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Pressure Drop Measurements of Oil (D80)-Water Flow in 6" Horizontal and Inclined Annulus Pipe

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Abstract

The flow of two immiscible liquids (such as oil and water) in pipes is a challenging subject that is rich in physics and practical applications. It is often encountered in many oil and chemical industries. The pressure gradient and flow patterns of immiscible liquids are still subject of immense research interest. This is partly because fluids with different properties exhibit different flow behaviors in different pipe's configurations under different operating conditions. More importantly, oil-water annular flow (oil surrounded by water) is a common occurrence in oil upstream petroleum industry and is generally used for the lubricated transportation of highly viscous oil. However, despite their importance, behavior of such flows has not been explored to an appreciable extent.

The present study reports pressure drop measurements of oil (D80)-water annular two-phase flow in a horizontal and inclined 6 inch diameter stainless steel pipe at different flow conditions. Experiments were carried out for different inclination angles including; 0°, 40°, 60° 90° and for different water cut (WC) ratios. Water cut ratios were varied from 0 to 100% in steps of 20 %. Inlet oil-water flow rates were varied from 2000 to 12000 barrels-per-day (BPD). For a given flow rate (for all angles) the frictional pressure drop has been found to increases from WC = 0 to WC 40 %. Further increase in WC, friction pressure drop has been found to decrease. In general, frictional pressure drop increases with flow rate and water cut and the effect of angle was not appreciable. The behavior of total pressure was asymptotic with increase in flow rate. Also the behavior of total pressure was linear with respect to WC up to 80%.

Keywords: Multiphase flow, Oil-water flow, Pressure drop, water cut, inclined pipe, annular flow.

INTRODUCTION

Heavy oils represent about one third of the world hydrocarbon resources, but, their production is associated with huge costs of transportation. Oil and water are often produced and transported together in pipelines that have various degrees of inclination from the horizontal. A possible transportation technique is core-annular flow (CAF). In this configuration, the oil flows at the center of the pipe (core) and the water flows as an annulus around it.

Also, the widespread occurrence of multiphase flows in pipes has motivated extensive research (a number of upstream practical applications in the petroleum industry involve oil–water annular two-phase flow phenomena). Significant savings in the pumping power required for oil transportation (water-lubricated transportation of crude oil) can be attained when water flows in the pipeline together with the oil, especially when the highly viscous phase is surrounded by a water annulus, giving place to the core annular flow configuration. As the establishment of a particular flow regime depends upon the interaction of gravitational, inertial and surface tension forces, annular flow is observed only under particular combinations of the oil and water flow rates. Moreover, knowledge of the friction loss in oil-water flows in pipes is essential in order to specify the size of the pump required to pump the emulsions. The measurement of phase flow rates is of particular importance for managing oil production and water disposal and/or water reinjection. Pressure is the key parameter for assessing individual phase (oil and water) flow rates in annular pipelines. Therefore, it is important to study behavior of pressure response to characterize two-phase annulus flow in upstream production pipelines. Several articles are available in literature on the two-phase flow of oil and water in pipes.

Kokal and Stanislav [1] calculated the pressure drop and liquid holdup for intermittent two phase flow in upward inclined pipes and flow patterns were presented. They compared experimental values of pressure drops with previous study and results showed a good agreement. Landman [2] discussed theory related to hold-up and pressure drop in two phase stratified inclined pipe flow. Sanchez and Alvarez [3] conducted two phase flow pressure drop experiments in inclined pipe for geothermal applications and compared their results with existing model for inclined pipes. Grolmann and Fortuin [4] studied liquid hold-up and pressure gradient in gas-liquid flow in slightly inclined pipes. Significant effect of small inclination angles were found at low gas flow rates.

Descamps et al. [5] performed experimental investigation of three phase flow in vertical pipes. Special attention was paid to phase inversion phenomenon. They noticed that the dispersed water phase has significant impact on the bubble size. Xu [6] presented a brief review of oil water two phase flow in horizontal pipes and highlighted future research trends of oil water pipe flows.

Grassi et al. [7] conducted experiments of two phase liquid-liquid (high viscosity ratio) flows in horizontal and slightly inclined pipes. The results were validated against theoretical models. However, they were unable to identify/explain flow transition parameters in stratified flows. Du et al. [8] conducted experimental investigation of vertical upward oil-water two phase flows in a 20 mm diameter pipe. They presented flow pattern map of oil water for different superficial velocities. They also obtained flow pattern transition boundaries in terms of water hold-up.

Yusuf et al. [9] have presented experimental data of flow patterns, pressure gradient and phase inversion in horizontal oil–water flow in a 25.4 mm acrylic pipe. One of the main findings is the large difference between the pressure gradient results which is attributed to the difference in oil viscosity. The differences between the results become bigger at higher oil velocities. The largest difference in pressure values was observed in flow region where oil is the continuous phase. On the contrary, for dispersed oil in water (Do/w), the pressure gradient values observed at the same conditions are approximately the same. At low oil velocities, the water velocity required to initiate the transition to non-stratified flow increased as the oil viscosity increased while it decreased at higher oil velocities.

Sotgia et al [10] performed experimental study of oil–water flow in horizontal pipes using mineral oil and tap water of viscosity ratio about 900 and density ratio 0.9. A set of seven different pipes of Pyrex and Plexiglas where used, with diameters ranging between 21 and 40 mm. Pressure drop measurements, flow pattern maps and pictures of the oil–water flow are reported in this article.

Ching and Pal [11] studied the pressure loss in a sudden expansion and a sudden contraction for two-phase oil/water mixtures covering a wide range of oil concentration: 0 to 97.3 vol. % oil. The emulsions were of oil-in-water type up to an oil concentration of 64 vol. %. Above this concentration, the emulsions were water-in-oil type. It is concluded that the loss coefficient is not significantly influenced by the type and concentration of emulsions flowing through a sudden expansion and a sudden contraction.

Domenico et al. [12] conducted experimental study on oil/water flow in horizontal and slightly inclined small pipe plexi glass tubes (with 21 mm ID, 9m long). They focused on core-annular flow pattern boundary, pressure drops, and oil hold-up measurements. Experimental data was compared with other models and a good agreement was observed.

Karolina et al. [13] have investigated phase inversion and its effect on pressure gradient during the dispersed flow of two immiscible (water and oil) liquids for two pipe materials (steel and acrylic) and two pipe sizes (60 and 32 mm ID) for a range of mixture velocities. No effect of initial conditions on the inversion point was found for the small acrylic pipe. Phase inversion was in all cases preceded by a large increase in pressure gradient, which was sharply reduced immediately after the new continuous phase was established. The pressure gradient peak was sharper and larger at high mixture velocities than at low ones and in the acrylic pipe compared to the steel one

The complexity of oil-in-water flow structures creates a challenge to flow measurement. Yousef et al. [14] have proposed a new method of two-phase flow metering which is based on the use of dual-modality system and multidimensional data fusion. The Electrical Resistance Tomography system (ERT) is used in combination with a commercial off-the-shelf Electromagnetic Flow meter (EMF) to measure the volumetric flow rate of each constituent phase. Experiments were carried out on a vertical upward oil-in-water pipe flow (50mm inner-diameter test section) at different total liquid flow rates covering the range of 8–16 m3/hr.

Talal [15] developed a simple power law pressure gradient correlation for horizontal oil–water separated flow (stratified and dual continuous flows). The new proposed correlation predicts the pressure gradient with higher accuracy. He prepared a pressure gradient database for oil–water flow which includes wide range of operational conditions, fluid properties, pipe diameters and materials.

Dongian et al. [16] studied experimentally local flow characteristics of oil–water dispersed flow in a vertical upward pipe. The inner diameter and length of the test section are 40 mm and 3800 mm, respectively. The water flow rates varied from 0.12 m/s to 0.89 m/s, while the oil flow rates ranged from 0.024 m/s to 0.198 m/s. The typical radial profiles of interfacial area concentration, oil phase fraction, interfacial velocity, and oil pressure drops were presented. The phase fraction represents the phase distribution in two-phase flow, while the interfacial area concentration describes available area for the interfacial transfer of mass, momentum and energy.

Angeli and Hewitt [17] made measurements of pressure gradients during the concurrent flow of a low viscosity oil (1.6 mPa s viscosity and 801 kg/m3 density) and water in two 1-inch nominal bore horizontal test sections made from stainless steel and acrylic resin, respectively. Measurements were made (in two horizontal test sections with different wall properties) for mixture velocities from 0.3 to 3.9 m/s and for water volume fractions from 0 to 100%. It has observed that the material of the tube wall (plays a large role) can strongly influence the pressure gradient during two-phase liquid-liquid flow. Pressure gradients under all conditions were higher in the steel than in acrylic tube for the same mixture velocities and flow volume fractions.

The formation of water-in-crude oil emulsions during oil production can cause a substantial reduction of the production rates. This occurs due to the high effective viscosity of the emulsion that increases with water content towards the phase inversion point. Knowledge of both the effective viscosity and the phase inversion point is important for the dimensioning of pipelines and equipment as well as for the assessment of production strategies. The effective viscosity of an emulsion can greatly exceed either the crude or the water single phase viscosities. Jose et al [18] made a comparative study of the pipe flow of water-in-crude oil emulsions in a closed loop system (pipe ID2.2cm). The pipe flow of emulsions based on six different crude oils (viscosities from 4.8 to 23.5 mPas) and salt water (3.5% NaCl w/v, pH¼7.3) were investigated experimentally using a small scale flow loop. The effective viscosity of the emulsions as a function of the water fraction was calculated from pressure drop measurements. The point of inversion was observed to be fluid dependent. Pietro et al [19] have studied experimentally the effect of air injection on liquid–liquid core annular flow of very-viscous-oil/water on the pressure drop. They have presented a new data set for pressure drop.

Lum et al. [20] have investigated experimentally the effect of upward and downward pipe inclinations on the flow patterns, hold up and pressure gradient during two-liquid phase flows for mixture velocities between 0.7 and 2.5 m/s and phase fractions between 10% and 90%. The investigations were performed in a 38 mm ID stainless steel test pipe with water and oil as test fluids. The oil to water velocity ratio was higher for the upward than for the downward flows but in the majority of cases and all inclinations oil was flowing faster than water. At low mixture velocities the velocity ratio increased with oil fraction while it decreased at high velocities. The increase became more significant as the degree of inclination increased. The frictional pressure gradient in both upward and downward flows was in general lower than in horizontal flows.

In the light of the above research studies, there is currently no work available in the literature on pressure drop measurements of oil (D80)-water two-phase annular flow in horizontal and inclined 6 inch diameter stainless steel annular (3 inch ID) pipe at different flow conditions. This is the motivation for the present experimental study and it focuses on the effect of flow rates, water-cuts, inclination angle on pressure drop measurements of oil (D80)-water two-phase annular flow.

In this work, efforts have been made to present pressure drop measurements of oil (D80)-water two-phase annular flow in a horizontal and inclined 6 inch diameter stainless steel annular (3 inch ID) pipe at different flow conditions. Experiments were carried out for different inclination angles including; 0°, 40°, 60° 90° and for different water cut ratios. Water cut ratios were varied from 0 to 100% in steps of 20 %. Inlet oil-water flow rates were varied from 2000 to 12000 barrels-per-day (BPD).

EXPERIMENTAL SETUP

The Oil-water two phase experiments were conducted at the multi-phase laboratory of King Fahd University of Petroleum and Mineral, Dhahran, Saudi Arabia.

The layout of the flow loop is presented in Figure 1a-b. Experimental set-up includes: four centrifugal variable speed pumps[2 pumpsfor water (WP) and 2 pumps for oil, (OP)], swing arm 6 inch stainless loop, a horizontal separator tank(WOST), which acts as storage tank, two level indicators for oil and water each. The loop is constructed on swinging arm platform (inclination can be varied from 0° - 90°), which toggles on roller bearings at the base. The loop can be positioned at any given angle using over-head jack as shown in Figure 1b.

The loop is instrumented with a turbine type oil flow meter(OFM), a turbine type water flow meters(WFM), line pressure transmitter (LPT), two flow differential pressure transmitters (DP1 and DP2). Details of the loop components and instruments are given in Table 1.

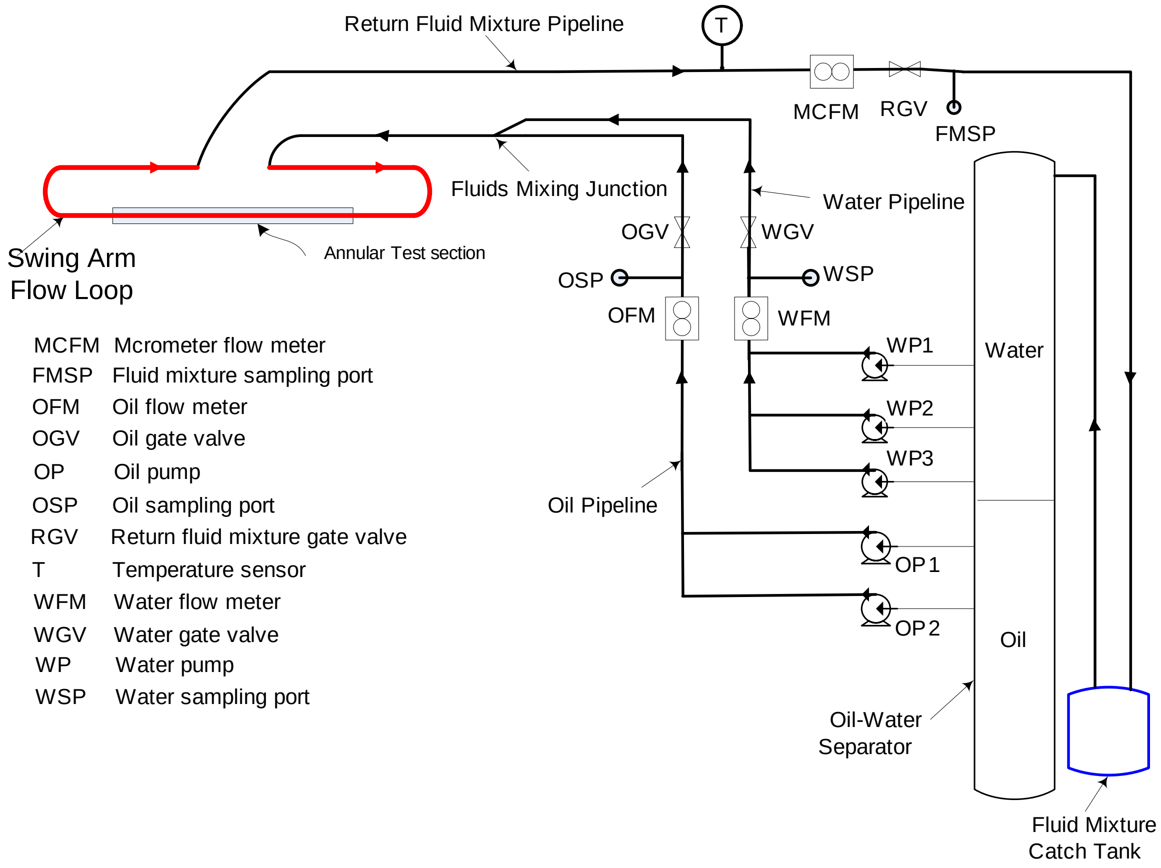

Figure1a: Schematic layout of the oil-water multiphase flow loop.

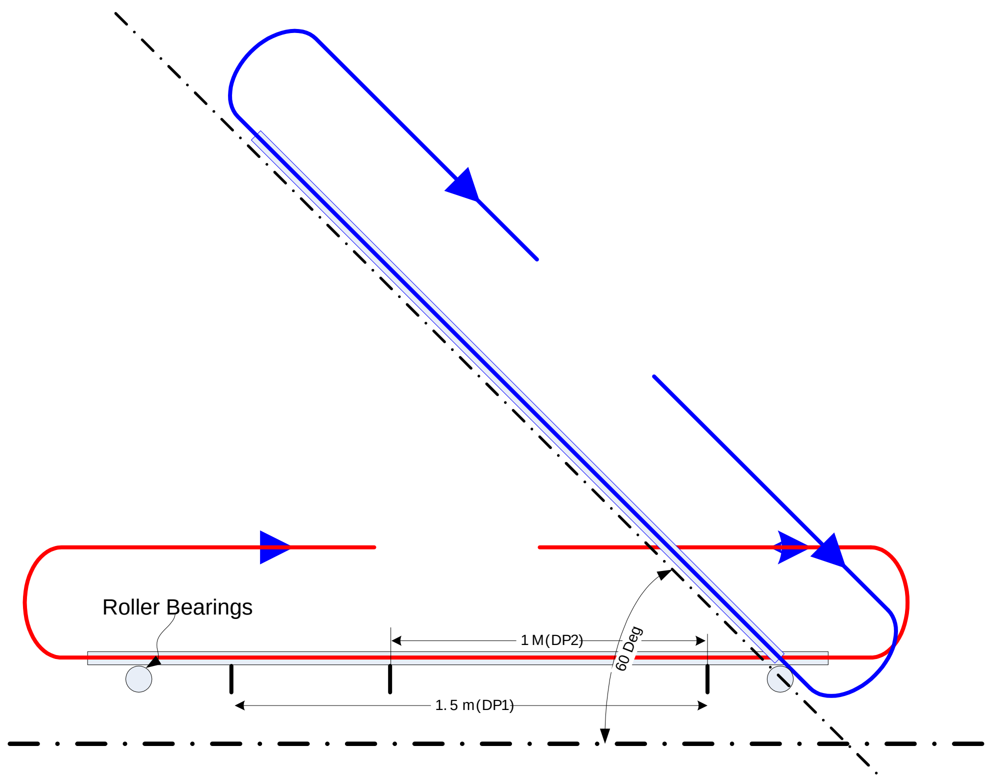

Figure 1b: Details of pressure tapping point (DP1 and DP2).

Table 1: Details of equipment of the flow loop.

Items	**Manufacturer**	**Model**	**Capacity/Range**	**Accuracy/Error**
Four pump(two water, two oil)	NEWAR FLOW SERVE	50-32CPX200	35 m^3/hr	-
Two turbine flow meter	Omega	EF10	±10 m/s	±1.0 %
Line pressure gauge	ROSEMOUNT	AOB-20	0-7 bar	±0.25%
DP1	ROSEMOUNT	300S2EAE5M9	0-70 inches of water column	±0.1%
DP2	ROSEMOUNT	300S2EAE5M9	0-12 inches of water column	±0.1%

EXPERIMENTAL PROCEDURE

Initially, experiments were conducted for water-onlyand oil-only single phase (in 4inch pipe)to validate the pressure drop measurements against available empirical models, and to ascertain effectiveness of pressure transmitters and flow meters of the loop.

In this regard, water was pumped in the loop using centrifugal pumps. Required volume flow rate was attained by varying speed of pumps through variable speed drives. Turbine flow meters installed on the discharged line of the pumps were used for measuring the flow rates. Return gate valve (RGV, Figure1) of the loop is throttled to set the required outlet pressure (eg. 1 bar or 2 bars).

For a given flow rate, experiments were conducted and pressure drop measurements were made at two different locations of the loop as shown Figure 1b. Once the steady state flow condition is achieved, differential pressure drops arerecordedacross 1m (DP1) and 1.5m (DP2). CR 1000 data logger was used to record experimental data. Similar procedure was followed for oil-only flow experiments.

Pressure drop data was used to calculate friction factor using Eq. (1) and compared with Eq. (2) and Eq. (3).

$$f = \frac{\Delta P}{L} \frac{2D}{\rho v^2} \quad (1)$$

ΔP	Pressure drop (Pa).
L	distance between the two pressure taps (m).
D	hydraulic diameter of the pipe (m).
ρ	fluid density (Kg/m^3).
v	average velocity of the fluid (m/s).
ε	pipe roughness (m).
Re	Reynolds number

$$f = 0.3164\, Re^{-1/4} \quad (2)$$

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7} - \frac{5.02}{Re}\log\left[\left(\frac{\varepsilon/D}{3.7}\right) + \frac{13}{Re}\right]\right] \quad (3)$$

The turbulent friction factor can also be determined using other correlations, such as the Zigrang& Sylvester 1985 correlation defined in equation (3) above.

Then experimental obtained friction factor (Eq. 1) was compared with the friction factors calculated by using Blasius correlation and Zigrang& Sylvester correlations as shown in the Figure 2. The result showed a close agreement particularly with the Blasius friction factor (Eq. 2).

For a given oil-water multiphase flow (for a given angle, 0° case), speeds of the oil and water pumps were varied to achieve required flow rate and water cut. Once the required water cut and flow rates are reached, pressure drop [across 1m (DP1) and 1.5m (DP2)] measurements were made. Similar procedure was followed for other anglesincluding; 40°, 60° 90° and for different water cut ratio 0 to 100%. Inlet oil-water flow rates were varied from 2000 to 12000 barrels-per-day (BPD).

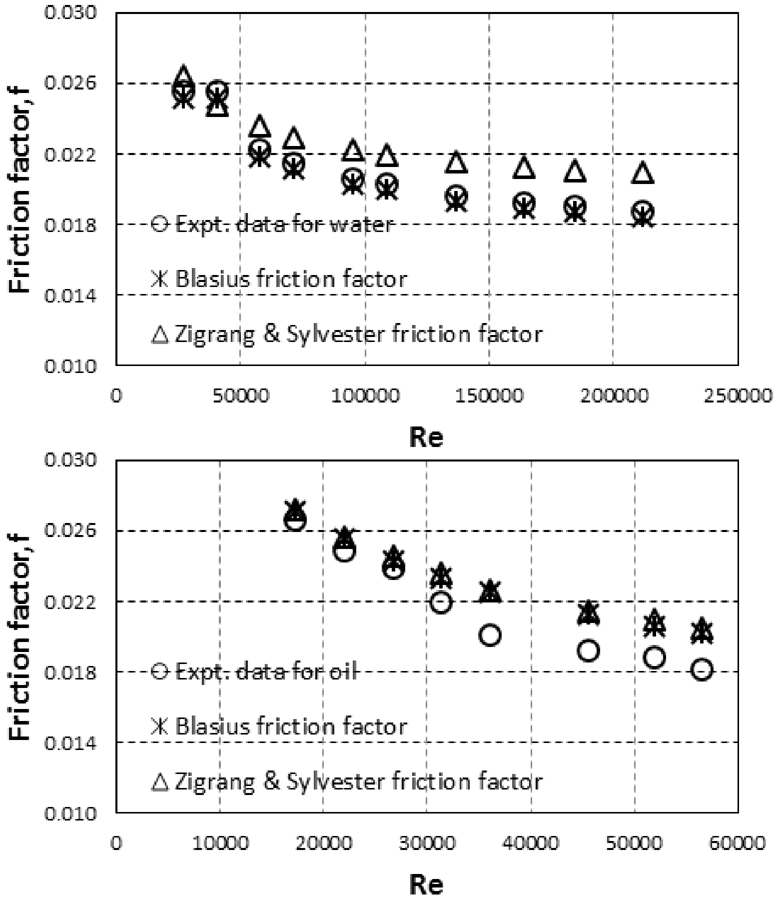

Figure 2. Friction factor comparisons with Blasius correlation and Zigrang& Sylvester correlations for oil-water.

Figure 2 shows the friction factor of single phase water and oil against Reynolds number. It can be noticed that thefriction factor decreases with increase in velocity. The experimental data is found to be in good agreement with established theoretical relation. Experiments were conducted at different times of the year, density variation with temperature was considered in the analysis.

RESULTS AND DISCUSSIONS

Oil-water multiphase flow experiments were carried out for different inclination angles including; 0°, 40°, 60° 90° and for different water cut ratio. Water cut ratios were varied from 0 to 100% in steps of 20 %. Inlet oil-water flow rates were varied from 2000 to 12000 barrels-per-day (BPD).

Effect of flow rate on oil-water pressure drop for different water-cuts

For a given angle(horizontal, $\theta = 0°$ case), the effect of water cut for different flow rates on pressure drop is shown in Figure 3a.In general, as it can be seen from Figure 3a, for a given flow rate the pressure drop increases from WC = 0 to WC 40 %. Further increase in WC, friction pressure drop has been found to decrease. This could be due to phase inversion or change in flow pattern regime. However, for WC = 100%, frictional pressure drop is higher as compared to frictional pressure at WC = 0%. This is due to higher density of water. Also,it can be seen from Figure 3a, for any given WC, the frictional pressure drop increases with increase in flow rate. This behavior is more pronounced for WC more than 40%.

For a given angle (horizontal, $\theta = 0°$), the effect of flow rate on pressure drop for different water cutsis shown in Figure 3b. As mentioned earlier, as it can be seen from Figure 3b, pressure drop increases with flow rate and WC. However, pressure drop is relatively higher for WC 40 % to 60%. This could be due to phase inversion or change in flow pattern regime.

The horizontal tests ($\theta = 0°$) for the total flow rates investigated give the frictional pressure drop at this orientation. This is because in the horizontal position, the total pressure drop measured by DP1 is equal to the frictional pressure drop. For a given total flow and water-cut, the frictional pressure drop does not change with inclination. DP1 only measures the total pressure drop between the measurement points. The frictional pressure drop results at θ = 40°, 60°, and 90° presented in Figures 4, 5 and 6.

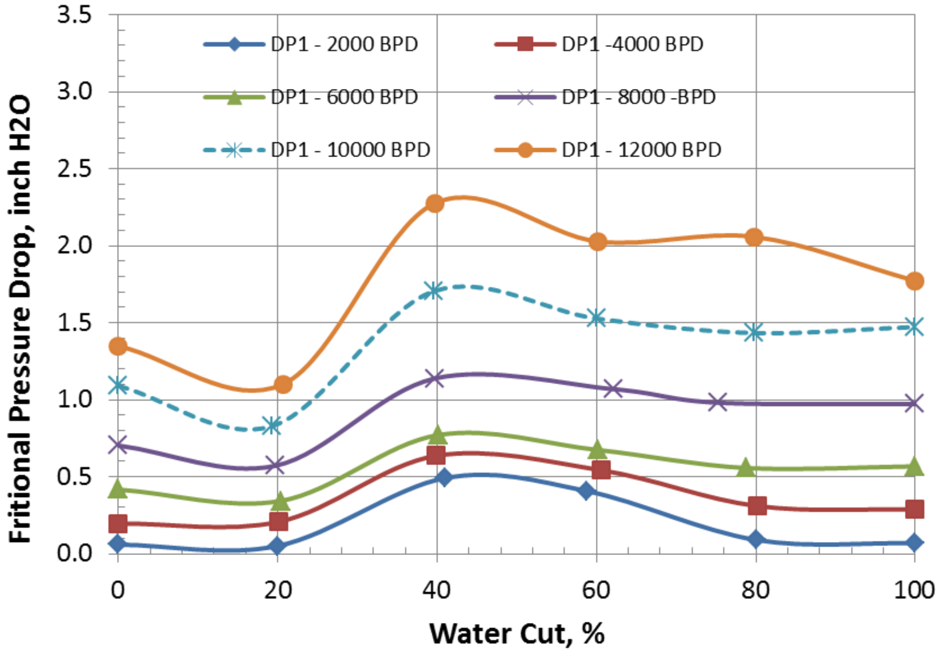

Figure 3a: Effect of water cut on pressure drop for different flow rates (0° case).

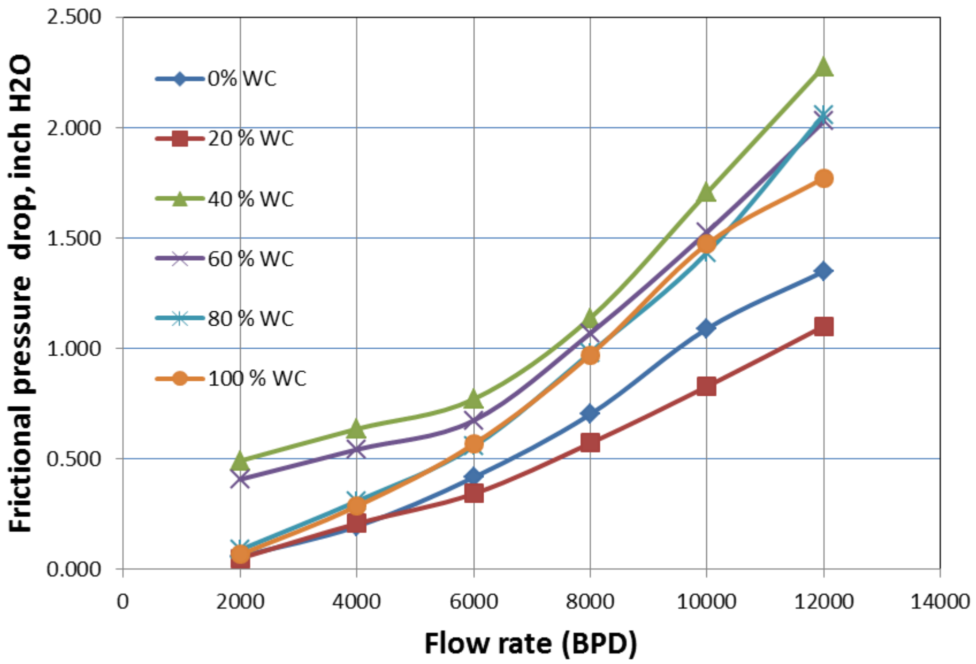

Figure 3b: Effect of flow rate on pressure drop for different water cuts (0° case).

For a 40° inclination, the effect of water cut for different flow rates on pressure drop is shown in Figure 4a. For a 40° inclination, the effect of flow rate on pressure drop for different water cuts isshown in Figure 4b. Similar behavior of pressure drop with flow rate and WC has been observed.

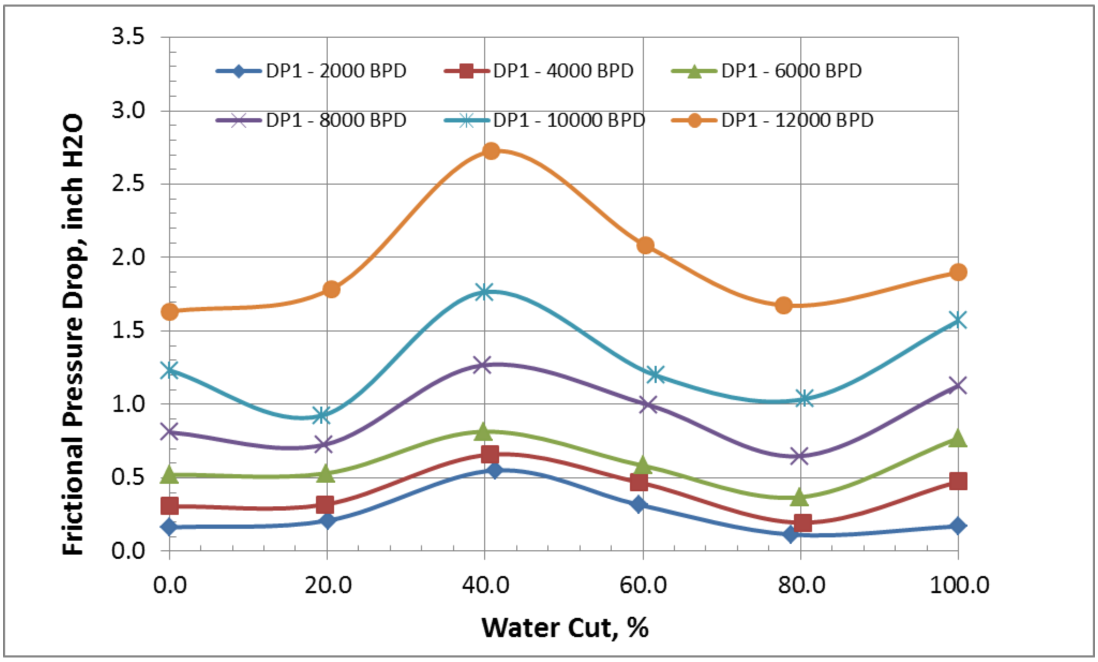

Figure 4a: Effect of water cut on pressure drop for different flow rates (40° case).

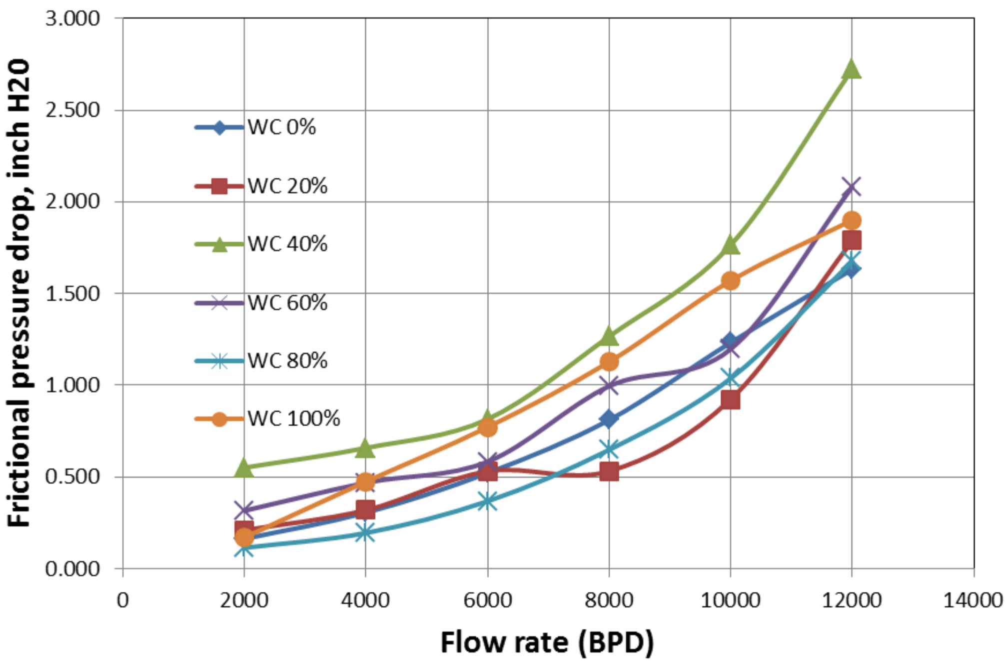

Figure 4b: Effect of flow rate on pressure drop for different flow rates (40° case).

For a 60° inclination, the effect of water cut for different flow rates on pressure drop is shown in Figure 5a. For a 60° inclination, the effect of flow rate on pressure drop for different water cuts are shown in Figure 5b.The behavior of pressure drop with flow rate and WC is similar to angles 0 and 40 ° cases.

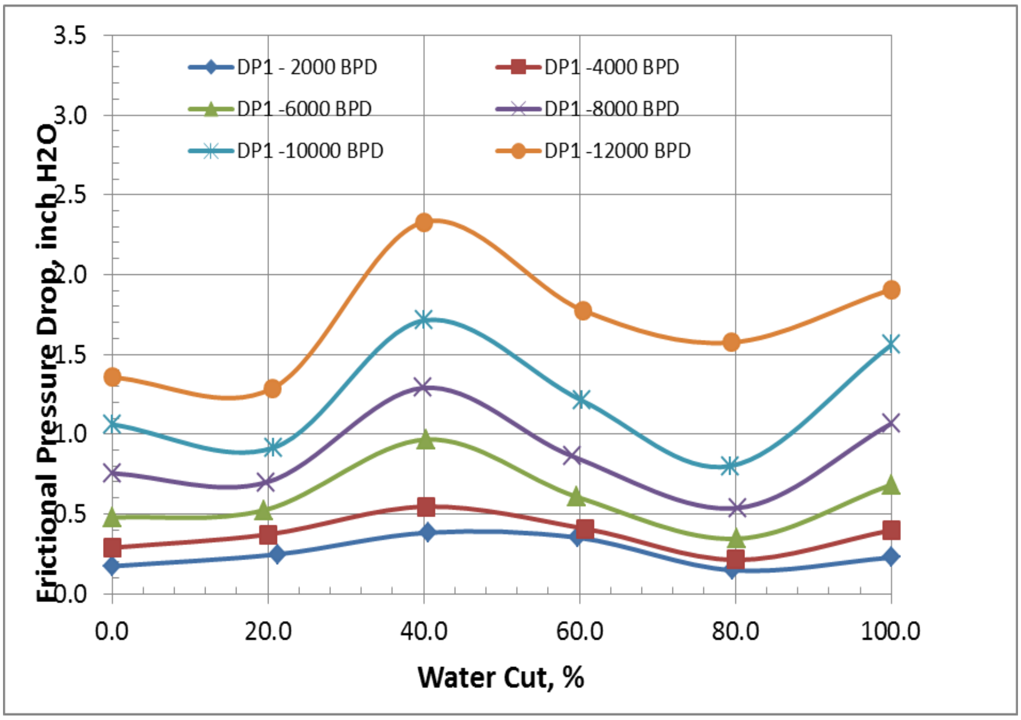

Figure 5a: Effect of water cut on pressure drop for different flow rates (60° case).

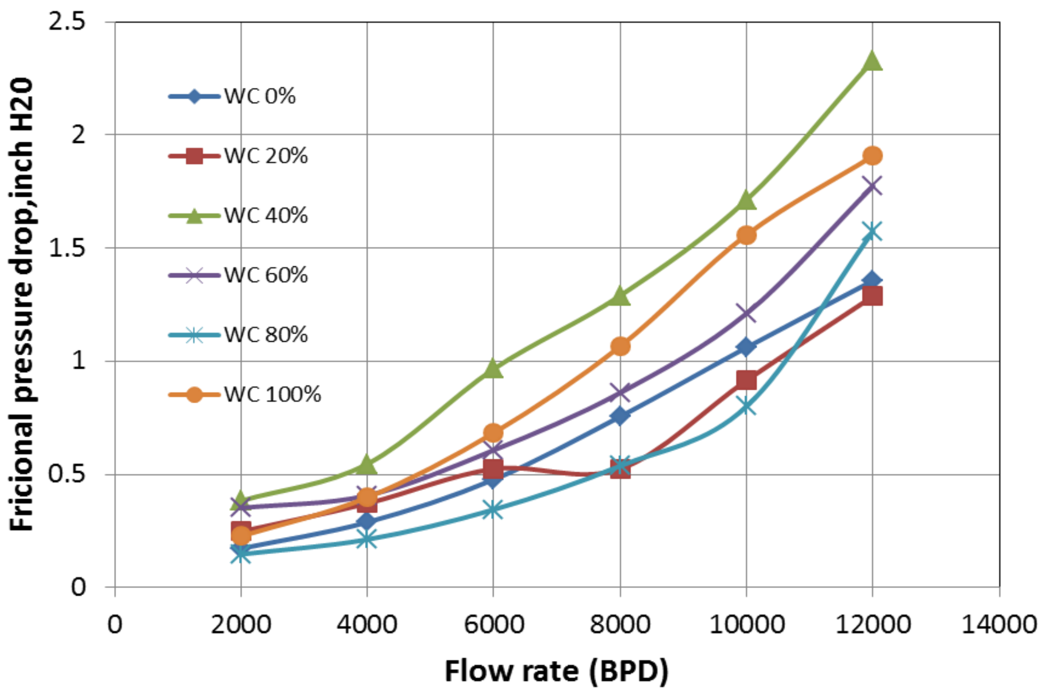

Figure 5b: Effect of flow rate on pressure drop for different flow rates (60° case).

For a 90° inclination, the effect of water cut for different flow rates on pressure drop is shown in Figure 6a. For a 90° inclination, the effect of flow rate on pressure drop for different water cuts is shown in Figure 6b. Again, similar behavior of pressure drop with flow rate and WC has be observed as in Figure 3 4, and 5.

From the above Figures, it can be concluded that the effect of inclination on pressure drop behavior is not appreciable. This is true because, theoretically the frictional pressure drop does not vary with inclination.

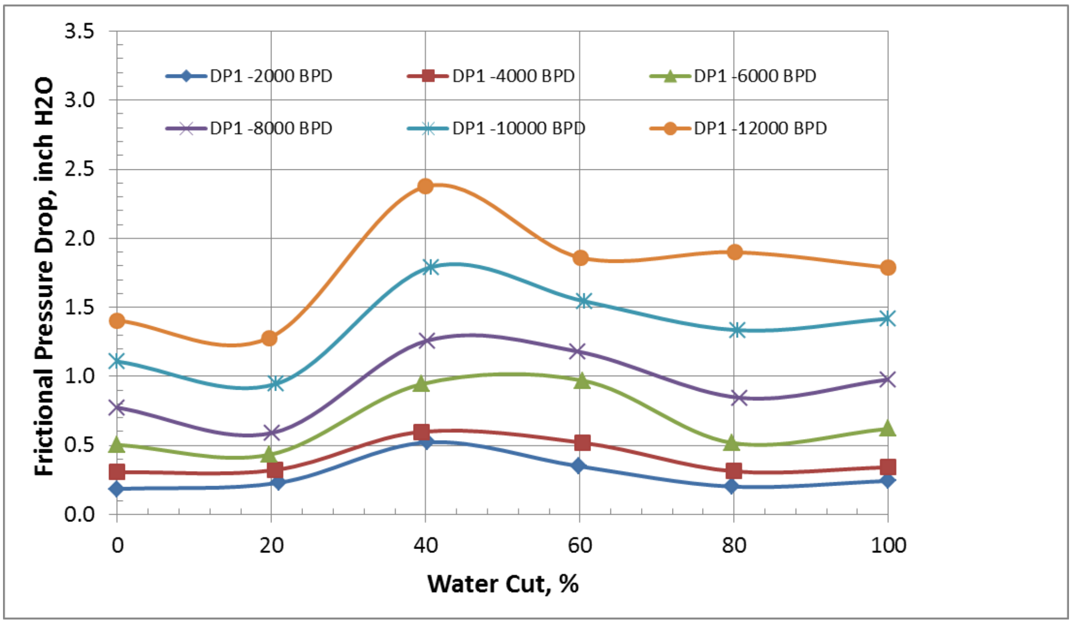

Figure 6a: Effect of water cut on pressure drop for different flow rates (90° case).

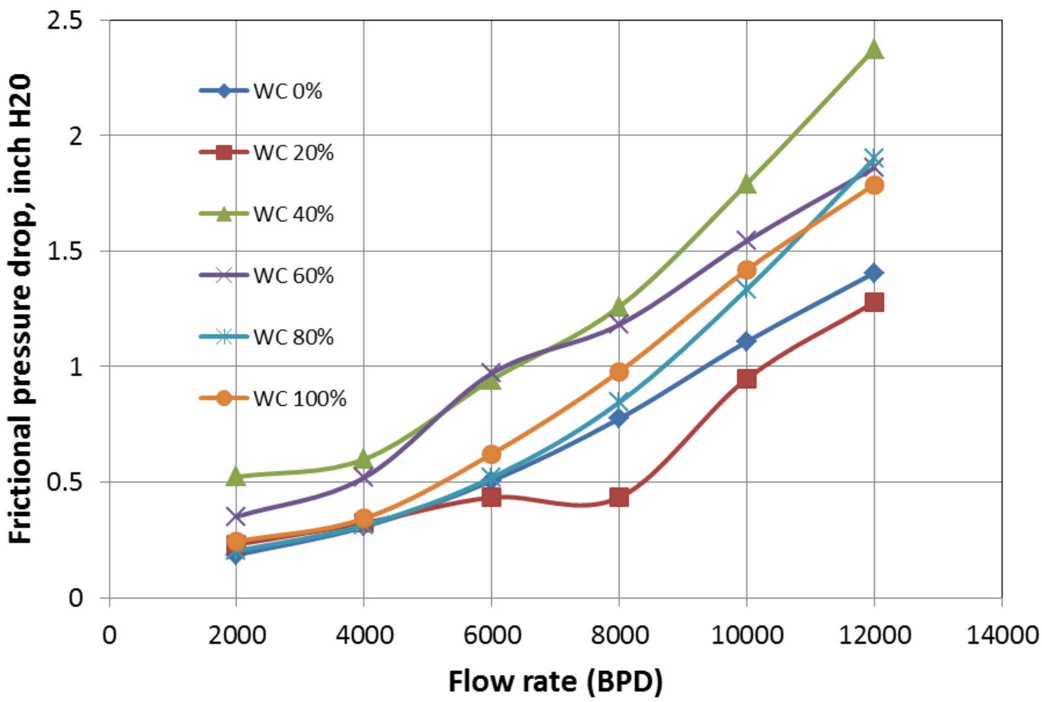

Figure 6b: Effect of flow rate on pressure drop for different flow rates (90° case).

Effect of inclination on oil-water pressure drop for differentflow rates for given water cuts

For the sake of brevity, and to show explicitly, the angle effect onpressure drop measurements for different flow rates, only two water cuts(WC 40 and WC 60) have been presented.

For a given water cut (WC 40%), the effect of inclination for different flow rates on pressure drop is shown in Figure 7a. For a given water cut (WC 60%), the effect of inclination for different flow rates on pressure drop is shown in Figure 7a. As mentioned earlier, in general, pressure drop increases with flow rate and water cut and the effect of angle is not appreciable.

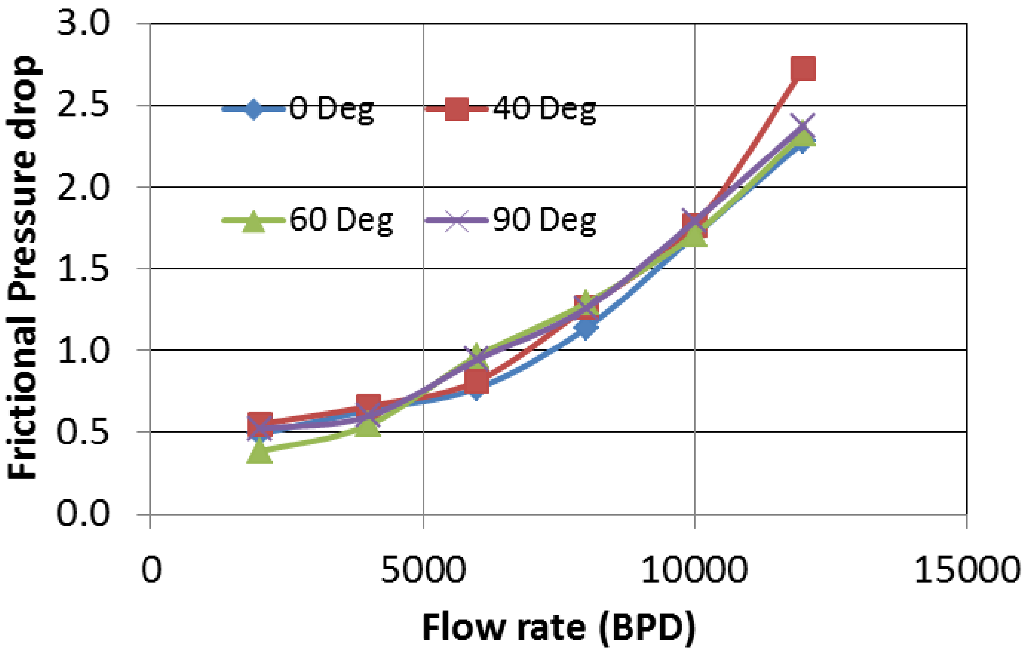

Figure 7a: Effect of inclination on pressure drop for different flow rates (40% WC).

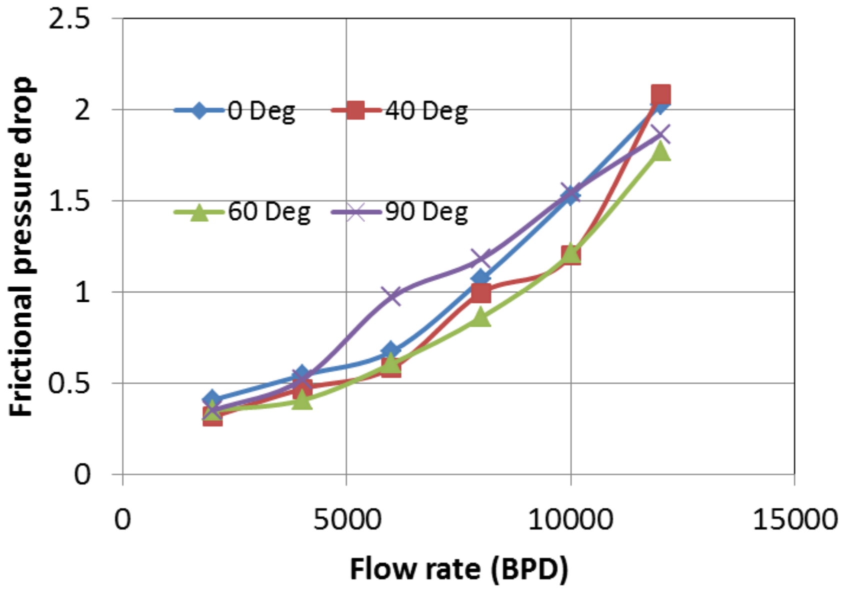

Figure 7b: Effect of inclination on pressure drop for different flow rates (60% WC).

Effect of inclination on oil-water total pressure drop for different flow rates and water cuts

To show explicitly the inclinationeffect on total pressure drop measurements for different flow rates and water cuts,0 and 90° angle have been considered as shown in Figures 8a and 8b.

It can be seen from the Figures, the behavior of total pressure is asymptotic with increase in flow rate. Also the behavior of total pressure is linear with respect to WC.

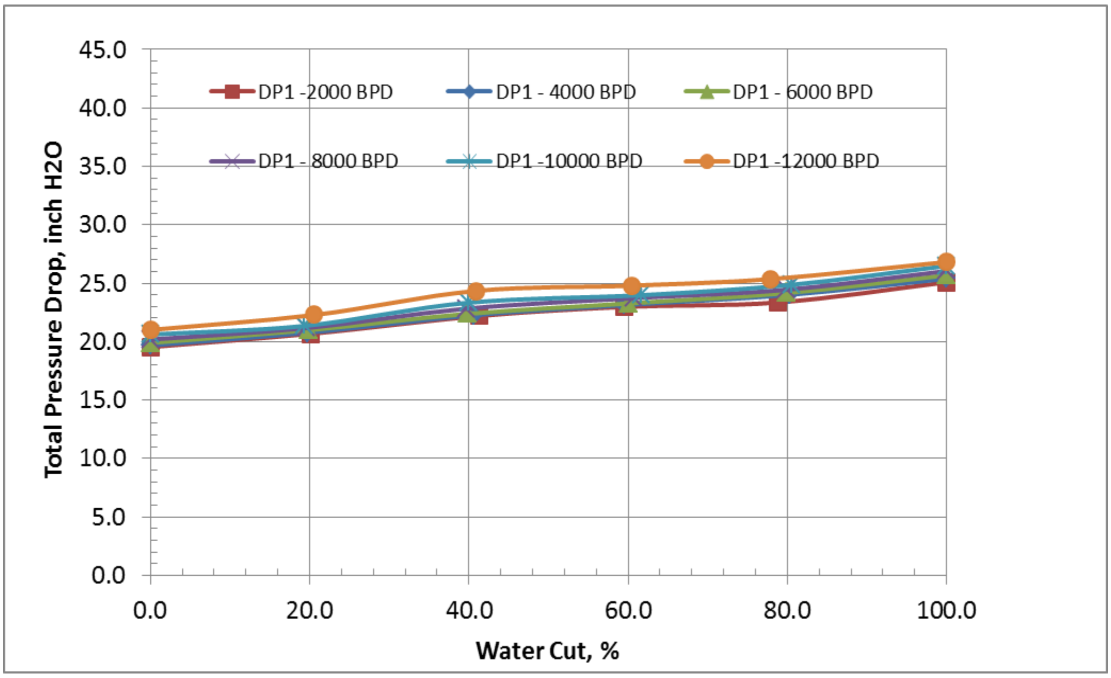

Figure 8a: Effect of inclination on total pressure drop for different flow rates and water cuts (40 Deg.).

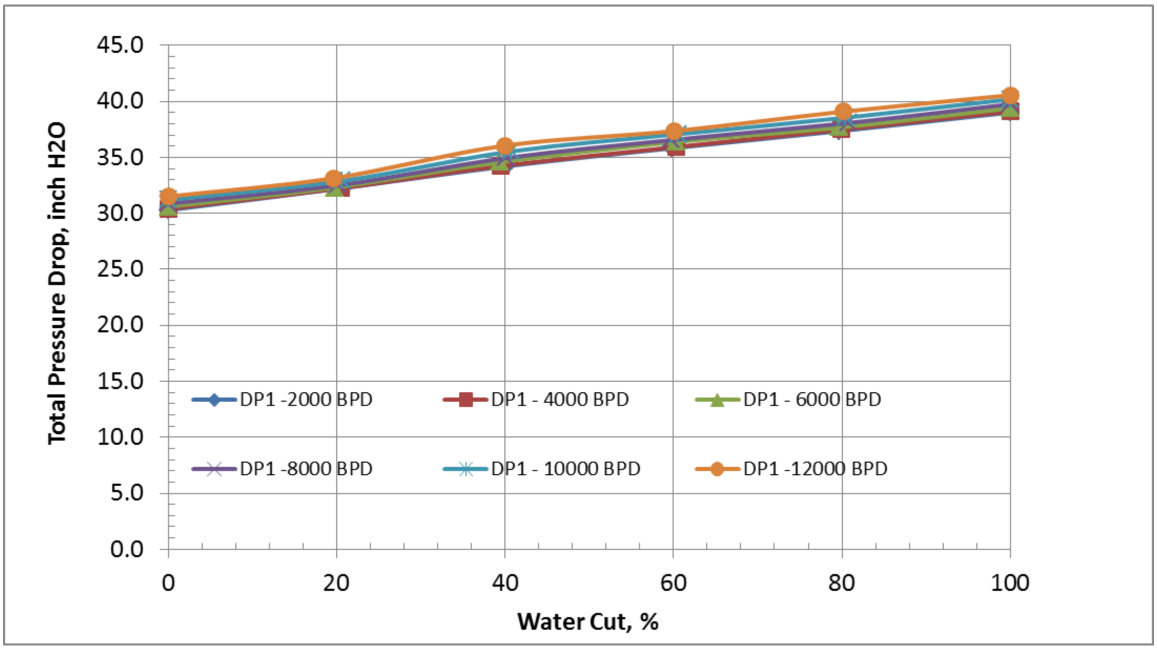

Figure 8b: Effect of inclination on total pressure drop for different flow rates and water cuts (90 Deg.).

CONCLUSIONS

In the present study, pressure drop measurements of oil (D80)-water two-phase flow in a horizontal and inclined 6 inch diameter stainless steel pipe at different flow conditions were made. Experiments were conducted for different inclination angles including; 0°, 40°, 60° 90° and for different water cut ratios. Water cut ratios were varied from 0 to 100% in steps of 20 %. Inlet oil-water flow rates were varied from 2000 to 12000 barrels-per-day (BPD).

Measured pressure drops and friction factor of single phase oil and single phase water were compared with existing empirical relations and good agreement was found.

For a given flow rate (for all angles) the frictional pressure drop has been found to increases from WC = 0 to WC 40 %. Further increase in WC, friction pressure drop has been found to decrease. In general, frictional pressure drop increases with flow rate and water cut and the effect of angle is not appreciable. The behavior of total pressure is asymptotic with increase in flow rate. Also the behavior of total pressure is linear with respect to WC upto 80%.

NOMENCLATURE

A	Cross-sectional area of the pipe $[m^2]$
bpd	Barrel per day
Dh	Diameter of the pipe $[m]$
f	Friction factor
ID	Inner diameter $[m]$
L	Length of the pipe $[m]$
Re	Reynolds's number
WC	Water cut

Greek Symbols

ρ_o	Density of oil $[kg/m^3]$
ρ_w	Density of water $[kg/m^3]$
μ_o	Viscosity of oil $[Pa.s]$
μ_w	Viscosity of water $[Pa.s]$
ΔP	Pressure drop $[inch\ H_20, pa]$
$\frac{\Delta P}{\Delta L}$	Pressure gradient $[\frac{Pa}{m}, \frac{inch\ H_20}{m}]$

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