

Article

## Drag Reduction with Biopolymer-Synthetic Polymer Mixtures in Oil-Water Flows: Effect of Synergy

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**Abstract.** The search for lower cost materials that reduce pressure drop in fluid transport systems in oil and gas industries to conserve pumping energy is of paramount importance. Polymers are known to reduce pressure drop in pipeline oil-water flows in a process referred to as drag reduction (DR). The effect of partially hydrolysed polyacrylamide, polyethylene oxide, Aloe Vera mucilage and their mixtures as drag reducing polymers (DRPs) on pressure gradient (pressure drop;  $\Delta p$ ) in pipeline oil-water flows were studied. The experiment was carried out in flow rig with 0.02-m diameter straight unplasticised polyvinylchloride (uPVC) pipe, two centrifugal pumps, control valves and two storage tanks. Tap water ( $\rho = 997 \text{ kg/m}^3$  and  $\mu = 0.89 \text{ cP}$ ) and diesel ( $\rho = 832 \text{ kg/m}^3$  and  $\mu = 1.66 \text{ cP}$ ) were used as the test fluid at ambient condition. The polymer mixture total concentration (MTC) of 30 and 400 ppm at different mixing proportion, mixture Reynolds number ( $Re_{\text{mix}}$ ) and oil input volume were investigated. The results show increase in pressure gradient with increase in oil input volume in both single-phase water flow and oil-water flow before adding drag reducing polymers (DRPs). However,  $\Delta p$  decreased after adding DRPs with increase in Reynolds number ( $Re$ ) or  $Re_{\text{mix}}$  and decrease in the oil-phase  $Re$ , and vice versa. The results further showed higher reduction in pressure drop by the polymer mixture than in each of the polymer used at the same conditions. The rigidity of the biopolymer was improved by adding synthetic polymers which resulted to increase in DR efficiency.

**Keywords:** Pressure drop, polymer, polymer-polymer mixture, synergism, oil-water flow, drag reduction.

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## 1. Introduction

From the recent past, there is an increase in the amount of water extracted from ageing oil wells [1]. Water is often added into crude oil pipelines to reduce frictional pressure drop ( $\Delta P$ ) and improve oil production. Thus, high pumping energy is needed due to high  $\Delta P$  experienced in transporting these liquids (oil-water mixture) over long distances which increase the operational cost [2–4]. Many authors reported that adding small drag reducing agents (polymers, surfactants, fibers as well as their mixtures) reduce  $\Delta p$  in pipeline fluid flow known as drag reduction (DR) which lead to conservation of pumping energy [5–9]. Industrial applications of DR such as drilling of oil from reservoir, crude oil pipeline transportation, and so on emanate from Tom's effect in 1948 [6, 7].

With regards to the different types of drag reducing agents (DRAs), polymers are considered to be efficient by many authors because of its rheological properties and resistance to shear force [8]. The selection of polymer to be used in DR in any particular application is guided by solubility; molecular weight ( $> 10^6$  g/mol); and flexibility or rigidity of the polymer in the fluid [9, 10]. Drag reducing polymers (DRPs) can be obtained from either artificial or natural sources (synthetic or biopolymer). Biopolymer (Guar gum, Xanthan gum, Aloe barbadensis miller, okra among others) are environmentally friendly, fairly shear stable, low resistance to biodegradation but less efficient on DR because they are highly rigid compared to synthetic DRPs [10–14]. Synthesized DRPs (polyethylene oxide, hydrolyzed polyacrylamide and polyacrylamide) are soluble in water and efficient in reduction of  $\Delta P$  in pipeline flow [2, 6]. Synthetic DRPs faces the problem of environmental impact challenges and degradation in shear-unstable in lengthened chaotic flow; hence their efficiency on DR declines [10, 11, 15]. Many efforts have been made to improve DR efficiency by combining synthetic DRPs with biopolymers and surfactants in other to have a synergistic effect in single-phase water flow [2, 6, 11, 14, 16–19].

In oil-water flows (multiphase flow; MPF), patterns such as stratified flow, annular flow, dispersed flow, slug flow and plug flow have been reported [3, 4, 20]. The flow patterns rely on velocity, pipe geometry and diameter, density, viscosity, surface wetting, interfacial tension and pipe roughness [1, 7, 20–23]. Parametric quantities such as pipe diameter, mixture velocity (summation of superficial velocity of oil and water phase), density, viscosity and volume fraction of each phase at constant temperature and pressure are responsible for  $\Delta P$  in oil-water flows [21–23]. Many researchers have shown that DRPs has positive effect on  $\Delta P$  and flow pattern in oil-water flows [1, 4, 7, 9, 20–26].

Their effect of two polymers (co-polymer of polyacrylamide and sodium acrylate) concentrations (20 and 50 ppm) on DR in oil-water flows was first reported by [20]. They achieved maximum DR of 50% in 14 millimeters internal diameter (mm ID) horizontal acrylic

pipe. Their findings also conformed to the work of [21] which showed that  $\Delta P$  decreases with increase in the water phase velocity. The effect of polymer addition on  $\Delta p$  and interfacial waves in oil-water was studied using HPAM in pipe (acrylic) 14 mm ID with a middle distillate as oil phase by [3]. They reported that mixture velocity alters  $\Delta p$  in MPF and 20 ppm of drag reducing polymer (DRP) significantly reduced drag in both single and MPF. [22] investigated the effect of pipe diameter in 0.019 m and 0.0254 m on drag reduction using magnafloc 1035 with concentration ranging from 2–30 ppm in horizontal MPF. They achieved DR of 60% and 45% in 0.0254 m and 0.019 m ID pipe respectively. [23] studied DR with polymer in MPF in horizontal pipe diameter of 0.0747 m and length of 12 m using a co-polymer (AN 105-SH polymer). They reported that DR declined with increase in oil input fraction and increased with increase in mixture velocity. The effect of DRP (magnafloc 1035) was studied on  $\Delta P$  with concentration ranging from 2 - 10 ppm in 0.0254 m ID horizontal pipe and 8-meter-long by [7]. They used high viscous oil (mineral oil) and tap water as the test fluid and achieved maximum DR of 60%. Two different polymers (oil-phase and water-phase soluble polymers) were used by [24] at mixture velocity of 1.5 m/s. They reported that DR in MPF increased with decline in oil input volume of the drag reducing polymer soluble phase. [25] also used two different molecular weight PEO and carboxymethyl cellulose with concentration ranging from 0-1 wt% each, in different horizontal pipe ID. They observed negative effect on  $\Delta P$  due to the insolubility of the DRP in the oil phase. [26] investigated the effect of pipe diameter using three different polymers (HPAM, PEO & AVM) of 30 ppm in oil-water flow. Their report showed that DR is a function of pipe diameter, flowrate, concentration and oil input fraction.

Though polymer-polymer mixture provides high DR yet there is limited research work reported on multiphase DR using combination of polymers. The effect of synergy on pressure gradient and DR with biopolymer-synthetic polymer mixtures in oil-water flows is the main focus of our work.

## 2. Materials

### 2.1. Flow Facility

The experimental flow rig is presented in Fig. 1. The flow rig is comprised of the handling part, pumping part and testing part. The handling part consists of three tanks where the fluids are stored: the oil, water and separator tanks have capacity of 200, 200 and 220 liters respectively. The separator tank allows settling under gravity where water is drained through the bottom opening and the oil is recycled. In the regulating or pumping part, 0.02-m unplasticized polyvinylchloride (uPVC) pipes were each attached to the 200 liters tanks of oil and water. Two centrifugal pumps (model Jet 102M/N.31227) with maximum flow rate of 65 l/min

were used to circulate each of the test fluids through the test section. The globe valves were used to adjust the flow rates which were measured with variable area flow meters (LZM-20);  $\pm 2\%$  accuracy), separate for each fluid. The water flow meter has maximum flow rate of 24 GPM or 100 l/min. The flow meter was calibrated before the commencement of experiments. The injection port for the polymer master solution is located by the side of the water pipeline ahead of the Y-junction. The new Era-programmable peristaltic injection pump (model

NE-9000;  $\pm 1\%$  accuracy) was used to inject the polymer mixture master solution into the water-phase. The straight 0.02-m pipe (acrylic) of 140 times the diameter of the pipe (140D) long from the Y-junction to the second pressure port made the test section. The pressure taps were small holes of 1.5 mm ID at the underneath of the acrylic pipe walls at a distance of 140D where fully developed flows are already attained, after the fluid entrance point

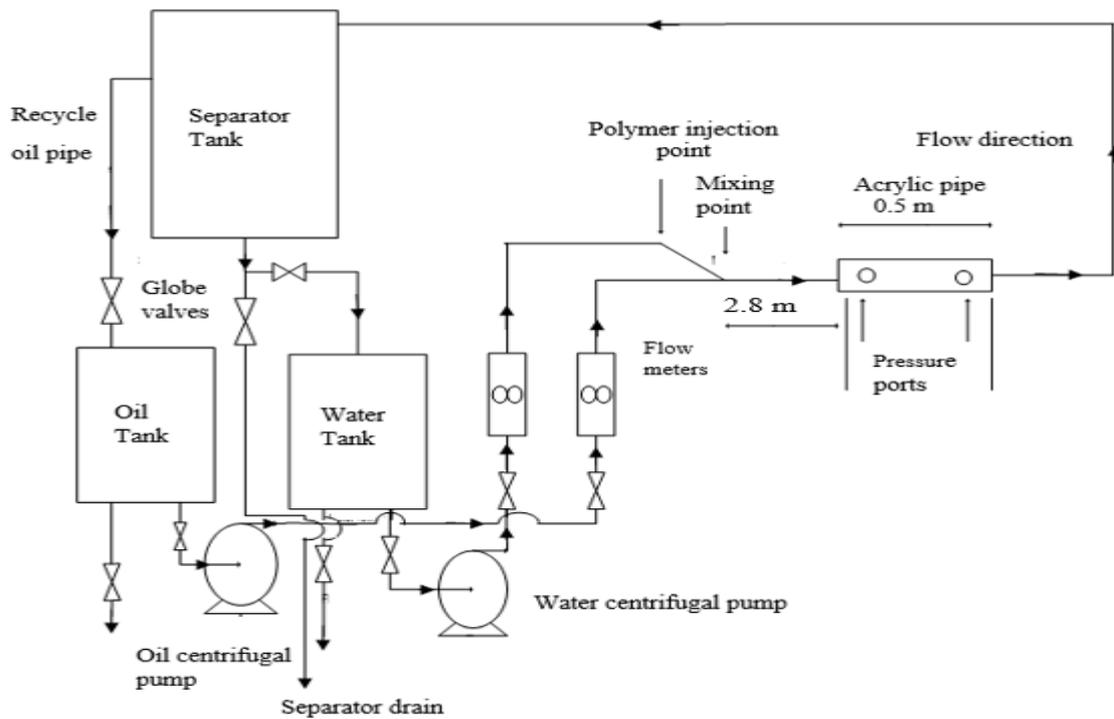


Fig. 1. Schematics of experimental setup.

## 2.2. Polymer Preparation

The polymers used are partially hydrolysed polyacrylamide, (HPAM,  $10 \times 10^6$  g/mol, purity  $> 98\%$ ) manufactured by BASF chemicals, polyethylene oxide (PEO,  $8 \times 10^6$  g/mol purity  $> 99\%$ ) manufactured by Sigma-Aldrich and Aloe Vera mucilage (AVM) extracted from Aloe Vera leaves (AVL) as the biopolymer. All the polymers are water soluble and were used without further purification. The individual polymers solutions were prepared first, before the mixture of polymer solution. A master solution of  $2 \times 10^3$  ppm of the synthetic polymers each were prepared as follows; ten grams (10 g) of each polymer powder were measured using weighing balance (Kerro, BLC 3002) and gently spread over 5 litres of water surface and gently stirred for 2 hours with a mechanical stirrer (Gilverson, L28) at low speed (to avoid degradation of the polymer mixtures) for complete homogenization. The stirred solution was left for 12 hours mostly overnight, to ensure complete dissolution of polymer particles, to form the master solution [27–30].

AVL (ages: 2–3 years, size: 3–4 feet tall, weight: approximately: 1 kg, colour: bright-green) were harvested from a botanical garden and identified at an herbarium as

Aloe barbadensis miller then washed thoroughly. The AVL were then cut vertically on both sides and soaked in water for 10 minutes, to remove the Aloin (an orange-yellow sap) within them. The AVL were then peeled and the mucilage was extracted by scraping and sieving the gel from the AVL [23]. Each AVL contains about 98% water while the remaining 2 % is the AVM by volume, which is equivalent to  $2 \times 10^4$  ppm as the master solution [31–33]. The AVM was utilized immediately after the extraction process due to biodegradation effect which affect the drag reducing properties of the AVM. Two polymer mixture total concentrations (30 ppm and 400 ppm) were the optimal concentration obtained from our preliminary experiment of turbulent single-phase water flow) were selected for the preparation of mixture HPAM & AVM and PEO & AVM in this work [2, 6]. The two polymers mixture total concentrations (MTC) were prepared from master solution of  $2 \times 10^3$  ppm and  $2 \times 10^4$  ppm at mixing ratio of 3:1 (1500 ppm HPAM/PEO + 500 ppm AVM for 30 ppm) and 1:19 ( $1 \times 10^3$  ppm HPAM/PEO +  $1.9 \times 10^4$  ppm AVM for 400 ppm) [2, 6].

Similar procedure was followed for the preparation of 1500 ppm of HPAM/PEO: 9 g of each of the synthetic polymer powder was measured and gently spread over 6 litres of water surface. For preparation of 500 ppm of AVM, 0.25 litres of  $2 \times 10^4$  ppm of AVM master solution was measured and diluted with 10 litres of water to achieve 500 ppm. Equal volume of 1500 ppm of the HPAM or PEO was mixed with 500 ppm of AVM and stirred for 3 hours and the stirred solution was left for 12 hours to form a master solution of  $2 \times 10^3$  ppm for the polymer mixtures. For MTC of 400 ppm, the master concentration of  $2 \times 10^4$  ppm at mixing ratio of 1 : 19 was prepared as follows. 5 g of each of the synthetic polymers against 5 litres of water to achieved  $1 \times 10^3$  ppm. 1 litre of  $2 \times 10^4$  ppm of AVM master solution was measured and diluted with 0.95 litres of water to achieve  $1.9 \times 10^4$  ppm. Equal volume of  $1 \times 10^3$  ppm of the synthetic polymers was mixed with  $1.9 \times 10^4$  ppm of AVM to form  $2 \times 10^4$  ppm polymer mixture. The required concentration & flow rate in the water flow line was calculated using Eq. (1).

$$Q_P = \frac{C_R \times Q_W}{C_M - C_R} \quad (1)$$

Where;  $Q_P$  is the polymer flow rate (ml/min),  $C_R$  is the required polymer concentration in the test section in the flow facility (ppm),  $Q_W$  is the inlet water flow rate (l/min),  $C_M$  is the polymer master solution concentration (ppm).

### 3. Methods

#### 3.1. Experimental Procedure

In other to ensure accurate delivery of the required amounts of oil ( $\rho_o = 832 \text{ kg/m}^3$ ,  $\mu_o = 1.7 \text{ cP}$ ) and water ( $\rho_w = 1000 \text{ kg/m}^3$ ,  $\mu_w = 0.89 \text{ cP}$ ) as well as the polymer master solution into the test section, all measuring devices were calibrated before starting the experiment. The experiment was carried out at ambient conditions (25 °C, 1 atm), horizontal pipe internal diameter (ID) of 0.02-m and length of 2.8 m (140D). GM510 portable USB Digital LCD differential pressure manometers was used for the pressure drop measurement. Each experimental was rerun three times and the average (with standard deviation less than 0.5%) of the  $\Delta p$  measured before addition and after addition of the DRAs. HPAM, PEO, AVM, HPAM & AVM and PEO & AVM were tested at different oil input volume fraction ( $v_o$ ) and mixture Reynolds number ( $Re_{mix}$ ; mixture velocity,  $U_{mix}$ ). The  $Re_{mix}$  was obtained from the summation of the water phase Reynolds number (Wp-Re) and that of the oil phase (Op-Re), at different superficial velocities of oil ( $U_{so}$ ) and water-phase ( $U_{sw}$ ). The MTC of 30 ppm (HPAM & PEO) and 400 ppm (AVM) were tested at Reynolds number of 37773. The various proportion of

the oil input fractions were 0, 0.25, 0.50, 0.75 and 1. The  $Re_{mix}$ ,  $U_{mix}$ , superficial velocity and  $v_o$  was calculated from the equation below.

$$Re_{mix} = \frac{\rho_w \times U_{mix} \times D}{\mu_w} \quad (2)$$

$$U_{mix} = U_{sw} + U_{so} \quad (3)$$

$$U_{sw} = \frac{Q_w}{A} \quad (4)$$

$$U_{so} = \frac{Q_o}{A} \quad (5)$$

$$v_o = \frac{Q_o}{Q_o + Q_w} \times 100\% \quad (6)$$

$$v_w + v_o = 1 \quad (7)$$

Where  $Re_{mix}$  is the mixture Reynolds number,  $\rho_w$  and  $\mu_w$  are the density and viscosity of the water phase,  $U_{mix}$  is the oil-water mixture velocity,  $U_{sw}$  and  $U_{so}$  are the superficial velocities of water and oil,  $Q_w$  and  $Q_o$  are the flow rate of water and oil and  $v_w$  and  $v_o$  are the input volume fraction of water and oil. The pressure drop was recorded and used for calculation of drag reduction, defined by Eq. (8):

$$DR = \frac{\Delta P_{WODRA} - \Delta P_{DRA}}{\Delta P_{WODRA}} \times 100\% \quad (8)$$

## 4. Results and Discussion

The values of pressure gradient and DR are computed using the  $\Delta P$  of the fluid without and with drag reducing agents at different Re,  $Re_{mix}$  and  $v_o$  in both single-phase water and oil-water flows (multiphase flow).

#### 4.1. Drag-reduced Pressure Gradient in Single-phase Water Experiments

The pressure gradient of single-phase water flow in 0.02-m pipe diameter before and after adding HPAM, PEO, AVM, HPAM & AVM and PEO & AVM at different Re and concentration of 30 ppm was presented in Fig. 2. The results showed decrease in pressure drop ( $\Delta P$ ) as the Re increased for the various DRPs. It can be seen that little or no appreciable reduction in  $\Delta P$  for the AVM at 30 ppm due to lower concentration because biopolymers are highly rigid or less flexible, which make them less efficient in DR compare to the synthetic polymers. The polymer mixture showed high reduction in  $\Delta P$  than each of the polymer at the same concentration due to the improvement in the rigidity of the biopolymer and molecules present in the mixture. The results obtained are in agreement with the work of [2, 6, 17, 18].

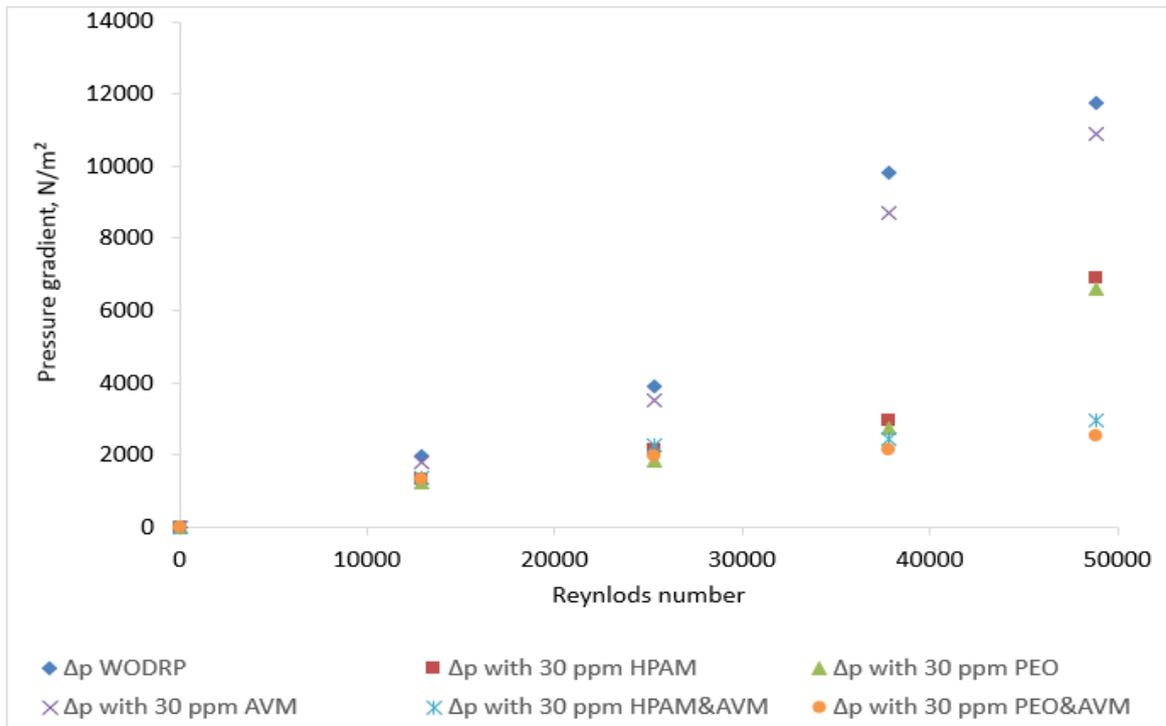


Fig. 2. Pressure gradient against Re of single-phase water flow before and after adding 30 ppm of DRPs in 0.02-m pipe diameter.

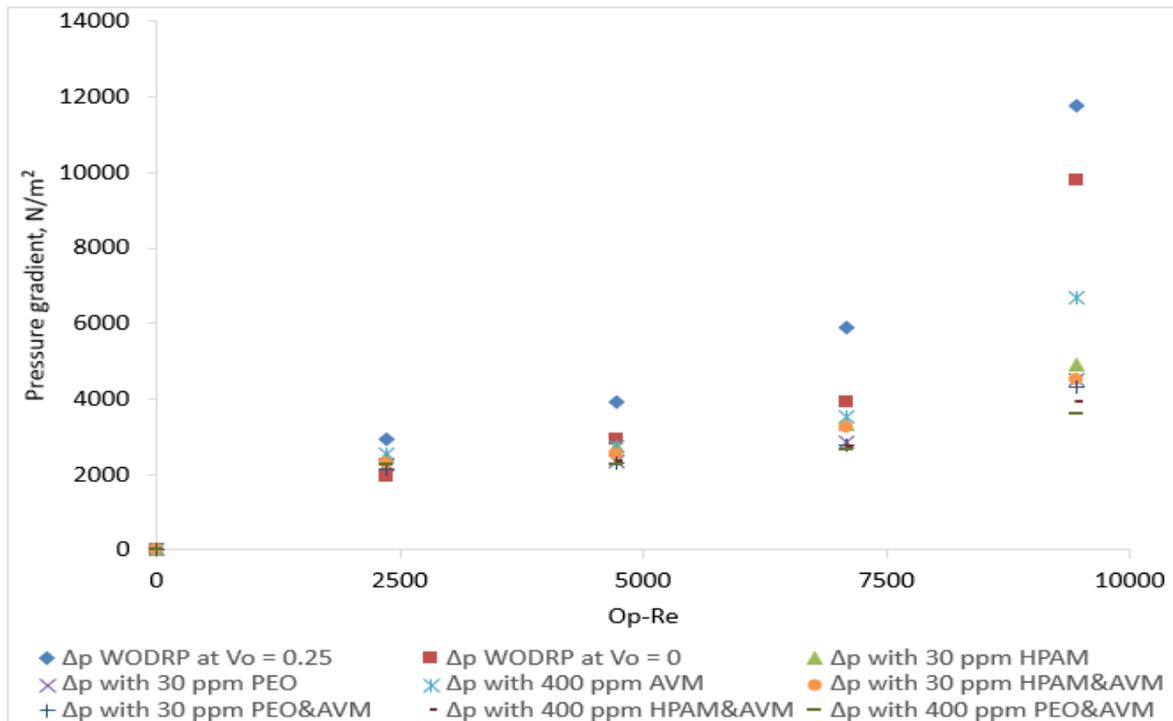


Fig. 3. Pressure gradient against oil-phase Reynolds number ( $Op-Re$ ) of oil-water flow before and after adding 30 ppm and 400 ppm of DRPs in 0.02-m pipe diameter at  $v_o = 0.25$ .

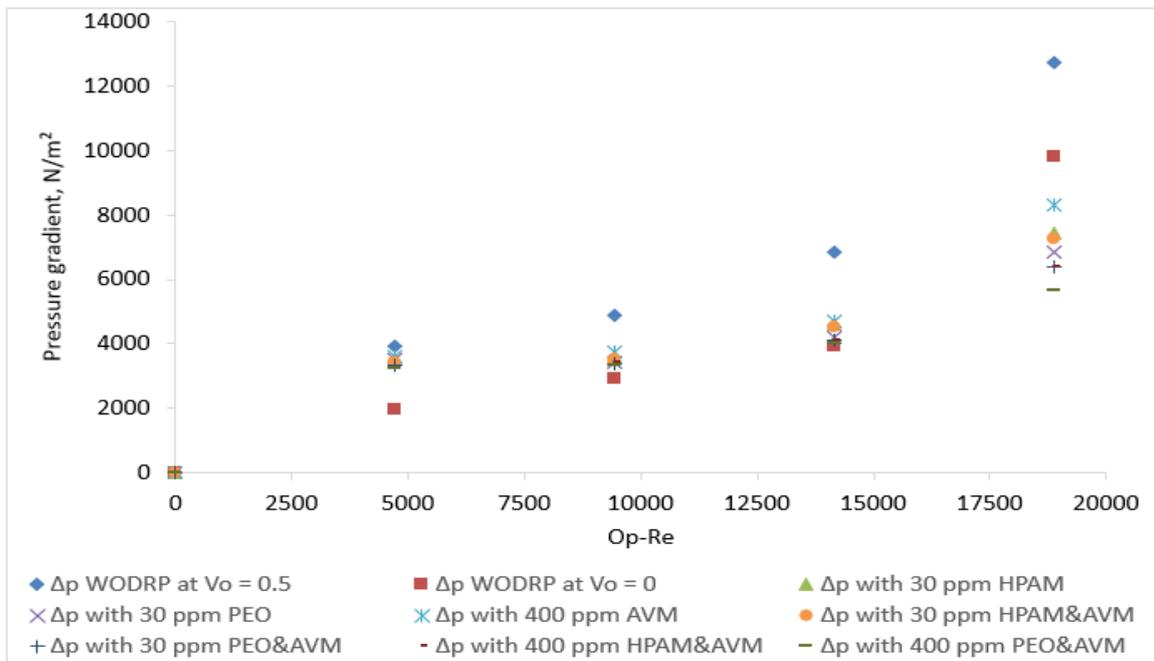


Fig. 4. Pressure gradient against oil-phase Reynolds number (Op-Re) of oil-water flow before and after adding 30 ppm and 400 ppm of DRPs in 0.02-m pipe diameter at  $v_o = 0.5$ .

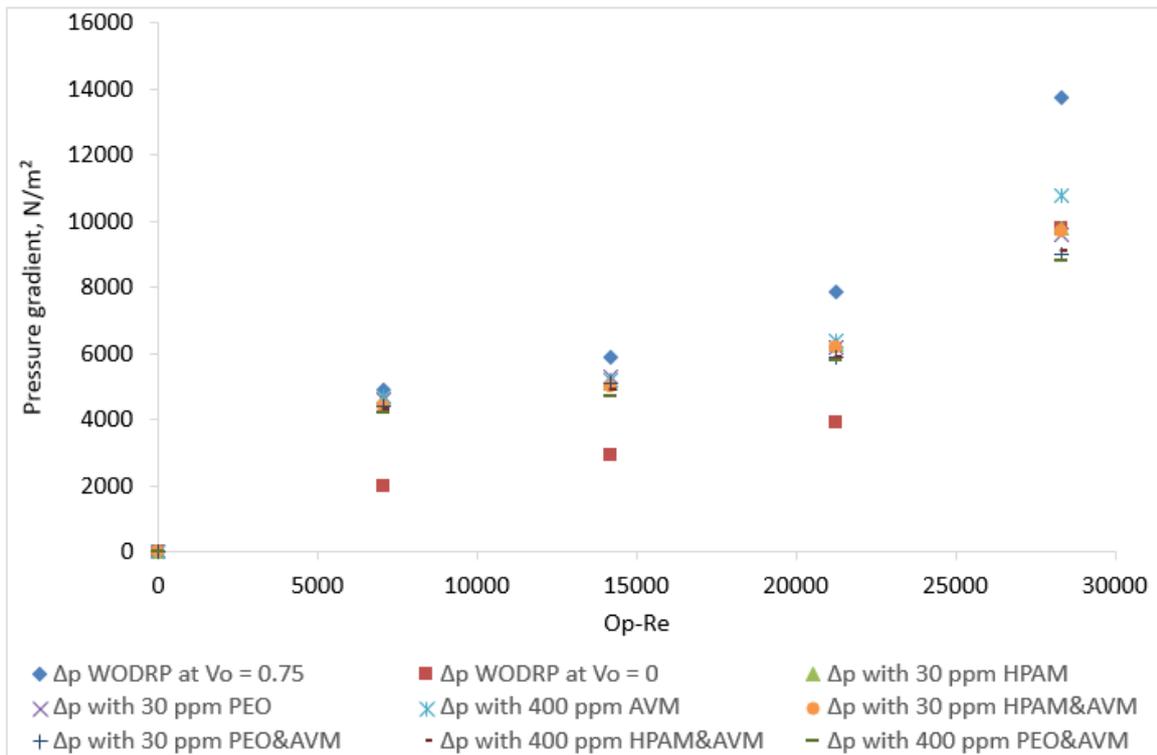


Fig. 5. Pressure gradient against oil-phase Reynolds number (Op-Re) of oil-water flow before and after adding 30 ppm and 400 ppm of DRPs in 0.02-m pipe diameter at  $v_o = 0.75$ .

**4.2. Pressure Gradient in Multiphase Flow Experiments**

The pressure gradient in multiphase flow in 0.02-m pipe diameter before and after adding HPAM, PEO, AVM, HPAM & AVM and PEO & AVM at different Op-Re,  $Re_{mix}$ ,  $v_o$  and MTC of 30 and 400 ppm are

shown in Figs. 3–5. Figure 3 shows increase in pressure drop in the water-phase before adding drag reducing polymers (DRPs) and oil-phase ( $v_o = 0$ ) due to increase in propagation of the eddies (turbulence) as a result of increase in Re. This result to chaotic motion of the liquid which dissipate energy provided by pumps in moving the liquid. High  $\Delta P$  was seen at  $v_o = 0.25$  before adding

DRPs owing to increase in the oil-phase  $Re$  and probably the weight exerted on the water by the oil-phase. It can be seen that appreciable reduction in pressure drop was observed after adding the DRPs because they help to suppress the formation and propagation of the eddies which allow the pump energy to be utilized by the fluid. The polymer mixture showed high reduction in  $\Delta P$  than each of the polymer at the same concentration due to the interaction of both polymer molecules present in the mixture. The results obtained are in conformity with previous reports [6, 34, 35].

In addition, the  $\Delta P$  increased with increase in oil input volume fraction from 0.5 to 0.75 ( $v_o = 0.5$  and  $v_o = 0.75$ ) before adding DRPs, as the  $Op-Re$  increased in Figs. 4 and 5. Owing to the fact that all the DRPs used in this work only dissolve in water as such increase in  $Op-Re$  led to decrease in the  $Wp-Re$  and vice versa. The decrease in the  $Wp-Re$  reduces the stretching of the DRPs in the buffer region of the turbulent flow thereby reducing their efficiency in  $\Delta P$  reduction. Similarly, appreciable reduction in  $\Delta P$  was observed after adding the DRPs in Figs. 4 and 5 and the polymer mixture show high reduction in  $\Delta P$  than each of the polymer at the same concentration. The results obtained are in agreement with other previous findings [1, 7, 20].

### 4.3. Drag reduction in multiphase flow experiments

The DR of the DRPs (HPAM, PEO, AVM, HPAM & AVM and PEO & AVM) in multiphase flow at different  $v_o$  and  $Re_{mix}$  and MTC of 30 ppm and 400 ppm was presented in Figs. 6–8. The results show decrease in DR as the oil input volume progresses leading to decrease in mixture Reynolds number. The increase in oil input into the system reduces the  $Wp-Re$  for a fixed  $Re$  because larger volume of the pipe was occupied by the oil-phase which has higher viscosity. The DRPs used does not show any significant DR in the oil-phase and this leads to decrease in DR. It can be seen that DR achieved by polymer mixture was higher than when each DRP is used at the same  $Re_{mix}$ ,  $v_o$  and concentration. The maximum DR achieved by polymer mixture were 62% & 67% for HPAM & AVM at MTC of 30 & 400 ppm; 63% & 68% for PEO & AVM at MTC of 30 & 400 ppm at  $v_o = 25\%$ . The combined effect of the polymer molecules presence in the mixtures and improvement in flexibility of the AVM could possibly cause high DR effectiveness by the polymer mixtures observed in the oil-water flows and corroborates some previously reported works [12, 29].

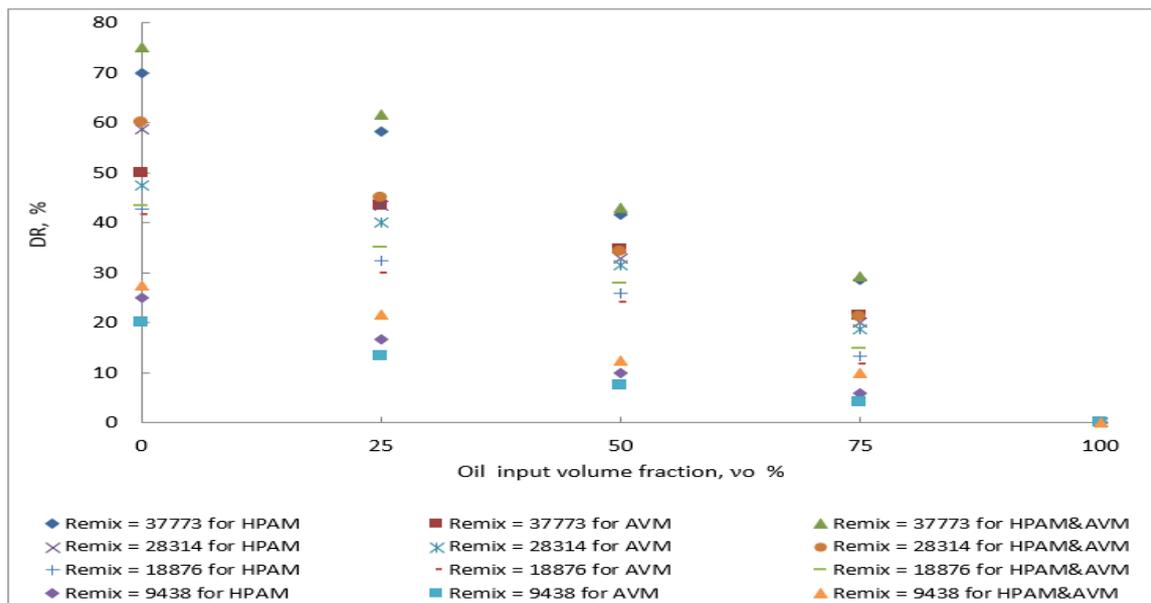


Fig. 6. Drag reduction against  $v_o$  for HPAM, AVM and HPAM & AVM at 30 ppm and different mixture Reynolds number ( $Re_{mix}$ ) in 0.02-m pipe diameter.

## 5. Conclusions

From the experimental results obtained, the following conclusions can be summarized:

I. DR obtained by polymer mixture was higher than that of each of the polymer solution alone due to synergistic effect of both polymer molecules.

II. DR decreased with increase in  $\delta_o$  due to decrease in the  $U_{sw}$  of the water phase.

III. No significant DR observed at 100% oil input volume fraction due to the fact that DRAs used were only soluble in the water-phase.

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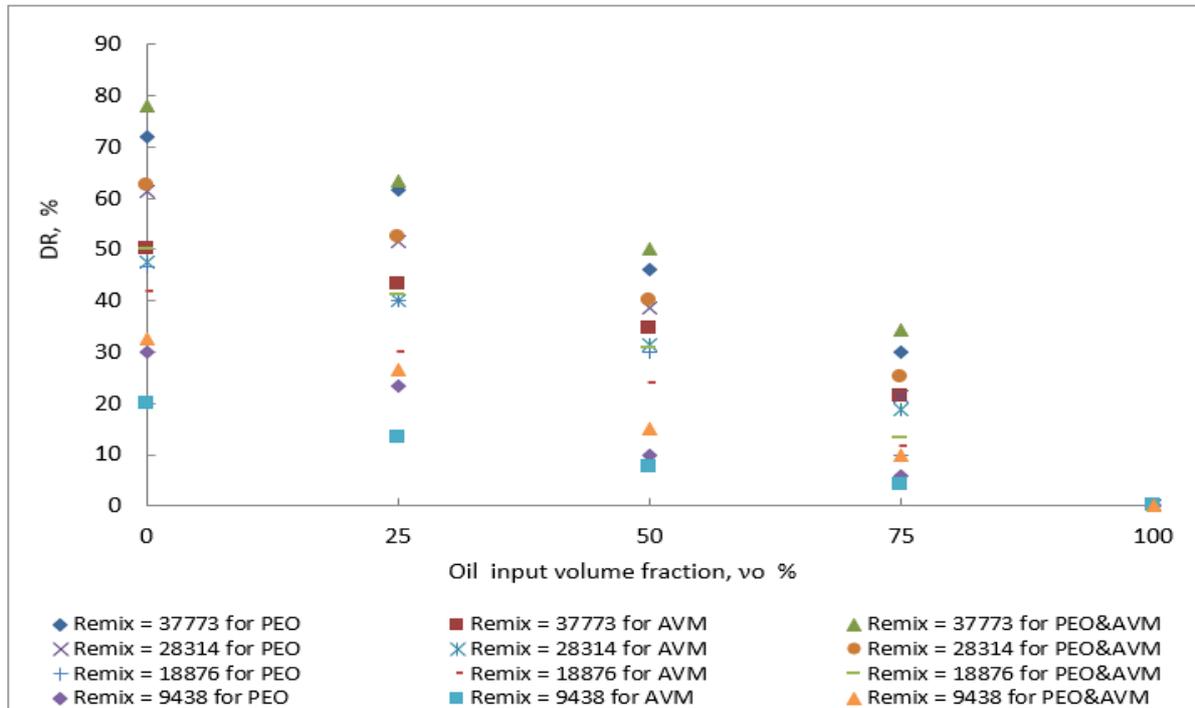


Fig. 7. Drag reduction against  $v_o$  for PEO, AVM and PEO & AVM at 30 ppm and different mixture Reynolds number ( $Re_{mix}$ ) in 0.02-m pipe diameter.

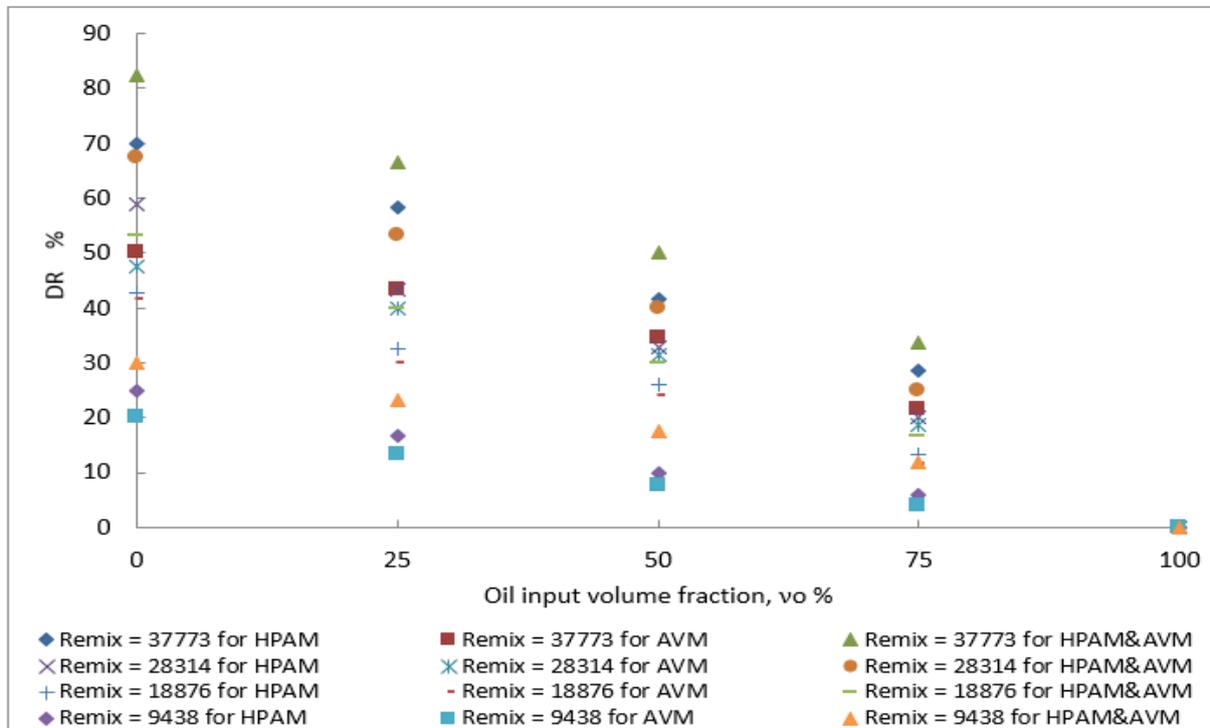


Fig. 8. Drag reduction against  $v_o$  for HPAM, AVM and HPAM & AVM at 400 ppm and different mixture Reynolds number ( $Re_{mix}$ ) in 0.02-m pipe diameter.

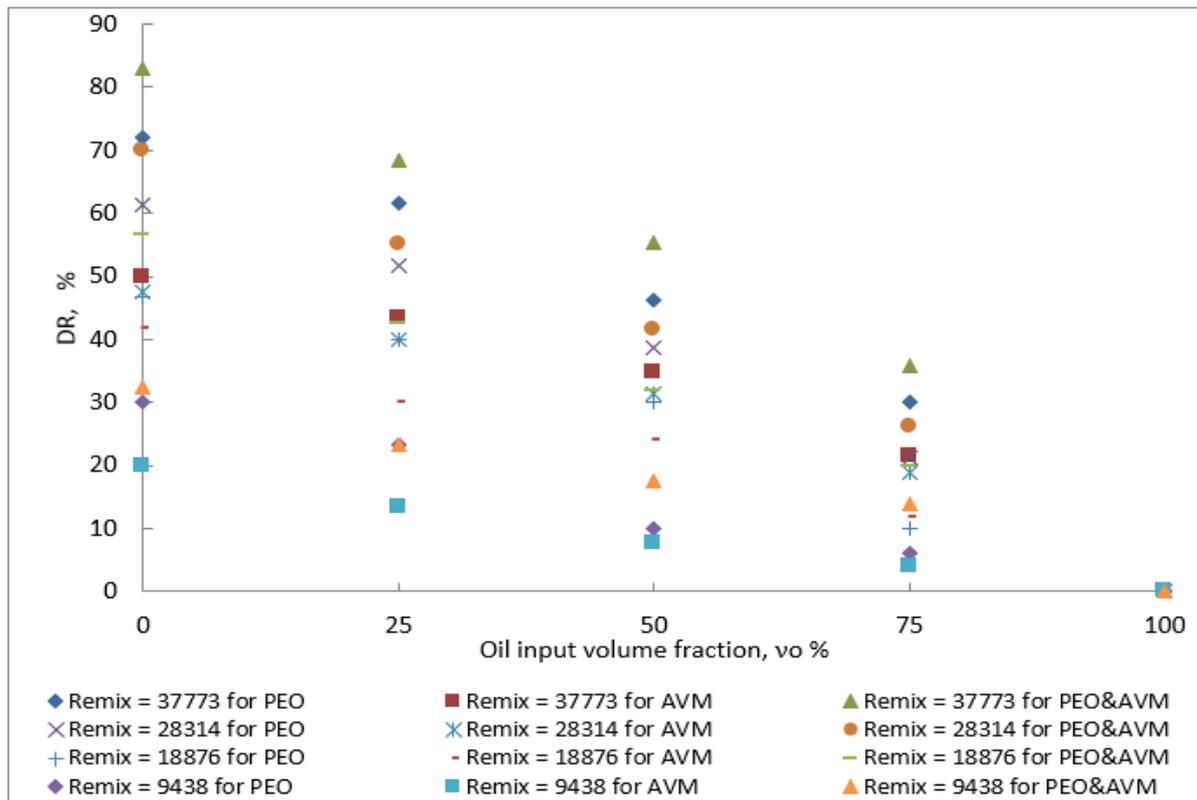


Fig. 9. Drag reduction against vo for PEO, AVM and PEO & AVM at 400 ppm and different mixture Reynolds number ( $Re_{mix}$ ) in 0.02-m pipe diameter.

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