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A Recipe for Optimum Mixing of Polymer Drag Reducers

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ABSTRACT

Preparation of large-scale homogeneous solutions of drag reducing polymers requires an appropriate mixing procedure to ensure full disentanglement of the polymer chains without chain scission due to over-mixing. The latter is known as mechanical degradation and reduces the performance of drag reducing polymers. The dominant large-scale mixing parameters including time, impeller type, impeller speed, and impeller-to-tank diameter ratio are investigated to obtain a recipe for maximum mixing with minimum polymer degradation. Three water-based solutions of 100 ppm Superfloc A-110 (flexible structure), Magnafloc 5250 (flexible structure), and Xanthan Gum (rigid structure) are considered. The performance of the mixing parameters for each polymer is evaluated based on the solution viscosity in comparison with the highest viscosity (i.e., optimum mixing) obtained by 2 hours of low-shear mixing of a small-scale polymer solution using a magnetic stirrer. The results demonstrate that optimum large-scale mixing is obtained at mean and maximum shear rates of ~17 s^{-1} and ~930 s^{-1}, respectively, after 2 – 2.5 hours of mixing for each of the polymers. This shear-rate is obtained here using a three-blade marine impeller operating at 75 rpm and at impeller - to -tank diameter ratio of 0.5. The resulting polymer solution has the highest viscosity, which is an indication of minimal degradation while achieving complete mixing. It is also confirmed that chemical degradation due to contact with a stainless steel impeller is negligible.

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INTRODUCTION

The addition of a small amount of high molecular weight polymer to a turbulent flow can reduce energy losses due to skin-friction drag by up to 80% [1]. This drag reduction (DR) phenomenon was first discovered by Toms [2] in 1948 and since then several investigations have been carried out on the performance and understanding of polymeric DR as reviewed by White & Mungal [3].

A challenge for application and also experimental investigation of DR polymers is the gradual chemical and mechanical degradation, and the consequent loss of DR performance [4]. In chemical degradation, the polymer structure is altered by a chemical reaction. For example, it has been speculated that contact of the polymer solution with the metal surface of a pipe can reduce DR [5]. However, Seright [6] observed that viscosity loss of a polymer solution as a result of contact with an iron surface is about 5% and negligible. Polymers may also degrade in the presence of dissolved oxygen although in some tests this has also been observed to be negligible [7, 8].

Mechanical degradation is caused by breaking of polymer chains to smaller segments due to the high shear of the flow field, mainly generated during mixing or pumping processes [8, 9]. Polymer molecules typically break up from the midpoint of the chain and this irreversible process is referred to as "scission" [10, 11]. The broken segments may not contribute to DR due to their lower molecular weight. Vanapalli et al. [10] stated that the interaction of the smallest scales of turbulence and the largest length-scale of the polymers determines the degree of mechanical degradation. The scission process results in a steady-state distribution of polymer molar mass in a flow facility for a given polymer structure and strain rate. The strength of the molecular bonds also plays a strong role in the scission process [12]. For example, Vanapalli et al. [13] reported that Polyacrylamide (PAM) is more resistive to mechanical degradation than

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Poly Ethylene Oxide (PEO). Minimizing mechanical degradation can enhance the amount and duration of DR.

Mechanical degradation of polymers during the mixing process is evident in the literature since different polymer concentrations were used to achieve a similar DR percentage. Table 1 shows the discrepancy between different experiments that were carried out with the same polymer type at comparable Reynolds numbers (Re = $\rho U D_p/\mu$), where ρ is the mixture density, U is the mean velocity, D_p is the pipe diameter, and μ is the mixture viscosity, but using different mixing procedures. Campolo et al. [14] and Escudier et al. [15] both tested 2,000 ppm of Xanthan Gum in turbulent channel flows at similar Re and obtained 60 and 46% DR, respectively. This is possibly caused by mechanical degredation since higher DR is expected at higher Re [1]. A similar discrepancy is observed for Sepran AP-271 polymer. Den Toonder et al. [4] and Gasljevic et al. [16] obtained 41-59% DR using 20 ppm of this polymer at Re = 12,400. About 22% discrepancy is observed in the DR percentage obtained by Warholic et al. [17] and Warholic et al. [18] using 1.25 ppm of Percol 727 at relatively similar of Re = 20×10^3. An important factor which has caused the variations in the DR percentages is the polymer preparation procedure and specifically, the lack of a standard mixing procedure.

Campolo et al. [14] mixed a master solution with a three blade impeller rotating at 150 to 360 rpm with unspecified mixing time. Escudier et al. [15] used a short mixing loop to mix the Xanthan Gum powder with the tap water using a Moyno pump without specifying the number of passes or time. Den Toonder et al. [4] prepared a high concentration master solution with 2 hour of stirring, then diluted and circulated it 3-4 times around the flow loop before DR measurements. Gasljevic et al. [16] wetted a polymer powder with alcohol and mixed it using a water jet without reporting the mixing time or speed. Ptasinski et al. [19] used a mixing vessel

for 10 hours, while Poursaeidesfahani [20] mixed their master solution with an unreported "lowest mixing speed" for 12 hours. Warholic et al. [17] prepared their solution by mixing the master solution with the deionized water for 4 hr with a 60 cm diameter four-finned impeller at 30 rpm. Warholic et al. [18] mixed the master solution then injected it to the main tank without reporting the mixing process. Although there is a myriad of investigations on polymer drag reduction, most researchers use an in-house mixing procedure without reporting critical details such as mixing time, impeller type, and speed.

Drag reducing polymers are classified into two groups: rigid and flexible polymers [21]. The filaments of the rigid-rod polymer (or rigid dumbbell polymer) are always fully extended (even in the absence of shear) as shown in Figure 1(a). This type of polymer does not need a relaxation time (or uncoiling time) to initiate DR and is expected to achieve drag reduction immediately after dissolution in the solvent [22]. Therefore, it is subject to the scission process from the early stages of the mixing process [23]. Rigid-rod polymers typically have a lower DR compared to flexible polymers [21].

Flexible polymers initially form a coil after the dissolution process (i.e., entanglement) and gradually uncoil by the shear stress of the flow field [24] as shown in Figure 1(b). DR occurs when a sufficient number of flexible polymers are fully extended [25]. The fully extended polymer chains interact with the turbulent eddies, reducing turbulent kinetic energy while they are also subject to the scission process. DR is maintained as long as there is a supply of coiled polymers to stretch and replace the broken polymers [22]. The scission process can also occur during the mixing process if prolonged mixing or mixing under excessive shear is applied. An optimum mixing process should disentangle the polymer molecules and fully extend them under moderate shear to prevent any degradation.

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To the authors' knowledge, only Fore et al. [8] investigated the effect of the polymer preparation on the DR percentage. In their study, the mixing time and the hydration time were investigated for 1,000 and 10,000 ppm master solutions to obtain final concentrations of 100 ppm of three different polymers: nonionic PAM, ionic Polyacrylamide (HPAM), and PEO. The mixing procedure was split into two steps; the first step was using a magnetic stirrer to dissolve the polymer before reaching the homogenous phase. The second step was rolling the mixture in a Cell Production Roll device to obtain a homogenous mixture with minimal shearing of the polymer mixture. The results showed that it was difficult to identify the effect of the stirring and rolling time for different types of polymers on the DR percentages. Consistent results were achieved with 12 hr of hydration time.

The current investigation involves a systematic evaluation of the effect of several dominant mixing parameters including impeller type, mixing speed (rpm), and time for preparation of large-scale polymer solutions. These parameters are investigated for three common drag reducing polymers (Superfloc A-110, Magnafloc 5250, and Xanthan Gum) with flexible and rigid structures. The mixing procedure is optimized based on achieving higher viscosity. The large viscosity is considered as a measure of complete entanglement and mixing of the polymer with minimum mechanical degradation. Finally, the recommended mixing condition is characterized by estimating the optimum shear rate.

METHODOLOGY

Mixing apparatus

A schematic of the experimental apparatus used to investigate the mixing parameters is shown in Figure 2. The mixing tank is cylindrical and not baffled, and is made from polyvinyl chloride with diameter of $T = 0.29$ m and height of $H = 0.3$ m. The experiments were carried out at a constant liquid height equal to the tank diameter (T) following the recommendation of

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Nienow [26]. The tank is filled with 18.0 liter of deionized water to avoid chemical degradation and ensure repeatability of the experiments [1]. Chloride or other additives such as salt can alter the solubility and molecular state (coil versus stretched) of the polymers [27]. Two stainless-steel impellers (marine and gate type) with diameter of D = 150 mm and 100 mm were used to mix the solutions, respectively. The selected impeller size results in impeller-to-tank diameter ratios of D/T = 0.34 and 0.51 as recommended by Özcan-Taşkin & Wei [28]. These impellers are commonly used in industry while they result in distincly different flow patterns. The different dismeters also result in tip vortices of different strength to evaluate the effect of strain rate.

A three-blade marine impeller generates a circulating pattern with downward axial flow as shown in Figure 3(a) [29]. It has a diameter of D = 0.15 m, depth of H_I = 33 mm, and shaft diameter of d = 10 mm. The second impeller is a gate-type impeller as shown in Figure 3(b) [30], which generates a double circulating flow pattern. The impeller has a diameter of D = 0.1 m, H_I = 95 mm, and d = 10 mm. Each impeller is placed at height C from the bottom of the tank, with C = H/2. Also these two impellers are made of stainless steel and are coated with polyvinyl chloride coating in one of the experiments to investigate any chemical degradation of the polymer solution due to metal contact. The impellers were connected to a variable speed mixer (Lightnin LabMaster L5U10F) to mix the solutions at different mixing speeds.

Mixing procedure

Water-based solutions with 100 ppm polymer were prepared using magnetic stirrer and also the impeller mixer. The magnetic stirrer can produce a relatively small amount of polymer solution (~1 liter) under low shear conditions to ensure minimum degradation. This is confirmed as the produced solution has a higher viscosity compared with the impeller mixing method. Different mixing speeds and mixing times are investigated in both methods. A polymer

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concentration of 100 ppm (0.01%) in water is investigated here since maximum DR can be reached in most DR studies with a concentration less than 100 ppm [1, 29, 30].

A glass beaker with 145 mm diameter was filled with 1 liter of deionized water and placed on the magnetic stirrer. Stirring was carried out using a 64 mm (2.5 in) stirrer bar located in the middle of the beaker. In order to obtain 100 ppm polymer solution, 0.1 gram of polymer was measured and gradually added. The mixture was inspected every 30 minutes to recirculate any possible polymer powder deposited on the beaker side-wall.

The large-scale polymer solution was prepared using the impeller mixer by pouring 14 liters of deionized water in the stirring vessel followed by addition of 1.0 gram of polymer to the vortex shoulder. An additional 4 liters of deionized water and 0.8 gram of polymer was gradually added. This procedure was followed to prevent agglomeration of polymer particles at the surface. All samples were degassed before viscosity measurement at least for 12 h [8]. Table 2 lists the mixing parameters and ranges investigated. Experiments were also carried out by coating the marine impeller with a paint layer (Rust-Oleum) to evaluate possible chemical degradation of the polymers from contact with stainless steel surface during the mixing procedure.

Polymer type

Three types of water soluble polymers: Superfloc A-110 (Kemira), Magnafloc 5250 (BASF), and Xanthan Gum (Baroid) are investigated. Both Superfloc and Magnafloc are flexible polymer chains with similar chemical structure but different molecular weight (MW). Magnafloc 5250 is a neutral (or non-hydrolyzed) polyacrylamide (PAM) with one repeated monomer. This polymer is broadly used in water treatment and has high MW of 10-25 $\times 10^6$ g/mol [33]. The strong steric repulsion between PAM chains is due to the strong hydrosolubility in water [34].

Superfloc A-110 is a long-chain polymer with MW of 6-8 $\times 10^6$ g/mol [9]. This polymer has been applied as a drag reducer in many studies since it has high resistance to mechanical

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degradation due to its strong chemical bonds [20, 35]. Superfloc A-110 is a partially hydrolyzed polyacrylamide (PAMH) and consists of two monomers [9]. This polymer has strong solubility in water, which does not significantly change in salty solutions [36].

Xanthan Gum (XG) is a nontoxic bio-polymer used in the food and medical industries. XG is extracellular polysaccharide (EP) and has a MW of 1-2 $\times 10^6$ g/mol [22]. Xanthan Gum is relatively sensitive to temperature and presence of salt in the solvent [37]. Also XG can undergo immediate mechanical degradation as it is a rigid (stiff) type polymer [22]. Xanthan structure formed by a repeated primary structure connected to a side chain [39].

Viscosity measurement

Viscosity measurements were carried out using an Anton Paar DG42/Q1 viscometer equipped with a double-gap measuring system (20649) allowing viscosity measurement at high shear rates (150 to 1100 1/s) relevant to turbulent pipe flows. This system allows measurement in low viscosity solutions as the small clearance prevents formation of Taylor vortices and transition to turbulent flow at high angular velocities [40]. The viscometer is equipped with a heat exchanger to keep the temperature at 25ºC. Samples with 12.0 ml volume were collected and degassed before viscosity measurement. Viscosity measurement at each shear rate is carried out for 6 seconds. The total duration of viscosity measurement for each polymer sample is 9 minutes covering shear rates from 50 to 1100 1/s.

Measurement uncertainties

It is important to identify the uncertainty of the mixing procedure and the subsequent viscosity measurement. Walker and Tiederman [41] verified the repeatability of their magnetic mixing by measurement of the viscosity of the 5000 ppm master solution of Separan AP-273, and also DR measurement using a diluted 100 ppm solution in a smaller flow loop facility.

Therefore, in this investigation, the repeatability of the mixing procedure is confirmed by preparing Magnafloc 5250 solution three times at 100 ppm using the marine impeller rotating at 75 rpm for 2.5 hours. Viscosity measurements were carried out on each sample and the results are shown in Figure 7. The error bars represent minimum and maximum of viscosity (peak-to-peak) for the three measurements. Therefore, the mixing procedure and viscosity measurements are repeatable and the uncertainties are smaller in a range of shear rates from 300 to 1100 s^{-1}.

The Carreau-Yasuda model, which is commonly used for shear thinning fluids [42], is used to evaluate the viscosity measurements shown in Figure 4. The Carreau-Yasuda model of μ_c is expressed as [43]:

$$\mu_c = \mu + (\mu + \mu_0)\left(1 + (\lambda + \dot{\gamma})^a\right)^{n-1/a}$$

(1)

where μ_0 is the zero shear rate viscosity, $\dot{\gamma}$ is the shear rate, n is the power-law flow index ($n = 0.55$), while a and λ are constants. The latter two constants are estimated using weighted nonlinear least square regression and are equal to $a = 2$ and $\lambda = 5$ s^{-1}. As seen in Figure 4, the viscosity measurments are in agreement with the Carreau-Yasuda model.

RESULTS

Viscosity measurement for different mixing parameters (mixing time, mixing rate, and impeller type and material) are reported in this section. The reference impeller is the marine type since it produces a lower shear rate and consequently less degradation. In addition, the reference polymer is Magnafloc 5250 as it is one of the common drag reducers. The impeller mixing is compared with a reference solution obtained using the magnetic stirrer as detailed below.

Reference polymer solution

The reference polymer solution refers to the 100 ppm solution obtained using the magnetic stirrer set at a stirring speed of 100 rpm. The use of the magnetic stirrer results in

higher viscosity due to its low shear mixing. The stirring bar (magnet) is smaller and has round edges which prevents formation of strong shear layers with large velocity gradients.

The effect of mixing time on the viscosity of the polymer solution prepared using the magnetic stirrer is shown in Figure 5. It is observed that the viscosity of the polymer solution increases with time and reaches a maximum within 2 hours. Further mixing results in mechanical degradation of the polymer molecules and reduction of viscosity through the scission process. The viscosity measurements indicate that the majority of the polymer chains are relaxed and have reached their maximum extension by 2 h of mixing. This solution with maximum viscosity is used as the reference for comparison with the large scale mixing tasks.

Mixing time

The polymer chains gradually extend (increase in length) until they reach full extension. Beyond this point, the polymer chains break down to two smaller segments by the shear stress of the flow field. Figure 6 shows the effect of mixing time using the marine impeller on Magnafloc 5250 mixed at 75 rpm for three hours. Every 30 minutes, a 25 ml sample was collected for viscosity measurement. It is noticed that viscosity rapidly increases within the first hour of mixing then gradually increases in the next 1.5 hours. Further mixing degrades the polymers and reduces the solution viscosity. It is also observed that the maximum viscosity obtained after 2.5 h using the impeller is still less than the viscosity of the solution obtained from the magnetic stirrer. This indicates degradation of some of polymer molecules during the mixing process.

The effect of mixing time on Superfloc A-110 was also investigated over 3 h of mixing at 75 rpm and shown in Figure 7. The results show that this polymer followed similar behavior as the Magnafloc 5250. The viscosity of Superfloc A-110 solution increases within the first hour of mixing then stays constant for 1.5 h before decreasing. This trend is expected to vary based on the rigidity of the polymer chain. For instance, in Figure 8, it can be seen that the viscosity of the

XG solution rapidly increases with the first hour, maintains the high viscosity for a relatively short duration (about 30 min) and is followed by a sudden large reduction of viscosity.

Figure 9 illustrates the average viscosity in the 500 to 1100 s^{-1} shear rate range as a function of mixing time for the three different polymers. The averaging procedure was chosen to avoid any bias in the results based on a selected shear rate. It was also shown in Figure 4 that the uncertainty level is smaller at shear rates larger than 500s^{-1}. The results show that the duration of maximum viscosity (optimum mixing) for the flexible polymers (Superfloc A-110 and Magnafloc 5250) is longer than the rigid polymer (XG). The flexible polymers have a gradual degradation while XG shows a sudden reduction in viscosity. This is associated with the rigid structure of the XG polymer which does not elongate overtime and thus the scission process starts immediately after disentanglement. In general, the maximum viscosity for different polymers using the marine impeller mixer was obtained after 2-3 h of mixing for the flexible polymers and after 1.5 to 2 h for the rigid polymer.

The mixing process is not stationary within the span of the investigated mixing time (i.e., up to 3 hours). As it was observed, the solution viscosity initially increases within the first 2 hours and then reduces. It is expected that the viscosity to reach a steady-state condition after a long mixing time (~10 hours). However, the final steady-state condition will not be the optimum solution since the maximum viscosity was passed after 2 hours of mixing. The final steady state-condition will have a steady distribution of molar mass depending on the strain field and molecular properties [10].

Mixing rate

Mixing speed is directly related to the intensity of shear stress within the flow, therefore, it affects the dissolution and degradation of polymer molecules. Here, various mixing speeds (from 50 to 150 rpm of the marine impeller) are investigated and compared with the magnetic

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stirrer results. It was not practical to mix the solution at speeds lower than 50 rpm as the polymer powders remained in the periphery of the tank and were not entrained into the flow. At mixing rates higher than 150 rpm, a large swirling cone was formed at the center of the tank.

The effect of mixing speed on rheological characteristics of a 100 ppm Magnafloc 5250 solution is shown in Figure 10, Figure 11, and Figure 12 for mixing rates of 50, 100, and 150 rpm, respectively. As can be seen in these figures, the viscosity curves follow a similar trend in time. There is an initial rapid increase of viscosity in the first hour, which is followed by a stable region with small changes in viscosity and finally a rapid decrease due to the scission process. However, the viscosity variation in time is smaller in Figure 12 when high rpm mixing is applied; the viscosity curves are relatively close to each other. It is also observed that the magnetic stirrer generates a solution with larger viscosity in Figure 10, 11, and 12. Therefore, the magnetic stirrer causes less degradation during the mixing process compared with the impeller mixer. The smaller degradation of the magnetic stirrer is associated with its round edges, which produce weaker tip vortices. The results are summarized in Figure 13 by plotting the viscosity averaged in 500 to 1100 1/s shear rate range as a function of mixing time. The mixing at 50 rpm was carried out over 4h as the dissolution process required a longer time (Figure 10). It is conjectured that the breakup of polymers also occurs during the mixing since there is a sharp reduction in average viscosity after reaching the maximum within 2.5 to 3 hours. The 100 rpm mixing of Figure 11 follows the same trend of the 75 rpm case (Figure 6). The faster mixing at 150 rpm did not reach the maximum viscosity achieved at lower mixing speeds.

Impeller type and material

It has been noticed from initial experiments that the impeller type can affect the degradation rate. Therefore, in addition to the conducted tests using the marine impeller, a gate impeller was included. These impellers are common in industry [26] and produce different flow

patterns as shown in Figure 3. The tip velocity, tested rpm, and the power number (N_p) of each impeller are listed in Table 3. The power number is estimated from:

$$N_p = \frac{P}{\rho N^3 D^5}$$

<div align="right">(2)</div>

where P is the input power in Watts which was measured by the load cell included with the mixer, N is the rotational speed (1/s), ρ is the density of fluid (kg/m^3), D is the impeller diameter (m). The two impellers were used to produce 100 ppm Magnafloc 5250 solution. The solution became quickly homogenous with the gate impeller and no particles could be seen in the solution after about 40 minutes. However, the polymer powders stayed visible until approximately 1 h with the marine impeller as it generates a low shear mixing. The results of Figure 14 show the maximum viscosity curves which occurred after 2.5 h for the marine impeller and after 1.5 h for the gate impeller. It can be seen that the marine impeller produced a higher viscosity solution although it required a longer mixing time. The gate impeller, with higher mixing intensity, results in more severe degradation and produces a lower viscosity solution.

The possibility of chemical degradation of the polymers due to contact with a stainless-steel (SS) impeller was also studied by coating the marine impeller and rod with an ultra-polyurethane (oil base paint). The 100 ppm Magnafloc 5250 solution was stirred for 2.5 h at 75 rpm using coated and non-coated marine impeller. The viscosity comparison shown in Figure 15 indicates negligible differences. The slightly larger viscosity of the non-coated impeller is associated with experimental uncertainties.

DISCUSSION

The results showed that optimum mixing is achieved at 75 rpm using the marine impeller after 2-2.5 h of mixing with impeller-to-tank diameter ratio of 0.51. This mixing recipe resulted in the same viscosity as the one obtained using the magnetic stirrer. In this section, the average

and maximum shear rate during the optimum mixing is estimated to provide guidelines for different mixing equipment. The estimated shear rates will allows us to adjust the rpm of different impellers and obtain a condition similar to the optimum mixing condition obtained here. The first step in estimation of the shear rates is to determine the flow region (laminar or turbulent) during the mixing process. The flow regime is estimated using the impeller Reynolds number defined as [44]

$$\text{Re}_T = \frac{\rho N D^2}{\mu}.$$

(3)

The estimated Re_T for the magnetic stirrer at 100 rpm is 2,100. For the marine impeller, $\text{Re}_T > 10^4$ for all mixing speeds (50 - 150 rpm) and polymer types. Therefore, the flow inside the magnetic stirrer tank is laminar while it is turbulent for the marine impeller. The average shear rate within a laminar mixer is a function of N and can be calculated using

$$\gamma_m = \left(\frac{N_p \text{Re}_T}{2\,\pi}\right)^{0.5} N.$$

(4)

where $N_p = 0.28$ for the magnetic (estimated from equation 2). The mean shear for the turbulent mixing condition is calculated using

$$\gamma_m = \left(\frac{N_p \rho D^2}{2\,\pi\,k}\right)^{\frac{1}{1+n}} N^{\frac{3}{1+n}}.$$

(5)

where k is the consistency index (Pa.s^n) based on $\tau = k\,\gamma^n$. For the Magnafloc 5250 solution prepared using the optimum recipe $k = 0.011$ Pa.s^n. Equation 5 is used for turbulent flow in non-Newtonian fluids.

Figure 16 shows the mean shear rate for different mixing speeds as a function of mixing time. As can be observed, the mean shear rate for the magnetic stirrer at 100 rpm is 17 s^{-1} during the mixing time (estimated based on equation 4). It should be noted that a similar shear rate,

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$\gamma_m \sim 21$ s^{-1}, is obtained with the marine impeller operated at 75 rpm. The similar values of the shear rate for the two flow fields agrees with the similar viscosities obtained using the magnetic stirrer at 100 rpm and the marine impeller at 75 rpm. In contrast, the gate impeller has created higher shear rates of about 48.3 s^{-1} and does not provide optimum mixing. Therefore, the impeller type has a strong effect on the shear rate, which in turn affects the rate of mechanical degradation of the polymer chains. The analysis of figure 16 shows that a mean shear rate of about 20 s^{-1} is ideal for polymer mixing.

Table 4 shows the values of the mean shear rates (γ_m) for different mixing speeds over 3 h of mixing for the three polymer types. The summary in this table shows that mixing at 75 rpm using the marine impeller provides the optimum shear rate of $\sim$20 s^{-1} in all three polymeric solutions. This mean shear rate is close to the shear rate of the magnetic stirrer, which provides a laminar mixing.

The maximum shear rate (γ_{max}) in the mixing tank is calculated from the theoretical expression reported by Wichterle et al. [45] from

$$\gamma_{max} = N(1 + 5.3n)^{1/n}\left(\frac{N^{2-n}\rho D^2}{k}\right)^{1/(1+n)}$$

(6)

It should be noted that Equation 6 was originally developed to estimate the shear rates around rotating flat disks. However, it was successfully evaluated for estimation of the maximum shear rate for turbine and marine impellers in Newtonian and non-Newtonian fluids by Wichterle et al. [45]. The estimations of γ_{max} for the marine impeller at different rpms is shown in Figure 17. As it is expected, γ_{max} generated by the marine impeller increases with increase of mixing speed. It is also observed that γ_{max} stays relatively constant in time although the rheology of the mixture (n and k parameters) changes. The summarized values of γ_{max} in Table 4 also show that the

optimum mixing condition (marine impeller at 75 rpm) produces a maximum shear rate of ~900 s^{-1} in all the three polymeric solutions.

CONCLUSION

The optimum mixing procedure for preparation of large-scale drag reducing polymer solutions has been experimentally investigated. The effect of several parameters including type and speed of the impeller, mixing time, and impeller coating are investigated. These parameters are studied for three common drag reducing polymers which include Superfloc A-110 (flexible structure), Magnafloc 5250 (flexible structure), and XG (rigid structure). The mixing procedure is optimized based on achieving maximum solution viscosity. The large-scale mixing results were compared with a reference polymer solution produced using a magnetic stirrer with $\gamma_m = 17 \ s^{-1}$.

The measurements have shown that the average viscosity of each polymer solution increases at the early stages of mixing as polymer chains disentangle and dissolve in the solvent. The process continues for about an hour until the average viscosity reaches a maximum. At this point, all the polymer chains are dissolved and further mixing results in degradation of the chains through polymer scission. The plateau of the maximum viscosity is achieved gradually and maintained for up to 2 h for the flexible polymer solutions (Superfloc A-110 and Magnafloc 5250). However, the viscosity plateau of the rigid XG polymer is quickly achieved and is followed by a rapid degradation. A similar mixing trend is observed in time for shear rate of 10 - 20 s^{-1} while a rapid degradation with lower viscosity is observed for higher shear rates (about 40 s^{-1}). The gate impeller resulted in more severe degradation and lower viscosity in comparison with the marine impeller. The contact of the polymer solution with the metal impeller during the mixing period did not result in chemical degradation.

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The results demonstrated that optimum mixing is obtained at 20 s^{-1} mean shear rate after 2 – 2.5 h of mixing. This shear rate was obtained at 75 rpm using the three-blade marine impeller and a $D/T = 0.5$. The resulting polymer solution has the highest viscosity, which indicates less degradation has occurred while achieving maximum mixing. Subsequent analysis showed that this optimum mixing procedure generates an average shear in the large mixing tank that is similar to that of the magnetic stirrer. The maximum shear rate calculations show that the three tested polymer experienced similar maximum shear rate ($\gamma_{max} = 930$ s^{-1}) when they were mixed using the optimum mixing recipe.

ACKNOWLEDGMENT

NOMENCLATURE

Re = Reynolds number in pipes

ρ = mixture density (kg/m^3)

μ = mixture viscosity (Pa.s)

μ_c = Carreau-Yasuda model viscosity (Pa.s)

μ = Newtonian viscosity (Pa.s)

μ_0 = zero shear rate viscosity (Pa.s)

a = Carreau-Yasuda model constant

λ = Carreau-Yasuda model constant (s^{-1})

U = mean velocity (m/s)

D_p = pipe diameter (m)

DR = drag reduction

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H = mixing tank height (m)

C = impeller distance from the tank base (m)

T = mixing tank diameter (m)

D = impeller diameter (m)

H_I = impeller height (m)

d = rod diameter (m)

Re_T = impeller Reynolds number

N = impeller rotational speed (s^{-1})

N_p = impeller power number

P = power input (W)

γ_m = mean shear rate in a mixer (s^{-1})

γ_{max} = maximum shear rate in a mixer (s^{-1})

γ = shear rate (s^{-1})

n = power-law flow index

k = consistency index ($Pa.s^n$)

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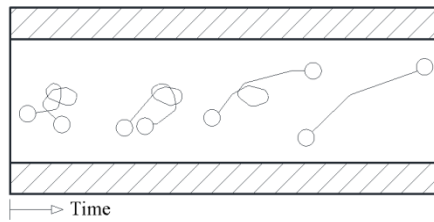
Figure Captions List

Fig. 1   Schematic of the stretching process (a) for rigid rod polymer and (b) for flexible polymer in time under shear stress. The rigid polymer does not evolve while the flexible polymer gradually uncoils to form an elongated structure
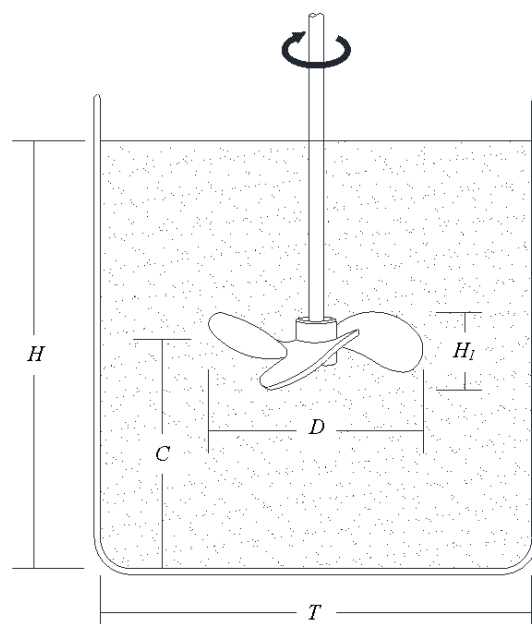
Fig. 2   Schematic diagram of the mixing apparatus for preparation of 18 liters of polymer solution at 100 ppm

Fig. 3   Flow pattern generated by (a) marine type, (b) gate type impellers according to Winardi and Yoichi Nagase [29] and Bakker et al. [30]

Fig. 4   Measurements repeatability for three Magnafloc 5250 solutions mixed with marine impeller for 2:30 h at 75 rpm. The error bars represent peak-to-peak viscosity for three measurements. Carreau-Yasuda model is included for validation [43].

Fig. 5   Rheological characterization of 100 ppm of Magnafloc 5250 in water at different mixing times using a magnetic stirrer at 100 rpm

Fig. 6   Rheological characterization of 100 ppm of Magnafloc 5250 in water for different mixing time. Mixing is carried out using marine impeller at 75 rpm in 18 liters of solution. The error bars show maximum variation based on uncertainty analysis of Figure 4

Fig. 7   Rheological characterization of 100 ppm of Superfloc A-110 in water for different mixing time using a marine impeller at 75 rpm

Fig. 8   Rheological characterization of 100 ppm of XG in water for different mixing time using a marine impeller at 75 rpm

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Table Captions List

(a) Rigid rod polymer

(b) Flexible polymer

Figure 1 Schematic of the stretching process (a) for rigid rod polymer and (b) for flexible polymer in time under shear stress. The rigid polymer does not evolve while the flexible polymer gradually uncoils to form an elongated structure
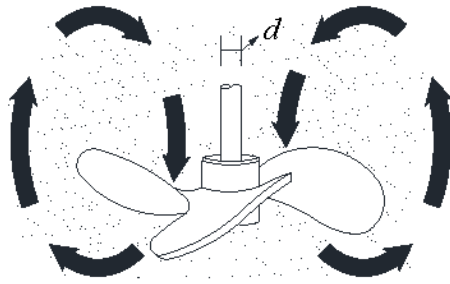
Figure 2 Schematic diagram of the mixing apparatus for preparation of 18 liters of polymer solution at 100 ppm
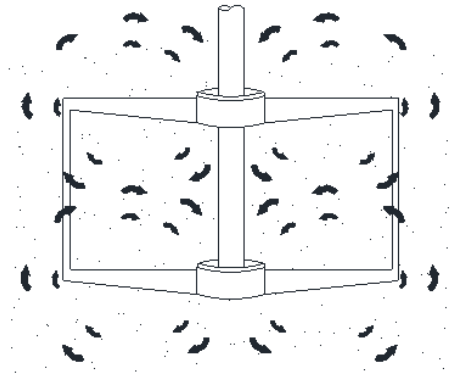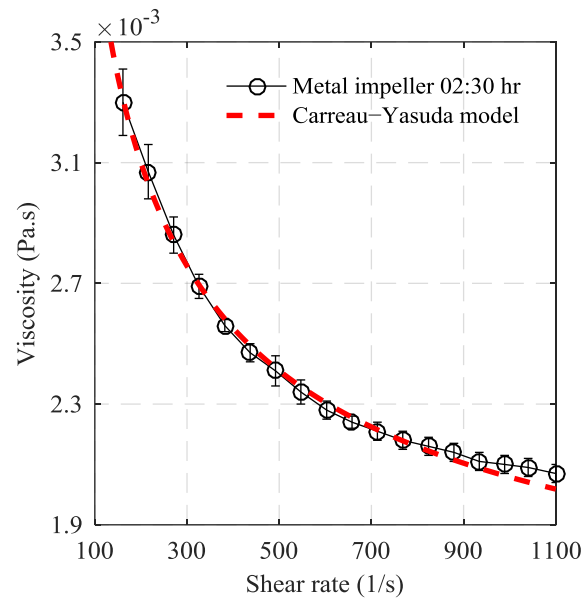
(a) Marine type

(b) Gate type

Figure 3 Flow pattern generated by (a) marine type, (b) gate type impellers according to Winardi and Yoichi Nagase [29] and Bakker et al. [30]

Figure 4 Measurements repeatability for three Magnafloc 5250 solutions mixed with marine impeller for 2:30 h at 75 rpm. The error bars represent peak-to-peak viscosity for three measurements. Carreau-Yasuda model is included for validation [43]
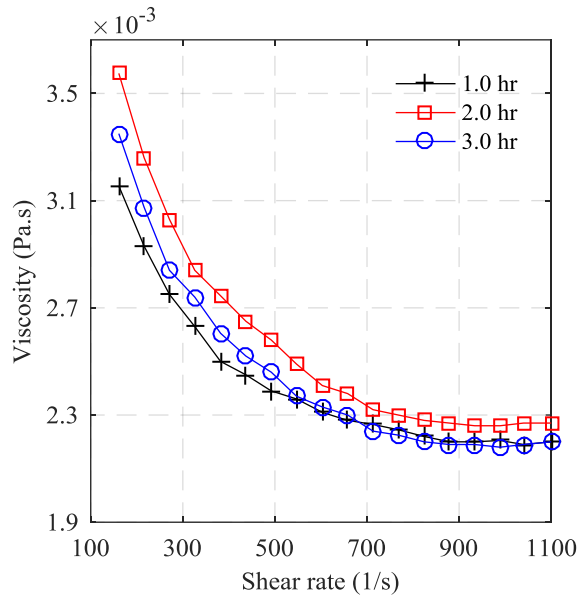
Figure 5 Rheological characterization of 100 ppm of Magnafloc 5250 in water at different mixing times using a magnetic stirrer at 100 rpm
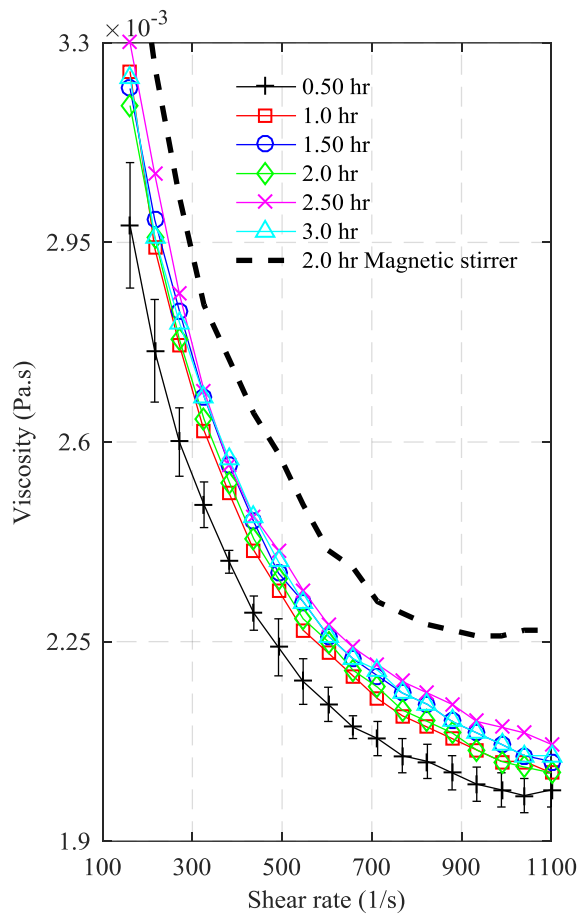
Figure 6 Rheological characterization of 100 ppm of Magnafloc 5250 in water for different mixing time. Mixing is carried out using marine impeller at 75 rpm in 18 liters of solution. The error bars show maximum variation based on uncertainty analysis of Figure 4
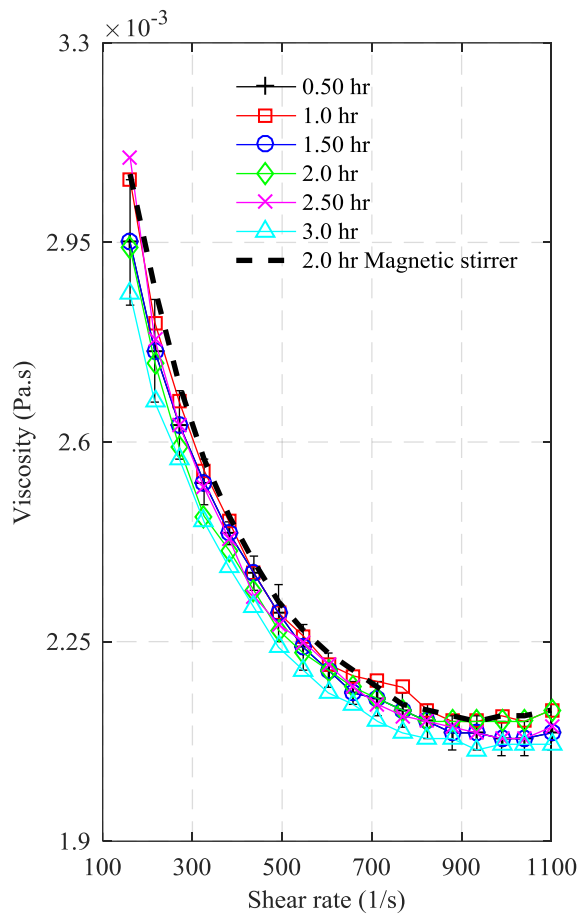
Figure 7 Rheological characterization of 100 ppm of Superfloc A-110 in water for different mixing time using a marine impeller at 75 rpm
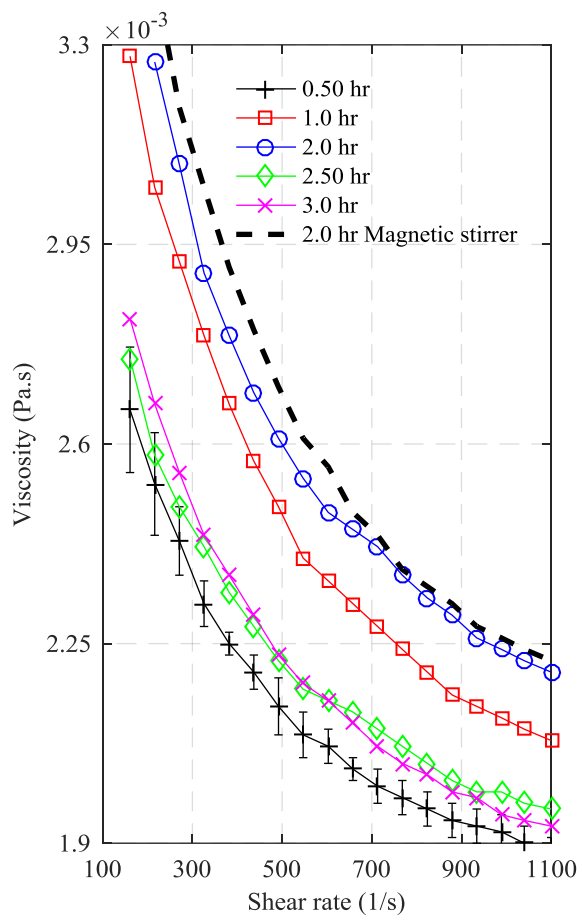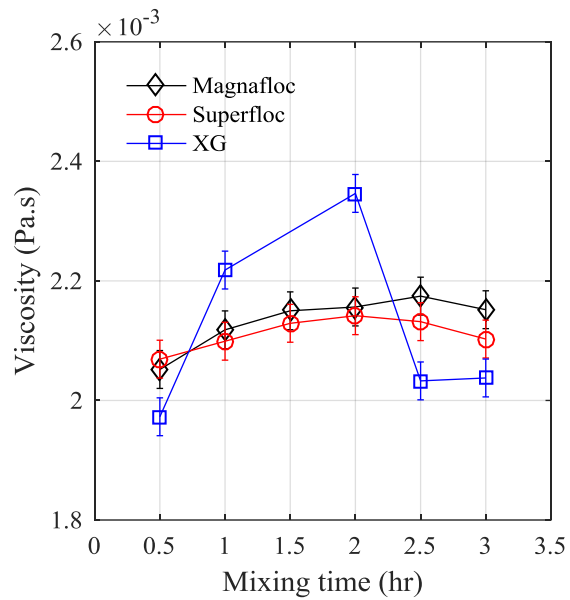
Figure 8 Rheological characterization of 100 ppm of XG in water for different mixing time using a marine impeller at 75 rpm

Figure 9 Viscosity versus time for the three polymers (Magnafloc 5250, Superfloc A-110, and XG) at average shear rate range of 500 to 1100 s^{-1}. Mixing is carried out using the marine impeller at 75 rpm
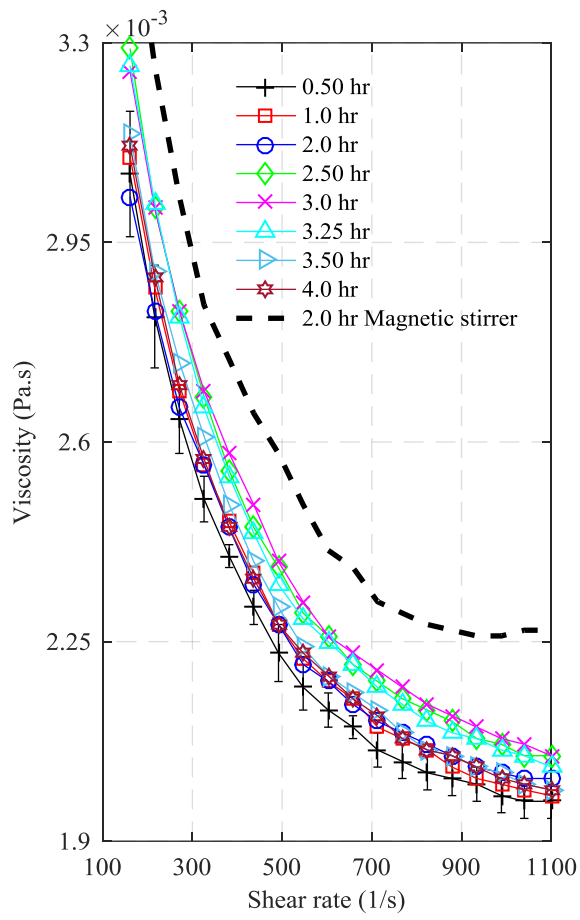
Figure 10 Rheological characterization of 100 ppm of Magnafloc 5250 in water for different mixing time using a marine impeller at 50 rpm
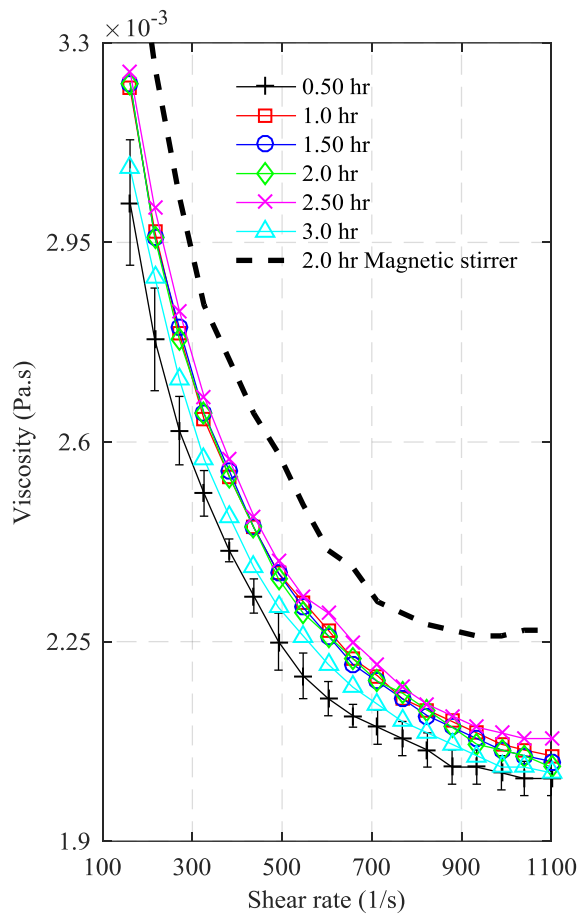
Figure 11 Rheological characterization of 100 ppm of Magnafloc 5250 in water for different mixing time using a marine impeller at 100 rpm
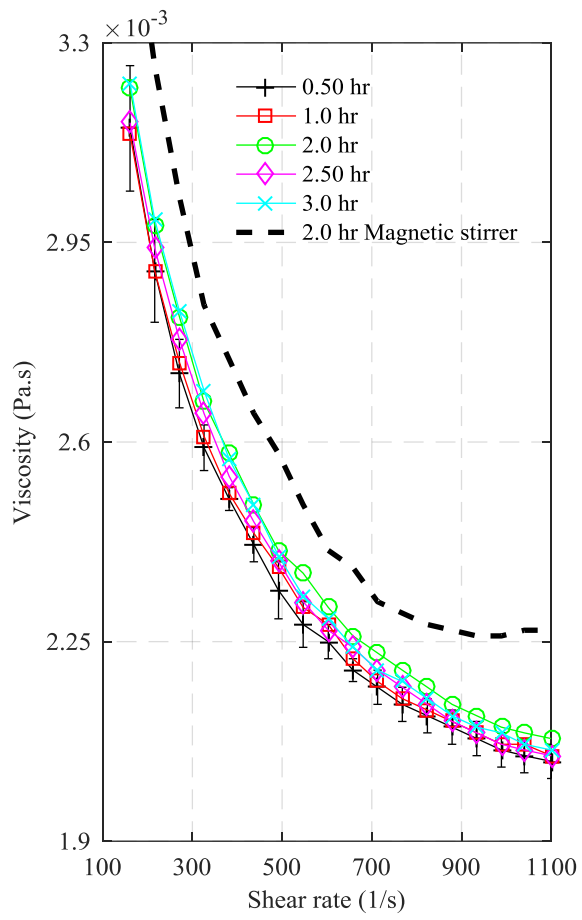
Figure 12 Rheological characterization of 100 ppm of Magnafloc 5250 in water for different mixing time using a marine impeller at 150 rpm
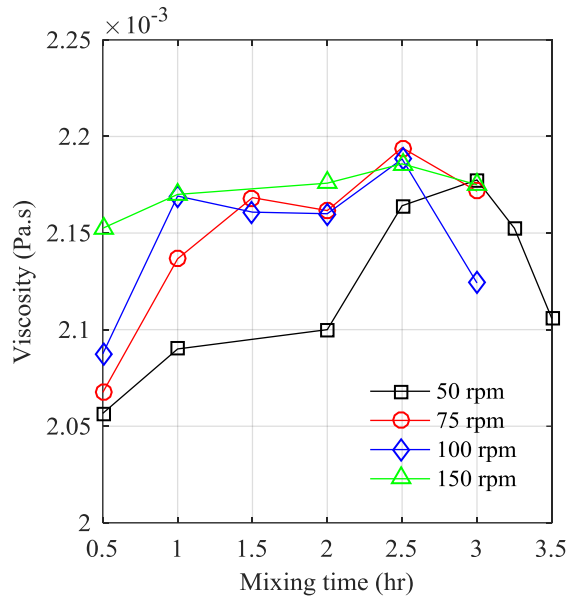
Figure 13 Comparison of different mixing rates of 100 ppm Magnafloc 5250 polymer solution using the marine impeller. The average viscosity was estimated for 500 to 1100 1/s shear-rate range
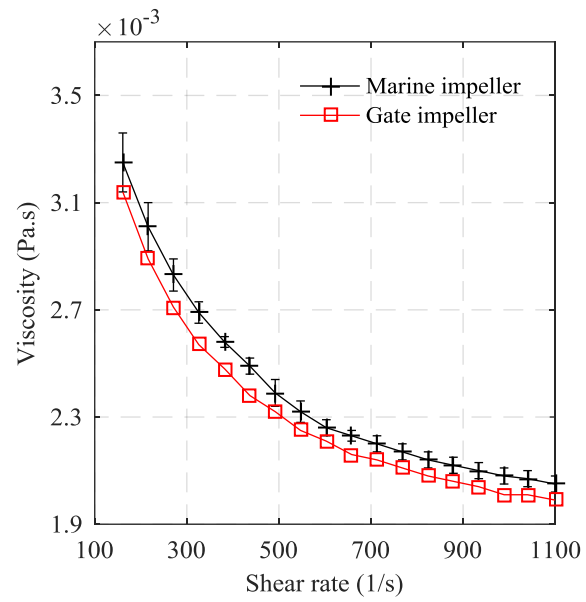
Figure 14 Comparison of 100 ppm Magnafloc 5250 solutions mixed over 2.5 h using the marine impeller and over 1.5 h using the gate impeller at 75 rpm
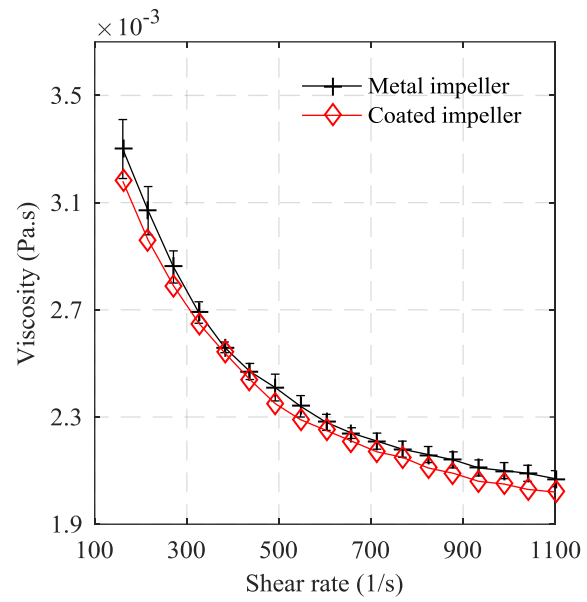
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Figure 15 Comparison between metal and coated impellers. Mixing is carried out on 100 ppm Magnafloc 5250 at 75 rpm over 2.5 hr
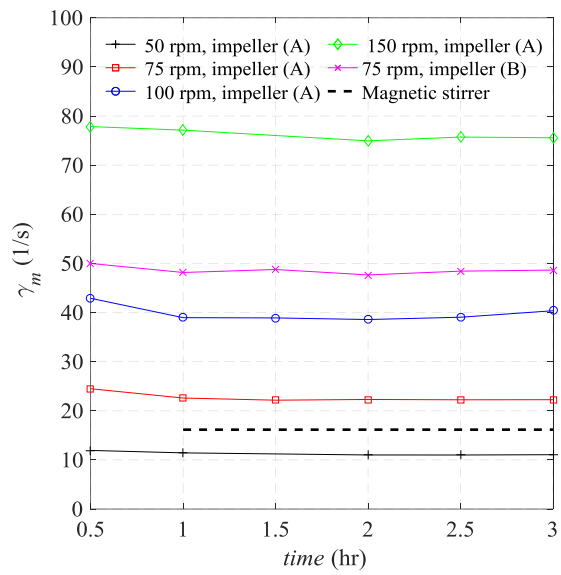
Figure 16 Average shear rates for different mixing speeds and impeller types for 100 ppm Magnafloc 5250 solution: impeller (A) is the marine impeller and impeller (B) is the gate impeller
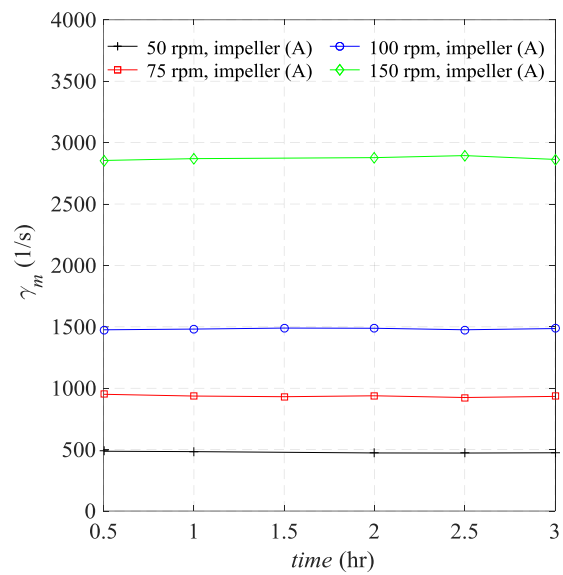
Figure 17 Maximum shear rates for different mixing speeds for 100 ppm Magnafloc 5250 solution where impeller (A) is the marine impeller

Table 1 An overview of the polymer concentration and achieved DR in previous experiments

Polymer type	Concentration (ppm)	Re	Preparation parameters			DR %	Reference
			Type	Speed (rpm)	Time (hr)		
Xanthan Gum	2000	3000	Impeller mixer	150-360	-	60	Campolo et al. [14]
Xanthan Gum	2000	5000	Mixing loop	-	-	46	Escudier et al. [15]
Separan AP-273	20	12,400	Stirrer	-	2	59	Den Toonder et al. [4]
Separan AP-273	20	12,400	Water jet	-	-	54	Gasljevic et al. [16]
Percol 727	1.25	19700	Impeller mixer	30	4	19	Warholic et al. [17]
Percol 727	1.24	19900	Impeller mixer	-	-	41	Warholic et al. [18]
Superfloc A-110	100	9,400	-	-	12	58	Poursaeidesfahani [20]
Superfloc A-110	100	14,000	-	-	12	62	Poursaeidesfahani [20]
Superfloc A-110	103	11,950	Mixing vessel	-	10	63	Ptasinski et al. [19]
Superfloc A-110	150	9,400	-	-	12	68	Poursaeidesfahani [20]
Superfloc A-110	175	9,760	Mixing vessel	-	10	65	Ptasinski et al. [19]

Table 2 The investigated parameters for preparation of large-scale polymer solution

Investigated parameter	Range/type
Mixing time	00:30 to 4:00 hours
Mixing speed	50 to 250 rpm
Impeller type	Marine / Gate
Impeller surface	Stainless steel / Paint

Table 3 Details of marin and gate impellers

Impeller type	Mixing speed (rpm)	Tip velocity (m/s)	Power number N_p
Marine impeller	75	0.6	0.34
Gate impeller	75	0.4	4.1

Table 4 Summary of the calculated mean and maximum shear rates based on the mixing conditions

Polymer	Impeller type	Speed (rpm)	$\gamma_m(s^{-1})$	$\gamma_{max}(s^{-1})$
Magnafloc 5250	Marine type	50	11	478
	Marine type	75	22	935
	Marine type	100	40	1482
	Marine type	150	76	2871
	Gate impeller	75	49	-
	Magnetic stirrer	100	17	-
Superfloc A-110	Marine type	75	25	927
	Magnetic stirrer	100	17	-
Xanthan Gum	Marine type	75	23	941
	Magnetic stirrer	100	17	-