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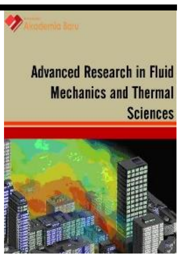

Effect of Viscosity on Pressure Drop of Oil-Water Two Phase Flow in 6” Horizontal and Inclined Stainless Steel Annulus Pipe

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ABSTRACT

Two phase annular fluid flow (oil in water) commonly found in petroleum industry and is generally used for the lubricated transportation of highly viscous oil. Despite their importance, behavior of such flows has not been explored to an appreciable extent. Liquid viscosity may change considerably because of changes in temperature as in deep-water oil production. The variations in liquid viscosity have a remarkable influence on flow characteristics. In this experimental work, attention has been focused on effect of viscosity on pressure drop measurements of oil-water annular two-phase flow in a horizontal and inclined 6-inch diameter stainless steel pipe at different flow conditions. Two different mineral oils Exxsol D80 and Exxsol D130 along with water were used as working fluids in the present experimental study. Experiments were carried out for different inclination angles including: 0° - 90° and for different water cut (WC) ratios (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 the frictional pressure drops (FPD) has been found to decrease from WC = 0 to WC 20%. Further increase in WC, FPD has been found to increase up to WC 40%. For WC more than 40%, the decrease in FPD is not appreciable. This could be due to phase inversion or change in flow pattern regime. For a given case with WC 40% (horizontal, $\theta = 0°$ case, flow rate = 10000 BPD), the FPD of Oil (D130) is more than FPD of Oil (D80) by 7%. This implies Oil (D80) is more suitable for transportation of oil-water two phase flows. For a given case (with WC 40%, 10000 BPD), for D80 oil, for increase in angle from zero degree to 90 degree, the increase in FPD is not appreciable. However, for the above scenario, for D130 oil, for increase in angle from zero degree to 90 degree, the percentage increase in FPD has been found to be 27 %.

Keywords:
Multiphase flow; Viscosity; Oil-water flow; Pressure drop; Water-cut; Inclined pipe; Annular flow

1. 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

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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] have presented pressure drop and liquid hold up for intermittent two-phase flow in upward inclined pipes. Their findings showed a good agreement with earlier studies. Landman [2] correlated liquid hold-up and pressure drop in two phase stratified inclined pipe flow. Sanchez and Alvarez [3] carried out two phase flow pressure drop experiments in inclined pipe for geothermal applications. Experiments conducted by Grolmann and Fortuin [4] focused on liquid hold-up and pressure gradient in gas-liquid flow in slightly inclined pipes. Effect of inclination was found to be appreciable at low gas flow rates.

Research study on three phase flow in vertical pipes was performed by Descamps *et al.,* [5] with emphasis on phase inversion. They concluded that the size of the gas bubble produced during experiments depends on water dispersion. A brief review of oil water two phase flow in horizontal pipes was presented by Xu [6]. High viscosity two phase liquid-liquid flow experiments in horizontal and slightly inclined pipes were conducted by Grassi *et al.,* [7]. The results were validated against theoretical models. Du *et al.,* [8] carried out experiments of vertical upward oil-water two phase flows in a 20 mm diameter pipe. Flow pattern map have been presented for different superficial velocities.

Flow patterns, pressure gradient and phase inversion experimental data of horizontal oil–water flow in a 25.4 mm acrylic pipe was presented by Yusuf *et al.,* [9]. Their results show that oil viscosity has an effect on pressure gradient and the effect is more pronounced at high oil velocity. Experimental study of high viscous ratio oil–water flow in horizontal pipes using mineral oil and tap water with density ratio of 0.9 was conducted by Sotgia *et al.,* [10]. Experiments were conducted with different Pyrex and Plexiglas pipes with different diameters (21 ~ 40 mm). They have presented pressure gradients, flow pattern maps and pictures of the oil–water flow.

Hwang 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.

Experimental study on oil/water flow in horizontal and slightly inclined plexi glass tubes (with 21 mm ID, 9m long) was conducted by Strazza *et al.,* [12]. The emphasis was on core-annular flow behavior, pressure drops, and oil hold-up measurements. Good agreement was observed between experimental data and other models.

The effect of phase inversion on pressure gradient in dispersed flow of two immiscible (water and oil) liquids for steel and acrylic pipes (60 and 32 mm ID) for various mixture velocities conducted by Ioannou *et al.,* [13]. For all cases large increase in pressure gradient was observed before phase inversion, which sharply reduces after occurrence of new continuous phase. Flow measurement of oil-in-water fluid flow is complex and challenging subject. A new method of two-phase flow metering has been proposed by Faraj *et al.,* [14], which is based on the use of dual-modality system and multidimensional data fusion. The method was validated conducting experiments 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.

Al-Wahaibi [15] proposed a correlation for prediction of pressure gradient with higher accuracy for horizontal oil–water separated flow (stratified and dual continuous flows). He prepared a pressure gradient database for oil–water flow which includes wide range of operational conditions, fluid properties, pipe diameters and materials. Local flow characteristics of oil–water dispersed flow in a vertical upward pipe were studied experimentally for different oil-water velocity by Zhao *et al.,* [16] The typical radial profiles of interfacial area concentration, oil phase fraction, interfacial velocity, and oil pressure drops were presented.

The measurements of pressure gradients during the concurrent flow of a low viscosity oil and water in two 1-inch diameter horizontal stainless steel and acrylic resin test sections were carried out for different mixture velocities and volume fractions by Angeli and Hewitt [17]. For all conditions, pressure gradients were found to be higher in the steel pipe than in acrylic tube for the same mixture velocities and flow volume fractions.

A comparative study of water-in-crude oil for emulsions of crude oils in a closed loop system (pipe ID2.2cm) was conducted by Plasencia *et al.,* [18]. 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. The effect of air injection on liquid–liquid core annular flow of very-viscous-oil/water on the pressure drop was experimentally conducted by Poesio *et al.,* [19]. A new data set for pressure drop was reported.

The effect of upward and downward pipe (38 mm ID stainless steel) 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% has been investigated experimentally by Lum *et al.,* [20]. The oil to water velocity ratio was higher for the upward than for the downward flows.

Daas and Bleyle [21] evaluated experimentally the effect of oil viscosity in two-phase oil-gas flow on the total pressure loss. They used two types of oil with considerably different viscosities in 10-cm inner diameter horizontal pipes. It was noticed that the pressure drop in the 50-cP oil was always more significant than in the 2.5-cP oil, especially with increase the gas flow rate.

An experimental study of influence of viscosity of oil-water core-annular flow in a horizontal pipe on the pressure drop was carried out by van Duin *et al.,* [22]. They concluded that with decrease in viscosity, the pressure drop becomes strongly dependent on the water cut.

Rocha *et al.,* [23] have presented new experimental data for a wide range of flow rates of gas, water and oil with three different viscosities (100 mPa s, 220 mPa s and 325 mPa s). The results highlight that the pressure gradient in three-phase flow can be considerably lower than in single-phase and two-phase flows.

Our earlier work [24-25] on multiphase flows focused on 4” inch diameter stainless loop/pipe. Flow rates were varied from 4000 to 8000 barrels-per-day (BPD). The present paper focuses on 6” inch diameter stainless annulus loop. The working fluids are is Exxsol D80 Mineral Oil, Exxsol D130 Mineral Oil, and water. The inlet oil-water flow rates are varied from 2000 to 12000 BPD (to mimic or simulate field conditions). Water cuts (WC) have been varied from 0-100%. Basic infrastructure/facility of earlier papers and present work is same but flow loops are different. The change in diameter of the flow loop changes flow behavior and makes all the difference and has a remarkable effect on flow characteristics. More importantly, the topic of the present research is still subject of immense research. This is because fluids with different properties exhibit different flow behaviors in different pipe configurations under different operating conditions. Oil and water are often produced and transported together in pipelines. The widespread occurrence of multiphase flows in pipes has motivated extensive research world-wide. Oil-water two-phase flows are often encountered in petroleum and petrochemical industries. Knowledge of the frictional pressure drop in oil-water flows in pipes is necessary to specify the size of the pumps and pipelines. The outcomes of the study will be helpful in mitigating multi-phase flow problems related to oil-gas industries and to reduce pumping power in transportation of oil from oil wells to central gathering stations. To the best of our knowledge, the present specific research work is first of its kind and is not available in literature.

In the light of the above research studies, there is currently no work available in the literature on effect of viscosity (of mineral oils Exxsol D80 and Exxsol D130) on pressure drop measurements of oil-water annular two-phase flow in a horizontal and inclined 6 inch diameter stainless steel pipe at different flow conditions. This is the motivation for the present experimental study and it focuses on the effect of viscosity, flow rates, water-cuts, inclination angle on pressure drop measurements of oil-water two-phase annular flow.

In this work, efforts have been made to present pressure drop measurements of oil(D80)-water and oil(D130)-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° - 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).

2. 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 [24].

The layout of the flow loop is presented in Figure 1(a) and Figure 1(b). Experimental set-up includes: four centrifugal variable speed pumps [2 pumps for 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 [25]. The loop can be positioned at any given angle using over-head jack as shown in Figure 1(b).

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. Properties of mineral oils Exxsol D80 and Exxsol D130 are listed in Table 2 and Table 3.

Table 1
Details of equipment of the flow loop [24]

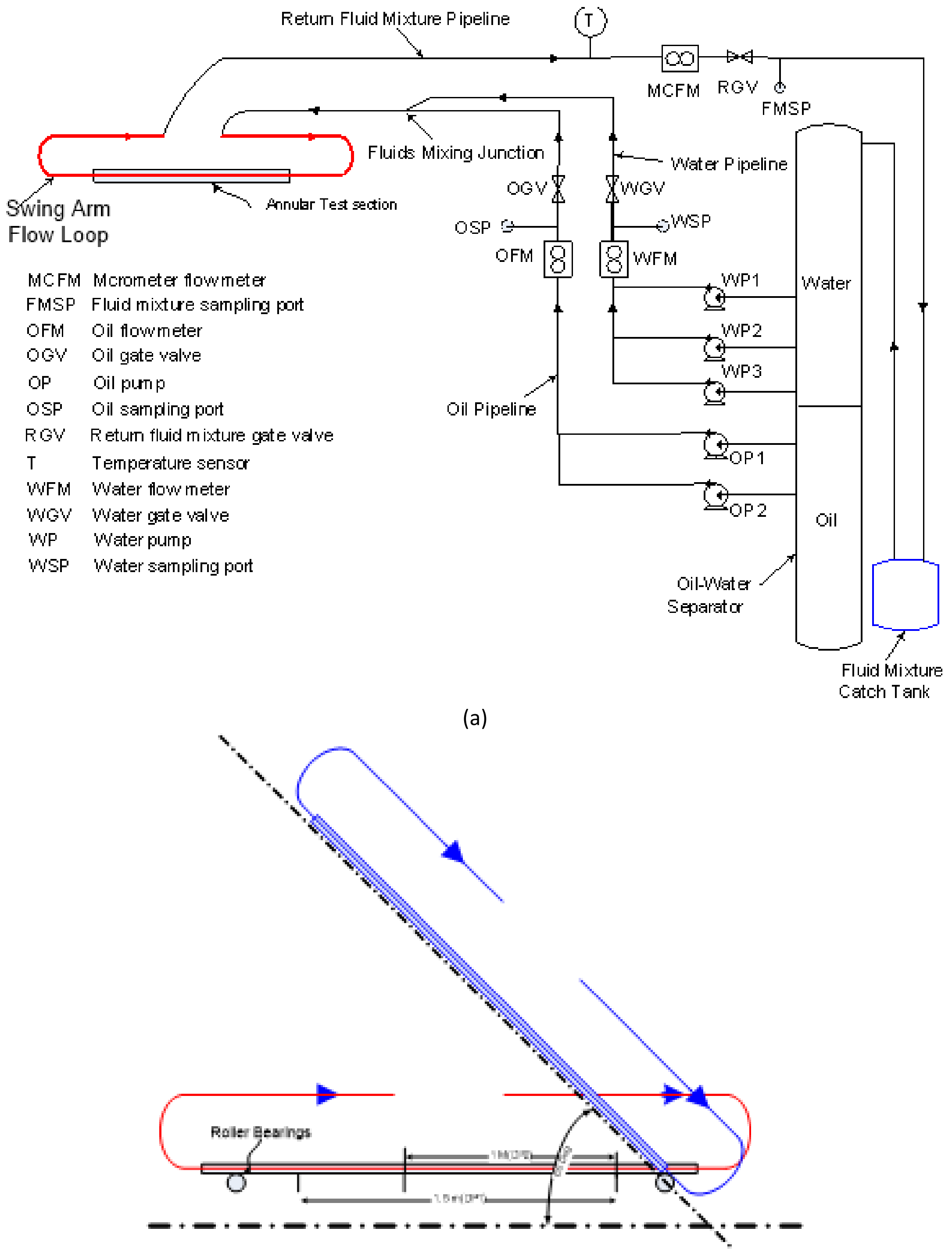
Items	Manufacturer	Model	Capacity/Range	Accuracy/Error
Four pumps (two water, two oil)	NEWAR FLOW SERVE	50-32CPX200	35 m^3/hr	-
Two turbine flow meters	Omega	EF10	±10 m/s	±1.0 %
Line pressure gauge	ROSEMOUNT	AOB-20	0-7 bar	±0.25%
DP1	ROSEMOUNT	300S2EAE5M9	0-70 inches of water column	±0.1%
DP2	ROSEMOUNT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

Table 2
Physical properties of the Exxsol D80 mineral oil [25]

Properties	EXXSOL D80	Units	Test Based On
Initial Boiling Point (IBP)	208	°C	N/A
Dry Point (DP)	236	°C	N/A
Flash Point (Method A)	82	°C	ASTM D93
Aromatic Content	0.2	wt%	ExxonMobil Method
Density (15.6°C)	795	kg/m^3	ASTM D4052
Vapor Pressure (20.0°C)	< 0.0402	Inch H_2O	ExxonMobil Method
Aniline Point (Method E)	77	°C	ASTM D611
Kinematic Viscosity (25.0°C)	2.18*10-6	m^2/s	ASTM D445

Table 3
Physical properties of the Exxsol D130 mineral oil

Properties	EXXSOL D130	Units	Test Based On
Initial Boiling Point (IBP)	279	°C	N/A
Dry Point (DP)	313	°C	N/A
Flash Point (Method A)	140	°C	ASTM D93
Aromatic Content	1.0	wt%	ExxonMobil Method
Density (15.6°C)	827	kg/m^3	ASTM D4052
Vapor Pressure (20.0°C)	< 0.0402	Inch H_2O	ExxonMobil Method
Aniline Point (Method E)	88	°C	ASTM D611
Kinematic Viscosity (25.0°C)	$6.89*10^{-6}$	m^2/s	ASTM D445



(a)

(b)

Fig. 1. (a) Schematic layout of the oil-water multiphase flow loop [24], (b) Details of pressure tapping point (DP1 and DP2)

3. Experimental Procedure

Initially, experiments were conducted for water-only and oil-only single phase (in 4 inch pipe) to validate the pressure drop measurements against available empirical models, and to ascertain effectiveness of pressure transmitters and flow meters of the loop [24].

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, Figure 1) 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 1(b). Once the steady state flow condition is achieved, differential pressure drops are recorded across 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 [25].

The friction factor was calculated from the experimentally obtained pressure drop and this friction factor was compared with friction factors obtained from Blasius and Zigrang & Sylvester 1985 correlations. A good agreement has been noticed specifically with the Blasius friction factor. The related equations and graphs are reported in our earlier studies [24-25].

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 angles including; 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) [24-25].

4. Results and Discussions

Oil (D80)-water and Oil (D130)-water two-phase annular flow experiments were carried out for different inclination angles including: 0° - 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).

4.1 Effect of Flow Rate on Oil-Water Pressure Drop for Different Water-Cuts for Different Oils

For a given angle (horizontal, θ = 0° case), the effect of water cut for different flow rates for different oils on pressure drop is shown in Figure 2. In general, as it can be seen from Figure 2(a), for a given flow rate the pressure drops decreases from WC = 0 to WC 20%. Further increase in WC, friction pressure drop has been found to increase up to WC 40%. For WC more than 40%, the decrease in friction pressure drop is not appreciable. 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 drop at WC = 0%. This is due to higher density of water. Also, it can be seen from Figure 2, for any given WC, the frictional pressure drops increases with increase in flow rate.

For a given case with WC 40% (horizontal, θ = 0° case, flow rate = 10000 BPD), the friction pressure drops of Oil (D130 is more than friction pressure drop of Oil (D80) by 7 %. This implies Oil (D80) is more suitable for transportation of oil-water two phase flows. For a given angle (horizontal, θ = 0°), the effect of flow rate on pressure drop for different water cuts for different oils is shown in Figure 3. As mentioned earlier, as it can be seen from Figure 3, pressure drop increases linearly with flow rate and WC.

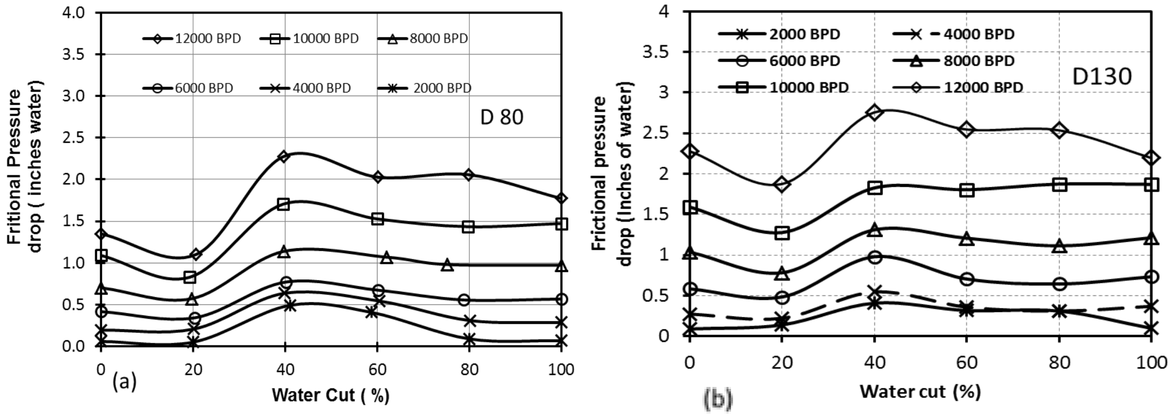


Fig. 2. Effect of water cut on pressure drop for different flow rates (0° case) for different oils. (a) D80, (b) D130

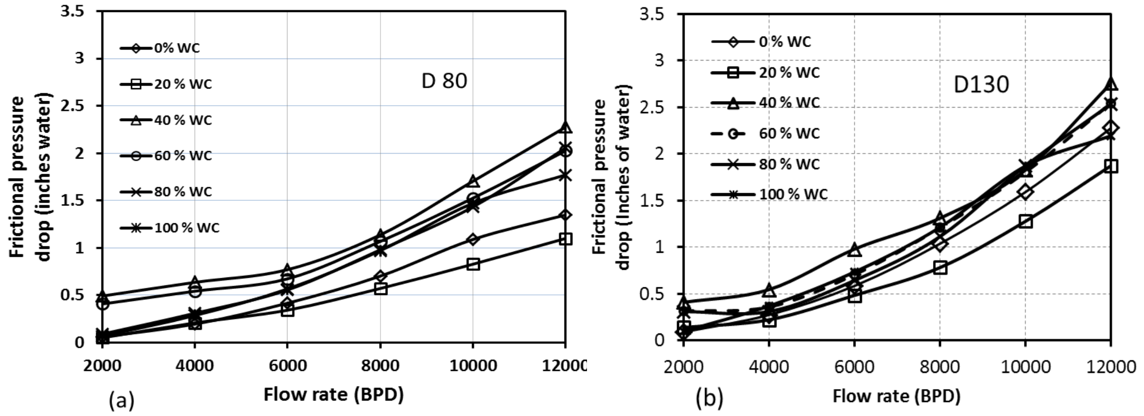


Fig. 3. Effect of flow rate on pressure drop for different water cuts (0° case) for different oils. (a) D80, (b) D130

For 90° inclination, the effect of water cut for different flow rates on pressure drop for different oils is shown in Figure 4. Also, for 90° inclination, the effect of flow rate on pressure drop for different water cuts for different oils is shown in Figure 5. Again, similar behavior of pressure drop with flow rate and WC has been observed as in Figure 2 and Figure 3.

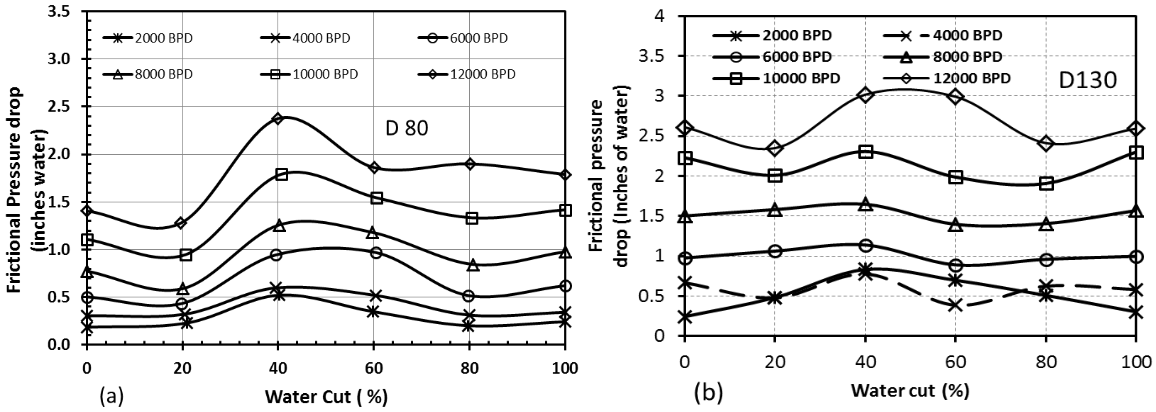


Fig. 4. Effect of water cut on pressure drop for different flow rates (90° case) for different oils. (a) D80, (b) D130

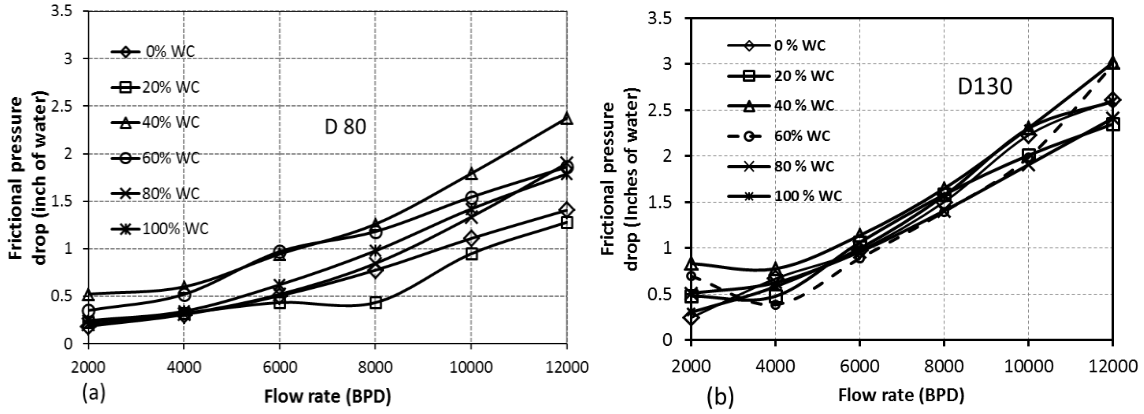


Fig. 5. Effect of flow rate on pressure drop for different flow rates (90° case) for different oils. (a) D80, (b) D130

4.2 Effect of Inclination on Oil-Water Pressure Drop for Given Flow Rate and for Given Water Cut for Different Oils

For the sake of brevity, and to show explicitly, the angle effect on pressure drop measurements for a given flow rate, for a water cut for different oils haves been presented in Figure 6.

For a given water cut (WC 40%) and flow rate (example 10000 BPD), the effect of inclination for different oils on pressure drop is shown in Figure 4. For the above case (WC 40%, 10000 BPD), for D80 oil, for increase in angle from 0 degree to 90 degree, the frictional pressure drop has been found to increase from 1.705 to 1.791. The increase is not appreciable for D80 oil.

However, for a given water cut (WC 40%) and flow rate (example 10000 BPD), for D130 oil, for increase in angle from 0 degree to 90 degree, the frictional pressure drop has been found to increase from 1.82 to 2.306 inches of water. The percentage increase is 27%. This indicates that the D80 oil is more suitable for transportation of oil-water in pipelines.

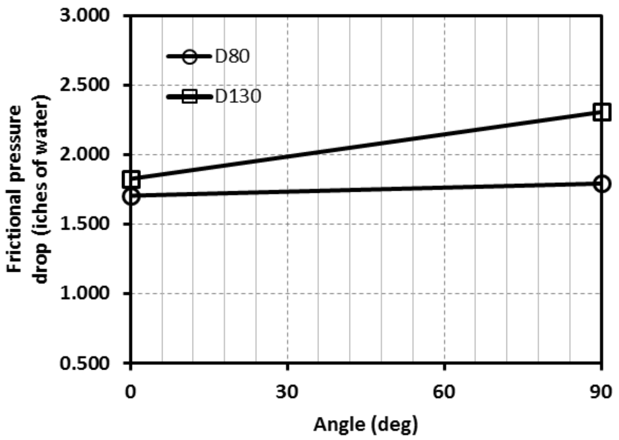


Fig. 6. Effect of inclination on pressure drop for a given flow rate (10000 BPD) for given WC (40% WC) for different oils

5. Conclusions

In the present study, pressure drop measurements of oil (D80)-water and oil (D130)-water two-phase annular flow in a horizontal and inclined 6 inch diameter stainless steel pipe at different flow conditions were made. Experiments were carried out for different inclination angles including: 0° -

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. 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. In general, for a given flow rate the pressure drop has been found to decrease from WC = 0 to WC 20%. Further increase in WC, friction pressure drop has been found to increase up to WC 40%. For WC more than 40%, the decrease in friction pressure drop is not appreciable.

For a given case with WC 40% (horizontal, θ = 0° case, flow rate = 10000 BPD), the friction pressure drop of Oil (D130) is more than friction pressure drop of Oil (D80) by 7%. This implies Oil (D80) is more suitable for transportation of oil-water two phase flows. For a given case (with WC 40%, 10000 BPD), for D80 oil, for increase in angle from zero degree to 90 degree, the increase in frictional pressure drop is not appreciable. However, for the above scenario, for D130 oil, for increase in angle from zero degree to 90 degree, the percentage increase in frictional pressure drop has been found to be 27%.

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