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Effect of drag reducing polymers on oil–water flow in a horizontal pipe

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ABSTRACT

Measurements of drag-reduction are presented for oil–water flowing in a horizontal 0.0254 m pipe. Different oil–water configurations were observed. The injection of water soluble polymer solution (PDRA) in some cases produced drag reduction of about 65% with concentration of only 10–15 ppm. The results showed a significant reduction in pressure gradient due to PDRA especially at high mixture velocity which was accompanied by a clear change in the flow pattern. Phase inversion point in dispersed flow regime occurred at a water fraction range of (0.33–0.35) indicated by its pressure drop peak which was disappeared by injecting only 5 ppm (weight basis) of PDRA. Effect of PDRA concentration and molecular weight on flow patterns and pressure drops are presented in this study. Influence of salt content in the water phase on the performance of PDRA is also examined in this paper.

1. Introduction

One of the common occurrences in the petroleum industry during transportation and production is oil–water flow in pipes. Moreover, two-phase liquid–liquid flow is common in the process and petrochemical industries In general; the introduction of water into oil transportation pipelines can have several effects such as a complex interfacial structure between oil and water which complicates the hydrodynamic prediction of the fluid flow. Water-in-oil or oil-in-water dispersions influence the pressure gradient dramatically. However, increasing the water fraction toward the phase inversion, where the continuous phase becomes water, leads to a high pressure gradient and high power consumption. This can result in a reduction in production capacity. At high water fraction, as the water continuous zone is entered, the pressure gradient decreases again (Soleimani, 1999). Ioannou et al. (2005) studied the phase inversion effect on pressure gradient in the dispersed flow of two immiscible liquids. Two different pipe diameters and pipe materials (steel and acrylic) were investigated. Water and oil were used as test fluids. In the acrylic pipe; the appearance of phase inversion was verified with the use of impedance ring probes. 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.

Piela et al. (2006) investigated experimentally the phase inversion in oil–water flow in a horizontal pipe. It was found that the inversion point could be postponed to high values of the dispersed phase volume fraction (higher than 0.8) when the experiments started with the flow of a single liquid in the pipe then the second liquid gradually added (using different injectors and different injection flow rates) until inversion took place. Multiple drops consisting of oil droplets in water drops were observed, but the opposite were never found.

It has been long known that the addition of a small amount of long-chain polymer molecules in organic or in water solvents can dramatically change the flow structure in turbulent flow which results in reduction in the drag on a solid surface (Toms, 1948). Liquids are mostly transported through pipes and a reduction in pressure drop by adding a small amount of polymers can offer substantial economic advantages and a higher effectiveness of this transportation.

One of the earliest experiments on drag reduction in gas–liquid flows were reported by Oliver and Young Hoon (1968) who used 1.3% polyethylene oxide (PEO) aqueous solution and air. They found that in slug flow the liquid showed considerably less circulation while in annular flow wave formation was damped resulting in a smoother liquid film. Greskovich and Shrier (1971) first used the term DRP in multiphase systems and found drag reduction that could reach 40% during slug air–water flow. Since then drag reduction has been documented by a number of investigators in a variety of systems with differing results (Otten and Fayed, 1976; Thwaites et al., 1976; Sylvester and Brill, 1976). During slug flow Rosehart et al. (1972), for example, found higher drag reduction than in single phase while Saether et al. (1989) found lower drag reduction. A comprehensive review of work on this area by Manfield et al. (1999) concludes that understanding of the influence of drag-reducing polymers on multiphase flows is not satisfactory.

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One of the most impressive successes in polymer applications for drag reduction was the use of 10 ppm oil-soluble polymers in the trans-Alaska pipeline system which increased pipeline flow rates significantly (Burger et al., 1982). This important finding has prompted a number of investigations to study the influence of polymers on gas–liquid flow. Drag reduction was reported but the most interesting aspect of these works is that the configuration of the phases can be changed. Al-Sarkhi and Hanratty (2001), Soleimani et al. (2002) and Al-Sarkhi and Soleimani (2004) found that the injection of a concentrated solution of a co-polymer of polyacrylamide and sodium acrylate into air–water flow in 1 in. ID and 4 in. ID pipe changed annular and slug flow patterns to a stratified wavy flow pattern by eliminating the disturbance waves in the liquid film. Soleimani et al. (2002) concluded that, drag reducing polymer is damping small wavelength waves on the interface between gas and liquid in stratified flow and this results in a lower interfacial friction factor.

Al-Wahaibi et al. (2007) studied the effect of a drag-reducing polymer on oil–water flow in a relatively small 14 mm ID acrylic pipe. Oil (5.5 mPa s, 828 kg/m^3) and a co-polymer (Magnafloc 1011) of polyacrylamide and sodium acrylate were used. The results showed a strong effect of DRP on flow patterns. The presence of DRP extended the region of stratified flow and delayed transition to slug flow. The addition of the polymer clearly damped interfacial waves. The DRP caused a decrease in pressure gradient and a maximum drag reduction of about 50% was found when the polymer was introduced into annular flow. The height of the interface and the water hold up increased with DRP.

The main focus of the present study is on the determination of the pressure gradient and flow pattern characteristics in different flow regimes when water soluble drag reducing polymer is injected at the beginning of the test section. It also investigates the effect of polymer drag reducing agent on pressure drop in the region of phase inversion at higher mixture velocities where a high pressure drop occurs in the pipeline and a high energy is needed for transportation. In general, oil pipelines contain brackish water rather than fresh or tap water and the salt content is usually above 5%. The effect of 5% salt in the water phase on the performance of the water soluble PDRA was also investigated. Furthermore, effects of polymer drag reducing agent concentration and molecular weight were studied.

Table 1
Properties of oil used in the present study.

Product name	SAFRA D60
Flash point	67 °C
Density	780 kg/m^3
Viscosity	1.57 cp at 25 °C
Interfacial tension oil–water	0.017 N/m at 20 °C

Unlike previous studies, a polymer solution was not circulated with a pump. Instead, a concentrated solution contained in a pressurized container was injected into the system in 25.4 mm pipeline. Different polymers molecular weight and concentrations were investigated. Effect of salt content in water phase was studied.

2. Description of the experimental setup and procedure

All experiments reported in this investigation were conducted using tap water and viscous oil known as SAFRA D60, produced in Saudi Arabia which is one type of kerosene with a density of 780 kg/m^3 and viscosity of 1.57 mPa s (the physical properties of this oil are listed in Table 1). Schematic of the oil–water experimental facility is shown in Fig. 1. The test section consists of a 10 m long acrylic (to allow visual observation) horizontal pipe with 25.4 mm ID. Pressure drop between two points along the pipe which are 1.51 m apart from each other was monitored. The first pressure tap is located at 6.44 m from the mixing tee to make sure that the flow is fully developed. Schematic of the polymer injection system is shown in Fig. 2.

One day before the experiment was performed; the polymer powder was gently mixed with water to form a master solution with concentration of 1000 ppm by a method described by Warholic et al. (1999). The polymer injection system consists of a 477 L stainless steel tank, where the master solution of polymers is made, with an electrical mixer made by Cole Parmer Instrument Company. This tank has a volume indicator and a draining valve. A stainless steel pressurized tank with a volume of 100 L is connected to the master solution tank by a rubber tube and has pressure and level indicators. An air compressor, connected to the pressurized tank. The pressure in the pressurized tank can be controlled by a pressure regulator and the set pressure value of the outlet of the compressor. The injection of the polymer into the system is not involving any pump to avoid polymer degradation, instead a pressurized tank is used. Two variable area flowmeters for polymer solution coming from the pressurized tank through an open-close valve and two control valves. The flowmeter were calibrated before every experiment. Polymer solution is continuously injected into the flow through a 2–3 mm hole, located at

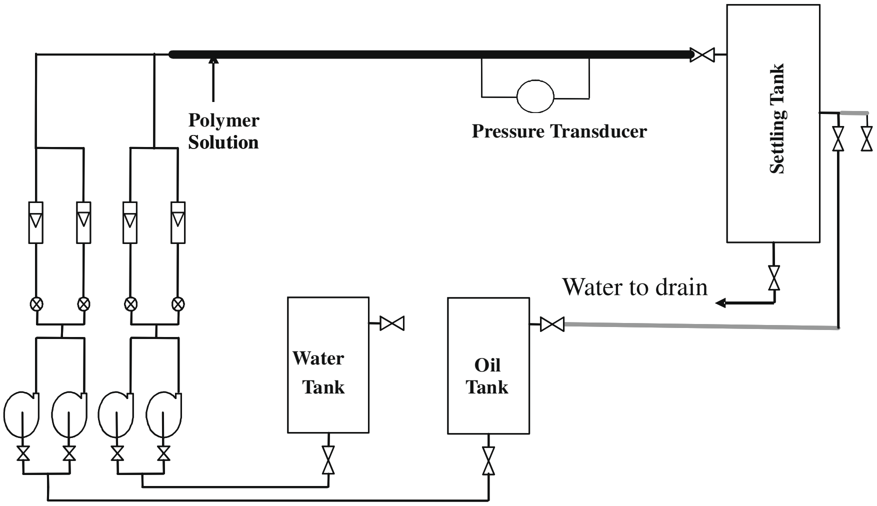

Fig. 1. Schematic of the flow loop.

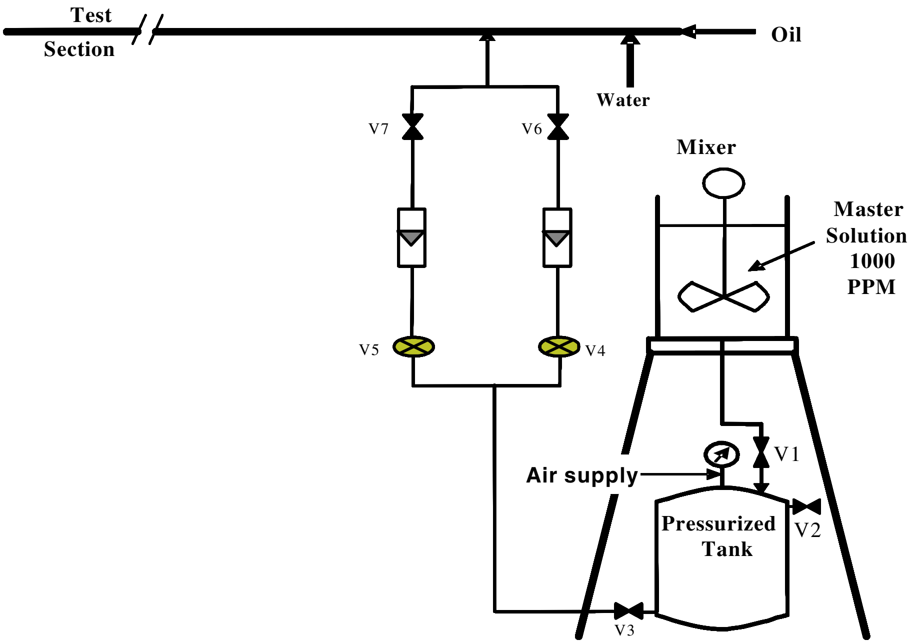

Fig. 2. Schematic of the polymer injection system.

Table 2
Physical properties of drag reducing polymer Magnafloc 1011.

Product name	Ciba Magnafloc 1011 supplied by Ciba Specialty Chemicals
Molecular weight	10^7 g/mol
Description	Anionic polyacrylamide flocculant; white granular powder
Bulk density	0.7 g/cm^3

Table 3
Physical properties of drag reducing polymer polyethylene oxide.

Product name	Polyethylene oxide supplied by Polysciences, Inc.
Molecular weight	300,000; 4,000,000; 8,000,000 g/mol
Description	Ammonia, ethylene oxide, monoethylamine, poly(ethylene oxide)

the bottom of the test section, at 0.5 m from the tee mixing point. The oil and water is separated in a large settling tank. After separation the water is dumped into drainage and the oil is re-circulated to the oil tank.

The effect of water soluble PDRA concentration was achieved by injecting dilute polymer solutions with polymer concentration of 2, 5, 10, 25 and 50 wppm. In addition, with polymer molecular weights of 3×10^5, 4×10^6 and 8×10^6 g/mol, the effect of PDRA molecular weight was investigated. The physicochemical properties of the polymers are shown in Tables 2 and 3. The effect of water fraction on the performance of PDRA was explored by using water volume fraction between 0.2 and 0.8. The effect of the mixture velocity was studied in the range of 0.5–3.5 m/s.

3. Results and discussion

3.1. Co-current oil–water flow in a horizontal pipe

3.1.1. Flow pattern

Different flow patterns were observed for a wide range of mixture velocities (0.5–3.5 m/s) and input water volume fraction (water-cut) range of (0.1–0.9). These observations were made at 5 m from the inlet of the test section. In general, the flow pattern map depends on several parameters such as the geometry, input flow rates of oil and water, liquid physical properties and wetting properties of the wall surface. The flow patterns classification was made based on visual observation. Fig. 3 shows the flow patterns observed in the present work which are defined as follows:

1. *Stratified wavy flow (SW).* The phases are completely segregated with the interface between them showing a characteristic wavy nature.
2. *Stratified wavy/drops (SWD).* The entrainment of one or both phases as drops in the other has begun, the droplets being concentrated near the interface zone (stratified wavy with mixing interface).
3. *Stratified mixed/water layer (SMW).* There are two layers in the flow: a lower clear water layer and an upper layer which can be oil continuous containing dispersion of water droplets or water continuous containing a dispersion of oil droplets or a combination of the two.
4. *Stratified mixed/oil layer (SMO).* There are two layers in the flow: an upper clear oil layer and a lower layer which can be oil continuous containing a dispersion of water droplets or water continuous containing a dispersion of oil droplets or a combination of the two.
5. *Three layers flow.* There are clear oil and water layers at the top and bottom of the pipe, respectively, with a dispersed layer between them.
6. *Dispersed flow.* One phase is completely dispersed as droplets in the other. The continuous phase changes from one fluid to the other at the phase inversion point.

The observed flow patterns data in the present study for oil–water flow are plotted in Fig. 4 in terms of superficial mixture velocity against input water volume fraction (water-cut). As illustrated in this figure, the stratified flow pattern was observed for the whole examined range of the input water volume fraction at a very low superficial mixture velocity (0.5 m/s). As the mixture velocity increased to 1 m/s, the stratified flow pattern changed to

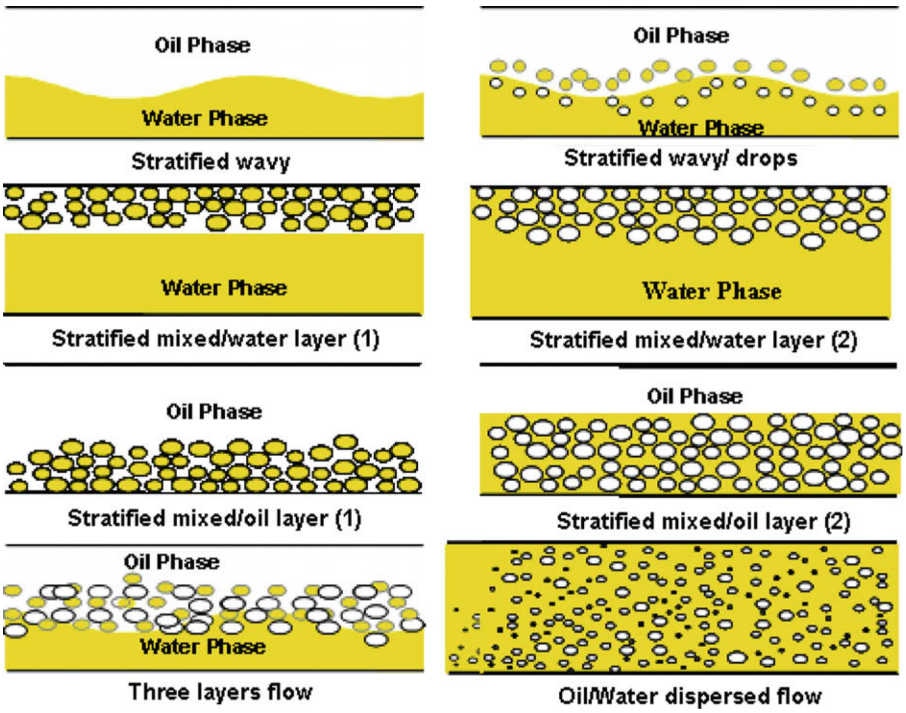

Fig. 3. Observed oil–water flow patterns in a horizontal 0.0254 m pipe.

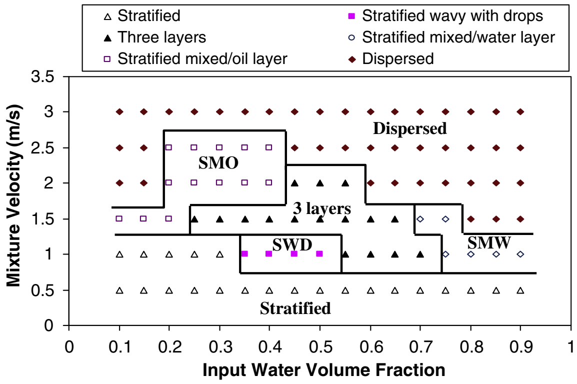

Fig. 4. Flow pattern map of oil–water flow.

stratified wavy with drops, three layers and stratified mixed/water layer flow patterns successively with increasing water fraction at input water volume fraction of 0.35, 0.55 and 0.75, respectively. For even higher mixture velocities, the flow pattern became stratified mixed/oil layer and changed to three layers and then to dispersed flow patterns with increasing water-cut. At high mixture velocities (3 m/s and above), the dispersed flow pattern was observed for the whole range of water fraction. An attempt has been made to compare the experimental flow pattern map with other flow pattern results. The observed flow pattern map is in good agreement with flow pattern map suggested by Angeli (1996) and Soleimani (1999) except for some transition points because of the slight difference in some physical properties of the fluids and observation methods.

3.1.2. Pressure drop

The pressure drop in oil–water flow was measured for all points on the observed flow pattern map. The measurements were made between the two points located at 6.44 m and 7.95 m from the mixing section (tee) for different mixture velocities. These results are presented in Fig. 5 which shows the variation of pressure gradient with water fraction at different mixture velocities. This graph indicates that the pressure drop is a function of the mixture velocity and the water fraction. A clear peak appeared in the curves of pressure gradient against water fraction when mixture velocity was higher than 2 m/s. This is associated with phase inversion phenomenon in the dispersed flow pattern across pipe cross section (the flow changes from oil continuous to water continuous as water fraction increases) and this peak becomes sharper as mixture velocity increases.

Phase inversion is assumed to occur at or after the peak in the pressure drop measurement. However, the peak in the pressure drop measurement occurred at different water fractions for different mixture velocities as shown in Fig. 5. This discrepancy can be associated with degree of mixing for different mixture velocities. The water and oil droplets tend to settle at the bottom and top of the pipe, respectively, due to gravity which is opposed and

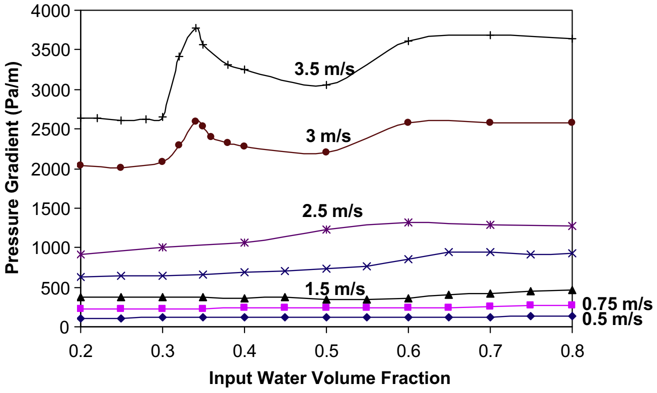

Fig. 5. Pressure drop measurements for mixture velocities between 0.5 and 3.5 m/s at different water fractions.

balanced by turbulent mixing across the cross section of the pipe. A lower degree of mixing allows a concentration gradient across the pipe cross section, which results in a gradual local phase inversion with different zones of oil and water continuous dispersed flow regime. Soleimani et al. (2000) quantified the spatial distribution in the cross section of a horizontal 0.0254 m stainless steel pipe using high frequency impedance probe and gamma densitometry system and confirmed that the degree of stratification is quite high at low mixture velocities and the degree of mixing increases with increasing mixture velocity.

Pressure drop results have been compared with Soleimani (1999) data measured in a horizontal 1 in. ID stainless steel pipe and it was noted that, the pressure drop in the present experiments (acrylic pipe) appears lower than that of Soleimani (1999). In addition Soleimani (1999) observed the phase inversion peak at 2 m/s mixture velocity while this peak has been identified at a higher mixture velocity in the present investigation. However, while oil and water properties are very similar for both sets of experiments, the pipe material is different. This discrepancy can be associated with a rougher surface of stainless steel pipe compared to acrylic pipe. Turbulent mixing degree increases in a rougher surface pipe which accelerates the formation of drops and leads to a dispersed flow regime at a lower mixture velocity compared with a smooth acrylic pipe.

3.2. Effect of water soluble polymer drag reducing agent (PDRA) on co-current oil–water flow

There is a need for experimental data in immiscible liquid–liquid flow with polymer drag reducing agents (PDRAs) in a horizontal pipeline since there are almost no experimental data available in the literature. Particularly, almost no research has been published to investigate the effect of PDRA on the flow characteristics of immiscible liquid–liquid in a horizontal nominal 1 in. ID. In order to investigate this phenomenon, two different water-soluble polymers were injected into the test section at 0.5 m from the beginning of the test section. PDRA solutions were injected into the test section from the bottom of the pipe into the water layer. The polymers used were Magnafloc 1011 (anionic polyacrylamide) with a molecular weight of 10^7 and polyethylene oxide with molecular weights of 3×10^5, 4×10^6 and 8×10^6. The water soluble polymer solution is continuously injected during the experiment and polymer solution influences the flow parameters (flow regimes and drag reduction) throughout the experiment and along the pipe length from few pipe diameters after the injection point to the end of the pipe. This statement has been explicitly added in the result section.

3.2.1. Effect of PDRA on oil–water flow pattern map

The observed flow patterns for oil–water flow with PDRA additives are plotted in Fig. 6, in terms of input water volume fraction against superficial mixture velocity. In this figure, the points (symbols) stand for flow patterns before the injection of 50 ppm of polyacrylamide solution (oil and water) and the lines represent flow patterns after the injection of PDRA (oil, water and PDRA). Whereas six flow patterns were observed visually for a (0.5–3.5 m/s) range of superficial mixture velocity and a (0.1–0.9) input water volume fraction range for co-current oil–water flow without PDRA additives, only five of them were identified after the addition of PDRA (stratified wavy with drops flow pattern disappeared). Furthermore, the injecting of PDRA into the water–oil flow extended the stratified wavy flow pattern over a wider range of mixture velocities and water fraction. Moreover, while the three layers flow pattern were expanded over a wider range of the studied flow conditions, the dispersed flow regime was reduced especially at high water fraction by adding water soluble PDRA.

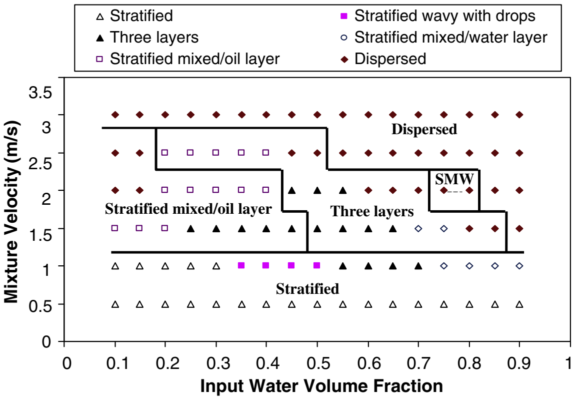

Fig. 6. Flow pattern map of oil–water flow with PDRA additives.

The viscosity of water is much less than the viscosity of oil then even for equal flow rate of oil and water phase (for some cases at low flow rate for which the oil layer Reynolds number is low), water layer Reynolds number is higher than that for oil layer, as a result of that, turbulent flow is initiated earlier and disturbance waves are produced. Brauner and Moalem Maron (1992) and Al-Wahibi and Angeli (2005) reported that flow pattern transition will occur when disturbance waves start to appear on water–oil interface, forms water droplets, entrains them into oil phase and changes the flow regime into stratified wavy with drops. Also, by increasing oil or water velocity, the amplitude of the interfacial waves is increased and entrainment increases further. This process continues until water or oil continuous dispersed flow regime is formed. Although no tangible experiment has been done in the present investigation to quantify interfacial waves and the effect of PDRA addition on theses waves, simple visualization methods determined that PDRA minimized most of the interfacial waves and reduced theirs frequencies. Damping of high amplitude waves by PDRA injection was observed by Soleimani et al. (2002) and Al-Sarkhi and Soleimani (2004) for air–water flow in horizontal pipe.

A possible explanation of the flow pattern change from water continuous dispersed flow to stratified flow is that the injection of PDRA into water continuous dispersed flow substantially reduces turbulent mixing forces. In addition, it increases the droplets coalescence rate which eventually leads to stratification due to a prevailing gravitational force.

By considering the previous paragraph, it can be postulated that adding water soluble PDRA maintains a stratified wavy flow pattern for even higher water velocities and delay stratified wavy with drops flow regime and damp high amplitude waves on interface which cause water drops formation and entrainment into oil layer. Consequently, transition into stratified mixed/water layer, three layers and water continuous dispersed flow regimes occur at higher oil and water velocities after the addition of PDRA.

3.2.2. Effect of PDRA on pressure drop

The effect of the addition of PDRA into oil–water flow for input water volume fraction range of (0.2–0.8) and superficial mixture velocity between 0.5 and 3.5 m/s was studied using 50 ppm water soluble polyacrylamide solution (Magnafloc 1011). The pressure gradient results of oil–water flow with and without PDRA are presented in Figs. 7–10. As presented in Figs. 7–9, pressure gradient reduction was associated with flow pattern change in oil–water flow system (the upper sketches are for the case of oil–water only and the lower is for oil–water and PDRA). In fact, pressure gradient reduction in stratified water layer by PDRA is governed by wall shear stress reduction and interfacial shear reduction between oil and water. This phenomenon was explained in Section 3.2.1.

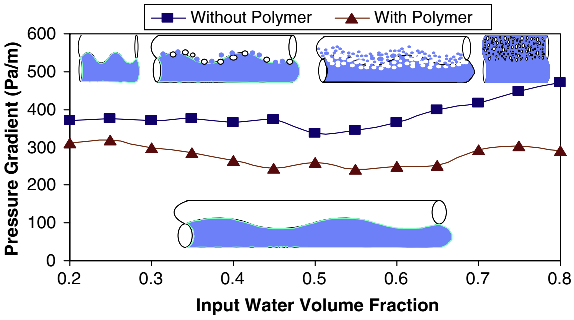

Fig. 7. Measurements of the effect of 50 ppm PDRA and water fraction on oil–water pressure drop at mixture velocity of 1 m/s.

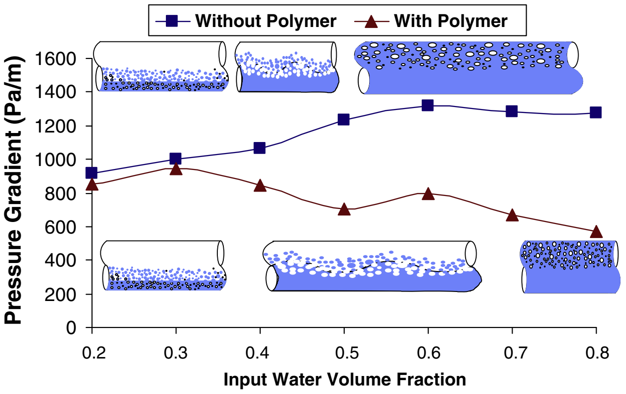

Fig. 8. Measurements of the effect of 50 ppm PDRA and water fraction on oil–water pressure drop at mixture velocity of 2 m/s.

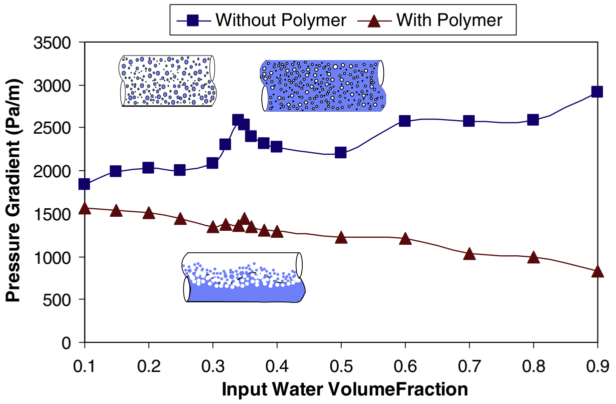

Fig. 9. Measurements of the effect of 50 ppm PDRA and water fraction on oil–water pressure drop at mixture velocity of 3 m/s.

The pressure gradient reduction increased as water fraction (since PDRA is water soluble) and mixture velocity increased and this is presented in Fig. 10. Generally, PDRA is more effective as mixture velocity increases and this is consistent with Warholic et al. (1999) results for single phase. In a dispersed flow regime, where a phase inversion indicated by pressure gradient peak was observed, there was a significant pressure drop reduction after the addition of PDRA. This could be due to sharp decrease in turbulence intensity after adding PDRA that increases droplets coalescence rate and a gravity force dominates leading to stratification of water phase. Consequently, mixture viscosity, caused by droplets interaction and modification of the continuous phase momentum transfer characteristics, was reduced.

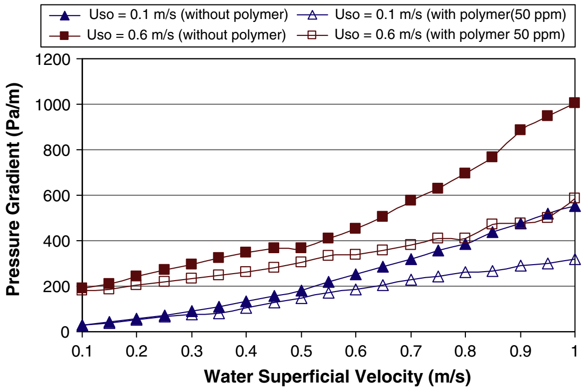

Fig. 10. Measurements of the effect of 50 ppm PDRA on oil–water pressure drop at different mixture velocities and water fractions.

The effectiveness of the polymer is expressed in terms of the drag-reduction (DR) defined as:

$$\mathrm{DR}\% = \left(\frac{\Delta P_{\mathrm{withoutPDRA}} - \Delta P_{\mathrm{withPDRA}}}{\Delta P_{\mathrm{withoutPDRA}}}\right) \times 100 \qquad (1)$$

where $\Delta P_{\mathrm{withoutPDRA}}$ and $\Delta P_{\mathrm{withPDRA}}$ represent the measured pressure drop before and after the addition of PDRA, respectively. A plot of DR verses input water volume fraction is presented in Fig. 11. As shown in the figure, drag reduction strongly depends on water fraction and mixture velocities. For example, at 1 m/s superficial mixture velocity, drag reduction reached approximately 38% and the observed flow patterns before the injection of the PDRA (stratified wavy, stratified with drops, three layers and stratified mixed and water layer) changed to stratified flow pattern as illustrated in Figs. 6 and 7. Drag reduction gradually decreased as water fraction decreased and this is due to stratification of water layer at the bottom of the pipe. In general, the maximum drag reduction reached due to the PDRA increased as mixture velocity increased and the drag reduction phenomenon was accompanied with stratification change in flow pattern (see Figs. 7–9). Drag reduction decreased for high mixture velocities at low water fraction because of formation of oil continuous dispersed flow (Figs. 8 and 9).

A peak appeared in Fig. 11 at mixture velocities above 1.5 m/s. This peak appeared around 50% water fraction at 2 m/s mixture velocity, that could be associated with local phase inversion in the pipe, and transfer to a lower water fraction as mixture velocities increased where turbulent mixing is higher and a possible full sectional phase inversion occurred. At a mixture velocity of 3.5 m/s, up to 58% drag reduction was achieved at the phase inversion

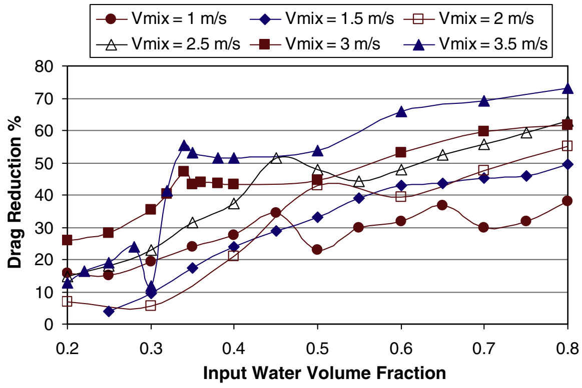

Fig. 11. Measurements of the PDRA effectiveness on oil–water pressure drop at different mixture velocities using 50 ppm of Magnafloc 1011.

point. As shown in Fig. 11, while there was a large drag reduction in the water continuous region, drag reduction decreased sharply in the oil continuous region. There was approximately 25% drag reduction below 0.3 input water volume fraction which is not exactly related to PDRA and it is attributed mostly to droplet coalescence and break up processes. The drops size plays a very important role, as the bigger drops size can suppress turbulence leading to a drag reduction. This was confirmed by Pal (1993) when he measured the pressure drop for a surfactant-stabilized emulsion and no drag reduction was observed. Also, the addition of PDRA at low water fraction increases the viscosity of the solution by a small coefficient which decreases the break up rate and results in drag reduction by suppression of turbulence by the bigger drops size.

3.2.3. Effect of PDRA concentration on drag reduction

In order to test the effect of PDRA concentration, Magnafloc 1011 water soluble polymer with concentrations of 2, 5 and 50 ppm (weight basis) were injected into water continuous dispersed flow regime at 3.5 m/s superficial mixture velocity. As shown in Fig. 12, the PDRA concentration had a clear drag reducing effect when the input water volume fraction was greater than the phase inversion water fraction (>0.34). The phase inversion peak disappeared when 5 ppm polymer solution was used. The pressure gradient at the phase inversion point reduced by 55% and 45% after the addition of 5 ppm and 2 ppm PDRA solutions, respectively.

The phase inversion point was shifted to a lower water fraction (0.28) when 50 ppm polymer solution was used but not for other concentrations and this could be related to a different flow pattern which formed at this particular concentration. As shown in Fig. 12, a stratified mixed water layer and three layers flow patterns were formed at higher water fractions for the three different PDRA concentrations. While there was a possible gradual change from three layers flow pattern to oil continuous dispersed flow as water fraction decreased at PDRA concentrations of 2 and 5 ppm, a stratified mixed oil layer flow regime formed at PDRA concentration of 50 ppm due to the higher degree of stratification as shown in the figure. A small peak in pressure drop after 50 ppm PDRA injection can be associated with local phase inversion from water continuous to oil continuous in the lower part of pipe cross section. The reduction in the pressure drop after the peak can be explained by a higher viscosity of water droplets after addition of high concentration PDRA which decreases the break up process. Large droplets can suppress the turbulence and decrease the pressure drop.

The positive effect of the PDRA concentration in reducing pressure drop could be explained in terms of the formation of aggregates. Increasing the PDRA concentration enhances the formation of aggregates which play a very significant role in the drag reduction phenomenon as reported by Cox et al. (1947).

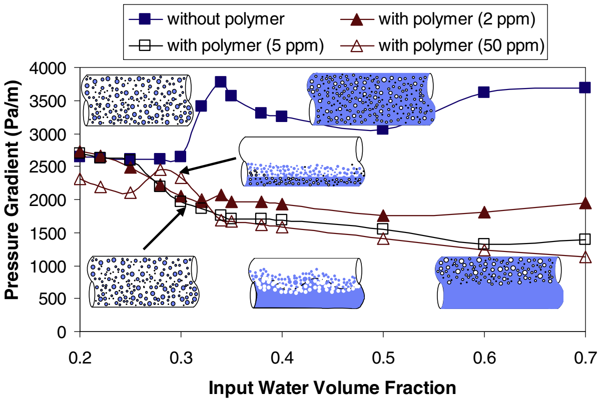

Fig. 12. Measurements of the effect of PDRA concentration and water fraction on oil–water flow characteristics at mixture velocity of 3.5 m/s.

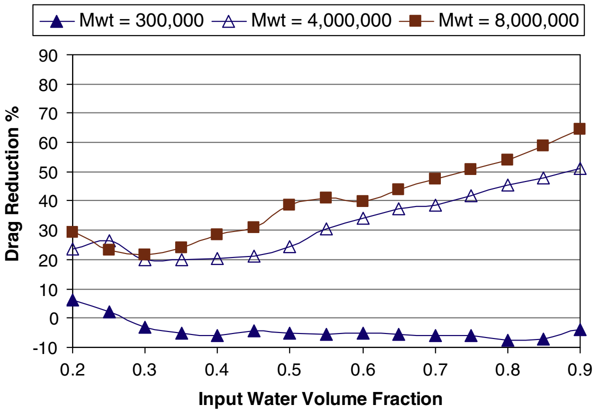

Fig. 13. Measurements of the effect of PDRA molecular weight and water fraction on oil–water pressure drop at mixture velocity of 2 m/s.

3.2.4. Effect of PDRA molecular weight on drag reduction

The effect of PDRA molecular weight on the drag reduction phenomenon in water–oil flow was studied by injecting polymer solutions, with identical chemical structures and concentrations but with different molecular weights into water continuous dispersed flow regime. 50 ppm polyethylene oxide polymer solutions with molecular weights of 3×10^5, 4×10^6 and 8×10^6 were used for an input water volume fraction range of (0.2–0.9) at a superficial mixture velocity of 2 m/s. The results of the effect of PDRA molecular weight on pressure drop reduction are presented in Fig. 13. When a 3×10^5 molecular weight was used, a negative effect was observed. On the other hand, pressure gradients were reduced significantly when 4×10^6 and 8×10^6 molecular weights were used. Drag reduction decreased slightly with increasing water volume fraction, and then increased gradually to 51.1% and 64.5% at 0.9 water fraction when 4×10^6 and 8×10^6 molecular weights were used, respectively.

Furthermore, when a 3×10^5 molecular weight was used, stratified mixed oil layer flow pattern became narrower and dispersed flow pattern was extended for a wider water fraction range (0.2–1). However, when 4×10^6 and 8×10^6 molecular weight were used, the three layers flow pattern was observed at lower water fraction, and the stratified mixed water layer flow pattern was created. In addition, the transition to dispersed flow pattern was delayed to higher water fractions.

A possible explanation of the increase in the PDRA effectiveness with increasing its molecular weight (4×10^6 and 8×10^6 g/mol) is that, increasing the molecular weight of the PDRA enhances polymer entanglement. As a result, the formation of aggregates, which plays an important role in the drag reduction phenomenon, is improved as reported by Cox et al. (1947) and Vlachogiannis et al. (2003).

However, the negative results of the PDRA with molecular weight of 3×10^5 g/mol are in close agreement with those reported by Sellin et al. (1982), who argued that drag reducing polymers are not effective unless their molecular weight is greater than a million.

3.3. Effect of salt content on PDRA performance

In general, oil pipelines contain brackish water rather than fresh or tap water and the salt content is usually between 5% and 10%. Therefore, salty water with 5% salt (weight basis) was prepared to study the effect of salt content on the performance of the water soluble PDRA as a drag reducing agent. Experiments were conducted at superficial mixture velocities of 1.5 and 3 m/s for input water volume fraction range of (0.2–1) using 50 ppm Magnafloc

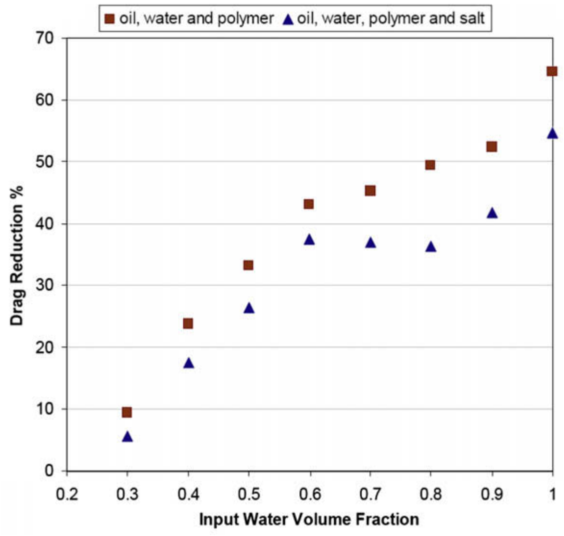

Fig. 14. Salinity effect (5% salt) on PDRA performance at 1.5 m/s mixture velocity.

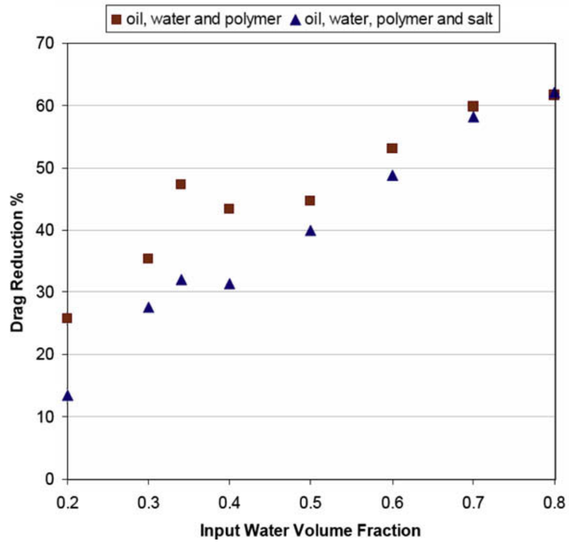

Fig. 15. Salinity effect (5% salt) on PDRA performance at 3 m/s mixture velocity.

1011 polymer solution. As mentioned earlier, Magnafloc 1011 polymer is a partially hydrolyzed polyacrylamide with negative charges. It has a 12% degree of hydrolysis. At mixture velocity of 1.5 m/s, as shown in Fig. 14, there was a negative salt effect on the PDRA effectiveness and that effect almost increased with increasing water fraction. However, at mixture velocity of 3 m/s, as illustrated in Fig. 15, the negative salt effect appeared clearly at the phase inversion point and at low water fraction and that effect disappeared at high water fraction.

A possible explanation of the negative effect of the salt on the PDRA effectiveness is that, in saline water, the electrolytes in the solution cause the ionic polymer molecules to coil (Carcoana, 1992) due to the electrostatic interaction between different parts of the same polymer. As a result, the polymer ability to expand and the formation of aggregates, which plays a major role in the drag reduction phenomenon, were reduced.

4. Conclusions

In this study, effect of drag-reducing polymers on the flow patterns and pressure drop during oil–water flows in horizontal 0.0254 m acrylic pipe was experimentally investigated. Two different polymers were examined (Magnafloc 1011 and polyethylene oxide). Effect of polymer concentrations and molecular weights on flow patterns and pressure drops were presented in this study. Influence of salt content in the water phase on the performance of drag-reducing polymer was also tested in this paper. The following conclusions can be drawn from this study:

- Injection of PDRA into the water continuous layer or the water continuous dispersed flow regime in oil–water immiscible flow changes the flow pattern map and causes a higher degree of stratification.
- The water continuous dispersed flow regime on the flow pattern map becomes narrow by PDRA injection.
- Pressure gradient is reduced significantly and this reduction depends on water fraction, mixture velocity, concentration and molecular weight of the PDRA.
- At high mixture velocities, where a dispersed flow regime exists, the addition of PDRA reduces the degree of turbulent mixing and can eliminate the phase inversion peak indicated by pressure gradient.
- As the injected PDRA molecular weight increases, oil–water flow pattern is affected in the direction of stratification and the transition to the dispersed flow pattern is delayed at higher water fraction.
- At the phase inversion from water continuous to oil continuous, a greater reduction in pressure gradient is achieved as PDRA molecular weight increases.
- Effect of salt content in water on the performance of PDRA was examined at mixture velocity of 1.5 and 3 m/s, a negative salt effect on the PDRA effectiveness was observed.

The findings of this study point to the important effect of DRPA into oil–water flows. Further investigations are needed to quantify the changes in the interfacial shape, and the drop sizes and its distribution in both oil and water phases. The mechanism of drag reduction for water soluble and oil soluble DRPA in oil–water flows are also needed.

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