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Experimental investigation of two-phase water–oil flow pressure drop in inclined pipes

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ABSTRACT

In this experimental work the effect of inclination on the pressure gradient in two phase oil–water flow is investigated. The experiments were performed in a 6 m long, 20 mm inner diameter and inclinable acrylic pipe using oil (3 mPa s viscosity and 830 kg/m^3 density) and water (1 mPa s viscosity and 990 kg/m^3 density) as test fluids. Pressure gradients between inlet and outlet of flow in pipe were measured for inclination angles of 0°, ±5°, ±15°, ±30° and ±45° with respect to the horizontal plane. The experimental results were compared with Homogeneous and Two-Fluid models. It was observed that in high mixture velocities, where dispersed flow prevails, there is a peak pressure gradient which is related to phase inversion. It was also found that, phase inversion appears at higher inlet water cut values in inclinations of −30° and −45° compared with other inclinations. However the two-fluid model and homogeneous model both over-predicted the pressure drop, but two-fluid model predicted the pressure drop with less average deviation. Several correlations for effective mixture viscosity in a homogeneous model were considered and the results were compared with experimental results. Acceptable agreement was seen between the computed and measured data.

The experimental two-phase friction factors were compared with the friction factors for single phase flow of oil and water, at the same velocities as the two phase mixture and it was found that the experimental friction factors were less than the predicted friction factors of single phase flow.

1. Introduction

In many chemical and oil industries, oil–water two-phase flows are important. So understanding the behavior of these kinds of flows is necessary. For instances, oil extraction from oil wells is often accompanied by a high water fraction which increases during the producing life of well [1], also in many cases in order to enhance oil transportation, water is injected into the pipe and so oil and water are transported together in pipelines that may experience various degrees of inclination respecting to the horizontal direction. For this reason, knowing two-phase liquid–liquid flow behavior in various pipe angles is important in designs related to the petroleum industry. Despite knowing this matter, two phase liquid–liquid flow is considerably less studied compared with two phase gas-liquid flow and theoretical models presented for analysis of pressure drop of two-phase liquid–liquid flow and these studies marked by considerable limitations [2]. Generally, pressure drop in oil–water pipelines is one of the most important design parameters and presenting an appropriate theoretical model for predicting pressure drop of liquid–liquid flow is needed for many applications.

Very early studies of oil–water flows were accomplished in decades 1950 and 1960. Charles et al. [3] and Russell et al. [4] discovered that adding water to oil decreases pressure drop. After an interval, the interest for liquid–liquid flows grew up due to increased applications of this kind of flow in various industries.

Flow patterns are known to be important for analysis of pressure drop in two-phase oil–water flows by many researchers [5,6]. Even if oil properties are close to water such that oil viscosity is only 2 or 3 times more than of water's viscosity, there would be no reliable model for predicting pressure drop [7,8] due to its highly nonlinear behavior. One of the matters that makes the pressure drop prediction more complicated is phase inversion phenomena. The phase inversion is a behavior occurs when with a small change in the operating conditions; the continuous and dispersed phase of flow spontaneously inverts [9]. The volume fraction in which, the phase inversion occurs is called a phase inversion point. According to previous studies, pressure drop considerably increases at phase inversion point [10,11]. Angeli and Hewitt [11] found that homogeneous model with viscosity calculated from the Brinkman model [12] is able to predict pressure drop at phase

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Nomenclature

dp/dz	pressure gradient (Pa/m)	U_m	mixture velocity (m/s)
U_{SO} and U_{SW}	oil and water superficial velocity (m/s)	Re_o and Re_W	oil and water Reynolds number
U_O and U_W	oil and water in-situ velocity (m/s)	μ_o and μ_w	oil and water viscosity (Pa s)
A_O and A_W	area occupied by oil and water (m^2)	ρ_O and ρ_w	oil and water density (kg/m^3)
D_o and D_w	hydraulic diameter of oil and water (m)	μ_m	mixture viscosity in homogeneous model (Pa s)
S_o and S_W	wall wetted perimeter for oil and water (m)	ρ_m	mixture density in homogeneous model (kg/m^3)
τ_O and τ_W	wall shear stresses for the oil and water (N/m^2)	μ_C and μ_d	continuous and dispersed viscosity (Pa s)
S_i	interfacial periphery (m)	H_O and H_W	oil and water hold-up
τ_i	interfacial oil–water shear stress (N/m^2)	α	volume fraction (hold-up)

inversion point but with high uncertainty. Poesio et al. [13] developed two fluid model based on the assumption that one of the phases is dispersed, but did not verify their model at a phase inversion point.

Despite the large number of studies currently available in the literature of pressure drop in horizontal and vertical pipes, very few works have tried to predict the pressure drop and other properties of two phase flow at phase inversion point. Also Most works done for two-phase liquid–liquid flow are related to pipes with diameters greater than 20 mm and less is done for the pipes with smaller diameters. Most of the articles that have studied two-phase flows in smaller pipes are done within recent years [14–17].

In this article, we have measured pressure drop for different inclination angles of a 6 meter long pipe. The inner diameter of the pipe was 20 mm and it is completely made of acrylic to be transparent. Various correlations are used for calculating effective viscosity in a homogeneous model to realize which one can predict pressure drop more precisely. Also, we have compared experimental pressure drop results with two-fluid model for separated flow presented by Taitel and Dukler [18] and two fluid model presented by Poesio et al. [13]. We have focused on dispersed flow pattern to observe and investigate effects of the phase inversion phenomenon on pressure drop, mixture viscosity and friction factor to find which model predicts these properties better at phase inversion point. One of the reasons that the small pipe observations was conducted in the current work is that in small pipes the dispersed flow pattern could be observed in laboratory scales with lower flow rates. So using a small pipe test is a suitable choice for the study of phase inversion in dispersed flows and according to Xiao-Xuan [1] results could be generalized for different pipe diameters to some extents.

2. Experimental setup

The experiments were performed in a multiphase flow facility with a pipe which is capable of having different inclination angles with respect to the horizontal direction. A schematic sketch of this test facility is given in Fig. 1. The test section has a 6 m acrylic pipe with an inner diameter of 20 mm and outer diameter of 30 mm. The test pipe could be inclined from 45° in a downward direction to 45° in upward direction. Working fluids for this experiment were water and oil, which kept in two separate storage tanks. Water and oil pumped by positive displacement pumps to test the line and were stored in a gravity separator tank in which oil and water separate due to density differences. Superstation tank is placed in a height well above water and oil tank. After returning the separated oil to its respective storage tank, the remained water

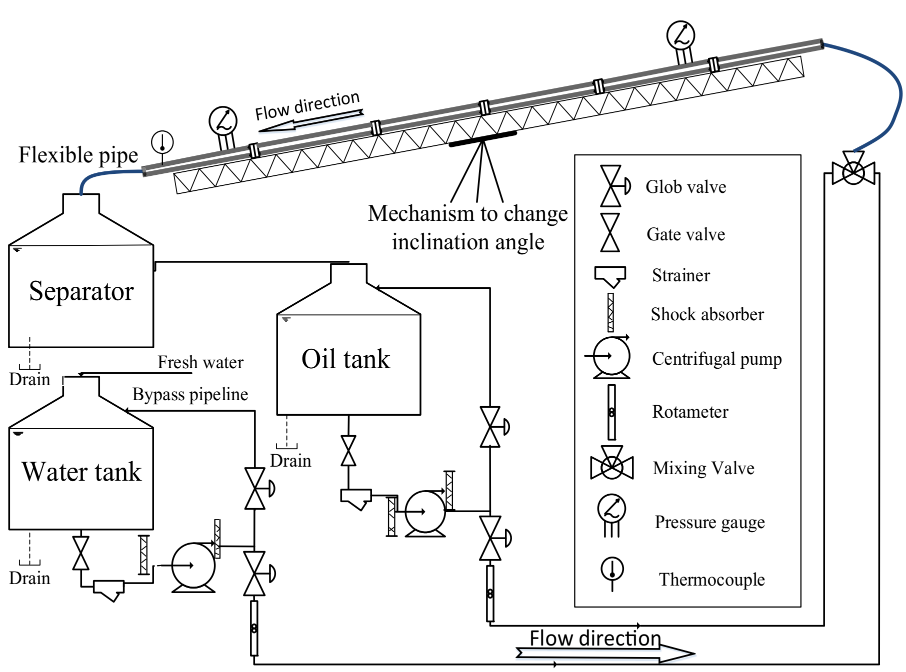

Fig. 1. Sketch of the experimental set-up.