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Experimental study on the effect of drag reducing polymer on flow patterns and drag reduction in a horizontal oil–water flow

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ABSTRACT

In this study, a HMW anionic co-polymer of 40:60 wt/wt NaAMPS/acrylamide was used as a drag reducing polymer (DRP) for oil–water flow in a horizontal 25.4 mm ID acrylic pipe. The effect of polymer concentration in the master solution and after injection in the main water stream, oil and water velocities, and pipe length on drag reduction (DR) was investigated. The injected polymer had a noticeable effect on flow patterns and their transitions. Stratified and dual continuous flows extended to higher superficial oil velocities while annular flow changed to dual continuous flow. The results showed that as low as 2 ppm polymer concentration was sufficient to create a significant drag reduction across the pipe. DR was found to increase with polymer concentration increased and reached maximum plateau value at around 10 ppm. The results showed that the drag reduction effect tends to increase as superficial water velocity increased and eventually reached a plateau at U_{sw} of around 1.3 m/s. At $U_{sw} > 1.0$ m/s, the drag reduction decreased as U_{so} increased while at lower water velocities, drag reduction is fluctuating with respect to U_{so}. A maximum DR of about 60% was achieved at $U_{so} = 0.14$ m/s while only 45% was obtained at $U_{so} = 0.52$ m/s. The effectiveness of the DRP was found to be independent of the polymer concentration in the master solution and to some extent pipe length. The friction factor correlation proposed by Al-Sarkhi et al. (2011) for horizontal flow of oil–water using DRPs was found to underpredict the present experimental pressure gradient data.

1. Introduction

The simultaneous flow of two immiscible fluids in pipes is a common phenomenon in chemical and petrochemical industries. The flows are usually stratified at low velocities, but as flow-rate increases, transition from stratified to non-stratified flow patterns occurs, and flow eventually transforms to disperse flow as flow velocities increase. In the disperse regime, significant pressure drop is experienced and phase inversion phenomenon, which is usually associated with high pressure drop in flow, also occurs (Ioannou et al., 2005). This leads to higher power consumption and ultimately high cost of production. Also, in two phase liquid–liquid separation along a T-junction, maximum separation is achieved in stratified flow regime (Yang, 2003). Therefore, a delay in flow pattern transition from stratified to non-stratified flow will go a long way in reducing energy consumption and enhancing effective separation in two phase liquid–liquid flow system.

The addition of small amounts of high molecular weight (HMW) polymers in minute amounts as low as few parts per million (ppm) was found to greatly reduce frictional resistance in a flowing fluid. This phenomenon is known as drag reduction (DR) and the polymers that have this ability are called drag reducing polymers (DRPs). The formal discovery of drag reduction using polymers is attributed to Toms (1948), who noticed this effect during his investigation on polymer degradation through pumps. The transportation of liquids is mostly through pipes and a reduction in pressure drop by the addition of small amount of DRPs can offer considerable economic return and a higher effectiveness in both its separation and transportation. Hence, many investigations were directed to DRPs to understand the mechanism by which DRPs has this effect as well as proposing the commercial and new chemicals for most effective applications (Otten and Fayed, 1976; Thwaites et al., 1976; Sylvester and Brill, 1976; Warholic et al., 1999, etc.). Amongst the successes in the applications of DRPs 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).

Oliver and Young Hoon (1968) were one of the first to investigate the effect of DRP in multiphase flows using polyethylene oxide (PEO). Three years later, 40% drag reduction was achieved when Greskovich and Shrier (1971) used a DRP in multiphase systems during slug air–water flow. During slug flow also, Rosehart et al.

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(1972) found higher drag reduction than in single phase while Saether et al. (1989) found lower drag reduction. Several works have been documented on drag reduction. Lately, some researchers concluded that the understanding of the influence of drag reducing polymers on multiphase flows is not satisfactory (Manfield et al., 1999; Al-Sarkhi, 2010).

Al-Sarkhi and Hanratty (2001a,b) investigated the influence of a co-polymer of polyacrylamide and sodium acrylate on annular air–water flow in 9.53 cm ID and 2.54 cm ID pipes. The observed drag reduction was attributed to the reduction of interfacial waves which cause drop formation and help the liquid to spread around the pipe as an annulus. The maximum drag reduction was found when all the liquid was flowing at the bottom of the pipe in a stratified manner with relatively smooth interface. Drag reduction up to 63% was observed in the small pipe while only 48% drag reduction was obtained in the large pipe.

The first documented work on the effect of DRP in liquid–liquid flow was by Al-Wahaibi et al. (2007). They investigated the effect of drag reducing polymer at concentrations of 20 and 50 ppm on horizontal oil–water flow in relatively small diameter acrylic pipe (14 mm ID) using oil with viscosity of 0.0055 Pa s and density of 828 kg/m^3. A strong influence of DRP on flow patterns and flow pattern transition was observed. Annular flow as an example changed to stratified or dual continuous flow, while slug flow changed in most cases to stratified flow. A maximum drag reduction of about 50% was achieved when the polymer was introduced into annular flow.

Subsequently, Al-Yaari et al. (2009) carried out their experiment with oil–water flow in a horizontal 25.4 mm acrylic pipe using different oil–water configurations (viscosity = 0.0016 Pa s and density = 780 kg/m^3). In their work, they investigated the effect of polymer concentration, polymer molecular weight and salinity of water on drag reduction. Their results showed that DRP has significant effect on flow pattern and drag reduction. The addition of 10–15 ppm of DRP caused drag reduction of about 65%, and phase inversion point in dispersed flow regime which occurred at a water fraction range of (0.33–0.35) disappeared when 5 ppm of DRP was injected. Akin with the work of Al-Wahaibi et al. (2007), polymer concentration did not have significant effect on all the parameters investigated in their study. Drag reduction was observed to decrease when 5% salt solution was added to the water phase.

This study presents results on the effect of polymer concentrations, master solution concentrations (initial concentration of polymer), water and oil velocities and pipe length on the efficiency of drag reducing polymer in horizontal oil–water flow using oil–water properties that were not investigated previously in the literature. This study uses oil with higher viscosity (12 cp) compared to a similar study conducted by Al-Yaari et al. (2009).

2. Experimental set-up

The experimental studies on the effect of DRP in horizontal oil–water flow were carried out at the experimental facility shown in Fig. 1. The test fluids were oil and water with average properties shown in Table 1. Each fluid was transferred from its storage tank with a pump to the test section made up of 25.4-mm acrylic pipe that consisted of two 8-m long parts connected via U-bend. The two fluids entered the test section from two pipes via a Y like-junction. The water phase was allowed to enter from the bottom while the oil joined from the top to reduce the effect of mixing. Two flow meters, one with a maximum capacity of 330 l/min and the other with a maximum capacity of 30 l/min, were attached to the water and oil flow lines which were regulated through pin valves to control the flow rate of the fluid. The flow meters have accuracy of 0.5% full scale. The mixture returned via a PVC pipe to a separator tank which allowed the two phases to separate and hence return to their respective storage tanks.

High-speed camera that can record up to 1000 fps (Fastec – Troubleshooter) and visual observation were used to identify the different flow patterns. The camera was located 6.5 m from the first eight-meter part of the test section. In this work, 250 fps was selected and the images were processed using MiDAS 4.0 express software. Pressure gradient experiment was conducted in the test section by measuring the pressure drop between two points 1 m apart along the flow line 6 m from the entry point. The pressure drop was measured with both manual and Dywer 490 digital differential manometers.

The polymer used in this study is a HMW anionic polyacrylamide manufactured by Ciba Speciality Chemicals under the commercial name Magnafloc 1035. It is a highly anionic co-polymer of 40:60 wt/wt NaAMPS/acrylamide provided in the form of white granules. It is a polydisperse linear polymer with an average molecular weight of 15×10^6 Daltons.

A 1000 ppm stock solution of polymer in distilled water was prepared by slowly adding one gram of the polymer to a liter of water under stirring using a paddle mixer. After the addition of polymer, the solution was stirred at lower speed for 4 h. After that, the solution was stored at room temperature for 24 h to allow the polymer to hydrate in the solution before use in the flow experiments. The same procedure was repeated for the preparation of 2000 and 3000 ppm master solutions. A syringe pump; Teledyne Isco, 500D model; was used to dose polymer into the flow system. The pump had capacity to supply a constant flow rate of up to 200 cc/min with an accuracy of ±1%. The pump was fitted with a control panel that allows dispensing and refilling of fluid at desired flow rate or pressure. The polymer master solution was fed into the reservoir of the pump through tubing at low pressure. The solution was continuously injected into the flowing water through an inlet with a diameter of 3 mm at the bottom of the pipe, 10 cm upstream of the Y-inlet junction. Visual observations showed that the polymer affected the flow and pressure gradient within few pipe diameters from the injection point. Moreover, the polymer used in this study is highly soluble in water, thus, it was assumed that the polymer is well mixed with the water phase at the location where the recordings were taken.

3. Results and discussion

3.1. Visual observation

Visual observation of the oil–water flow revealed six different flow patterns. These are:

- Stratified (stratified smooth, SS, and stratified wavy, SW): where the two fluids flow in separate layers at the top and bottom of the pipe according to their densities.
- Dual continuous (DC): where both oil and water form continuous layers at the top and bottom of the pipe respectively but drops of one phase appear in the continuum of the other phase.
- Annular (AN): where water forms an annular film at the wall and oil flows in the pipe core.
- Bubbly (Bb): where the oil appears in the form of elongated drops (slightly longer than the pipe diameter) within water continuum.
- Dispersed oil in water (Do/w): where the pipe cross sectional area is occupied by water containing dispersed oil droplets.
- Dispersed water in oil (Dw/o): where oil is the continuous phase and water is present as droplets across the pipe cross sectional area.