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Pressure Drop of Secondary Gas-Liquid-Solid Flow in Helical Curved Pipe

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ABSTRACT

The three-phase frictional pressure drop for gas-liquid-solid mixture secondary flow through helical curved pipe in vertical orientation is investigated and reported in this article. Effects of different operating variables on the three phase pressure drop are enunciated and the experimental results were analyzed and Lockhart-Martinelli and Davis model are incorporated to predict the three-phase frictional pressure drop. A correlation for parameter for the model is also proposed to predict frictional pressure drop for gas-liquid-solid mixture flow through helical curved pipe by dimensional analysis.

Introduction

Generation and its application of secondary flow is an important parameter to intensify a process in application to the chemical and biochemical industries. When fluid flows through a curved pipe, centrifugal force acting right angle to main flow generates due to the curvature of pipe, which results in secondary flow. The strength of that secondary flow depends on the curvature of the surface. There are numerous publications which deal with flow phenomenon and the pressure drop in single-phase flow through helical tubes. Two-phase flow through helical coils is much more complex than flow in straight pipes and single-phase flow through helical tubes. When flow enters the curved part, the heavier density phase is subjected to a larger centrifugal force and this force causes the denser phase to move away from the center of curvature, while the lower density phase flow towards the center of curvature. The process is continuous function of coil geometry. Even there are varying applications, the literature on two phase-flows through helical coiled tube is hard to find. Helical coils are widely used in industries including Aerospace, Boiler Repair, Chemical, Electronics, Food Processing, Hospitals, Housing, Paper, Petroleum and Pharmaceuticals. They are extensively used in compact heat exchangers, heat-exchanger network, heating or cooling coils in the piping systems, intake in air-crafts, fluid amplifiers, coil steam generators, refrigerators, nuclear reactors, thermo siphons, and other heat transfer equipment involving phase change, chemical plants as well as in the food and drug industries. Banerjee et al. [1] reported the effect of two-phase frictional pressure drop and hold-up on coil radii, tube radii, and helix angle and liquid viscosities for gas–Newtonian liquid flow through coils. They correlated the experimental frictional pressure drop and hold-up data by the Lockhart–reported that the small helix angles have no effect on two-phase pressure drop.

Kasturi and Stepanek [3] compared their experimental two-phase frictional pressure drop data with the Lockhart–Martinelli correlation and were found that there was a systematic displacement of the curves for various systems with the Lockhart–Martinelli plot. Therefore, in their subsequent study, they reported the correlation for the frictional pressure drop in terms of new correlating parameters that consist of a combination of known dimensionless groups were obtained using the separated flow model. Rangacharyulu and Davies [4] developed a new correlation for two-phase flow frictional pressure drop based on a modified extension of the Lockhart–Martinelli theory. The experimental data are well correlated in terms of dimensional groups other than the Lockhart-Martinelli correlation. Hart et al. [5] reported experimentally that the axial pressure drop of two-phase flow in the helical coils increases as a function of the volume flow rate of the gas, but no attempt was made to correlate the data. Akagawa et al. [6] confirmed that frictional pressure drops of two-phase flow in helical pipes was 1.1–1.5 times higher than that in a straight pipe. Three types of empirical equations for the frictional pressure drop were proposed and also the experimental data were correlated by a modified Lockhart-Martineili approach independent of the pipe diameter to coil diameter ratio. Mandal and Das [7] reported the experimental investigation of gas–Newtonian liquid flow through coils in horizontal and vertical orientation. They developed empirical correlation for frictional pressure drop and hold-up. Mujawar and Rao [8] and Krishna Bandaru and Chhabra [9] pointed out that in the gas–non-Newtonian liquid two-phase flow the frictional pressure drop could be successfully correlated by the Lockhart–Martinelli method. Biswas and Das [10] carried out investigations to evaluate the two-phase frictional pressure

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drop for gas–non-Newtonian liquid flow through helical coils in vertical orientation. They illustrated the effects of gas and liquid flow rate, coil diameter, and liquid properties on two-phase frictional pressure drop.

Also, they presented comparison between predicted and measured values of the frictional pressure drop for different methods such as Eisenberg and Weinberger [11] correlation, Aoki [12] correlation, Davis [13] correlation, and Xin et al. [14] correlation. Rippel et al. [15] worked on the two-phase flow of gas and liquid in a helicoidally pipe. Chen and Zhou [16] found that the major factors affecting the two-phase friction factor are the gas fraction, liquid Reynolds number, gas Reynolds number and the pipe to coil diameter ratios. The correlation for the prediction of a two-phase friction factor was provided by using dimension analysis. Saxena et al. [17] proposed another method to correlate the pressure drop data obtained in two-phase flow in a helicoidally pipe, which retains the identity of each phase and separately accounts for the effects of curvature and tube inclination resulting from the torsion of the tube. The area of gas–non-Newtonian flow has received increasing attention over past few decades. The primary reason for this is the many industrial applications in which the systems exhibit complex rheological behaviors but the area of liquid-solid mixture flow has not increased that much attention even now as not much research has been done on this area. The present work aims to investigate the hydrodynamic characteristics of gas-liquid-solid flow in the helical coil system with various geometric and operating variables with catalyst Kieselguhr which is important in the petroleum downstream processing.

Materials and Methods

The schematic diagram of the experimental setup is shown in Fig. 1. The experimental apparatus consisted of an air supply system, a slurry storage tank, centrifugal pump, a test section, control and measuring systems for both liquid and air flow rate and pressure drop.

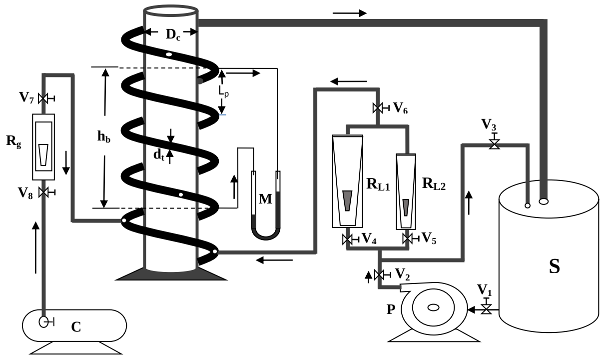

Figure 1. Schematic Diagram of Experimental Setup. M: Manometer, RL1 and RL2: Liquid Rota meters, Rg: Gas Rota meter, S: Storage tank, P: Centrifugal Pump, C: Compressor, V1-V8: Valves.

Thick walled flexible transparent PVC pipes with internal diameter of 0.009 m, 0.015 m and 0.02 m having the total length of the pipe as 4.94 m (5.4 m for pipe with 0.02 m internal diameter) are used for the experiment. The details of the procedure are given in our previous paper [18]. The slurry consists of water and Kieselguhr. A U-tube manometer (M) is used to measure the pressure difference. The slurry and air flow rates used in the experiments are in the range of 3.35×10^{-5} to 1.67×10^{-4} m3/s and 0.25×10^{-4} to 6.90×10^{-4} m3/s respectively. The temperature of the liquid is maintained in the range of 30 ± 1° C. Experiments have been carried out using water as a liquid phase, atmospheric air as gas phase and Kieselguhr is used to make liquid-solid slurry for the present system. In present study three different concentrations of Kieselguhr (5 kg/m3, 10 kg/m3, 15 kg/m3) are used. Effective viscosity of slurry and density of slurry can be calculated using Thomas correlation [19] which is given as:

$$\frac{\mu_{ls}}{\rho_{ls}}=\frac{\mu_l}{\rho_{ls}}\left[\begin{array}{l}1+2.5\dfrac{C_c}{\rho_p}+10.05\left(\dfrac{C_c}{\rho_p}\right)^2\\ +2.73\times10^{-3}\exp\left(16.6\dfrac{C_c}{\rho_p}\right)\end{array}\right] \tag{1}$$

$$\rho_{ls}=\rho_l+C_c\left(1-\frac{\rho_l}{\rho_p}\right) \tag{2}$$

All physical properties of present system are shown in Table 1.

Table 1. Physical properties of the liquid-solid slurry measured at 30 ±1°c.

System	Concentration (wt%)	Density (kg/m^3)	Viscosity x 10^3 (kg/m-s)	Surface Tension N/m
Liquid-Solid slurry	5	990.418	1.041	0.0712
	10	981.137	1.084	0.0712
	15	971.855	1.131	0.0712
Water	-	999.7	1.004	0.0712
Air	-	1.185	0.018	-

Theoretical Background

Two-phase flow in straight tubes has been described by Lockhert-Martinelli in order to develop correlations for pressure drop as a function of the flow variables as well as other parameters such as viscosity and density. The same concepts of Lockhert-Martinelli correlation have been made for three-phase flow in helically coiled tube where slurry as a liquid phase which converts the problem into two-phase from three-phase. The total pressure drop through vertically helical coiled tube of length L may be expressed as

$$\Delta P_{f3p}+\Delta P_h+\Delta P_a=\Delta P_t \tag{3}$$

The acceleration component ΔP_a is negligible as compared to the total pressure drop ΔP_t in a vertically helical coiled tube of uniform cross section. Hence, Eq. (3) becomes

$$\Delta P_{f3p}+\Delta P_h=\Delta P_t \tag{4}$$

The hydrostatic head component ΔP_h may be calculated by assuming that the gas and slurry form a homogeneous mixture which gives

$$\Delta P_h=\rho_m g h_y \tag{5}$$

$$\rho_{\mathrm{m}}=\frac{\rho_g\rho_{ls}}{\rho_g(1-x)+\rho_{ls}x} \tag{6}$$

$$x=\frac{Q_g\rho_g}{Q_g\rho_g+Q_{ls}\rho_{ls}} \tag{7}$$

$$h_y=h_b\left(\frac{Q_L}{Q_L+Q_g}\right) \tag{8}$$

Then by using the above equations (2) and (5-8) the frictional pressure drop can be calculated by

$$\Delta P_{f3p} = \Delta P_t - \left(\frac{\rho_g \rho_{ls}}{\rho_g (1-x) + \rho_{ls} x} \right) \times \left[h_b \left(\frac{Q_L}{Q_L + Q_g} \right) \right] g \tag{9}$$

Results and Discussion

In this section the effect of various operating parameters on the three-phase pressure drop in helical coil system are explained. Also a correlation has been developed for three phase frictional pressure drop based on Lockhart-Martinelli model.

Variations of frictional pressure drop with different operating variables

Variation of frictional pressure drop with slurry flow rate is shown in Figure 2. It is observed that frictional pressure drop for three phase system increases with increase in slurry flow rate. Variation of frictional pressure drop with gas flow rate is shown in Figure 3. It is observed that frictional pressure drop for three-phase system increases with increase in gas flow rate and increases with increase in slurry flow rate.

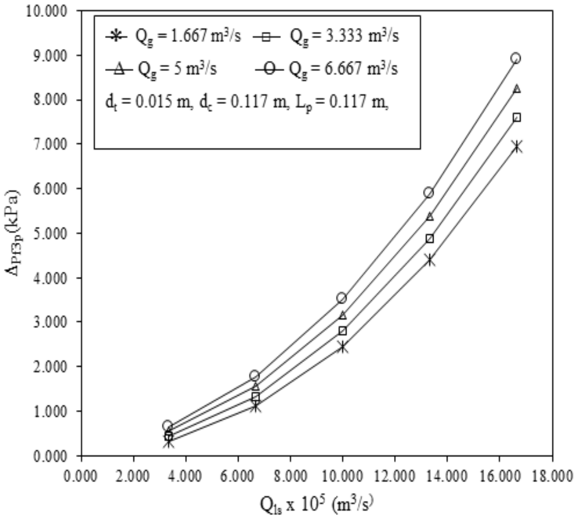

Figure 2. Variation of Frictional Pressure Drop with Slurry Flow Rate

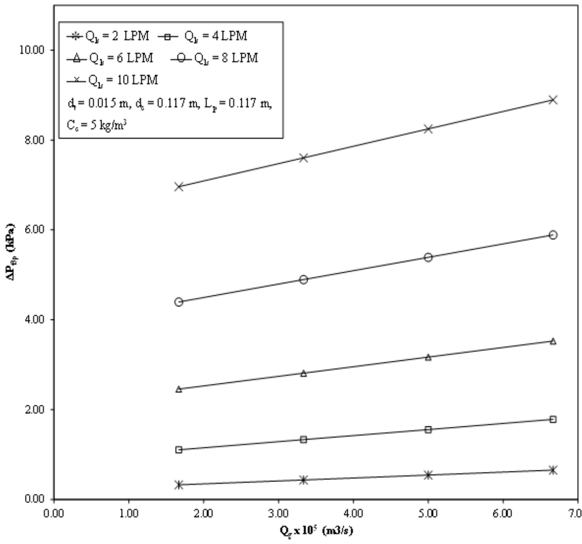

Figure 3. Variation of Frictional Pressure Drop with Gas Flow Rate

The variation of frictional pressure drop for three-phase system is shown in Figure 4. From the figure it is observed that three- phase frictional pressure drop decreases with increase in pitch at constant gas flow rate and constant slurry flow rate. The variation of frictional pressure drop for three-phase system with Kieselguhr concentration is shown in Figure 5. The frictional pressure drop increases with increase in Kieselguhr concentration at constant gas flow rate and constant slurry flow rate due to increase in viscosity with concentration.

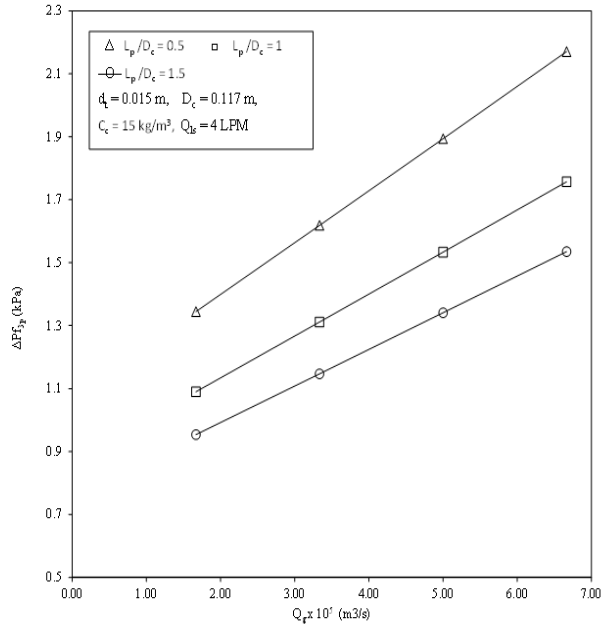

Figure 4. Variation of Frictional Pressure Drop with Pitch

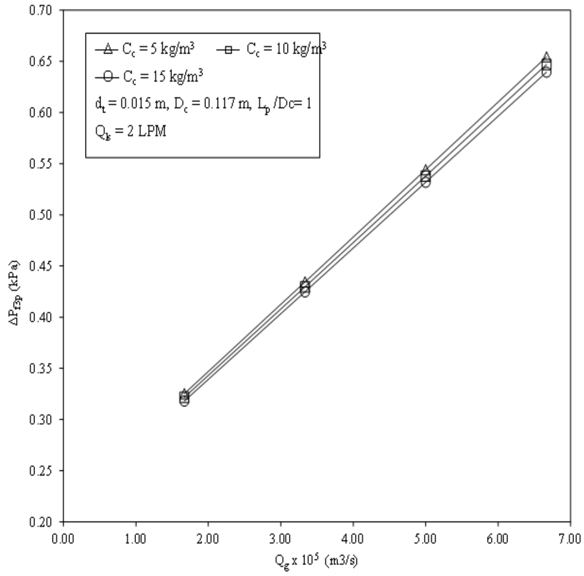

Figure 5. Variation of Frictional Pressure Drop with Kieselguhr Concentration

Analysis of three phase frictional pressure drop using L-M Correlation

The Lockhart-Martinelli correlation is a recognized method usually used to describe the two-phase pressure drop in different process equipment. It has also been used with proper modifications and assumptions in flow through channels like helical coil, bubble column etc. Originally Lockhart-Martinelli had proposed a graphically correlation for the analysis of frictional pressure drop in horizontal two phase gas-Newtonian liquid system for different combinations i.e. laminar-laminar, laminar-turbulent, turbulent-laminar and turbulent-turbulent of gas and liquid flow. They defined the parameters Φ_{ls}, Φ_g and X as follows:

$$\Delta P_{f,3p} = \phi_{ls}^2 \Delta P_{f,o,ls} \tag{10}$$

$$\Delta P_{f,3p} = \phi_{ls}^2 \Delta P_{f,o,g} \tag{11}$$

$$X = \frac{\phi_g}{\phi_{ls}} = \sqrt{\left(\frac{\Delta P_{f,o,ls}}{\Delta P_{f,o,g}}\right)} \tag{12}$$

The single phase frictional pressure drop $\Delta P_{f,o}$ over a distance of Δz of the coil can be evaluated by the relation:

$$\Delta P_{f,o} = \frac{2\rho_o f_o u_o^2 \Delta z}{d_t} \tag{13}$$

The single phase friction factor (f_o) is calculates for laminar and turbulent flow in a hydraulically smooth straight tube as [20] respectively:

$$f_o = 16/\mathrm{Re}_o \tag{14}$$

$$f_o = 0.079/\mathrm{Re}_o^{0.25} \tag{15}$$

For transition flow, the single phase friction factor (f_o) can be calculated as [20]:

$$f_o = 0.125\left(0.112 + \mathrm{Re}_o^{-0.3185}\right) \tag{16}$$

The single phase friction factor for curved pipes/tubes can be calculated as [21]:

If He < 3000

$$f_{co} = f_o\left[1 + 0.033\left(\log_{10} He\right)^4\right] \tag{17}$$

and if He < 10^5

$$f_{co} = \left[0.0791 He^{-0.25} + 0.0075\left(d_t/d_c\right)^{0.50}\right] \tag{18}$$

where, He is defined as Helium number which is given by:

$$He = \mathrm{Re}\left[\frac{d_t/d_c}{\left\{1 + \left(L_p/\pi d_c\right)^2\right\}}\right]^{0.5} \tag{19}$$

Square of the slurry phase frictional multiplier was correlated empirically with the physical variables, i.e., properties of slurry and gas e.g., density of slurry (ρ_{ls}), density of gas (ρ_g), viscosity of slurry (μ_{ls}), viscosity of gas (μ_g), surface tension of slurry (σ_{ls}), concentration of Kieselguhr in slurry (C_c); geometric variables, e.g., coil diameter (d_c), tube diameter (d_t), tube length (L_t), pitch length (L_p), bed height (h_b) and dynamic variables, e.g., superficial velocity of slurry (u_{ls}) and superficial velocity of gas (u_g) which are included in the form of dimensionless numbers, Reynold's of slurry (Re_{ls}) and Reynolds number of gas (Re_g). By dimensional analysis and fitting the experimental data, following correlation is obtained:

$$\Phi_{ls}^2 = 5.82\times10^6\left(\mathrm{Re}_{ls}\right)^{-1.018}\left(\mathrm{Re}_g\right)^{0.644}\left(\frac{\sigma_{ls} d_t \rho_{ls}}{\mu_{ls}^2}\right)^{-0.241} X^{0.639}\beta \tag{20}$$

$$\beta = \left(\frac{d_c}{d_t}\right)^{-0.063}\left(\frac{L_p}{d_t}\right)^{0.091}\left(\frac{h_b}{d_t}\right)^{-0.017}\left(\frac{L_t}{d_t}\right)^{-0.020}\left(\frac{C_c}{\rho_{ls}}\right)^{0.032}\left(\frac{\mu_g}{\mu_{ls}}\right)^{2.024} \tag{21}$$

The correlation coefficient (R^2) and the standard error of Eq. (20) have been calculated and are 0.931 and 0.062, respectively. Using Eq. (10) and Eq. (20) predicted values of three phase frictional pressure drop can be calculated as:

$$\Delta P_{f,3p} = \Phi_{ls,pred.}^2 \Delta P_{f,o,ls} \tag{22}$$

The calculated values of Φ_{ls}^2 using Eq. (20) have been plotted against the experimental value which is shown in Figure 6.

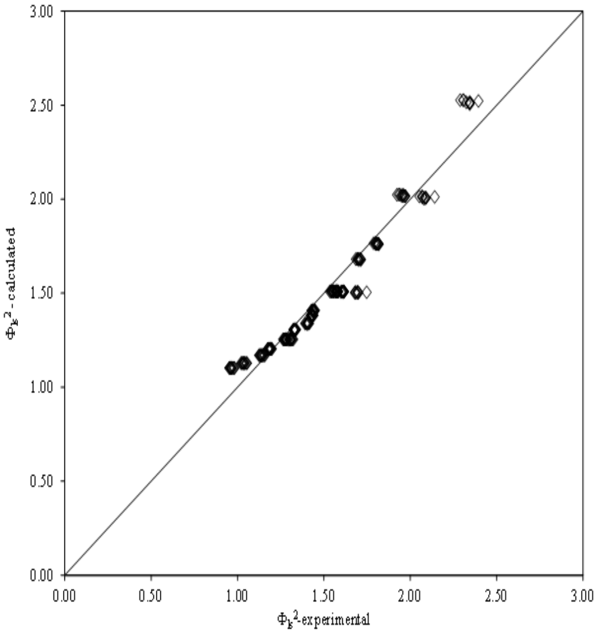

Figure 6. Comparison between experimental and calculated Φ_{ls}^2

Analysis of three-phase frictional pressure drop using Davis Correlation:

Davis extended the applicability of Lockhart-Martinelli's correlation to the vertical flow through modification of the parameter X by incorporating the Froude number (Fr), to account for the effect of gravity and velocity. The modified parameter, X_{mod} is expressed as:

$$X_{\mathrm{mod}} = 0.19 Fr^{0.185} X \tag{23}$$

where the Froude Number is Fr = V_m^2/gD_c. By dimensional analysis and fitting the experimental data, following correlation is obtained:

$$\Phi_{ls,Devis}^2 = 1.94\times10^7\left(\mathrm{Re}_{ls}\right)^{-2.965}\left(\mathrm{Re}_g\right)^{1.200} \left(\frac{\sigma_{ls} d_t \rho_{ls}}{\mu_{ls}^2}\right)^{0.625} X_{\mathrm{mod}}{}^{2.027}\beta' \tag{24}$$

$$\beta' = \left(\frac{d_c}{d_t}\right)^{0.037}\left(\frac{L_p}{d_t}\right)^{0.446}\left(\frac{h_b}{d_t}\right)^{-0.203}\left(\frac{L_t}{d_t}\right)^{-0.047}\left(\frac{C_c}{\rho_{ls}}\right)^{0.021}\left(\frac{\mu_g}{\mu_{ls}}\right)^{2.077} \tag{25}$$

The correlation coefficient (R^2) and the standard error of Eq. (24) have been calculated and are found to be 0.985 and 0.031 respectively. Using Eq. (10) and Eq. (24) predicted values of three phase frictional pressure drop can be calculated as:

$$\Delta P_{f3p} = \Phi_{ls,Davis}^2 \Delta P_{fols} \tag{26}$$

The calculated values of $\Phi_{ls,Davis}^2$ using Eq. (24) have been plotted against the experimental values and are shown in Figure 7.

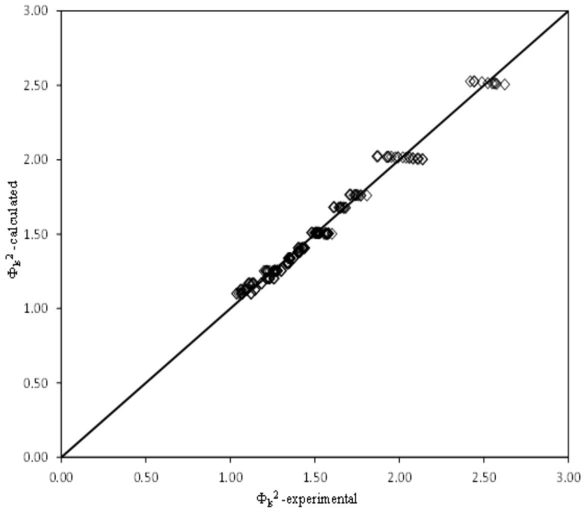

Figure 7. Comparison between experimental and calculated $\Phi^2_{ls,Davis}$

Conclusions

The three-phase frictional pressure drop has been measured for air-water-Kieselguhr solution flowing through helical coils. It has been found that three-phase frictional pressure drop increases with increase in gas and slurry flow rate. Also it decreases with increase in pitch. As pitch increases bed height increases due to which hydrostatic pressure drop increases which results into decrease in frictional pressure drop. While change in frictional pressure drop with respect to solid particle concentration was very minimal but change is easily visible in frictional pressure drop with respect to other variables i.e. slurry flow rate, gas flow rate and pitch. The three-phase pressure drop is correlated with different physical and geometrical variables using Lockhart-Martinelli correlation and Davis correlation. The correlation developed for frictional pressure drop may be use full for the designing of equipment where helical coils are used.

Nomenclature

d_t	Diameter of tube (m)
d_c	Coil diameter (m)
f	Friction factor (-)
Fr	Froude Number (-)
He	Helical Number (-)
L_p	Pitch length (m)
L_t	Tube length (m)
ΔP	Pressure drop (N/m)
Q	Flow rate (m^3/s)
Re	Reynold’s Number (-)
u	Velocity (m/s)
X	Lockhart-Martinelli parameter

Greek Letters

Φ	Two phase multiplier
σ	Surface Tension (N/m)
μ	Viscosity (Pa.s)
ρ	Density (kg/m^3)

Subscripts

c	Curve
co	Single phase and curved pipe
fg	Frictional gas
fl	Frictional liquid
ftp	Frictional two-phase
f3p	Frictional three-phase
fo	Single phase
g	Gas
htp	Hydrostatic two-phase
ls	Slurry
o	Single phase and Straight Pipe
l	Liquid
m	mixed
mod	Modified

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