Degradation of drag reducing polymers in aqueous solutions

Hamid Reza Karami, Masoud Rahimi, and Saeed Ovaysi[†]

Faculty of Chemical and Petroleum Engineering, Razi University, Kermanshah, Iran

Abstract−The performance of drag reducing polymers in turbulent flow is restricted by their mechanical degradation. This study examines how the working fluid can affect the degradation behavior of diluted drag reducing polymeric solutions. Solutions having different proportions of tap water and de-ionized water served as the working fluids. Three commercially available water soluble polymeric agents, namely, an anionic copolymer of polyacrylamide, xanthan gum, and polyethylene oxide, were then added to these solutions. All experiments had identical flow rates corresponding to turbulent conditions in a laboratory scale pipe line. Variation of pressure drop in the pipe line was then measured for 2 hours. It was found that polymer degradation is accelerated in tap water solutions compared to that in de-ionized water solutions. However, this is dependent on the specification of the polymer used, namely, the molecular weight of the polymer and the rigidity of its molecular backbone. Furthermore, a new mathematical relation has been developed to investigate degradation of the polymers over time.

Keywords: Turbulent Flow, Drag Reduction, Specification of Water, Degradation

INTRODUCTION

Various ways are proposed to overcome the negative consequences of pressure losses in pipe lines under turbulent flow conditions. Among them, employing chemical additives known as drag reducing agents (DRA) is a practical way to lower the resulting pressure losses. DRAs represent a great potential benefit to many industrial processes. Their main function is to suppress the energy of turbulent eddies and hence decrease the friction factor in the pipe line [1]. A practical benefit of this phenomenon is reduction of the required pump power at a constant flow rate, or increase of the piping system capacity at constant pressure drop under identical conditions [2]. Toms [3] was a pioneer researcher who introduced drag reduction concept. Consequently, drag reduction is also known as Toms' effect in the literature. The desirable effects of drag reducing agents have attracted many researchers to describe the concept and develop its applications over decades. Many studies have been carried out to understand the various aspects of the phenomenon and to adequately utilize it. Theses researches investigate drag reduction experimentally [4-10], or theoretically [11-14]. Unlike the numerous studies, the exact mechanism of drag reduction has remained unclear. Some studies have described the phenomenon based on the intraction between DRAs and turbulent structures [15-19].

Well-known drag reducing agents are mainly divided into various categories such as long chain polymers, surfactants, suspensions of particles or fibers, and micro-bubbles [2]. In addition to these, compliant coating can be utilized to overcome pressure losses in both laminar and turbulent flow on the surface [20]. Under turbulent flow conditions, fluid-soluble ultrahigh molecular weight polymers with a linear structure are considered the most effective drag reducing agents. The properties that define polymers as efficient drag reducing agents are ultrahigh molecular weight, i.e., $M_w > 1,000,000$ Da (the higher the molecular weight, the higher the drag reduction), quick solubility in the working fluid, acceptable resistance against mechanical shears, as well as thermal, chemical, and biological degradation resistance [21].

Drag reduction can be influenced by many parameters. Karami and Mowla [2,21] proposed a mathematical model to investigate the impacts of various experimental parameters on drag reduction. They found that drag reduction increases with the concentration and molecular weight of DRA, flow rate and temperature of the fluid, and the relative roughness of the pipe. Their model matched the data appropriately. Based on a statistical study, Karami et al. [22] showed that the most effective parameters for drag reduction are the Reynolds number and concentration of the polymers.

Despite numerous studies on drag reduction, its relevant mechanism is not precisely understood. However, some studies suggest energy transfer from energetic turbulent vortices to polymer chains as the main mechanism of drag reduction. High molecular weight polymers may become elongated under turbulent flow and hence suppress the energy of the turbulent vortices. Consequently, smaller eddies with lower amount of stored energy are formed. This may be accepted as the main reason for drag reduction [15,16,23].

Mechanical degradation of the polymer backbone lowers the effectiveness of polymer chains and it is considered to be the main drawback of DRAs. In the worst case, complete degradation may show an inverse effect on skin friction of the flow. Thus, many studies have investigated degradation of diluted solutions of polymers in both pipe line and rotating disc apparatus (RDA) [24-33]. Shear stability of the polymers is mainly controlled by their molecular weight and flexibility of their backbone. It is demonstrated that

Table 1. Specifications of the employed polymers as drag reducer

Polymer	Abbreviation	Supplier	Average molecular weight (Da)
SuperFloc A-150HMW	SF150	Kemira	$>8\times10^6$
Polyethylene oxide	PEO	Sigma-Aldrich	8×10^6
Xanthan gum	XG	Sigma-Aldrich	2×10^6

stability of the polymer against shear degradation increases with molecular weight [25,34], while flexibility of the backbone inversely impacts resistance against shear degradation. Additionally, rigid polysaccharide polymers show higher mechanical stability against degradation when compared to flexible synthetic polymers in the same molecular weight range [26,27], though these agents are highly susceptible to biological degradation [35].

Sohn et al. [25] investigated drag reduction of a minute amount of a homologous series of polysaccharide xanthan gum (XG) in an aqueous solution using a rotating disk apparatus. They revealed that degradation of the molecules is accelerated at higher speeds of the disk. They found that drag reduction depends on various factors, including polymer molecular weight, polymer concentration, rotation speed, ionic strength of the solution, and temperature. They concluded that xanthan gum having higher molecular weights exhibit higher shear stability.

Hong et al. [36] investigated the efficiency of water soluble polymers, polyethylene oxide (PEO) and polyacrylamide (PAM), as a function of either polymer concentration or temperature. Mechanical degradation behavior of the DRA in a turbulent regime was analyzed using exponential decay equations. They found higher amount of drag reduction and shear stability for PAM under the same concentration. Kim et al. [24] employed a high-precision RDA to simulate external flow and found higher degradation at lower concentrations of the employed polymer, i.e., PEO. Also, degradation range of the solutions was slightly decreased at higher DRA concentrations. Similar results were found by Choi et al. [37] when investigating the impact of the concentration of polymeric solutions on shear degradation. In another work [38] they investigated turbulent drag reduction induced by DNA and found a diffrent mechanism of degradation from that of the conventional flexible long-chain polymers.

Other studies have focused on ways to enhance the strength of polymeric DRAs against mechanical degradation. Among them, polymer-solution interaction [29], polymer-surfactant interaction [39], polymer-fibre interaction [40], polymer-polymer interaction [41], copolymerization and grafting of the polymers [35,42,43] have been thoroughly examined.

In the current study, the degradation behavior of three commercial DRAs with either flexible or rigid backbone was investigated. This is accomplished by addition of the above mentioned DRAs to a 1 inch pipe line under turbulent flow of water. The experiments were carried out by circulating the diluted polymeric flow in a loop for 2 hours at relatively high Reynolds numbers, i.e., 18280. The employed experimental setup, we believe, fairly represents the real world conditions from an industrial perspective rather than conventional studies carried out in a rotating disk apparatus. Additionally, the impact of physic-chemical specification of the working fluid on drag reduction is thoroughly examined by employing

different blends of de-ionized and tap water. This is a novel achievement which simply shows the accelerated degradation of the drag reducing polymers due to the specification of working fluid. Finally, based on the degradation curves obtained in this study, a new mathematical function with particular attention to complete degradation of the polymers was developed to model the experimental findings.

MATERIALS AND METHODS

1. Materials

Three different water soluble high molecular weight polymers were used to study their performance as drag reducers. These polymers are a commercially available copolymer of polyacrylamide (PAM), polyethylene oxide (PEO), and xanthan gum (XG). The first two polymers are cathegorized as synthetic flexible molecules, while the last one is considered a natural rigid polymer. The complementary information and approximated molecular weights of the polymers is shown in Table 1. The commercially copolymer is also known as SuperFloc A-150HMW (SF150), which is widely used as a flocculant agent in the water treatment industry.

The polymers were selected based on some preliminary experiments which showed the desirable efficiency in the employed experimental conditions. Polymers having different molecular weights for each family of polymers were tested to find their optimum molecular weights. Polymers with lower molecular weights, especially in the case of PEO, did not show acceptable drag reduction. On the other hand, those with too high molecular weights were not compatible with the experimental conditions. These heavy polymers formed aggregates which could not dissolve in the working fluids (experienced with PEO and XG).

The desired concentration of the polymers was obtained by gently mixing the appropriate w/w ratio of polymer powder and water using a magnetic stirrer for around 2 hours. The solutions were then allowed to rest for 24 hours to ensure they were free of bubbles. As expected, addition of minute concentrations of polymers to water induces a non-Newtonian behavior to the fluid. Fig. 1(a)-(c) depict the rheological behavior of the polymeric solutions versus shear rate. The measurements were counducted using a double gap cylinder type rotational rheometer (RheolabQC, Anton-Paar, Graz, Austria).

Deviation from Newtonian behavior is increased when higher concentrations of the polymers are used. This leads to extra viscous forces and, consequently, negative effects on pressure drop under turbulent flow conditions, especially at higher concentrations. This phenomenon will be discussed in the next section.

The polymeric solutions were first added to de-ionized water (DW) to obtain the optimum concentrations of the polymers which show the highest amount of drag reduction (the lowest pressure drop) during the experiments. Performance of the obtained opti-
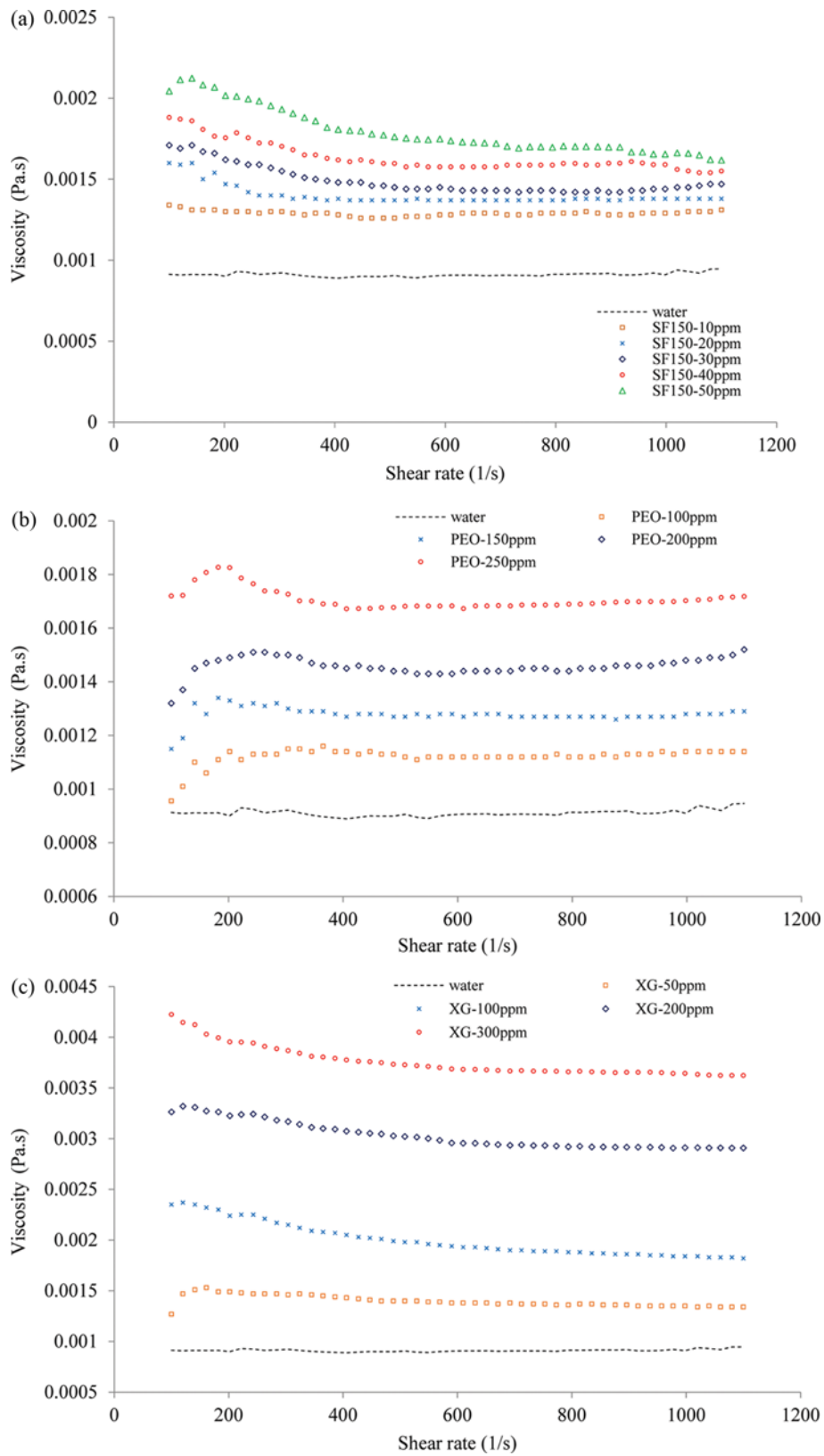
Fig. 1. Viscosity of the diluted polymeric solution in terms of applied shear rate: (a) SF150, (b) PEO, (c) XG.

mum concentrations was then evaluated using other working fluids with different specification. The experiments were performed

for tap water (TW) and blends of tap water and de-ionized water at two different ratios of TW/DW, i.e., 2 : 1 and 1 : 2. These were then

Table 2. Characteristics of the different working fluids

Physicochemical properties	TW	2TW/1DW	2DW/1TW	DW
EC (μs/cm)	435	302	158	6
TDS	271.9	188.8	98.8	3.8
pH	7.7	7.61	7.64	8.08
Total hardness (mg/L)	214.41	152.85	79.48	0.91
Total alkalinity (mg/L)	188	136	72	8
Ions (mg/L) ↓				
HCO_3^- (bicarbonate)	229.36	165.92	87.84	9.76
SO_4^{2-} (sulfate)	14.2	9.06	4.08	0
Cl^- (chloride)	15.18	10.10	5.03	0.67
NO_3^- (nitrate)	10.43	6.84	3.43	0.5
Ca^{2+} (calcium)	56.33	40.91	21.17	0
Mg^{2+} (magnesium)	17.88	12.29	6.45	0.22
Na^+ (sodium)	12.05	7.94	3.8	0
K^+ (potassium)	0.48	0.3	0.16	0

compared against the results for pure de-ionized water. Clearly, ionic content of the working fluid has a profound impact on degradation rate of the polymers. This, alongside other physico-chemical properties of the employed working fluids, i.e., electrical conductivity (EC), total dissolved solids (TDS), pH, total hardness, and total alkalinity, is presented in Table 2. Ion chromatography was used to determine concentrations of the main ions. Other ions not reported in this table were not detectable.

2. Experimental Apparatus

The experimental apparatues consisted of a 3 meters long 1 inch Plexiglass transparent pipe which was installed in a loop (Fig. 2). A simple 60 Lit tank was used to supply the working fluid, mix the diluted solution, and circulate the fluid in the loop via a Moyno pump. The special structure of this pump applies low shear on shear-sensitive fluids and circulates them at a lower rate of degradation under high Reynolds numbers. This facilitates maintaining slow degradation rates through avoiding the induced negative effects of the impeller. A variable frequency drive (VFD) was used to set the flow rate by adjusting the frequency of the pump. This flow rate was kept constant throughout all the experiments to ensure turbulent conditions, and to evaluate drag reduction of the solutions in a meaningful way. The flow rate was measured and monitored via a digital flowmeter installed between the pump and the main pipe. A laboratory computer stored the obtained data using a data acquisition (DAQ) card.

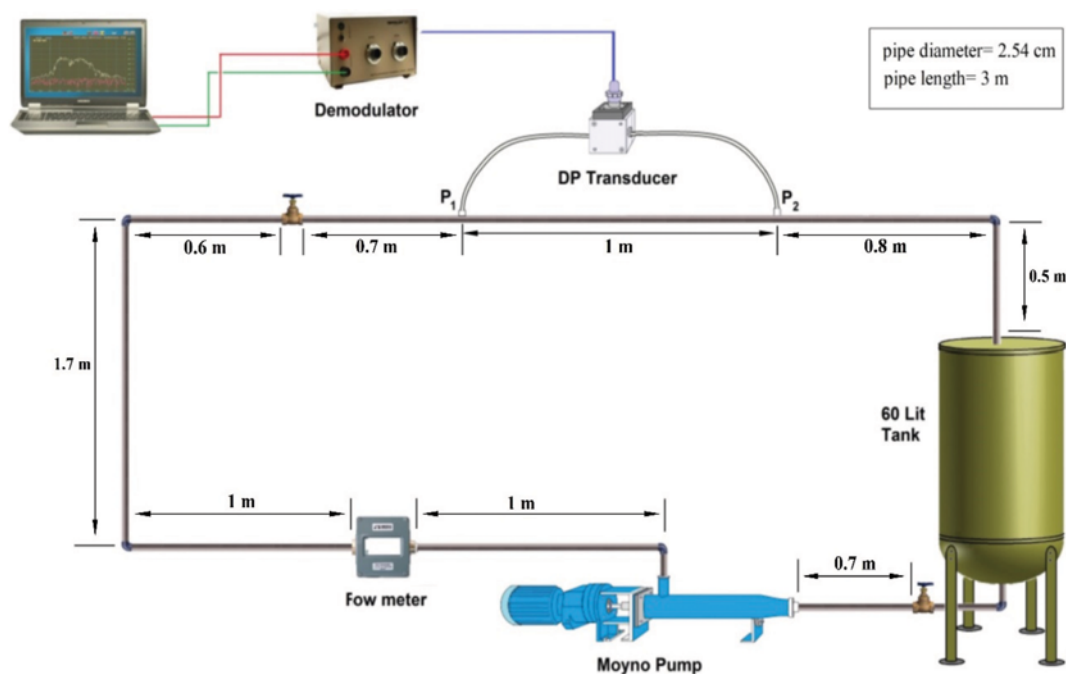A good way to evaluate the hydraulic impact of polymer addi-

Fig. 2. The employed circulating system to investigate degradation of the solutions.

tion to turbulent flow is measurement of the pressure drop and comparing the measured number against a base case. Percentage of drag reduction (DR%), defined below, is the well-established criteria to evaluate the performance of any drag reducing agent.

$$DR\% = \left(1 - \frac{\Delta P_{DRA}}{\Delta P_{No\text{-}DRA}}\right) \times 100 \qquad (1)$$

In which ΔP_{DRA} and $\Delta P_{No\text{-}DRA}$ are the measured pressure drop of the polymeric solution and the working fluid under the same flow rate, respectively. The relation considers how the addition of polymers may change the pressure drop of water. This formula is also useful in investigating the performance of the polymers and their degradation during the experiment.

In the experimental setup, a differential pressure transducer, supplied with a demodulator, was employed to measure the pressure drop between two points on the pipe line 1m apart (P_1 and P_2 in Fig. 2). The location of the two ports allows fully developed flow conditions at the upstream, and, at the same time, avoids end effects at the outlet. Note that the entire laboratory scale piping was about 8 m long.

The measured pressure drops were collected using a DAQ card as voltage, and stored on the computer. The collected voltages were converted to pressure drop (psi) using a produced calibration curve. This allowed careful examination of the performance of DRAs over time. All experiments were at 20 ^{o}C to eliminate any thermal effects that might interfere with the results.

RESULTS AND DISCUSSIONS

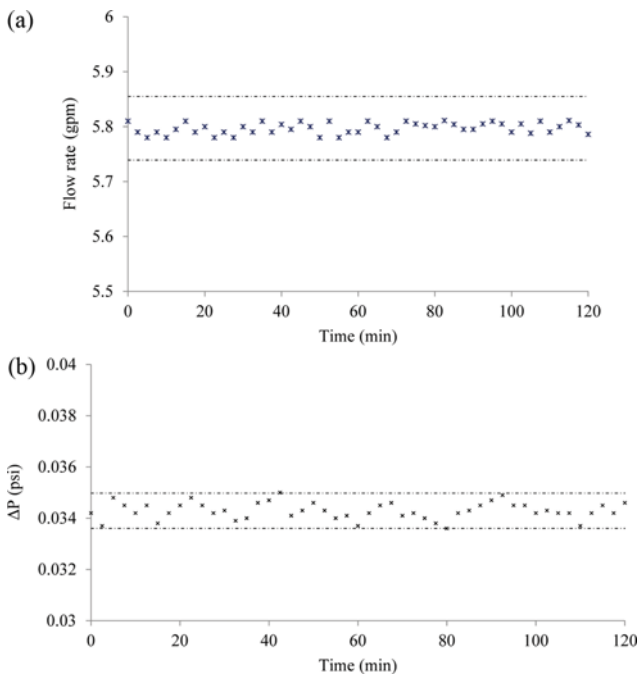All the experiments were at a constant flow rate of 5.8 gal/min,

yielding Re=18280, which marks relatively high turbulent flow conditions. Furthermore, the average pressure drop was found around 0.034 psi for all the working fluids. Fig. 3 depicts the variations of measured pressure drop and flow rate of de-ionized water under steady state conditions. The constant trend of the measured pressure drop and flow rate proves consistency of the experimental apparatus and the absence of any leaks. The obtained flow rates in each time step show reasonable fluctuations within ±1% from the average value. Also, as illustrated in Fig. 3, variation in pressure drop is less than 2%. In the following subsections, it is discussed how addition of DRAs may impact pressure drop in turbulent flow.

1. Shear Degradation of the Solutions

To find the optimum concentration of each polymer, several; experiments were carried out by circulating the diluted polymeric solutions in de-ionized water for 2 hours. Note that addition of DRAs can both increase and decrease the frictional drag. These two opposite effects can be due to either increased viscosity or interaction of DRAs with turbulent eddies, respectively, depending on DRA concentration. Therefore, it is important to select a DRA concentration at which the balance of forces is tilted in favor of decreasing the frictional drag. Clearly, there is a concentration at which DR% is the highest. In this study, a concentration that yields the highest DR% and the lowest degradation of the DRA is considered as optimum.

Evolution of pressure drop when different concentrations of the above mentioned DRAs are added to de-ionized water is shown in Figs. 4-6. Note that the data were reported as soon as the rich solution of the DRAs and the circulating water were well mixed and formed a homogeneous diluted solution. This usually took less than 3 minutes.

The above figures reveal that drag reduction is strongly dependent on the characteristics of the employed DRA. The results also indicate that the highest amount of drag reduction is achieved at very low concentrations of the anionic copolymer (SF150) while maintaining an acceptable degradation behavior during 2 hours. Although, 20 ppm solutions of the copolymer initially yielded the best DR%, it was the 30 ppm solutions of this DRA that maintained the highest DR% throughout the experiment by experiencing negligible degradation. Higher concentrations of the copolymer

Fig. 3. (a) Flow rate of the de-ionized water, dashed lines shows ±1% around mean value; (b) pressure drop of the de-ionizedwater in terms of time, dashed lines shows ±2% around mean value.
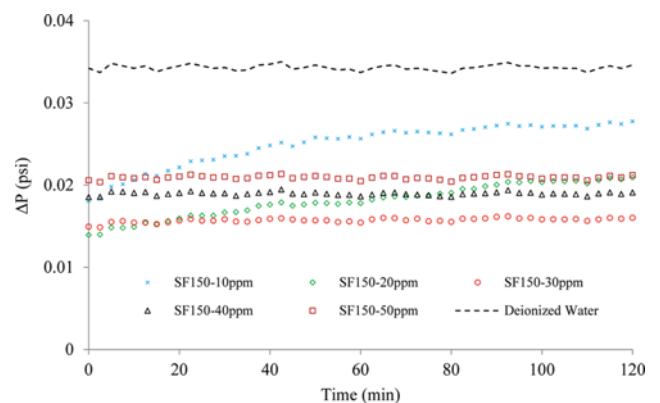

Fig. 4. Evolution of pressure drop for diluted solutions of SF150 in de-ionized water.
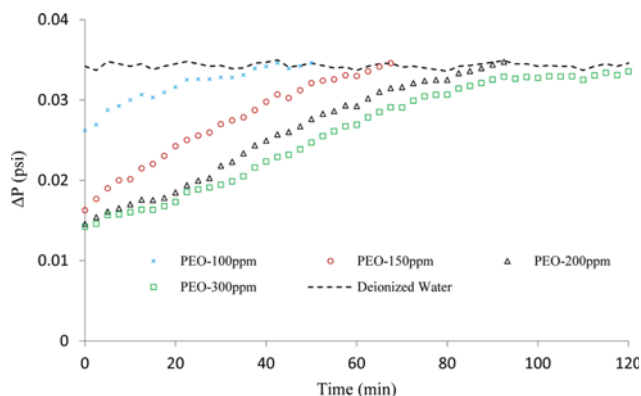
Fig. 5. Evolution of pressure drop for diluted solutions of PEO in de-ionized water.

Fig. 7. Variations of DR% for various concentrations of the employed polymers.

show lower DR% due to the adverse effects of viscous forces as discussed earlier.

The second DRA tested in this study, PEO, did not yield any significant DR%, especially at low concentrations. This DRA degraded rapidly during the experiment. Even though the degradation behavior of PEO improved at higher concentrations, nevertheless, it cannot be considered as a stable DRA under the applied experimental conditions.

Regarding XG, the third DRA studied, it is easy to notice that it is less susceptible to degradation, though its optimum concentration, i.e., 200 ppm, was higher than that of SF150.

The above findings can be better understood by careful examination of chemical structures of the three DRAs studied and the information given in Table 1 in light of the previous findings [25,26]. We note that SuperFloc A-150HMW is an anionic, viscous, and linear polymer with a very high molecular weight. The latter characteristic of this polymer makes it a good drag reducer, though, due to its linear structure, it is less resilient against shear stress and can be degraded rather quickly. Also, PEO is a linear polymer with a lower molecular weight compared to SF150. This, combined with its simple chemical structure, makes PEO a very unstable DRA that contributes very little to drag reduction as evidenced in Fig. 5. In contrast to this polymer, XG, similar to other natural polysaccha-
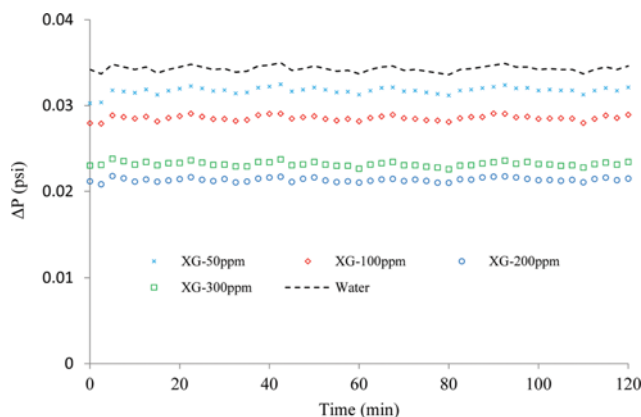
rides, has a nonlinear rigid backbone that yields a great resiliennce against shear stresses and hence experiences negligible degradation under turbulent flow conditions. The above-mentioned properties of XG, along with its medium molecular weight and biodegradable nature, make XG a reliable DRA. From a molecular point of view, XG, similar to cellulose, possesses a linear main chain of (1-4)-b-D-glucose with a trisaccharide side chain on every second D-glucose [44]. It is this complex structure which is responsible for the rigidity and stability of XG under the strong shear forces exerted by turbulent eddies. Despite its positive properties as a DRA, XG has a lower molecular weight and lower solubility compared to SF150. This implies that significant drag reductions with this DRA can only be achieved at higher concentrations when compared to the anionic copolymer, though the best DR% of XG is still lower than that of SF150.

Shown in Fig. 7 is the variation of DR% for all the three DRAs studied at different concentrations. In this figure, a broad range of variations at a given concentration implies a high degradation rate.

It is clear that PEO is the most unstable DRA, whereas XG and concentrated SF150 solutions, i.e., above 30 ppm, show an acceptable level stability. Also, as expected, the desired effect of the polymers on damping the turbulent eddies may be decelerated by induced resulted viscous forces, so there is a concentration at which DR% is the highest for all the DRA solutions tested in this study.

Previous authors have developed empirical relations to better correlate degradation of polymers under turbulent flow conditions [37,45,46]; however, these relations suffer from either lack of accuracy or inability to predict complete degradation after extended exposure to turbulence. To overcome these issues, we propose the following relation:

$$\frac{DR(t)}{DR_0} = \frac{A_1t + A_2}{1 + A_3[1 - \exp(-t/A_4)]} \qquad (2)$$

where, DR_0 and $DR(t)$ are drag reduction at the onset of the experiment and at any given time, respectively. Parameters A_1, A_2, A_3 and A_4 are evaluated through least squares of the experimental data. As illustrated in Figs. 8, 9, the proposed model can successfully fit the experimental data for diluted solutions of SF150 and PEO. Obviously, it is not necessary to use a degradation model for stable solutions, e.g., XG solutions, when $DR(t)/DR_0 \approx 1$.

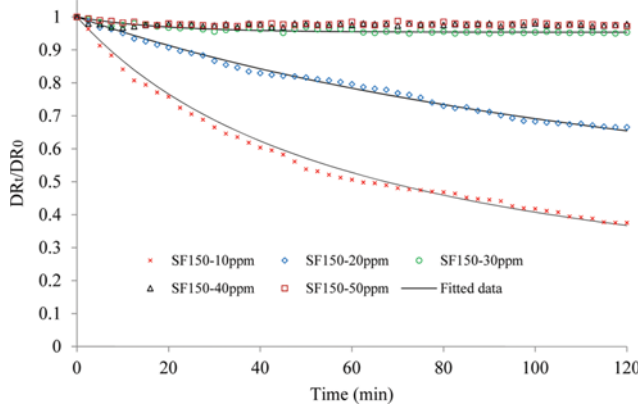Fig. 6. Evolution of pressure drop for diluted solutions of XG in de-ionized water.

Fig. 8. Closeness of fit of the proposed model for diluted SF150 solutions.
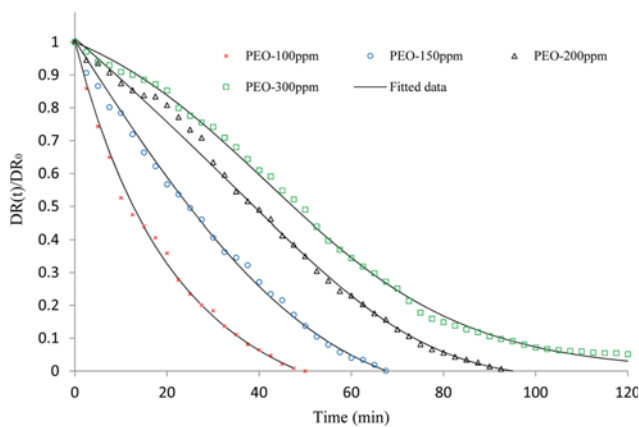
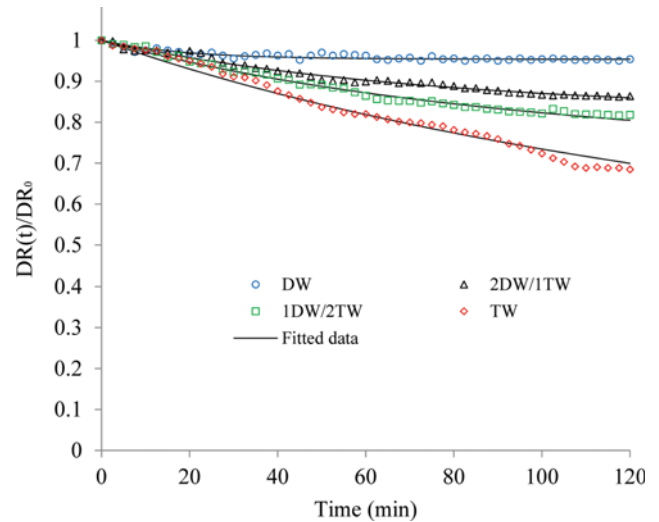Fig. 9. Closeness of fit of the proposed model for diluted PEO solutions.

Fig. 10. Degradation of the 30 ppm solutions of SF150 in various working fluids.
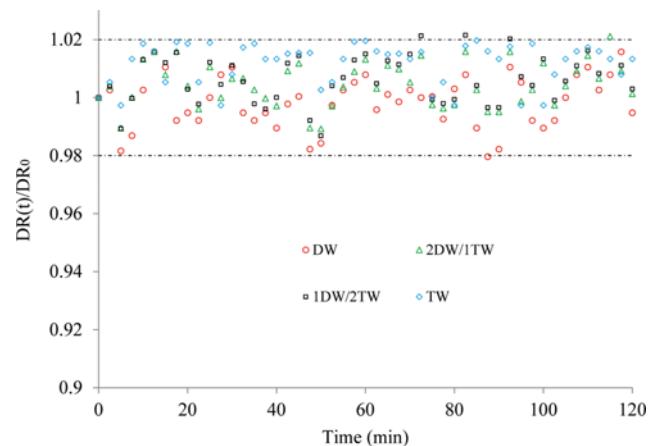

Fig. 11. Degradation of the 200 ppm solutions of XG in various working fluids, dashed lines show ±2% variations.

We believe the above model can find applications in industry where the actual conditions of pipelines are reliably simulated by the experimental setup used in this study. This is in contrast to other studies in this area where the proposed models are based on data acquired from rotating disk apparatus [37,45,46].

2. Effect of Water Specification on Shear Stability

To examine the impact of working fluid on degradation behavior of DRAs, diluted solutions of SF150 and XG in different mixtures of de-ionized water and tap water, as listed in Table 2, were studied. Due to its weak performance, PEO is not included in this part of the study. Furthermore, only the optimum concentrations found in the previous section, 30 ppm for SF150 and 200 ppm for XG, were used. As shown in Table 2, electrical conductivity (EC) of tap water, due to its higher ion content, is significantly higher. It is expected that these ions would negatively impact the degradation behavior of the DRAs they come in contact with.

Figs. 10, 11 illustrate the shear degradation of SF150 and XG, respectively. As expected, the higher ion content of tap water drastically accelerates the degradation of the anionic copolymer during its continued exposure to turbulence. Negative results on the flexible polymer backbone induced by ions are the suspected culprit. It seems the ions attack functional groups of the main chain of the

copolymer and involve with them to form a complex. This undesired interaction may weaken the main chain and accelerate the degradation of the polymer. It is known that, from the supplier, the commercial copolymer (SuperFloc A-150HMW) is widely used as flocculant agent in water treatment to adsorb some cations like calcium and magnesium, so forming complex with the ions is expected.

Unlike SF150, which has a flexible molecular structure, the molecular structure of XG is considered rather rigid. Therefore, as seen in Fig. 11, no reliable shear degradation of XG solutions is observed. As discussed elsewhere, i.e., [26,47], the salinity of the working fluid alters the ionic forces of XG, which leads to a shift in the helical configuration of the DRA molecules to a coiled one. In this study, the amount of the salinity of the working fluid is not too much to find a desirable effect on the rigid polysaccharide backbone of XG. Consequently, the different working fluids leave no additional effect on degradation of XG. As a result, this polymer is a more sustainable DRA.
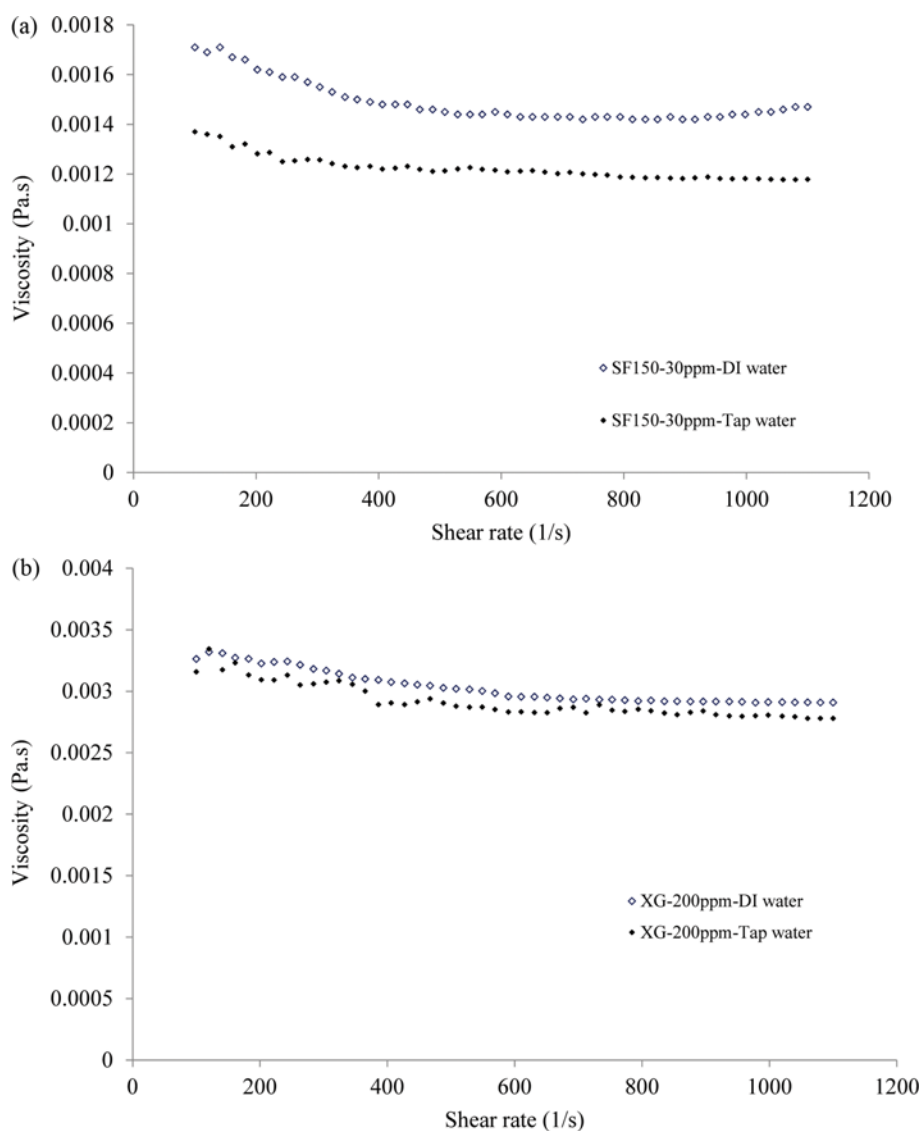
Fig. 12. Comparison of the viscosity of the diluted polymeric solution in different working fluids, (a) SF150, (b) XG.
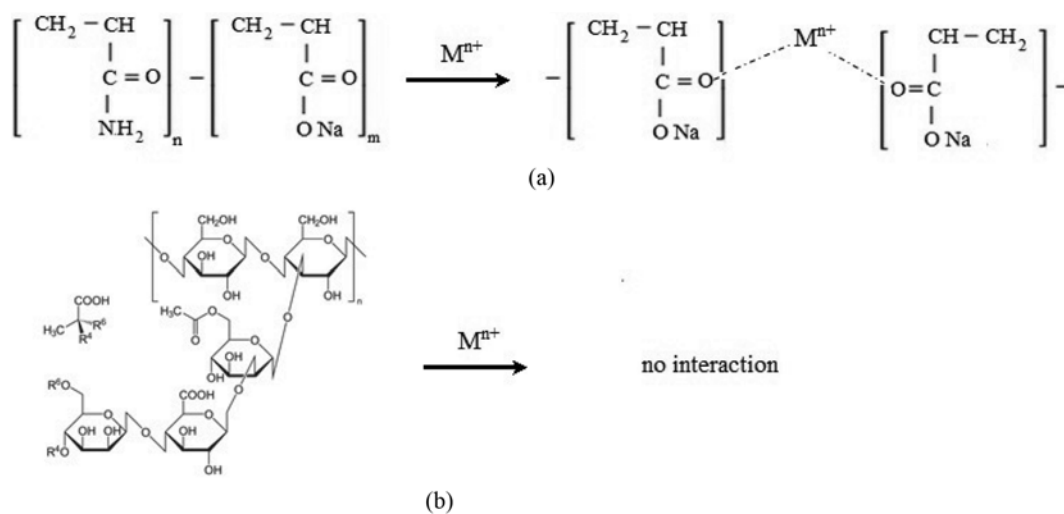

Fig. 13. Schematic interaction between the cations dissolved in the working fluids (M^{n+}) and the polymer backbone.

Table 3. Summarized of rounded values for constants of Eq. (2)

Polymer	Concentration (ppm)	Solvent	Constants of Eq. (4)			
			A_1	A_2	A_3	A_4
SF150	10	DW	0	1	12.41	802.71
SF150	20	DW	0	1	3.23	672.44
SF150	30	DW	0	1	0.05	19.01
SF150	30	2DW/1TW	0	1	0.22	90.52
SF150	30	1DW/2TW	0	1	0.42	138.93
SF150	30	TW	0	1	3.49	914.56
PEO	100	DW	-0.021	1.003	-2.31	-66.27
PEO	150	DW	-0.015	1.005	-0.22	-30.27
PEO	200	DW	-0.011	1.012	-0.03	-19.90
PEO	250	DW	0	1	-0.13	-21.71
XG	50	DW	0	1	0.60	6.89

This is anticipated from the viscosity behavior of the polymers in the working fluids. Fig. 12 shows the viscosity of the two additives in de-ionized and tap waters. It could be concluded that SF150's chain cannot be fully extended in tap water. Therefore, a lower viscosity is expected for diluted solutions of SF150 in tap water compared to de-ionized water. This agrees with previous observations [48,49]. But note, our measurements show no significant difference between the viscosity of XG in the two working fluids. This can be justified by the fact that XG has a rigid body and therefore is not influenced by ionic interactions suspected in the case of flexible DRAs.

Fig. 13 suggests how the cations (M^{n+}) interact with the functional group of the anionic polymer. Here, poly(acrylamide-co-acrylic acid) partial sodium salt is considered an anionic polymer. As shown, ionic strength of tap water can restrict elongation of the polymer chain and hence reduce performance of the additive. As pointed out earlier, coiling of the polymer is responsible for lower viscosities of the diluted solution in tap water compared to de-ionized water. This effect is absent in the case of XG solutions where strong hydrogen bonding dominates the polysaccharide chain.

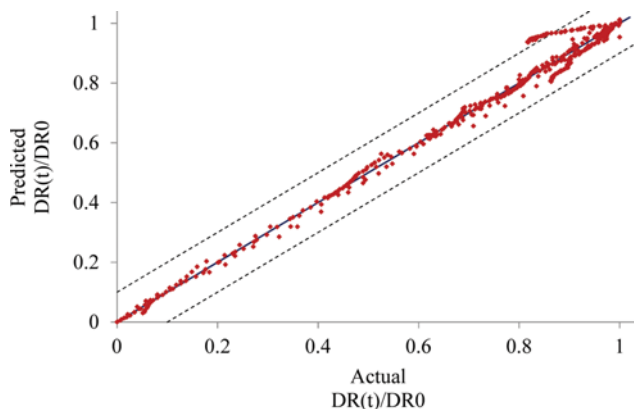Fitting these experimental data to the proposed model yields

Fig. 14. Comparison of actual relative drag reduction with the predicted ones via Eq. (2). The dashed lines are ±10% error and the solid line is the identity line y=x.

greater numbers for A_3 and A_4 as ion content of the working fluid increases (Table 3).

Also, Fig. 14 depicts the performance of our proposed model in predicting the degradation behavior of the various DRAs studied here. Statistically, all the predicted values fall within 10% of the experimental data. A good agreement was found between the model and experiment, in which most of the data are in the vicinity of y=x.

CONCLUSIONS

Time-dependent drag reduction can be strongly affected by some parameters like shear forces induced by pumps. Degradation behavior of polymers is an important parameter which shows their ability as an effective drag reducing agents. A shear resistance polymer is one that resists against mechanical forces and protects its chain against degradation. In this study the effects of addition of three water soluble polymers, an anionic copolymer of polyacrylamide (SF150), polyethylene oxide (PEO) and xanthan gum (XG), into some working fluids were evaluated. The objective was investigation of the shear resistance ability of the polymers under relatively high Reynolds number. The results confirmed that anionic copolymer (SF150) has a higher drag reduction potential and represents higher DR% with low concentrations. Polyethylene oxide did not show any reliable performance and degraded rapidly. Xanthan gum, however, did not represent high amounts of DR%, but no considerable degradation was found during the experiments.

The other parameter which can accelerate degradation of the polymer is the specification of the working fluids. To evaluate this effect, some working fluids with different physico-chemical specifications were employed. The results, which were evaluated with optimum concentration of SF150 and XG, showed no interaction between XG and working fluids, but SF150 degraded slightly in the water with higher ion content, due to interaction of dissolved ions in those fluids with the functional groups on the backbone. The cations dissolved in the working fluids can partially neutralize the charge on the polymer chain. Therefore, the polymer chain may collapse and find little chance to elongate. This limitation restricts the performance of the additive as drag reducer. All the relevant

results of degraded polymers were successfully correlated with a mathematically developed model, with some individual constant in each case.

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