

Experimental Investigation of Two-Phase Oil (D130)-Water Flow in 4" Pipe for Different Inclination Angles

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Abstract. Oil and water are often produced and transported together in pipelines that have various degrees of inclination from the horizontal. The flow of two immiscible liquids oil and water in pipes has been a research topic since several decades. In oil and chemical industries, knowledge of the frictional pressure loss in oil-water flows in pipes is necessary to specify the size of the pump required to pump the emulsions. An experimental investigation has been carried out for measurement of pressure drop of oil (D130)-water two-phase flows in 4 inch diameter inclined stainless steel pipe at different flow conditions. Experiments were conducted for different inclination angles including; 0°, 15°, 30° (for water cuts “WC” 0 - 100%). The flow rates at the inlet were varied from 4000 to 8000 barrels-per-day (BPD). For a given flow rate the frictional pressure drop has been found to increase (for all angles) from WC = 0 - 60 %, and thereafter friction pressure drop decreases, this could be due phase inversion. For a given WC 40%, the frictional pressure drop has been found to increase with angle and flow rate. It has been noticed that inclination angle has appreciable effect on frictional pressure drop.

1. Introduction

The multiphase flow is a complex phenomenon involving simultaneous flow of two or more physically immiscible fluids (such as: oil and water) in pipelines. Also, the widespread occurrence of multiphase flows in pipes is the driving force for extensive research in this area (a number of upstream practical applications in the petroleum industry involve oil–water two-phase flow phenomena).

The physical understanding of two-phase flow characteristics in pipes is of importance since appreciable 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. More importantly, fluids with different properties exhibit different flow regimes in different pipe configurations under different operating conditions. Considerable literature exists on the two-phase flow of oil and water.

Jing et al. [1] investigated phase inversion and frictional pressure gradients during simultaneous vertical flow of oil and water two-phase through upward and downward pipes. They concluded that the frictional pressure gradient reaches to its lower value at the phase inversion point. Pedram et al. [2] investigated flow patterns of two-phase oil–water flow in an inclined pipe. They inferred that non-stratified flows such as bubbly and slug flows are dominant flow patterns in the upward flows and stratified flows are dominant flow patterns in the downward flows. Descamps et al. [3] performed investigation of three phase flow in vertical pipes. Attention was paid to phase inversion phenomenon.



They noticed that the dispersed water phase has significant impact on the bubble size. Grassi et al. [4] conducted experiments of two phase liquid-liquid (high viscosity ratio) flows in horizontal and slightly inclined pipes. The results were validated against theoretical models. Du et al. [5] 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. Domenico et al. [6] 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.

Karolina et al. [7] investigated phase inversion and its effect on pressure gradient of immiscible (water and oil) liquids for two pipe materials and two pipe sizes for a range of mixture velocities. Phase inversion was observed in all cases preceded by a large increase in pressure gradient.

Dongian et al. [8] studied local flow characteristics of oil–water dispersed flow in a vertical upward pipe. 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. Lum et al. [9] investigated the effect of upward and downward pipe inclinations on the flow patterns, hold up and pressure gradient during two-liquid (water and oil) phase flows for mixture velocities between 0.7 and 2.5 m/s and phase fractions between 10% and 90%. The oil to water velocity ratio was higher for the upward than for the downward flows but in the majority of cases and for all inclinations oil was flowing faster than water.

In the wake of the above literature review, currently no studies are available on frictional pressure drop (FPD) measurements of oil (D130)-water two-phase flow in inclined 4 inch diameter stainless steel pipe at different inclinations (at different flow conditions). This is the motivation for the present experimental study and it places emphasis on the effect of flow rates, water cuts, and inclination angles on pressure drop measurements of oil (D130)-water two-phase flow. In this work, attention has been focused on FPD measurements of oil (D130)-water two-phase flow in an inclined 4 inch diameter stainless steel pipe at different inclinations (at different flow conditions). Experiments were carried out for different inclination angles including; 0°, 15°, 30° (for water cuts 0%, 20%, 40% 60% 100%). The oil-water flow rates at the inlet were varied from 4000 to 8000 BPD in steps of 2000. The above information is helpful in effectively handling the frictional pressure loss issues.

2. Experimental setup

The Oil-water two phase experiments were conducted in the flow loop of the multiphase flow laboratory of King Fahd University of Petroleum and Mineral, Dhahran, Saudi Arabia. Details of the loop components and instruments are given in table 1.

The schematic diagram of the flow loop is shown in figure 1. Experimental set-up includes: 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 acts as storage tank, two level indicators for oil and water each. The loop is constructed on swinging platform (inclination can be varied from 0° - 30°). The flexible connection (FC) helps in positioning loop at any given angle. 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).

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 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%
DPT1	ROSEMOUNT	300S2EAE5M9	0-70 "of H ₂ O	±0.1%
DPT2	ROSEMOUNT	300S2EAE5M9	0-12 "of H ₂ O	±0.1%

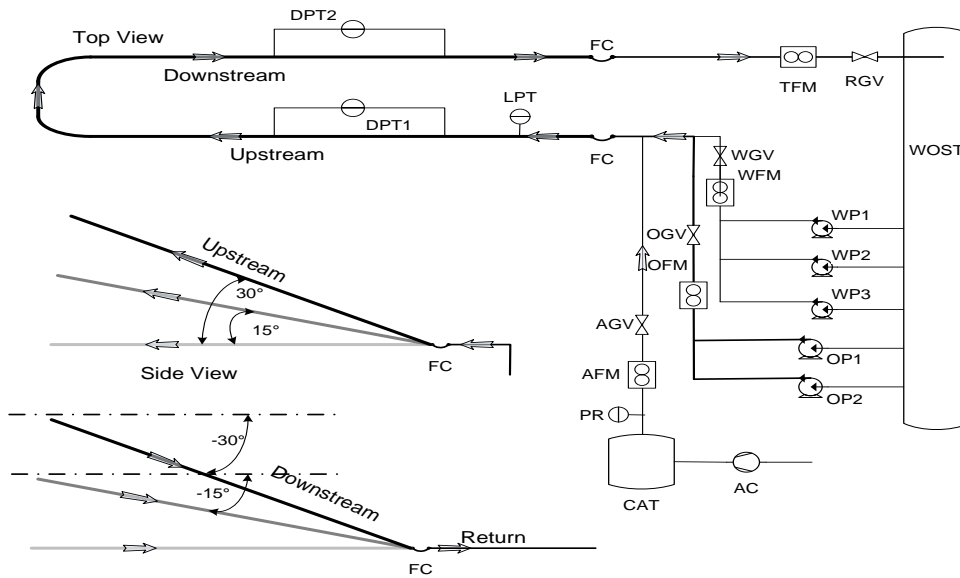


Figure 1. Schematic layout of the oil-water multiphase flow loop

3. Experimental procedure

In-order to validate the pressure drop measurements against available empirical models, experiments were performed for water-only and oil-only single phase (in 4inch pipe).

To achieve the above, water was pumped in the loop using centrifugal pumps. Required volume flow rate was attained 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. Turbine flow meters installed on the discharge 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 (e.g. 1 bar or 2 bars).

For a given flow rate, experiments were conducted and pressure drop measurements were made at different locations of the loop as shown figure 1. Once the steady state flow condition is achieved, differential pressure drops are recorded across 3m (DPT1). 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).	v	Average velocity of the fluid (m/s)
L	Distance between the two pressure taps (m)	ϵ	Pipe roughness (m)
D	Hydraulic diameter of the pipe (m)	Re	Reynolds number
ρ	Fluid density (Kg/m^3)		

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

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

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

Then experimentally 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 results showed a close agreement particularly with the Blasius friction factor (Eq. 2).

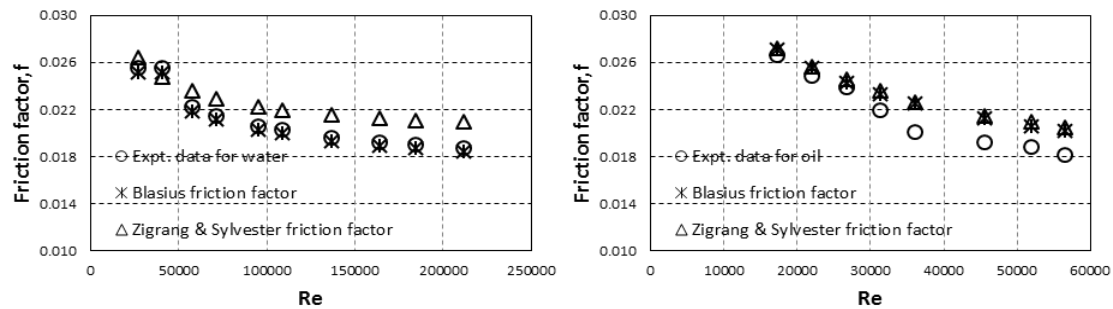


Figure 2. Friction factor comparisons with Blasius and Zigrang & Sylvester correlations for oil-water flow

Figure 2 shows the friction factor of single phase water and oil against Re. It can be noticed that the friction factor decreases with increase in velocity. The experimental data is found to be in good agreement with established theoretical relation. The above experiments were for single phase oil only and water only. However, for a given oil-water multiphase flow, speeds of the oil and water pumps was varied to achieve required flow rate and water cut. Once the required water cut and flow rates are reached, pressure drop [across 3m (DPT1)] measurements were made. Similar procedure was followed for other angles including; 15°, 30° and for different water cut ratio 0 to 100%. The oil-water flow rates at the inlet were varied from 4000 to 8000 BPD.

4. Results and discussions

Oil-water two phase flow experiments were carried out for different inclination angles including; 0°, 15°, 30° and for different water cut ratios (0%, 20%, 40%, 60% and 100%). The oil-water flow rates at the inlet were varied from 4000 to 8000 BPD.

4.1. Effect of water-cut on oil-water frictional pressure drop (FPD) for different flow rates

For a given angle $\theta = 15^\circ$ case, the effect of water cut for different flow rates on pressure drop is shown in Figure 3a. As it can be seen from figure 3a, for a given flow rate the pressure drop increases from WC = 0 to WC 60%. Further increase in WC, shows decrease in FPD has been found to decrease. This could be due to phase inversion or change in flow pattern regime. Also, it can be seen from figure 3a, for any given WC, the FPD increases with increase in flow rate.

For $\theta = 30^\circ$ case, the effect of flow rate on FPD for different water cuts is shown in figure 3b. As it can be seen from figure 3b, FPD increases with flow rate and WC. However, FPD is relatively higher for WC 20 - 60% as compared $\theta = 15^\circ$ case. This could be due to increase in inclination angle.

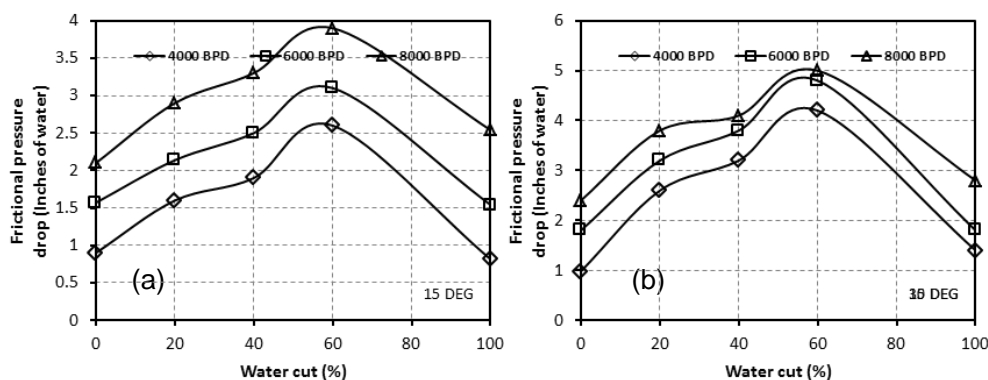


Figure 3. Effect of water cut on pressure drop for different flow rates. (a) 15° case, (b) 30° case

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

For a given angle $\theta = 15^\circ$, the effect of flow rate on frictional pressure drop (FPD) for different WC is shown in figure 4a. As it can be seen from figure 4a, pressure drop increases with flow rate and WC. The FPD drop has been found to increase linearly with respect flow rate. For a given flow rate of 6000 BPD, for increase in water cut from WC 0 to 20, percentage increase in FPD is about 36%. For angle $\theta = 30^\circ$ case, the effect of flow rate on FPD for different water cuts is shown in figure 4b. Again, as it can be seen from figure 4b, FPD increases with flow rate and WC. However, pressure drops are relatively higher as compared $\theta = 15^\circ$ case. This could be due to increase in inclination angle. For a given flow rate of 6000 BPD, for increase in water cut from WC 0 to 20, percentage increase in frictional pressure drop is about 77%. From the these figures, it can be concluded that the effect of inclination on pressure drop behaviour is appreciable.

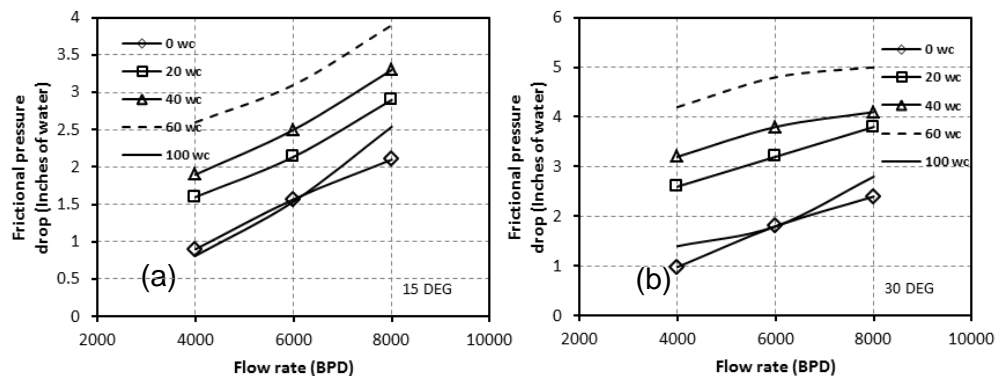


Figure 4. Effect of flow rate on pressure drop for different water cuts (a) 15° case, (b) 30° case

4.3. Effect of inclination on oil-water pressure drop for different flow rates for given water cut

For the sake of brevity, the angle effect on pressure drop measurements for different flow rates, only water cut (WC) = 40% has been presented.

For a given water cut (WC = 40%), the effect of inclination for different flow rates on pressure drop is shown in figure 5. As mentioned earlier, in general for all angles, pressure drop increases with flow rate and water cut. The effect of angle has found to be appreciable. For a given flow rate 8000 BPD, WC = 40%, increase in angle from 0 to 15° , percentage increase in frictional pressure drop is about 50%. However, for further increase in angle from 15° to 30° , percentage increase in frictional pressure drop is about 24%.

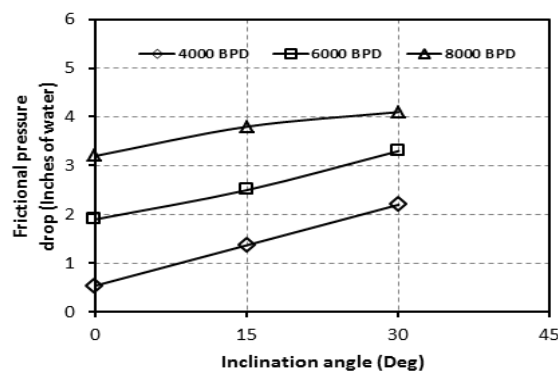


Figure 5. Effect of angle on pressure drop for different flow rates (for a given water cut, WC = 40%)

The total pressure head (TPH) is sum of frictional and gravitational pressure head (GPH). The present work has focused on frictional pressure head (FPH). However, GPH is a constant term which may be added to FPH to obtain the TPH. For a given angle, $\theta = 15^\circ$, GPH ($\rho gh = \rho g \sin \theta h$, ρ is mixture density, h is distance between pressure tapping points, g is gravity) is 23.13 inches of water.

5. Conclusions

The present work has focused attention on the pressure drop measurements of oil (D130)-water two-phase flow in a horizontal and inclined 4 inch diameter stainless steel pipe at different flow conditions. Experiments were performed for different inclination angles including; 0°, 15°, 30° and for different water cut ratios (0%, - 100%). The flow rates at the inlet were varied from 4000 to 8000 BPD. In order to validate the experimental work, the measured pressure drops and friction factor of single phase oil and single phase water were compared with existing empirical relations and good agreement was noticed.

For a given flow rate (for all angles) the frictional pressure drop (FPD) has been found to increase from WC = 0 - 60 %. Further increase in WC causes FPD to decrease. For a given flow rate of 6000 BPD ($\theta = 15^\circ$), with increase in WC from 0 to 20, percentage increase in FPD is about 36%. Further increase from 15° to 30°, percentage increase in FPD has been found to be about 77%.

6. Nomenclature

A	Cross-sectional area of pipe [m^2]	ρ_w	Density of water [kg/m^3]
BPD	Barrel per day	ρ_o	Density of oil [kg/m^3]
Dh	Diameter of the pipe [m]	μ_o	Viscosity of oil [$Pa.s$]
f	Friction factor	μ_w	Viscosity of water [$Pa.s$]
ID	Inner diameter [m]	ΔP	Pressure drop [$inch H_2O, pa$]
L	Length of the pipe [m]	$\frac{\Delta P}{\Delta L}$	Pressure gradient [$\frac{Pa}{m}, \frac{inch H_2O}{m}$]
Re	Reynolds's number		

Acknowledgments

The authors acknowledge the support of Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals for this research work.

References

- [1] Jing-yu Xu, Dong-hui Li, Jun Guo, Ying-xiang Wu (2010). Investigations of phase inversion and frictional pressure gradients in upward and downward oil–water flow in vertical pipes. *International Journal of Multiphase Flow*, v. 36, pp. 930–939.
- [2] Pedram H., Alireza H.i, Amir K (2015). Experimental investigation of oil–water two phase flow regime in an inclined pipe. *Journal of Petroleum Science and Engineering*, 136, pp. 12–22.
- [3] Descamps M. N., Oliemans R. V. a., Ooms G., and Mudde R. F. (2007), Experimental Investigation Of Three-Phase Flow In A Vertical Pipe: Local Characteristics Of The Gas Phase For Gas-Lift Conditions, *Int. J. Multiph. Flow*, 33(11), pp. 1205–1221.
- [4] Grassi B., Strazza D., and Poesio P. (2008), Experimental Validation Of Theoretical Models In Two-Phase High-Viscosity Ratio Liquid–Liquid Flows In Horizontal And Slightly Inclined Pipes, *Int. J. Multiph. Flow*, 34(10), pp. 950–965.
- [5] Du M., Jin N.-D., Gao Z.-K., Wang Z.-Y., and Zhai L.-S. (2012), Flow Pattern And Water Holdup Measurements Of Vertical Upward Oil–Water Two-Phase Flow In Small Diameter Pipes, *Int. J. Multiph. Flow*, 41, pp. 91–105.
- [6] Domenico S., B.Grassi., M. Demori, V. Ferrari, and P. Poesio (2011). Core-annular flow in horizontal and slightly inclined pipes: Existence, pressure drops, and hold-up. *Chemical Engineering Science*, v. 66, pp. 2853–2863.
- [7] Karolina I., O.J. Nydal, and P. Angeli (2005). Phase inversion in dispersed liquid–liquid flows. *Experimental Thermal and Fluid Science*, v. 29, pp. 331–339.
- [8] Dongjian Z., L. Guo, X. Hu, X. Zhang, and X.Wang (2006). Experimental study on local characteristics of oil–water dispersed flow in a vertical pipe. *International Journal of Multiphase Flow*, v. 32, pp. 1254–1268.
- [9] Lum J.Y. L., T. Al-Wahaibi, and P. Angel (2006). Upward and downward inclination oil–water flows. *International Journal of Multiphase Flow*, v. 32, pp. 413–435.