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Drag reduction with polymer in oil-water flow in relatively large pipe diameter

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A B S T R A C T

It is well known that finding sustainable solutions to the unavoidable high pressure losses accompanying pipeline flows so as to increase the pumping capacity without necessarily adding more pump stations is inevitable. In this study, the drag reduction by polymer in horizontal oil-water flow was investigated in 3 inch pipe diameter. This was achieved by injecting the master solution of the polymer which was prepared at 2000 ppm into the water phase before mixing of the oil and the water occurred. The polymer master solution was injected at controlled flow rate to provide 40 ppm of the polymer into the oil-water flow in pipe of 0.0747-m ID. The flow conditions were in the ranges of 0.1 – 1.6 m/s mixture velocities and 0.05 – 0.9 input oil volume fractions. Being a water-soluble polymer, the drag reductions were mainly observed at the water-dominated regions. In these regions, the drag reduction increased with increase in mixture velocity and decrease in the input oil volume fraction such that the maximum drag reductions of about 51 % at the highest mixture velocity and lowest input oil volume fraction were achieved.

1. Introduction

Oil-water flows are often encountered in chemical industries, and even more so in petroleum industries because of the simultaneous production of oil and water from aging oil wells especially in recent years. The study of the oil and water flow in pipelines was initially necessitated by the discovery that, under certain conditions, the injection of water into a crude oil pipeline results in a significant reduction of pressure loss, thereby facilitating oil transportation (Russell et al., 1959; Charles et al., 1961). After a relatively quiescent period, the increase in the amount of water produced together with oil from maturing oil fields, which are now commonly encountered, has revived the interests of researchers towards this area in recent time.

Three flow characteristics which are very crucial in the study of oil-water flow are pressure drop, flow pattern and holdup. Pressure drops in pipeline flow are mainly due to friction (drag) caused by molecules colliding against each other and against the pipe wall. In single phase flow, this friction-induced pressure drop, apart from the little influence of system pressure and temperature on it, is dominated by Reynolds number, which is a function of density, viscosity and velocity of fluid as well as pipe diameter. However, more parameters in addition to ones for single phase flow are responsible for pressure drop in two-phase oil-water flow. They include density, viscosity and volume fraction of each phase, mixture/superficial velocities, diameter of the pipe, and the system pressure and temperature. These parameters control the distribution of fluid interfaces, which reflects the mechanism of momentum, heat and mass transfer among the fluids; and thus inducing different pressure drops (Guo et al., 2005).

There are several works on oil-water related to pressure drops without DRPs (Arirachakaran et al., 1989; Angeli and Hewitt, 1998; Lovick and Angeli, 2004; Lum et al., 2006; Rodriguez and Oliemans, 2006; Kumara et al., 2009).

Drag reduction has been defined as the decrease in pressure loss at constant flow rate in turbulent pipe, tube or channel flow caused by the addition of small amounts of additives to the carrier fluid. Among all the drag reducing additives, polymers have been found to be effective. This is because only few parts-per-million levels of the polymers in the working fluid are enough to cause significant drag reduction. Drag reducing polymers (DRPs) are long chain, ultra-high molecular weight (typically ranging from 1 to 15 million Daltons) polymers which can be water- and/or oil-soluble.

Having taken full advantage of this fascinating drag-reducing ability of DRPs, as first revealed from

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Toms' experiment (Toms, 1948), to extensively study the effect of the DRPs on single-phase and two-phase gas-liquid flow characteristics, researchers have been encouraged by positive results obtained to extend the study just in the last decade to oil-water flows (Al-Wahaibi et al., 2007; Al-Yaari et al., 2009; Omer and Pal, 2010; Al-Yaari et al., 2012; Langsholt, 2012; Yusuf et al., 2012).

The first documented work on oil-water flow with DRP was carried out by Al-Wahaibi et al. (2007). They injected two concentrations (20 and 50 ppm) of a polymer (Magnafloc 1011), into oil-water flow in a horizontal acrylic pipe and found that there was reduction in the pressure drops, which became more pronounced as the water superficial velocity was increased. They recorded maximum drag reduction of about 50% when the polymer was introduced into annular flow. The subsequent study was the work of Al-Yaari et al. (2009, 2013). Using kerosene as the oil phase, they injected 10 – 15 ppm from different 1000 ppm polyethylene oxide master solutions with molecular weights of 3 x 10^5, 4 x 10^6 and 8 x 10^6 Da into oil-water flow in a 10-m long acrylic horizontal pipe of 25.4-mm ID. It was found that pressure drop reduction was significant and depended on water fraction, mixture velocity, concentration and molecular weight of the DRP. The presence of salt content in the water phase negatively affected the effectiveness of the DRP but the phase inversions observed disappeared as only 5 ppm of the polymer solution was injected.

Omer and Pal (2010) conducted their study in oil-continuous dispersed flow regime otherwise known as water-in-oil emulsion (w/o). They injected water-soluble polyethylene oxide of two different molecular weights (4 and 7 million Da) and carboxymethyl cellulose (0.7 million Da) into three emulsions, each containing 30 % water by volume and prepared from three different oil viscosities of 2.5, 5.4 and 6 cP. They observed negative effect of the DRPs on the pressure drops. That is the pressure drops increased after adding the DRPs. This is because the external (i.e. continuous) phase which is oil is not soluble in the DRPs, which only dissolved in th internal (dispersed) phase. Therefore, the interaction between the polymer molecules with turbulence eddies which brings about drag reduction was not achieved. Al-Yaari et al. (2013) observed similar behaviour when they also injected watr-soluble DRP into surfactant stabilized water-in-oil emulsions. Meanwhile, Omer and Pal (2010) also attributed this negative behaviour to several factors such as increase in droplet viscoelasticity, increase in droplet viscosity, decrease in interfacial tension between oil and aqueous phase, and decrease in the droplets size. They stated further that the presence of these factors especially the viscoelasticity of the polymer in the emulsion droplets inhibited the dynamic break-up and coalescence of the droplets in turbulent flow, thereby resulting in a decrease in the suppression of turbulence and hence a decrease in drag reduction.

Yusuf et al. (2012) investigated the effect of DRP on pressure drops using a mineral oil in a 25.4-mm ID, 8-m long acrylic pipe. It was observed that the drag reduction increased with the polymer concentration from 2 to 10 ppm beyond which no further increase in the drag reduction occurred. At a fixed oil superficial velocity, the drag reduction was observed to increase with increase in water superficial velocity until it reached a maximum value at water superficial velocity of 1.3 m/s. In the contrast, the drag reduction decreased when the oil superficial velocity was increased at water superficial velocity greater than 1.3 m/s while fluctuations in the drag reduction were noticed when oil superficial velocity was increased at water superficial velocity less than 1.3 m/s. this confirm that the effectiveness of any DRP will decrease if it the phase in which it is not soluble is increased. They also found out that the concentration of the polymer master solution and pipe diameter did not affect the drag reduction.

The study of Langsholt (2012) was carried out at only 1.5 m/s mixture velocity with water cut ranging from 0 -100 %, using both water- and oil-soluble DRPs in dispersed flow region. It was reported that drag reduction in the oil-water flow increased with increase in inlet volume fraction of the phase in which DRP was injected and drag reduction (though very much smaller) occurred even when the liquid carrying DRP was not the continuous phase in dispersed flow. Phase inversion was also observed without DRPs at 50 % water cut. However, the water-soluble polymer, showed no effect on the phase inversion point but the addition of oil-soluble polymer, on the contrary, slightly shifted the phase inversion point towards higher water cut.

Al-Wahaibi et al. (2013) used two pipe diameters (19 and 25.4 mm) to examine the influence of a small change of pipe diameter in the effectiveness of drag reducing polymer (DRP) in horizontal oil-water flow. The results showed a remarkable influence of pipe diameter on the polymer efficiency in modifying flow patterns and drag reduction. Drag reductions up to 60% were observed in the 25.4-mm pipe in comparison with up to 45% achieved in the 19-mm pipe.

Abubakar et al. (2015) investigated the effect of DRP on flow patterns, drag reduction and slip velocity ratio of oil–water flow in a 30.6-mm ID, 12-m long horizontal acrylic pipe. It was observed that the drag reduction increased with increase in the polymer concentration reaching plateau values effectively at polymer concentration of 30 ppm for the whole range of mixture velocity and input oil volume fractions covered. Also, it was found that drag reductions increased with increase in the mixture velocity and decrease in the input oil volume fraction, leading to maximum drag reduction of about 64% at the highest mixture velocity and at 0.05 input oil volume fractions. The addition of the polymer affected the flow characteristics especially at lower mixture velocities and input oil volume fractions. The stratified, dual continuous and dispersed oil in water and water layer flow patterns were extended to higher mixture velocities but the oil-continuous flow patterns were not affected by the addition of the polymer. Finally, they found that the addition of the polymer increased the slip velocity ratios especially at lower mixture velocities.

From the available works in open literature, the studies involving the use of the DRPs in oil-water flow are still very limited and there is no documented study that deals with drag reduction by DRPs in relatively large pipe diameter. Hence, the motivation for this study is to investigate the effect of drag reducing polymer on the drag reduction of oil-water flow in 3inch pipe diameter.

2. Experimental setup

2.1. Description of the flow loop

The pilot-scale oil-water flow facility used for this study is schematically shown in Fig. 1. The flow loop is made up of three sections namely handling section, regulating section and test section. The handling section where the fluids are stored consists of two storage tanks (one for water and another for oil) of 1,600 Litres capacity and separator tank of 2,000 Litres capacity. The separation process is enhanced by reducing the flow rate of the mixture into the separator tank with the help of a baffle plate inside the separator tank.

In the regulating section, two steel pipes of 1- and 2-in. 1D are each connected to water and oil tanks. The fluids are pumped using centrifugal pumps (Lowara, Italy) through the 2-in. ID pipes while the 1-in. ID pipes serve as recycle and bypass by connecting each of them to their respective 2-in. ID pipes after the pumps. The essence of the recycle and bypass pipes is to properly regulate the flows since each pump which can generate 240 L/min flow rate is operating at full capacity. With the help of the globe valves, recycled streams can be produced if the flow rate needed is less than the full capacities of the pumps. In addition, the bypass flows are required when dealing with small flow rates by completely closing the globe valves in the 2-in. ID pipes before joining each of the 1-in. ID pipe to their respective 2-in ID pipe, the four pipes are each connected to an *EESIFLO* Sonalok 5000 series ultrasonic flow meter to measure the flow rates. The flow meters, which are non-invasive, utilise ultrasonic technology for the accurate flow measurement of liquids in full pipes and they have a flow velocity range (which automatically converts to volume depending on the pipe diameter inputted) of 0.01-25 m/s, with volume flow accuracy of 2 % of the measured value. After measuring the flow rates, the oil and water are joined via a Y-junction. The test section consists of three acrylic pipe configurations (each of which is made up of two parallel pipes of 12-m long of the same diameters that are joined together by U-tube) with different ID of 30.6, 55.7 and 74.7 mm and they are arranged above one another with the biggest pipe at the bottom and the smallest one at the top.

Honeywell ST 3000 Smart differential pressure transmitter was connected to each pipe configuration at 10 m from the inlet of the test section. The pressure differential transmitters which have a full scale accuracy of 0.0375% measure the pressure drops through two pairs of pressure tapping ports placed over a distance of 1 m. Injection port is also provided at 0.4 m before the mixing junction through which the polymer master solution is injected into the main water stream before the water is mixed with the oil.

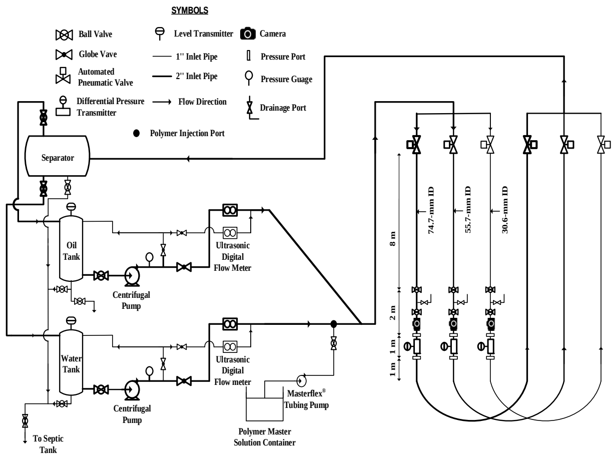

Fig. 1: Schematic of two-phase oil-water flow loop

2.2. Polymer preparation

The chemical composition of the AN 105-SH polymer, which was used as the DRP, has been described in full details in Abubakar et al. (2014). A master solution with a concentration of 2000 ppm from each polymer was prepared using a paddle mixer. This was done by setting the mixer to a fixed speed and inserting the paddle into a measured mass of tap water. A known mass of polymer powder as measured using analytical balance was thereafter gently added to the shoulder of the vortex formed by the water as the stirring continued. The continuous stirring was allowed for 3 hours for the mixture to be completely homogenized, after which the master solution was left overnight to ensure complete dissolution. The master solution was injected into the water phase and at a specific flow rate so that polymer concentration of 40 ppm can be achieved in the main water flow line.

2.3. Experimental procedure

This study was carried out in the 74.7 mm horizontal pipe which is made up of 12-m long acrylic material. The working fluids used in this study were tap water and hydraulic fluid based on mineral oil (Shell Tellus S2 V 15), with properties shown in Table 1.

The full detailed descriptions of the experimental procedure on measuring the pressure drops can also be found in our earlier published work in which the effect of the DRP on horizontal oil-water flow in only

30.6-mm ID pipe was investigated (Abubakar et al., 2015).

Table 1: Properties of the working fluids at 25 ^{0}C

Fluid	Density (kg/m³)	Viscosity (cP)	Interfacial Tension (mN/m)	Surface Tension (mN/m)
Water	997	1	12.9	71.4
Oil (Shell Tellus S2 V 15)	872	24		29.5
Water with 40 ppm DRP	997	1.2	12.5	70.5

Meanwhile, there are some important points which are worth repeating here. The 40 ppm concentration was arrived at from preliminary experiment conducted to determine the polymer concentration required to produce maximum drag reduction. This was done by measuring the drag reductions of oil–water flow at different polymer concentrations in the water flow line. The results of this preliminary work have been published in (Abubakar et al., 2015). The concentration of master (pre-mixed) polymer solution which was 2000 ppm (0.2% w/w) was chosen to ensure that it is within the range of dilute solution to achieve homogeneous drag reduction in which the polymer solution can dissolve and distribute uniformly after a very short distance from the injection point. After ensuring that the DRP was adequately injected, the flow pattern observation and the pressure drop and holdup measurements were repeated.

The pressure ports for the pressure transmitters, which measured the pressure drops were located at intentionally chosen positions far enough to ensure fully developed flow in the test section before the measurements were made. Before every experimental run, efforts were made to ensure that the pressure transmitters returned to zero pressure gradient. This was done in order to have repeatable and accurate measurements.

The experimental uncertainties of the pressure drop measurements were estimated to be within ±10%. With the measured pressure drops before and after polymer injection, the percentage drag reduction was determined as follows:

$$\% DR = \frac{\Delta P_{without\ DRP} - \Delta P_{with\ DRP}}{\Delta P_{without\ DRP}} \quad (1)$$

$\% DR$ = percentage drag reduction,
$\Delta P_{without\ DRP}$ = pressure drop without DRP,
$\Delta P_{with\ DRP}$ = pressure drop with DRP

3. Results and discussion

The percentage drag reductions determined using Equation 1 were presented graphically in two forms; firstly against input oil volume fractions for different mixture velocities and secondly against mixture velocities for different input oil volume fractions. These are shown in Figs. 2 and 3. The percentage drag reduction increased with increase in the mixture velocity (U_{MIX}) but it decreased with increase in oil volume fraction (α_o).

One of the most important observations is the dependence of the drag reductions by DRP on the flow structures of the oil-water flow as the drag reduction was majorly achieved in water-dominated regions. This is because the DRP is only water-soluble and hence it is difficult for the DRP to perform in oil-dominated regions according to (Usui, 1990; Fu and Kawaguchi, 2013). Meanwhile, in the low input oil volume fractions where water is the continuous phase, the drag reduction decreased with increase in the input oil volume fractions.

There were sharp increases in drag reductions immediately after water-dominated regions. This occurrence was caused by a phenomenon known as phase inversion and at the input oil volume fractions where this occurred are called phase inversion points. The very high turbulence intensity usually associated with phase inversion process is responsible for the sharp increase in the drag reduction.

In addition, there were no drag reductions immediately after phase inversion points where oil-dominated regions occurred. At some input oil volume fractions, the addition of the DRP even caused an increase in the pressure drops (i.e. negative drag reductions). Omer and Pal, (2010) found similar behaviour in water-in-oil emulsion region and they attributed it to several factors such as increase in droplet viscoelasticity, increase in droplet viscosity, decrease in interfacial tension between oil and aqueous phase, and decrease in the droplets size.

Finally, by comparing these results which were obtained using 74.7 mm horizontal pipe with those of (Abubakar et al., 2015) which were measured using 30.6 mm horizontal pipe, it is obvious that drag reduction decreased with increase in the pipe diameter. However, the relative increase in the percentage drag reduction with respect to the mixture velocity became smaller as the mixture velocity increased. The comparison revealed that a maximum drag reduction of about 64% was observed by (Abubakar et al., 2015) at 1.6 m/s mixture velocity and 0.05 input oil volume while 51% was found in the present study at the same conditions fraction.

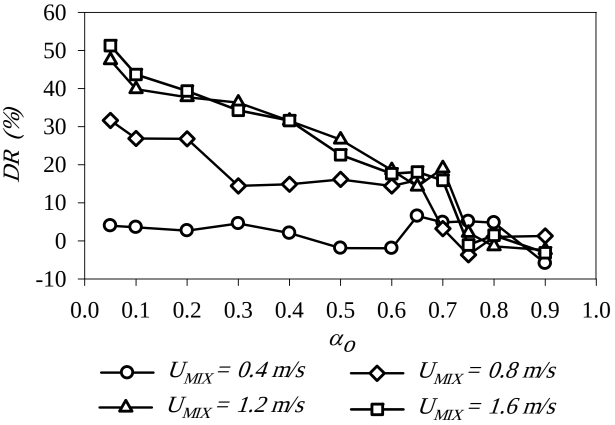

Fig. 2: Drag reduction against input oil volume fraction at different mixture velocities in 74.7-mm ID pipe after adding 40 ppm DRP

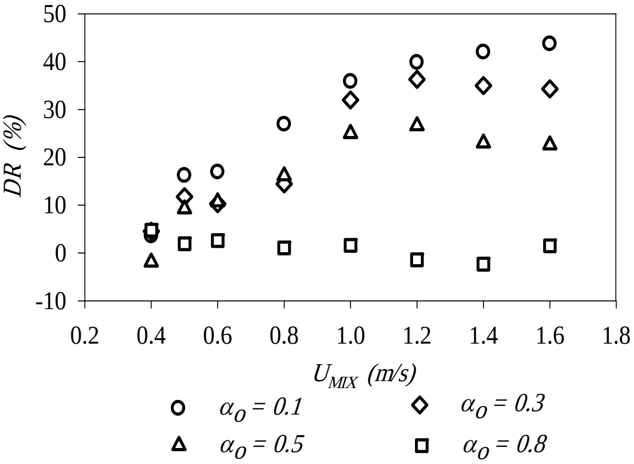

Fig. 3: Drag reduction against mixture velocity at different input oil volume fractions in 74.7-mm ID pipe after adding 40 ppm DRP

4. Conclusion

Drag reduction in horizontal oil-water flow in 74.7 mm horizontal pipe diameter was investigated in this work. The drag reduction increased with increase in the mixture velocity but decreased with increase in the onput oil volume fraction. Also, drag reduction was found to be negatively affected by the increase in the pipe diameter when compared the results in our earlier publication. Equally important is the fact that the drag reduction only occurred in the water-dominated regions. Phase inversion was also observed which resulted to sharp increase in the drag reduction because of the increased turbulence intensity associated with phenomenon.

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