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Analysis of Frictional Pressure Drop based on Flow Regimes of Oil-water Flow in Pipeline

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This article presents the analysis of frictional pressure drop, flow regimes of oil-water flow in an inclined pipeline. The analysis is done based on the Lockhart-Martinelli principle. The Lockhart-Martinelli model is modified and incorporated to predict the frictional pressure drop of oil-water flow in inclined pipeline. The effects of operating variables such as oil and water flow rates on frictional pressure drop are investigated. To predict the frictional pressure drop, friction factor of oil-water two-phase flow, correlations have also been developed for different flow regimes as a function of different dimensionless groups by introducing the operating variables and physical properties. The studies of the pressure drop of oil-water flow in pipeline may give insight into a further understanding and modeling of the liquid-liquid two-phase flow characteristics in chemical industries.

Keywords: Two-phase flow, frictional pressure drop, friction factor, oil-water, inclined pipeline

Introduction

Flow behavior of fluid in pipeline earns feasibility of the flow when it flows along with fraction of individual fluid. Water fractions often increase during the transportation of oil. So it requires accounting the presence of water properly for designing and predicting the flow behavior in pipelines. Large numbers of studies have been published in recent years on multiphase flow through pipes[1-5, 8]. From the literature it is observed that different flow regimes multiphase flow are as a functions of flow velocity, gas holdup, physical properties of the phases and inclination angle of the pipeline. Most work has involved flow through either horizontal or vertical pipe. Studies in inclined flow believed to be a variation of these two cases. Recent studies reports that in horizontal pipe high pressure gradients are resulted due to the presence of water. This phenomenon is imputed to an increase in the apparent viscosity of the liquid mixture near the oil or water phase inversion which results in decrease capacities of pipelines. Commercial simulators usually rely on empirical correlations such as the classical Lockhart and Martinelli[6] correlation, which is obtained by fitting a significant amount of experimental data, regardless the flow pattern. Pressure losses during oil-water flow are a function of the oil-water ratio and are largely dependent on the properties of the external phase of the dispersion. Higher mixture velocities increase the pressure drop near the inversion point.So formulation of models to predict the systems behavior, flow regimes, pressure drop as a function of fluid properties and flow conditions is very important to reproduce the flow phenomena. There is lack of studies on the frictional pressure drops in inclined pipeline with liquid-liquid system.The aim of the present study is to examine the effects of fluid flow on pressure gradient and flow regimes in two-phase, oil-water flow in inclined pipe.

Theoretical background

The Lockhart–Martinelli correlation[6] is a recognized tool to describe the two-phase pressure drop in different flow process system. The Lockhart and Martinelli (L-M) correlation because of its simplicity has been widely used in oil and gas industry to predict two-phase flow in pipes especially for low gas and liquid flow rates and small pipe sizes. The correlations of L-M parameter will be useful for predicting two-phase heat transfer coefficients using pure phase thermo-physical properties especially for heat exchanger design in industry. The concept of two-phase system is used here in the present study to analyze the oil-water system.

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Materials and Method

The pressure drop and the flow regimes of oil-water flow were studied in an inclined pipe. The experimental setup equipped with a test section, storage and separation tanks, centrifugal pump, flowmeter, differential pressure transducer to measure pressure drop and high viscous fluid system as shown in Figure 1. Water is circulated by using centrifugal pump from water inlet tank to rotameters at a specific flow rates to test section. Oil is circulated by using gear pump from oil inlet tank. The sufficient length between entry section and test section is provided to get the fully developed flow. Test section is made up with 0.025 m internal diameter Perspex pipe of 1 m length at an angle 5°. Transparent Perspex pipe with a view box provision is selected for better flow visualization and continuous photography. Fully developed flow is obtained from test to exit section to minimize the end effect of the fluids. A Camera (Sony, DSC 100 HX, and 16.2 MP) is used for this experiment to observe the flow regimes. Reproducibility of the experimental data was checked by performing the experiment at least four times. Liquids selected for the study are lube oil (Society of Automotive Engine (SAE)-40 grades; density: 889 kg/m^3) and filtered tap water (density: 999.5 kg/m^3). The oil density was measured by specific gravity bottle. The viscosity for this oil (0.107 Pa.s) was determinedby an Ostwald viscometer. To aid the visual observation of the flow pattern, a dark brown transmission fluid dye was added to the oil.

Results and Discussion

Flow pattern map and variations of pressure drop with variables

The observed flow patterns are represented in a graphical form known as flow pattern map. Flow pattern map with oil Reynolds number and water Reynolds number is shown in Figure 2. Flow pattern map of plug and slug flows were identified at lower Reynolds number of oil phase, which occupied small region in the flow pattern map. Flow pattern map is dominated by stratified wavy flow and stratified mixed flow. Annular flow pattern was occurred at moderate Reynolds number of oil and water where the oil core fluid is enveloped by water. Dispersion of oil in water flow pattern obtained at higher Reynolds number of water. On the other hand, dispersion of oil in water (DOW) flow pattern was obtained at higher Reynolds number of water. Dispersion of water in oil (DWO) flow pattern was identified at higher Reynolds number of oil phase. Seven different types of flow patterns were observed in all flow rates oil and water. In stratified flow (SF) regime less pressure gradients were observed which may be due to lower phase velocities. In dispersed flow pattern, pressure gradient got increased sharply because of predominant velocity effect. With increase in the velocity of the fluids, friction factor changes which directly affect the pressure drop. In annular flow pattern (AF) the friction factor associated is only of water so that in this particular region less pressure drops occurred. The results for experimental pressure drop are is plotted as a function of oil phase Reynolds number for given water Reynolds number. The pressure drop variations with Reynolds number of oil for five different Reynold number of water are shown in Figure 3. It is observed that the pressure drop is increased with increase in the oil Reynolds number

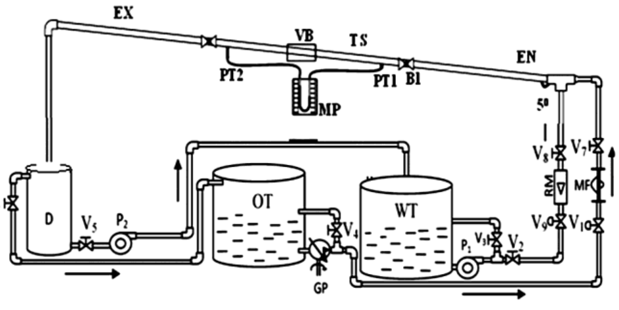

Fig. 1—Schematic diagram of experimental setup. Legend**:** B_1-B_2: Quick closing valves, D:Decanter, Ex: Exit section, EN: Entrance section, TS: Test Section GP: Gear pump, MP: Manometer panel, MF: Flow meter, PT_1-PT_2: Pressure ports, P_1-P_2: Pumps, OT: Oil tank, RM: Rotameter, WT: Water tank, V_1-V_9: Valves, VB: View box.

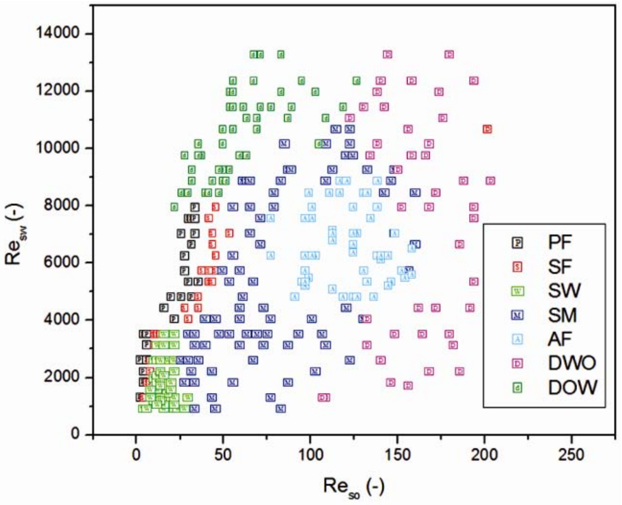

Fig. 2—Flow pattern map of oil-water flow. PF: Plug flow; SF: Slug flow; SW: Stratified wavy; SM: Stratified mixed; AF: Annular flow; DWO: Dispersed water in oil; DOW: Dispersed oil in water

for constant water Reynolds number. Most of the pressure drop increase is due to increase in velocity of oil phase. Pressure drop also increases with enhancement in water flow rate. As the flow rate of the water is increased the friction factor of the pipe covered by the rough interface formed between the oil and water lead to an increased friction factor and pressure drop. Based on the Lockhart-Martinelli[6] concept, in the present case the parameters, ϕ_{sw} and ϕ_{so} have been correlated by incorporating the effect of different dimensionless groups developed by dimensional analysis as:

$$\phi^2_{sw} = f(X) = \lambda' \times Re^p_{so} \times Re^q_{sw} \times X^r \qquad \ldots (1)$$

The values of λ′, p, q and r with correlation coefficient (R^2) and the standard error (SE) of equation (1) for different flow patterns found are shown in Table 1. Figure 4 represents the comparisons between the predictions of the proposed modified Lockhart–Martinelli parameter equation and the experimental data of the present system which gives the satisfactory prediction for frictional pressure drop in the two-phase oil-water flow of the present system for the range of the variables of $0 < Re_{sw} < 13275$, $0 < Re_{so} < 240$.

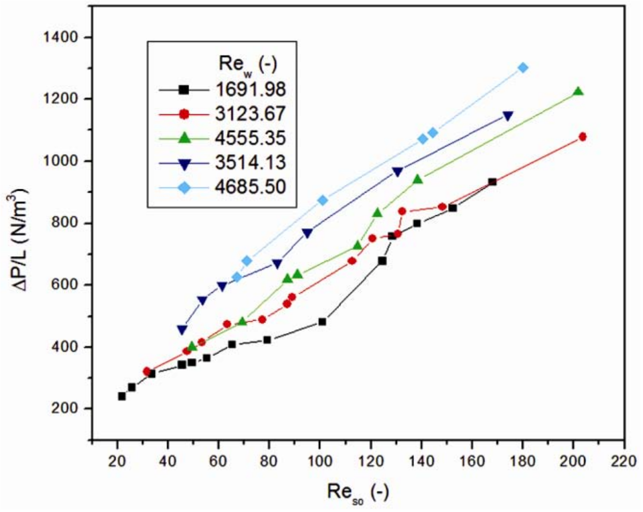

Fig. 3—Variations of pressure gradient with Oil Reynolds number

Analysis of friction factor

From this frictional pressure gradient, the friction factor ($f_{o\text{-}w}$) can be calculated. From the present study single phase flow theory does not satisfy well to for the correlation of friction factor. So a new correlation is developed to predict the friction factor as a function of variables which is represented as

$$f_{o\text{-}w} = f_{sw} \times [\{(\phi^2_{sw}/\alpha_w)/(1+\rho_{RO})\} \times \{1+ v_{RO}\}^{-2}] \qquad \ldots (2)$$

where $\rho_{RO} = \alpha_o\rho_o/\alpha_w\rho_w$, $v_{RO} = v_{so}/v_{sw}$. The equation (2) shows the satisfactory prediction for friction factor in the two-phase flow of the present system in the range of the variables of $0 < Re_{sw} < 13275$, $0 < Re_{so} < 240$.

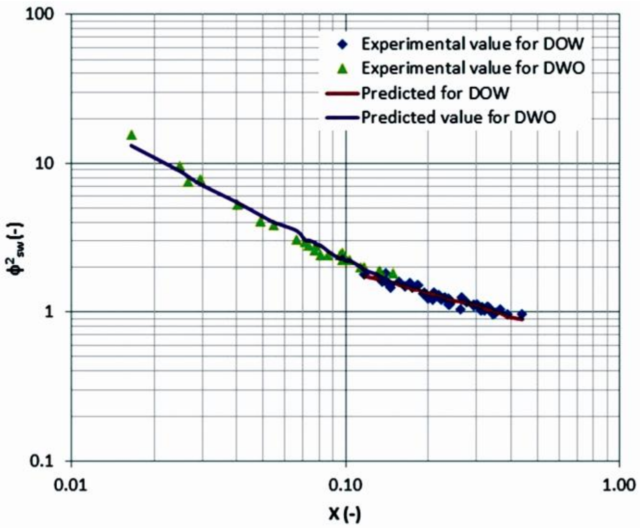

Fig. 4—Variations of frictional pressure drop multiplier with Lockhart–Martinelli parameter X

Table 1—The values of λ′, p, q, r for different flow patterns

Flow patterns	λ′	p	q	r	R^2	SE
PF	3.373×10^{-01}	-0.257	0.142	-0.536	0.972	0.039
SF	2.571×10^{2}	0.109	-0.641	-0.080	0.969	0.041
SS	3.219×10^{8}	1.932	-2.894	0.490	0.991	0.159
SW	1.018×10^{12}	3.340	-3.934	1.663	0.993	0.071
SM	5.410×10^{-01}	-0.222	0.000	-1.019	0.978	0.063
AF	1.962×10^{-01}	0.114	0.000	-0.765	0.951	0.098
DOW	5.227×10^{-01}	0.050	0.000	-0.453	0.908	0.051
DWO	1.723×10^{4}	0.608	-1.347	-0.238	0.992	0.089

The wall shear stress acting on each phase is expressed in terms of the local velocity of the phase and corresponding friction factor[3]. The interfacial friction factor (f_i) is related to this friction factor (f_k) as given by Rodriguez and Baldani[3].The suffix k stands for phase indicator (*o* for oil and *w* for water). Rodriguez and Baldani[3] developed an expression for the interfacial friction factor based on the equivalent-sand-roughness concept from Wallis[7] where interfacial wave amplitude governs the interfacial friction factor. The interfacial wave amplitude depends on the water holdup and can be represented by a correlation[3]developed by fitting the experimental data of de Castro *et al.*[4] A correction factor (C_i) is to be incorporated for stratified liquid– liquid flow pattern. Rodriguez and Baldani[3] reported that the correction factor C_i for stratified liquid– liquid flow in the inclined pipe is to be 50 with least error with experimental data where f_k is for water phase. From our experimental results it is seen that the C_i value for stratified oil-water flow varies from 3 to 50 depending on the Reynolds number of both oil and water. The C_i value increases with the increase in oil Reynolds number whereas it decreases with the increase in water Reynolds number. A correlation is developed based on the present experimental data to predict the correction factors to interpret the interfacial friction factor as:

$$C_i = 3.60\times Re^{2.02}_{so}\, Re^{-0.594}_{sw} \qquad \ldots (3)$$

The correlation coefficient and the standard error for the correlation are found to be 0.985 and 0.01.

Conclusions

In the present work, pressure drop and flow patterns of oil-water flow in an inclined pipeline are analyzed by modified Lockhart-Martinelli's model. The frictional pressure drop and flow patterns are strongly dependent on the motive fluid flow rate and system properties. The Martinelli parameter has been modified by incorporating different dimensionless number obtained by dimensional analysis with the help of different operating variables. From the present experimental study it is observed that the frictional pressure drop increased with increasing oil and water flow rates. A generalized correlation has been made for total pressure drop and friction factor as a function of individual oil and water Reynolds number for different flow patterns. The correlations have been found to be satisfactory within the range of the experimental operation. This study may be useful tool for further understanding of multiphase flow in chemical process systems possible scale up of three-phase column for different chemical processes.

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Nomenclature

C_i	Correction factor defined in Equation (3), (-)
d	Diameter of the pipe, (m)
f_s	Friction factor for single phase flow, (-)
ΔP	Pressure drop for oil-water flow, (Pa)
p, q, r	Parameters (-)
Re_{so}	Reynolds number based on single oil phase,(-)
Re_{sw}	Reynolds number on single water,(-)
R^2	Correlation coefficient, (-)
v_{so}	Superficial velocity of the oil, (m/s)
v_{sw}	Superficial velocity of the water, (m/s)
X	Lockhart – Martinelli parameter, (-)
ΔL	Length of the pipe across which pressure drop is measured, (m)
ρ_o	Density of oil, (kg/m^3)
ρ_w	Density of water, (kg/m^3)
$\phi_{so},$	Lockhart–Martinelli parameters of oil, (-)
ϕ_{sw}	Lockhart–Martinelli parameters of water, (-)
μ	Viscosity, (Pa.s)
λ'	Constant, (-)

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