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Synergistic Effect of Polymer-Polymer Mixtures as Drag Reducing Agents in Turbulent Pipeline Water Flow

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ABSTRACT

Synthetic polymers such as partially hydrolyzed polyacrylamide (HPAM; magnafloc 1011) and polyethylene oxide (PEO) in parts per million (ppm) are more effective in drag reduction (DR) (reducing pressure drop) in turbulent pipeline water flow. They are less susceptible to biodegradation which leads to environmental concerns. The incorporation of natural polymer such as Aloe Vera mucilage (AVM) onto HPAM & PEO can improve the efficacy of DR and reduce environmental impact. In this work, HPAM, PEO, AVM, mixture of HPAM-AVM and PEO-AVM were investigated in an experimental flow facility which consists of liquid storage tanks, pumps and unplasticised polyvinylchloride (uPVC) horizontal pipe system with 12 mm ID. The concentration ranging from 2.5 – 100 ppm (HPAM & PEO), 5 – 500 ppm (AVM) and total concentration (TC) of 30 ppm and 400 ppm for the polymer mixture were used. Master solution of 2000 ppm, 20000 ppm and Reynolds number (Re) ranging from 21519 to 81424 were investigated. Mercury U-tube manometer was used to measure the pressure drop of the pipeline water flow. The results showed that drag reduction of 80% and 82.5% for HPAM-AVM (30 ppm and 400 ppm) and 81.6% and 83% for PEO-AVM (30 ppm and 400 ppm) were obtained for the polymer mixtures, which was higher than the DR of individual polymers alone at the same conditions. The increase in the dimension of the macromolecular coil of the polymer mixture solutions due the co-presence of the other polymer molecule and rigidity of the polymer molecule may be responsible for the observed synergism in DR.

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1. INTRODUCTION

Transporting liquids in pipelines over long distances require high amount of energy which results to high cost of installing pumping stations and maintenance (Edomwonyi-Otu and Angeli, 2014). The active and

passive method of drag reduction (DR) reduces such cost. The passive technique involves modifications of walls and structures such as wavy and oscillating walls, dimples, riblets and compliant surfaces. This method is also expensive since it involves wall heating and cooling. The active (additive) techniques require some energy input which is the addition of minute amount of high molecular weight long chain polymers, polymer-polymer mixture, surfactants and fibers known as drag reducing agents (DRAs) (Bewarsdorff and Gyr, 1995; Abdulbari et al., 2014; Abdulbari et al., 2015).

Although Toms was the earliest to report the DR results at the first international Rheological congress in 1948. He added small amounts of long-chain polymers in turbulent flow which caused large decrease in frictional pressure drop (DR) in pipes. This has found a wide range of application in process industries such as crude oil pipeline transportation over a long distances, irrigation, floodwater disposal and sewage (Edomwonyi-Otu and Angeli, 2014). Other application includes marine and biomedical systems, drilling of oil from reservoir, firefighting, extraction, filtration, heat and mass transfer application (Marmy et al., 2012; Edomwonyi-Otu and Angeli, 2014). Edomwonyi-Otu and Adalakun (2018) suggested that it could also be used for transportation of drinking water due to its harmless properties.

Natural drag reducing agents (rigid polymers) such as Aloe Vera mucilage (AVM) are less effective in reducing pressure drop (DR), but are more susceptible to biodegradation and hence more environmentally friendly when compared with synthetic drag reducing polymers like polyacrylamide (PAM), partially hydrolyzed polyacrylamide (HPAM) and polyethylene oxide (PEO) (Deshmukh and Singh, 1986; Nour et al., 2012). Efforts have been made to improve the drag reduction effectiveness as well as reducing the environmental impact of the synthetic polymers (HPAM, PAM, and PEO among others). This can be done by combining synthetic polymers with natural polymers (AVM; Guar-gum, GG; Xanthangum, XG among others) in order to have more environmentally friendly drag reducing polymers (DRPs) and increase DR efficiency (Deshmukh and Singh, 1986; Singh, 1995).

It has been reported that combining polymer-polymer, polymer-fiber and polymer-surfactants mixtures can improve the drag reduction effectiveness and shear stability (Lee et al., 1974; Reddy and Singh, 1985; Malhotra et al., 1988; Abdulbari et al., 2015; Edomwonyi-Otu et al., 2016; Gustavo & Soares, 2016). The first DR by polymer-polymer mixture work was reported by Dingilian and Ruckenstein (1974) where polymer mixtures of polyethylene oxide and carboxymethyl cellulose (PEO-CMC), polyacrylamide and carboxymethyl cellulose (PAM-CMC) and polyacrylamide and polyethylene oxide (PAM-PEO) were used at a mixing ratio of 1:1. They observed positive synergistic effect on PEO-CMC and PAM-CMC combination and negative effect on PAM-PEO combination. DR of the binary polymer system was higher than the sum of DR caused by individual polymers when present alone in a solution at the same conditions. They suggested that, to achieve a synergy, at least one polymer or both of the polymers must have rigid structure. Parker and Joyce (1974) studied DR in mixtures solution of polyethylenimine with PAM, PEO and polyacrylic acid using fluorescence polarization measurements. They observed loss of drag reducing property of the linear polymers in the interaction of polyethylenimine with anionic polymers. Lee et al. (1974) investigated DR in mixtures of polymers and fibers in a pipe diameter of 2.5, 5.0 and 7.0 cm. They observed synergistic effect for their combinations which was in agreement with that of Dschagarowa and Bochossian (1978) findings. Reddy and Singh (1985) studied DR of polymer-polymer and polymer-fiber mixtures in a flow system of pipe diameter of 25.4 mm and length of the test section of 2 meters. They used mixing ratio of 4:1, 3:2, 2:3 and 1:4 at total concentration of 250 ppm for PAM-GG mixture and 5:1, 2:1, 1:1, 1:2 and 1:5 at a total concentration of 300 ppm for CMC-PAM. They observed that, a mixture of rigid and flexible polymer gives maximum DR efficiency than a mixture of two flexible polymers, which was in agreement with the reports by Dingilian and Ruckenstein (1974). They also reported that, the synergy in DR observed in the mixture of flexible and rigid polymers is due to increase in the polymer coil dimension as a result of the co-presence of molecules of both polymers in the solution and the rigidity of the polymers. Malhotra et al. (1988) studied DR by polymer-polymer mixtures in steel capillary tube of diameter 1.575 mm and concentration of 20 and 100 ppm at Reynolds number of 14000. They used mixing ratio of 0:1; 1:3;

1:1; 3:1 and 1:0 (for total concentration of 20 ppm) and 1:0; 19:1; 9:1; 17:3 and 4:1 (for a total concentration of 100 ppm) for mixture of Polyacrylamide and Purified guar gum (PAM-PGG). They observed that, at lower concentration and Reynolds number (Re), synergism in DR was not achieved. They suggested that, synergism in DR can be only be achieve at higher Re and concentration. Edomwonyi-Otu et al. (2016) investigated synergistic effect of drag reducing agents in pipe of different diameters (30 mm and 50 mm) using aqueous solution of PEO with long Nylon fibers. They observed synergistic effect in DR at lower fiber concentration and Reynolds number. Gustavo and Soares (2016) studied mixtures of PAM-XG and PEO-XG in a straight tube. A clear synergy in DR was observed for the two different polymer combinations. They also suggested that the co-presence of different polymer molecules may possibly cause the formation of aggregates which lead to the increase in DR effectiveness. This agreed with the findings of Shetty and Solomon (2009), Wyatt et al. (2011), Pereira and Soares (2012), Mohsenipour and Pal (2013), Steele et al. (2014) and Andrade et al. (2016).

In spite of the available works done in understanding the interaction between natural and synthetic polymers on DR, the literature is rather limited. There is also the need to develop robust models for accurate prediction of DR in binary systems which is dependent on sufficient experimental data. Hence, the main focus of this work is to study and generate data on the synergistic effect of partially hydrolyzed polyacrylamide (HPAM), polyethylene oxide (PEO) and Aloe Vera mucilage (AVM) in horizontal pipeline turbulent water flow.

2. MATERIALS AND METHODS

2.1. Description of the Flow Facility

The schematic diagram of the experimental set-up is shown in Figure 1. The flow facility is divided into three sections which are: the handling section, pumping or regulating section and test section. The handling section consists of water and separator tank with a capacity of 200 and 220 liters where the water is stored. The separator tank allows draining of water through the bottom opening.

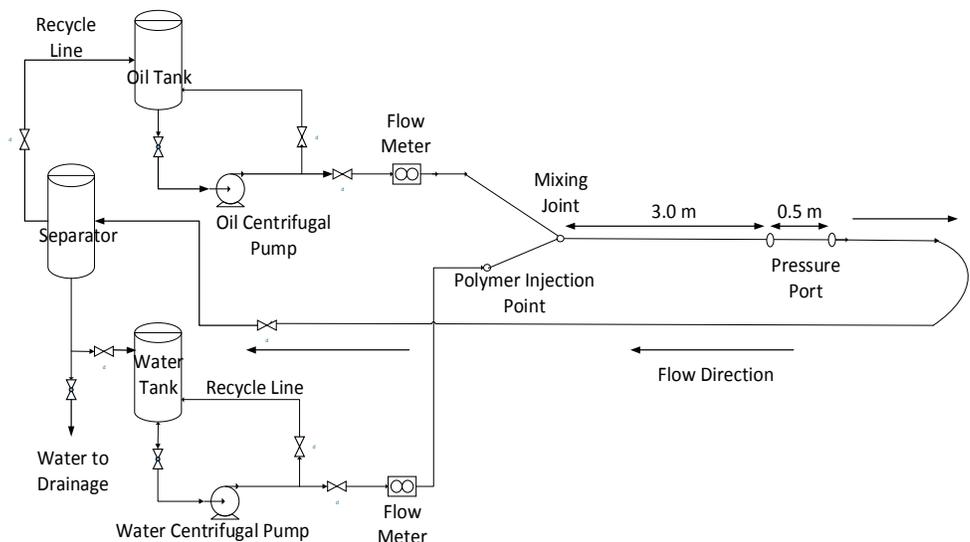


Figure 1: Schematic of experimental flow facility

In the regulating or pumping section, 20 mm ID unplasticised polyvinylchloride (uPVC) pipes are each connected to the water and separator tanks. The centrifugal pumps (model Jet 102M/N.31227) were used to circulate the test fluids into the test section. The globe valves were used to regulate the flow rates which

were measured with variable area flow meters (LZM-20J; $\pm 5\%$ accuracy). The valves are located between the pumping section and the test section. The globe valves also regulate the recycle and bypass flows. The water flow meter has a maximum flow rate of 24 GPM or 100 LPM. The flow meter was calibrated before starting any experiments. The injection port for the polymer master solution is located by the side of the water pipeline before Y-junction. The new Era-programmable peristaltic injection pump (model NE-9000; $\pm 2\%$ accuracy) was used to inject the polymer master solution into the water phase. The test section was made up of straight acrylic pipe of 20 mm ID and 140 times the diameter of the pipe (140D) long from the Y-junction to the second pressure port. The pressure taps were created by making small holes at the bottom of the acrylic pipe walls at the distance of 140D which provides fully developed flow in the test section. U-tube manometer (Pyrex) was used for the measurement of pressure drop.

2.2. Polymer Preparation

The polymers used were polyethylene oxide (PEO) manufacture by Sigma-Aldrich with average molecular weight of 8×10^6 g/mol, partially hydrolysed polyacrylamide, HPAM (Magnafloc 1011) manufactured by BASF chemicals with average molecular weight of 10×10^6 g/mol, and Aloe Vera mucilage (AVM) extracted from Aloe Vera plant. All the polymers are water soluble and were used without further purification. The individual polymers solutions were prepared first, before the polymer mixture solution. A master solution of 2000 ppm of each of the synthetic polymer was prepared as follows. Ten grams (10 g) of each of the polymer powder was measured using weighing balance (Kerro, BLC 3002) and gently spread over 5 liters of water surface and stirred for 3 hours with a mechanical stirrer (Gilverson, L28) at a very low speed (to avoid degradation of the polymer) for the mixture to be completely homogenized. The stirred solution was left for 12 hours overnight to ensure complete dissolution of the polymer particles and removal of trapped gas bubbles to form the master solution (Abubakar et al., 2014a; Edomwonyi-Otu et al., 2015). Aloe Vera leaves were acquired from Edomwonyi-Otu garden in Zaria and identified at an herbarium as Aloe barbadensis miller and then washed thoroughly. The leaves were then cut vertically on both sides and soaked in water for 10 minutes, to remove the Aloin within them. The leaves were then peeled and the Aloe Vera mucilage (AVM) was extracted by scraping and sieving the gel from the aloe leaves. Aloe Vera leaf contains about 98% water while the remaining 2% is the AVM (Davis, 1997; Bozzi et al., 2007). This implies that Aloe Vera leaf contains 20,000 ppm of the AVM by volume. AVM suffers biological degradation in 24 hours. Therefore, its solution was aged for 4 hours for thorough mixing (Abdulbari et al., 2011). After the preliminary experiments with each of the polymer solutions in single phase water flow, the total concentration (TC) for any mixture was chosen based on the fact that at least one of the polymers in the mixture gave maximum DR at that concentration (Reddy and Singh, 1985). In case of this work, 30 ppm and 400 ppm were selected as the total concentration for the mixture of HPAM-AVM and PEO-AVM. The mixtures master solution of 2000 ppm and 20,000 ppm were prepared at different mixing ratio to achieve the require concentration of the polymer mixtures in the flow line as described by Reddy and Singh (1985) and Malhotra et al. (1988). The master solution of 2000 ppm at mixing ratio of 3:1 (1500 ppm of HPAM/PEO + 500 ppm of AVM) was prepared as follows. Similar procedures above were followed; 9 g of each of the synthetic polymers powder (HPAM & PEO) against 6 liters of water to achieved 1500 ppm. 1 liter of 20,000 ppm of AVM master solution was measured and diluted with 5.4 liter of water to achieved 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 2000 ppm for the polymer mixtures. For TC of 400 ppm, the master of 20000 ppm at mixing ratio of 1:19 was prepared as follows. 5 g of each of the synthetic polymers against 5 liters of water to achieved 1000 ppm. 1 liter of 20,000 ppm of AVM master solution was measured and diluted with 0.1 liter of water to achieved 19000 ppm. Equal volume of 1000 ppm of the synthetic polymers was mixed with 19000 ppm of AVM to form 20000 ppm polymer mixture. Similar procedures were used to prepare the rest of the master solutions of the polymer mixtures at mixing ratio of 0:1; 1:3; 1:1; 3:1 & 1:0 (TC of 30 ppm) and 0:1; 1:39; 3:77; 1:19; 5:75 & 3:37 (TC of 400 ppm). It was injected into the water phase at specific flow rate in order to achieved the required concentration

in the water flow line. The mixing of the polymers can also be guided using Equation 1 (Gustavo and Soares, 2016).

$$C_1 + C_2 = 1 \quad (1)$$

Where, C_1 and C_2 are concentration of each of the polymer.

2.3. Experimental Procedure

The flow meters and injection pump were calibrated before running the experiments to ensure accurate delivery of the required amounts of water and polymer concentration into the test section. The experiment was carried out in horizontal pipe of test section of 20 mm ID at ambient conditions (25 °C, 1 atm). The pressure drop was measured using the U-tube manometer. Each experimental run was repeated three times and the average of the pressure drop measured before and after the addition of the drag reducing agents (DRAs). HPAM, PEO, AVM, HPAM-AVM and PEO-AVM were tested at different concentrations and Reynolds numbers. The concentrations of HPAM and PEO ranged from 2.5 - 100 ppm while the concentration of Aloe Vera mucilage (AVM) ranged from 5 - 500 ppm at flow rates of 10 l/min, 20 l/min, 30 l/min and 40 l/min (Re from 21519 - 81424). The optimal polymer concentration of 30 ppm (for HPAM and PEO) and 400 ppm (for AVM) were obtained from our single-phase water flow experiments. The optimal concentrations were selected to be the total concentration (TC) of the polymer mixture (Reddy and Singh, 1985). The mixing ratio of 0:1, 1:3, 1:1, 3:1 and 1:0 (for TC of 30 ppm) and 0:1, 1:79, 1:39, 3:77, 1:19, 5:75, and 3:37 (for TC of 400 ppm) at different Re ranging from 21519, 42229, 62923 and 81424. The pressure drop was recorded and used for calculation of drag reduction defined by the given Equation.

$$DR = \frac{\Delta P_{wo} - \Delta P_w}{\Delta P_{wo}} \times 100\% \quad (2)$$

Where ΔP_{wo} and ΔP_w represent pressure drop of the fluid without and with DRAs

3. RESULTS AND DISCUSSION

3.1. Effect of Polymer Concentration and Reynolds Number

Figures 2, 3 and 4 show the results of the effect of polymer concentration and Reynolds number on drag reduction in single-phase water flow (SPF) at different Reynolds numbers and concentrations for HPAM, PEO and AVM. It was observed that DR was found to be more dependent on polymer concentration at high Re of 62923 (38% DR for 2.5 ppm; 76% DR for 30 ppm for PEO) than at lower Re of 21519 (18.75% for 2.5 ppm; 43.75% for 30 ppm for PEO). Again, DR increased with increase in polymer concentration at different Re due to the increase in the number of the additive molecules which increase the extensional viscosity of the transported liquid. This leads to a decrease in the numbers of eddies formed in the turbulent core, and subsequently brings about the increase in DR. This observation is in conformity with the work of Virk (1975); Bewardoff and Gyr, (1995); Abubakar et al. (2014b); Edomwonyi-Otu et al. (2015).

Furthermore, DR increased with increase in Re, because increase in Re increase the degree of the turbulence in the turbulent pipeline water flow. This creates an environment for the additive-turbulent eddies interaction, which lead to the drag reduction. This observation is also in agreement with the work of Virk (1975); Japper-Jaafar et al. (2009); Abubakar et al. (2014b); Edomwonyi-Otu et al. (2015); Eshrati et al. (2015). It was also observed that, there was high level of instability in the flow as the Re increase above 62923. Besides, at Re of 81424, it was also observed that DR decreased for AVM, which may be attributed to the polymer chain entanglement due high velocity of the water flow. This observation agrees with the findings of Bhambri and

Fleck (2016). Maximum DR of 73.6% (HPAM), 76% (PEO) and 64% (AVM) were obtained. Grafting synthetic polymers (HPAM and PEO) with AVM can enhance the DR effectiveness.

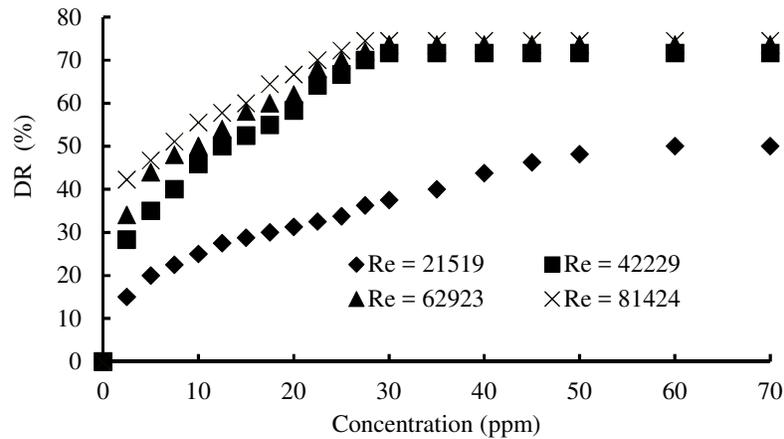


Figure 2: Effect of polymer concentration on drag reduction in single-phase water flow at different Reynolds number for HPAM in 12 mm pipe diameter

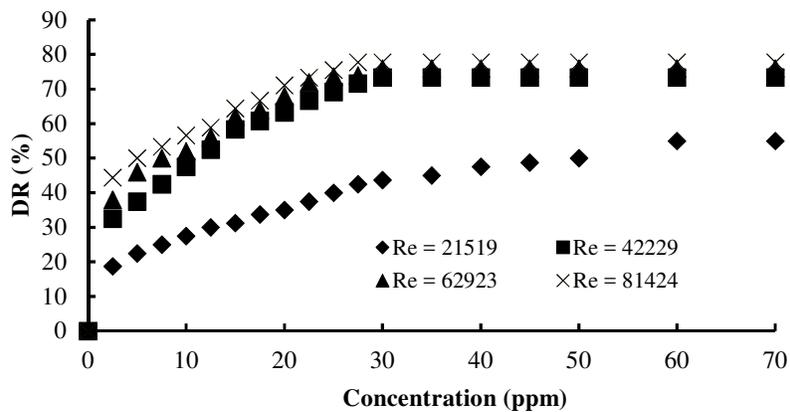


Figure 3: Effect of polymer concentration on drag reduction in single-phase water flow at different Reynolds number for PEO in 12 mm pipe diameter

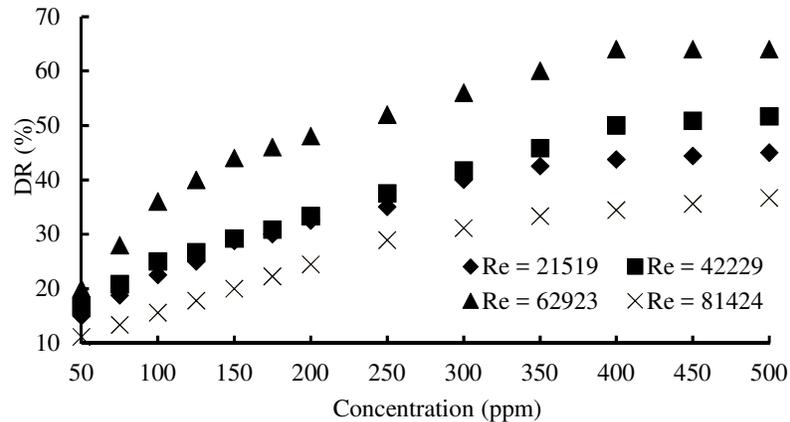


Figure 4: Effect of polymer concentration on drag reduction in single-phase water flow at different Reynolds number for AVM in 12 mm pipe diameter

3.2. Effect of Polymer Mixture Concentration and Reynolds Number

The DR of two polymer mixtures (HPAM-AVM and PEO-AVM) was studied in single phase water flow (SPF) at different polymer mixture concentrations, mixing ratio and Reynolds number. Figures 5 - 8 show the results of the effect of polymer mixture concentration and Reynolds number on drag reduction in single-phase water flow at different Reynolds number and concentration for mixture of HPAM-AVM and PEO-AVM. It was observed that DR increased rapidly with increase in the proportion of HPAM and PEO in the polymer mixtures solution and Re. Maximum DR was obtained at the mixing proportion of 3:1 (for TC of 30 ppm) and 1:19 (for TC of 400 ppm). It was also observed that, at lower Reynolds number of 21519 and 42229, DR obtained for polymer mixtures (35% and 65% for HPAM-AVM; 38.75% and 68.33% for PEO-AVM at 3:1) was less than the additive values (sum of DR of the individual polymers; 40% and 72.5% for HPAM-AVM; 45% and 75% for PEO-AVM). This indicates low degree of synergism in DR. But the DR obtained at lower flow rate was higher than that of each of the polymer alone in the polymer mixture solution at the same conditions, which corroborate with previous findings (Malhotra et al., 1988).

High degree of synergy in DR was observed at higher Re of 62923 and 81424 at all mixing ratios for both polymer mixtures (HPAM-PEO and PEO-AVM) at total concentration of 30 ppm, showing a positive deviation from additive line. The maximum DR for both of the polymer mixtures (80% and 81.6% for HPAM-AVM; 81.11% and 82.22% for PEO-AVM) was achieved at mixing ratio of 3:1 and Re of 62923 and 81424. These DR obtained were higher than the additive values (76.8% and 78.89% for HPAM-AVM; 80.8% and 81.11% for PEO-AVM) of each of the polymer DR. These are in agreement with the work of Dingilian and Ruckenstein (1974), Reddy and Singh, (1985) as well as Gustavo and Soares (2016). DR of 50.5% was obtained by Dingilian and Ruckenstein (1974) for PEO-CMC mixture (mixing ratio of 1:1) at Re of 200000 and mixture concentration 80 weight parts per million (wppm). The synergistic effect observed in DR may be attributed to the change in random coil dimension due to the co-presence of both polymer molecules in the polymer mixture solution, and rigidity of the polymer (Dingilian and Ruckenstein, 1974; Reddy and Singh, 1985). The increase in flow rate (Re) increased the stretching of polymer molecules which lead the high degree of synergy in DR (Malhotra et al., 1988).

Furthermore, a similar trend was observed for the total concentration of 400 ppm. DR increased with increase in the proportion of the HPAM and PEO in the polymer mixtures solution. This may be due to the increase in the extension of their molecules in the mixture than in their individual solution, which brings more interaction of the polymer mixture molecules with the turbulent eddies (Malhotra et al., 1988; Gustavo and

Soares, 2016). Maximum DR of 84% and 84.44% for HPAM-AVM; 84.8% and 84.89% for PEO-AVM at Re of 62923 and 81424 and mixing ratio of 1:19 was obtained. However, a positive deviation from additivity was observed at all Reynolds number and mixture concentration which also corroborate with other findings (Lee et al., 1974; Dingilian and Ruckenstein, 1974; Dschagarowa and Bochossian, 1978; Reddy and Singh, 1985; Malhotra et al., 1988; Pereira and Soares, 2012). Among the two polymer mixtures studied, the mixture of PEO was more effective (with 81.6% DR at mixture proportion of 22.5 ppm PEO-7.5 ppm AVM and 84.8% at mixture proportion of 20 ppm PEO-380 ppm AVM) than the mixture of HPAM, which may be attributed to the flexibility of the mixture of PEO. PEO (linear polymer) is more flexible than HPAM (branch polymer) which is in agreement with the previous findings (Reddy and Singh, 1985; Singh, 1995).

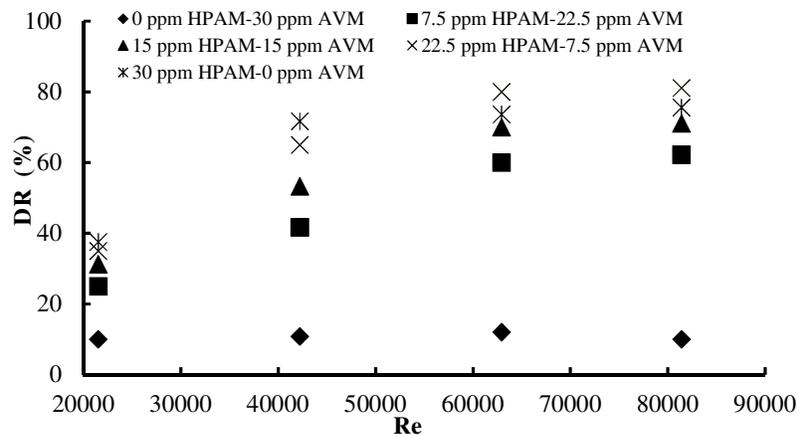


Figure 5: Drag reduction against Reynolds numbers (Re) at different mixtures concentration (HPAM-AVM) in 12 mm ID pipe and total concentration of 30 ppm

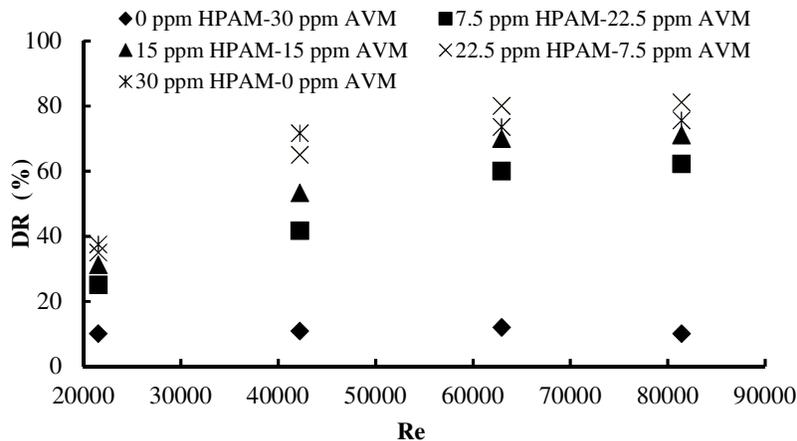


Figure 6: Drag reduction against Reynolds numbers (Re) at different mixtures concentration (PEO-AVM) in 12 mm ID pipe and total concentration of 30 ppm

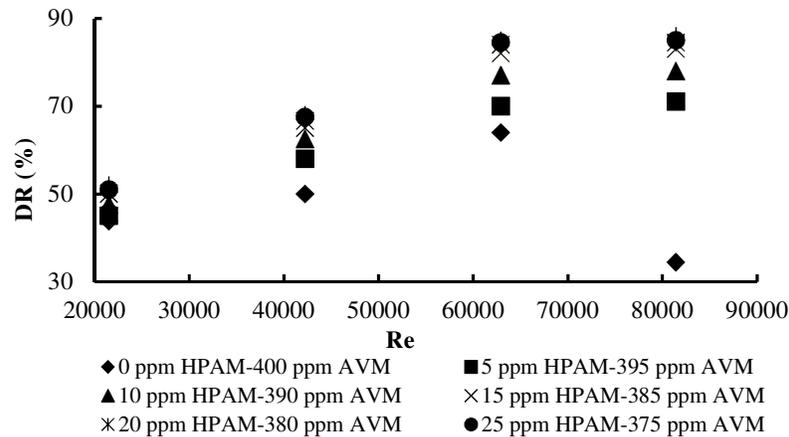


Figure 7: Drag reduction against Reynolds numbers (Re) at different mixtures concentration (HPAM-AVM) in 12 mm ID pipe and total concentration of 400 ppm

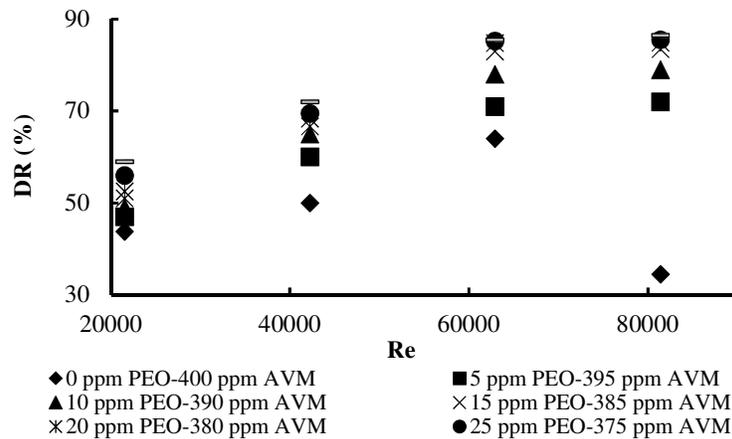


Figure 8: Drag reduction against Reynolds numbers (Re) at different mixtures concentration (PEO-AVM) in 12 mm ID pipe and total concentration of 400 ppm

4. CONCLUSION

The synergistic effect of natural and synthetic polymers as drag reducing agents in single phase turbulent water flow in 12 mm horizontal pipe diameter has been studied. From the results obtained, it can be concluded that:

1. DR of 64% (400 ppm), 73.6% and 76% (30 ppm) were achieved for AVM, HPAM and PEO respectively at Re of 62923.
2. DR of 80% and 82.5% (3:1 & 1:19, HPAM-AVM) and 81.6% and 83% (3:1 and 1:19, PEO-AVM) at TC of 30 ppm and 400 ppm were achieved for the polymer mixtures at Re of 62923.
3. DR and synergism in DR for the polymer mixtures are functions of polymer mixture concentration and Reynolds number.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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