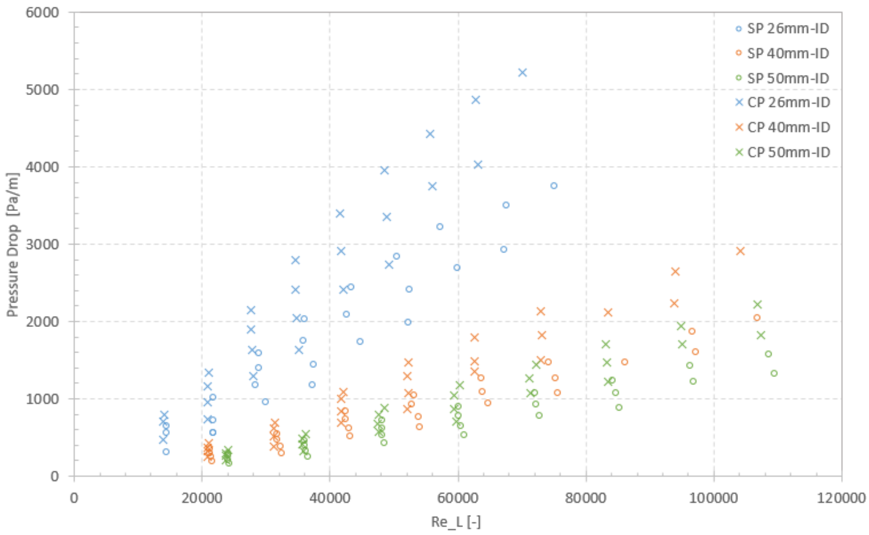


Figure 5: Experimental results for pressure drop of air-water slug flow in smooth pipe (SP) and corrugated pipe (CP) for three different diameters.

The experimental pressure drop multiplier as function of the Lockhart-Martinelli parameter is presented in Figure 7. The tendency of the experimental pressure drop multiplier with Lockhart-Martinelli parameter is equal for both corrugated and smooth pipes. This is a common behavior according to Lockhart and Martinelli (1949) and Chisholm (1967). Due to the fact the pressure drop is bigger in corrugated pipes when compared with smooth pipes, the pressure drop multiplier has the same behavior.

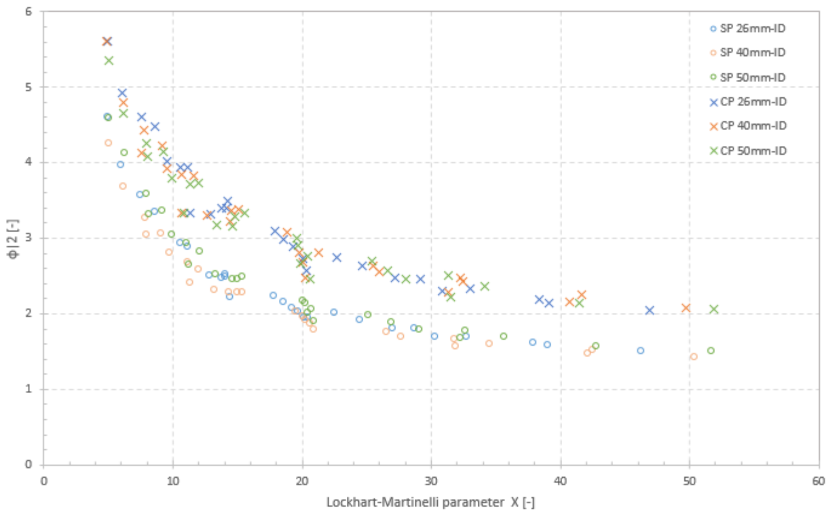


Figure 7: Experimental data pressure drop multiplier $\left(|\phi|^2\right)$ for corrugated pipes (CP) and smooth pipes (SP) as a function of the Lockhart-Martinelli parameter (X).

A comparison between the experimental data of pressure drop in corrugated pipes with the pressure drop predicted by Naidek's correlation, Eq. (7), is presented in Figure 6.

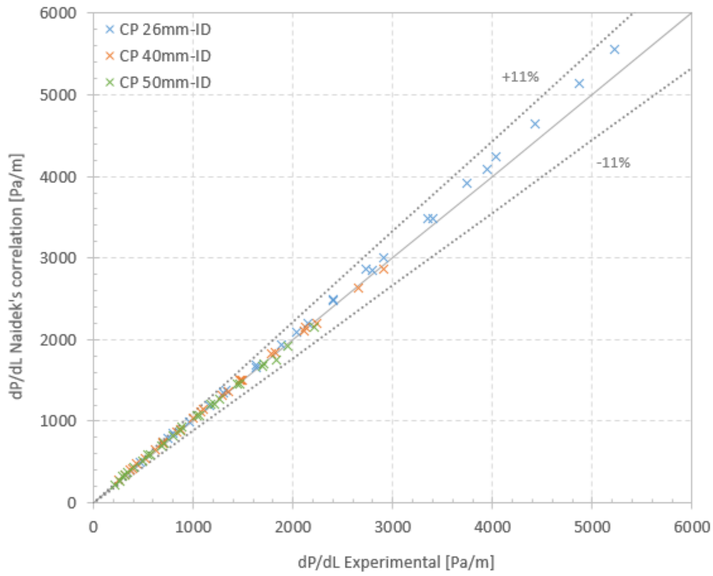


Figure 6: Comparison between the experimental pressure drop data with the pressure drop predicted by Naidek's correlation.

Absolute average percentage deviations of 3.7 %, 3.5% and 3.4% and maximum percentage deviations of 6.8%, 8.6% and 10.2 % for the inner diameters of 26 mm, 40 mm and 50 mm were observed, respectively. Only the experimental results for the 26 mm-ID agree with the accuracy of 7% proposed by Naidek *et al.* (2017). These disagreements for 40 mm-ID and 50 mm-ID were probably due to the fact of not following exactly the recommendations suggested by Naidek *et al.* (2017). In this experimental work the cavity's width was w=1.2 mm while w=1 mm was used by Naidek *et al.* (2017) to proposed the correlation. The pressure drop multiplier that represents the insertion of corrugated cavities' coefficients *C1* and *C2*, Eq. 9, were regressed from the experimental data and the values *C1*=0.15 and *C2*=1.74 was found.

$$\left.\frac{dP}{dL}\right|_{LG}^{c} = \underbrace{\max\left[C1\ln\left(\frac{w}{D}\right)+C2;\,1\right]}_{\text{Corrugated cavities effect}}\left[1+\frac{1,6\,\mathrm{Re}_L^{0.31}\,\mathrm{Re}_G^{-0.07}}{X}+\frac{1}{X^2}\right]\left.\frac{dP}{dL}\right|_{SL}^{s} \quad (9)$$

Comparing the pressure drop experimental data with the predicted using the new coefficients C1 and C2, Eq. (9), absolute average percentage deviations of 1.1 %, 2.6% and 2.9% and maximum percentage deviations of 3.3%, 5.6% and 7.6 % for the inner diameters of 26 mm, 40 mm and 50 mm were observed, respectively. These results suggested the necessity of analyzing different cavities width to better propose a correlation to predict pressure drop in d-type corrugated pipes. In future studies, corrugated pipes with three different cavities width will be tested and the influence of the inner diameter pipe and corrugated cavity width will be analyzed to propose a new correlation to predict pressure drop in corrugated pipes.

## 4. CONCLUSIONS

This work presented a comparison between experimental pressure drop in three different inner diameters of d-type corrugated pipes with pressure drop predicted by Naidek's correlation. It was observed that only the results for 26 mm-ID agreed with the accuracy of 7% proposed by Naidek *et al. (2017).* Pressure drop multiplier's coefficients were regressed by the experimental data and a better accuracy was observed. These results suggested a necessity of evaluating different corrugated cavity widths to propose a new correlation that predict the pressure drop in d-type corrugated pipes.

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