Drag reduction using high molecular weight polyacrylamides during multiphase flow of oil and water: A parametric study

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A B S T R A C T

Five linear, water-soluble, sulfonated polyacrylamides of relatively high molecular weights were used to investigate drag reduction in oil–water multiphase flow through a horizontal, 30.6-mm pipe. The polymers were negatively-charged due to the presence of different density of the acrylamido tert-butyl sulfonic acid, ATBS, side groups along with acrylamide. They have different molecular weights and sulfonation degrees to investigate the effect of these polymer parameters in drag reduction during oil–water multiphase flow. Tap water was used as the aqueous phase and model oil with a density of 0.886 g/cm^3 and a viscosity of 18.6 cP at 30 °C was used as the oil phase. The two phases were used in the tests at different oil fractions and mixture velocities to achieve a dispersed flow pattern. The maximum drag reduction was obtained for polymer concentrations higher than 20 ppm in the test section. Drag reduction effectiveness was negatively affected by the increase in oil fraction in the test section leading to negative drag reduction when the oil is initially the continuous phase. Moreover, drag reduction increased with the increase in mixture velocity especially above 1.0 m/s for polymer concentrations higher than 10 ppm. Using this family of polymers, it was concluded that flexibility (or rigidity) of polymer chains in solution is a primary factor in polymer's effectiveness as a drag reducing agent. In this study, drag reduction was higher for more flexible polymer chains, which was enhanced by using higher molecular weight polymers and lower charge density.

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1. Introduction

Since Toms discovery of drag reduction due to the introduction of minute amounts of high molecular weight polymers to single phase flow in 1948 (Toms, 1948), drag reducing polymers (DRPs) has been extensively studied (Elperin et al., 1967, Sylvester and Tyler, 1970, Liaw et al., 1971, Mowla et al., 1995, Al-Sarkhi and Hanartty, 2001). This technology has been applied to reduce the pumping cost in the transport of a single phase oil in the Trans-Alaska pipeline (Burger et al., 1982). Parameters of DRPs such as chemical structure, morphology, molecular weight and intrinsic viscosity were investigated at different flow parameters such as fluid velocity and pipe diameters (Zakin and Hunston, 1980; Witold et al., 1990; Schulz Donald et al., 1991; Mumick et al., 1994a,b; Abubakar et al., 2014a). The drag reduction in single phase flow was attributed to mechanisms such as polymer elasticity and hydrodynamic volume, as well as intra- and inter-molecular polymer associations (Morgan and McCormick, 1990; McCormick et al., 1990, Abubakar et al., 2014a).

Multiphase flow of oil and water from the wellhead to separation facilities widely exists in oilfield operations. One of the technologies suggested to reduce the transportation cost of extra heavy crude oils is through its transportation along with a fraction of water in the pipeline to reduce the overall viscosity (Martínez-Palou et al., 2011). However, DRPs in oil–water multiphase flow have not received interest before the pioneering work of Al-Wahaibi et al. (2007).

Several measurement techniques have been utilized to study DRPs in single- and multi- phase flows. Techniques consist of visual observation, pressure drop, holdup and velocity measurements (for comprehensive review, see Abubakar et al., 2014b).

Drag reduction in multiphase flow is complex due to the occurrence of different flow patterns at different oil–water ratios and mixture velocities. These flow patterns can be categorized into stratified (ST), dual continuous (DC), dispersed oil in water (Do/w) and dispersed water in oil (Dw/o). In a stratified flow pattern, the two phases flow in distinguishably separate layers. On the other hand, continuity of the two phases in dual continuous flow is observed away from the interface region in which one phase exists as droplets in the other phase. Dispersed oil in water and dispersed water in oil flow patterns occur when one phase exists as

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droplets in the other continuous phase in the bulk of the flow section.

The boundaries of these flow patterns with respect to mixture velocities and oil–water fractions depend on physical properties of the two phases such as density and viscosity, and pipe diameter, (Al-Wahaibi and Angeli, 2007; Russell et al., 1959; Arirachakaran et al., 1989; Trallero, 1995; Valle and Utvik, 1997; Al-Yaari et al., 2009). The complexity of drag reduction in multiphase liquid–liquid flow arises from the mutual effect of DRPs on the friction and/or their effect of the boundaries of the flow patterns. For example, Al-Wahaibi et al. (2007) showed that the addition of DRP caused extension of the stratified flow region and delayed transition to slug flow. Similar effect of the DRPs on the flow pattern map was reported (Al-Yaari et al., 2009; Yusuf et al., 2012). Moreover, the injection of the high molecular weight, sulfonated polyacrylamide (Magnafloc 1011) into oil–water annular flow in a horizontal acrylic pipe caused a maximum drag reduction of around 50% (Al-Wahaibi et al., 2007). On the other hand, drag reduction of around 70% was achieved at mixture velocity of 3 m/s and oil fractions higher than 0.7 (Al-Yaari et al., 2009). The initially dispersed flow pattern region was compressed by the addition of the DRP, which was attributed to the decrease in turbulent mixing and coalescing of the oil droplets after the DRP addition (Al-Yaari et al., 2009; Yusuf et al., 2012). Along with decreasing the frictional pressure drop in the continuous water phase, DRP has its highest drag reduction when added to dispersed oil-in-water flow pattern (Al-Yaari et al., 2009). The performance of a highly sulfonated DRP (Magnafloc 1035) was studied by Al-Wahaibi et al. (2013). The extension of the stratified flow region and the compression of the dispersed flow region were found to be more pronounced when smaller pipe diameters were used (19-mm and 25.4-mm pipe diameters). The drag reduction reached its plateau values at 10 ppm of the DRP in both pipes but higher drag reduction at the plateau region was obtained in the 25.4 mm pipe (60% and 45% in the 25.4-mm and 19-mm pipes, respectively).

The influence of water- and oil-soluble DRPs on pressure drop in dispersed flow region was also investigated (Langsholt, 2012). It was shown that drag reduction in the oil–water flow increased with increasing the inlet volume fraction of the phase in which DRP was soluble and drag reduction occurred even when the liquid carrying DRP was not the continuous phase in dispersed flow regime.

This study was conducted to investigate the effect of polymer molecular parameters such as molecular weight, and charge density on drag reduction during oil–water dispersed flow in a horizontal pipeline. High molecular weight, sulfonated polyacrylamides were used with different molecular weights and charge densities as the DRPs. Up to the knowledge of the authors, this study is the one of the pioneering investigations of the effect of polymer molecular parameters on drag reduction of oil–water flow.

2. Experimental

2.1. Materials

Five linear, sulfonated polymers supplied by SNF Floerger Co., France, under the commercial names AN105SH, AN113SH AN125VLM, AN125 and AN125SH were used. They were provided as solid granules. Their chemical structure contains acrylamide and acrylamido tert-butyl sulfonic acid, ATBS, as shown in Fig. 1. These polymers are anionic in water due to the negatively-charged ATBS groups, whose percentage is represented by their sulfonation degree. In solution, the molecules of these polymers have stiffened chain due to the electrostatic repulsion between these charged
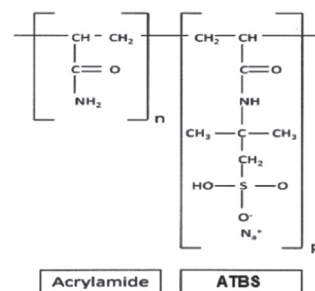

Fig. 1. Chemical structure of the sulfonated polymers used in this study.

groups on the backbone of the polymer molecule and intramolecular hydrogen-bonding interactions (McCormick et al., 1990). The AN105SH, AN113SH and AN125SH were supplied with a quoted average molecular weight of around 12 million Daltons and a sulfonation degree of 5%, 13%, and 25%, respectively. The AN125VLM and AN125 have a sulfonation degree of 25% and quoted molecular weights of around 2 and 6–8 million Daltons, respectively. These polymers have been characterized with respect to their intrinsic viscosity and overlap concentrations in tap water at 30 °C as has been recently published by Abubakar et al. (2014a), which are listed in Table 1.

Model oil (Shell Tellus S2V) was used as the oil phase. It is a type of industrial hydraulic fluid for a wide temperature range. At 30 °C, it has a viscosity and density of 18.6 cP and 0.886 g/cm^3, respectively. Tap water was used as the aqueous phase.

2.2. Preparation of polymer master solutions

Polymer master solutions with a concentration of 1000 ppm were prepared. The required weight of the dry polymer granules was added to tap water by sprinkling it to the shoulder of a well-developed vortex using a paddle mixer initially set at high speed. After the dissolution of the solid particles and once the solution become more transparent, the speed of mixing was decreased and left for 3 h. The solution was then left aside overnight to assure total hydration.

2.3. Flow loop and procedure of flow measurements

A schematic process flow diagram of the rig used in this study is illustrated in Fig. 2. The drag reduction investigation was conducted in an in-house flow loop made of acrylic pipe with inner diameter (ID) of 30.6 mm and a test section consisted of two 12-m long parts connected via U-bend. The water and the oil were pumped from their respective tanks and the two streams were mixed via a Y-junction. The oil flowing horizontally was joined by the water flowing with gradual inclination from the bottom to reduce the effect of mixing.

A high speed camera (Fastec–Troubleshooter; FASTECIMAGING, USA) was used for visual observation of the flow patterns 8 m downstream the pipe entrance. In this work, 500 fps was selected and the images were processed using MiDAS 4.0 express software.

The flow rate of the oil and the water streams was controlled through the inlet valves. The flow rates of the oil and water streams before the mixing point were measured by EESIFLO 5000 ultrasonic flow meters (produced by EESIFLO INTERNATIONAL, Pennsylvania-USA). After the flow section, the mixture was returned to a separator tank. The separation was allowed for 30 min or occasionally 1 h and the separated oil returned to its respective tank by gravity while the water from the separation was discharged to a septic tank.

The rig is equipped with a computer data acquisition system to