Effect of Water Cut on Pressure Drop of Oil (D130) - Water Flow in 4" Horizontal Pipe

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Abstract. The oil-water flow 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 of two phase flow is still subject of immense research. The present study reports pressure measurements of oil (D130)-water flow in a horizontal 4" diameter stainless steel pipe at different flow conditions. Experiments were carried out for different water cuts (WC); 0-100%. Inlet oil-water flow rates were varied from 4000 to 8000 barrels-per-day in steps of 2000. It has been found that the frictional pressure drop decreases for WC = 0 - 40%. With further increase in WC, friction pressure drop increases, this could be due to phase inversion.

1. Introduction

Heavy oils represent about one third of the world’s hydrocarbon resources, but, their production is associated with huge costs of transportation. Multiphase flow is commonly seen in industrial processes such as pipeline transportation, fluidized beds and power plants. This is the motivation for research in this field. Water desalination using multistage flashing (MSF) process is a simple two-phase flow problem. Blood oxygenation used during open-heart surgery is a multiphase flow process. A typical multiphase oil–water two-phase flow is often encountered in petroleum industries. The measurement of phase flow rates is of particular importance for managing oil production and water disposal and/or water reinjection. There is a need to measure the flow rates of multiphase flow fluids and this is a very challenging process and is of great importance in the petroleum industry.

Pressure (frictional pressure drop) is the key parameter for assessing individual phase (oil and water) flow rates in pipelines. Therefore, it is important to study behaviour of pressure response to characterize two-phase flow in upstream production pipelines. Several articles are available in literature on the two-phase flow of oil and water in pipes.

Xu [1] presented a brief review of oil-water two phase flows in horizontal pipes and highlighted future research trends of oil water pipe flows. Yusuf et al. [2] 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, 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 [3] 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. Talal [4] 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. Pressure gradient database was prepared for oil–water flow which includes wide range of operational conditions, fluid properties, pipe diameters and materials.

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 [5] 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 [6] 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.

The modeling of the pressure gradient of oil-water flow in pipelines is very crucial. Accurate prediction of pressure gradient will lead to better design of energy efficient transportation systems. Al-Wahaibi and Mjalli [7] developed an artificial neural network (ANN) model with five inputs (oil and water superficial velocities, pipe diameter, pipe roughness, and oil viscosity) to predict the pressure gradient of horizontal oil-water flow based on a databank of around 765 measurements collected from the open literature. Statistical analysis showed that the ANN model has an average error of 0.30%. Hasanvand and Berneti [8] have also used artificial neural networks (based on 600 data set of Persian Gulf oil) in their study to obtain the oil flow rate as output measurement, The input variables included temperatures and line pressures. Tan et.al [9] conducted experiments (in a 50 mm diameter horizontal pipe) to measure the individual phase rates of oil-water two phase flow using a Conductance Ring Coupled Cone (CRCC) meter. The accuracy of this method in measuring oil flow rate is 2.3% and for water flow rate is 4.8%. The proposed method improves the accuracy of the measurement by measuring the water holdup in the annular channel.

An experimental investigation to study the slip (holdup) phenomenon between phases in water-oil two phase flows in horizontal pipes was conducted out by Jing et al. [10]. Emphasis was placed on the effects of input fluids flow rates, pipe diameter (0.05m and 0.025 m) and viscosities of oil phase on the slip. Results showed that at low input flow rate, there is a large deviation on the holdup between two flow systems with different oil viscosities and the deviation becomes gradually smaller with increased input water flow rate.

In the light of the above literature survey, there is no work available on pressure drop measurements of oil (D130)-water two-phase flow in horizontal 4 inch diameter stainless steel pipe at different flow conditions. This is the driving force for the present experimental study and it focuses on the effect of flow rates, water-cuts on pressure drop measurements of oil (D130)-water two-phase flow.

In this study, efforts have been made to present pressure drop measurements of oil (D130)-water two-phase flow in a horizontal 4 inch diameter stainless steel pipe at different flow conditions. Experiments were conducted for different water cuts; 0%, 20%, 40% 60% 100%. Inlet oil-water flow rates were varied from 4000 to 8000 barrels-per-day (BPD).
2. Experimental setup
The Oil-water two phase experiments were carried out 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 1. Experimental set-up consists of: four centrifugal variable speed pumps [2 pumps for water (WP) and 2 pumps for oil, (OP)], 4 inch stainless loop, a horizontal separator tank (WOST), which serves as a storage tank, two level indicators for oil and water each. The loop is mounted on swinging platform (angle can be varied from 0° - 30°). The fixing of loop at a given angle is done by flexible connection (FC).

The instruments of the loop include: a turbine type oil flow meter (OFM), a turbine type water flow meters (WFM), line pressure transmitter (LPT), two flow differential pressure transmitters (DPT1 and DPT2). More information of the loop components and instruments is given in table 1.

![Figure 1. Schematic layout of the oil-water multiphase flow loop](image)

**Table 1. Details of equipment of the flow loop.**

| Items                          | Manufacturer          | Model             | Capacity/Range | Accuracy/Error |
|-------------------------------|-----------------------|-------------------|----------------|----------------|
| Four pumps (two water, two oil) | NEWAR FLOW SERVE      | 50-32CPX200       | 35 m³/hr       | -              |
| Two turbine flow meter        | Omega                 | EF10              | ±10 m/s        | ±1.0 %         |
| Line pressure gauge           | ROSEMOUNT             | AOB-20            | 0-7 bar        | ±0.25%         |
| DPT1                          | ROSEMOUNT             | 300S2EAE5M9       | 0-70 inches of water | ±0.1% |
| DPT2                          | ROSEMOUNT             | 300S2EAE5M9       | 0-12 inches of water | ±0.1% |

3. Experimental procedure
Initially, experiments were conducted for water-only and 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. The desired volume flow rate was obtained by varying speed of pumps through variable speed drives and also by regulating oil globe valve (OGV) and water globe valve (WGV) of oil and water flow streams respectively. The
flow rates on the discharge line of the pumps were measured by Turbine flow meters. The required outlet pressure (e.g. 1 bar or 2 bars) of the loop is set by throttling the Return gate valve (RGV, figure1).

The experiments were carried out for a given flow rate and pressure drop measurements were made at different locations of the loop as shown figure 1. After achieving the steady state flow condition, differential pressure drops are recorded across 3m (DPT1). The experimental data was recorded using CR 1000 data logger. The above procedure was repeated for oil-only flow experiments.

The friction factor was calculated using the pressure drop data by using Eq. (1) and compared with Eq. (2) and Eq. (3).

\[
f = \frac{\Delta P}{L \rho v^2}
\]  

\[
f = 0.3164 Re^{-1/4}
\]  

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

The Zigrang & Sylvester 1985 correlation defined in equation (3) above can also be used to determine the turbulent friction factor.

The comparison of experimentally obtained friction factor (Eq. 1) with the friction factors calculated by using Blasius correlation and Zigrang & Sylvester correlations is shown in the Figure 2. A good agreement has been noticed specifically with the Blasius friction factor (Eq. 2).

![Friction factor comparisons with Blasius correlation and Zigrang & Sylvester correlations for oil-water flow](image)

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

The variation single phase water and oil friction factor against Reynolds number is shown in figure 2. The friction factor has observed to decrease with increase in velocity. A good agreement is can be noticed between the experimental data and established theoretical relation.

For a given oil-water multiphase flow, the required flow rate and water cut is obtained by varying the speeds of the oil and water pumps. After the required water cut and flow rates are achieved, pressure drop [across 3m (DPT1)] measurements were made. The above procedure was repeated for different water cut ratio 0 to 100%. Inlet oil-water flow rates were varied from 4000 to 8000 barrels-per-day (BPD).
4. Results and discussions

Oil-water multiphase flow experiments were conducted for different water cut ratios (0%, 20%, 40%, 60% and 100%). Inlet oil-water flow rates were varied from 4000 to 8000 barrels-per-day (BPD).

4.1. Effect of water-cut on oil-water pressure drop for different flow rates

Figure 3a shows the effect of water cut for different flow rates on pressure drop. It can be seen from figure 3a that at a given flow rate the pressure drop decreases from WC = 0 to WC 40% whereas for WC 40% to WC 60%, friction pressure drop has been found to increase. This could be due phase inversion. However, for WC = 100%, frictional pressure drop is lower as compared to frictional pressure at WC = 0%. This is due to lower viscosity of water. Also, it can be observed from figure 3a, that at any given WC, the frictional pressure drop increases with increase in flow rate. For a given water cut WC = 40, increasing in BPD from 4000 to 6000, percentage increase in frictional pressure drop is about 150%.

![Figure 3a](image1.png)

**Figure 3a.** Frictional pressure drop behavior. (a) Effect of water cut on pressure drop for different flow rates, (b) Effect of flow rate on pressure drop for different water cuts (0° case)

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

Figure 3b shows the effect of flow rate on frictional pressure drop for different water cuts. As stated earlier, it can be seen from figure 3b, pressure drop increases with flow rate and WC. The frictional pressure has been found to increase linearly with respect flow rate. However, effect of water cut on frictional pressure drop is not linear. For a given flow rate 6000 BPD, increasing in water cut from WC 20 to 40, percentage increase in frictional pressure drop is about 17%.

![Figure 3b](image2.png)

**Figure 3b.** Frictional pressure drop behavior. (a) Effect of water cut on pressure drop for different flow rates, (b) Effect of flow rate on pressure drop for different water cuts (0° case)

5. Conclusions

In the present study, pressure drop measurements of oil (D130)-water two-phase flow in a horizontal 4" diameter stainless steel pipe at different flow conditions were made. Experiments were conducted for different water cut ratios (0%, 20%, 40%, 60% and 100%). Inlet oil-water flow rates were varied from 4000 to 8000 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, the frictional pressure drop has been found to decrease for WC = 0 to WC 40 %. Further increase in WC, friction pressure drop has been found to increase. The frictional pressure has been found to increase linearly with respect flow rate. However, effect of water cut on frictional pressure drop is not linear.
6. Nomenclature

A \hspace{1cm} \text{Cross-sectional area of pipe [m}^2\text{]} \\
BPD \hspace{1cm} \text{Barrel per day} \\
Dh \hspace{1cm} \text{Diameter of the pipe [m]} \\
f \hspace{1cm} \text{Friction factor} \\
ID \hspace{1cm} \text{Inner diameter [m]} \\
L \hspace{1cm} \text{Length of the pipe [m]} \\
Re \hspace{1cm} \text{Reynolds’s number} \\
\rho_w \hspace{1cm} \text{Density of water [kg/m}^3\text{]} \\
\rho_o \hspace{1cm} \text{Density of oil [kg/m}^3\text{]} \\
\mu_o \hspace{1cm} \text{Viscosity of oil [Pa.s]} \\
\mu_w \hspace{1cm} \text{Viscosity of water [Pa.s]} \\
\Delta P \hspace{1cm} \text{Pressure drop [inch H}_2\text{O, pa]} \\
\frac{\Delta P}{\Delta L} \hspace{1cm} \text{Pressure gradient [\frac{\text{pa}}{\text{m}}, \frac{\text{inch H}_2\text{O}}{\text{m}}]} \\

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