

HT-FED04-56432**Mechanical Degradation Effects on Turbulent Flows with Macro-Molecular Polymer Structures**

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ABSTRACT

Macro-molecular polymer structures due to either the entanglement of polymer molecules or the ionic character of the polymer, have been shown in the literature to enhance the drag reducing abilities of polymer solutions in internal water flows. The purpose of this study is to contrast the performance of an ionic and a non-ionic polymer as drag reduction agents with and without the presence of such macro molecular polymer structures. The endurance of such polymer structures to mechanical degradation is also assessed and documented herein. It will also be shown that special attention needs to be paid to the design of optimum polymer delivery systems since they can contribute to the formation or to further enhancing the drag reducing abilities of homogeneous polymer solutions.

I. INTRODUCTION

Wall shear stress can be reduced by the presence of small amounts of water soluble polymer additives in turbulent flows. While this phenomena is well known since the mid 1940s, the physical mechanism by which drag reduction takes place in turbulent polymer flows is still not fully understood. Among the many theories developed in time, the one by Lumley [1] seems to be the one most commonly accepted. It proposes that the mechanism for drag reduction is an increased viscosity near the wall, caused by the elongational deformation of the polymer molecules by the turbulence. Studies of heterogeneous polymer flows indicate that the presence of polymer structures in the flow might also play a significant role and in fact enhance the drag reduction abilities of single polymer molecules (Dunlop and Cox [2], Warholic [3], Kim et al. [4], Shen et al. [5],

Vlachogiannis and Hanratty [6] among others). The presence of such polymer structures can be due to polymer aggregation considered here to be caused mainly by the ionic character of the polymer (such as hydrolyzed polyacrylamides (HPAM)) in which case structures can be found with relatively smaller polymer concentrations than in the case of non-ionic polymers. It is presumed herein that in the case of non-ionic polymers the majority of the polymer structures might be due to the mechanical entanglement of the polymer molecules. In these cases a much larger polymer concentration might be required. In fact, the studies of Warholic et al. [3], Vlachogiannis and Hanratty [6] and Vlachogiannis et al. [7] show that concentrations of HPAM of 500ppm can produce structured solutions when injected in the wall of a channel flow. Studies such as those by Vlegaar and Tels [8], Smith and Tiederman [9], Bewersdorff et al. [10], etc. focus on the study of highly concentrated non-ionic polymer solutions injected into the core region of turbulent pipes or channels. They show that if the polymer concentration is larger than 4,000ppm a single coherent thread is formed that preserves its identity for long distances after injection. The studies of Shen et al. [5] and Kim et al. [4] show that when polymer solutions of PAM with concentrations lower than 3,000ppm are injected at the wall of a channel flow there are no appreciable polymer structures formed for a channel Reynolds number of 5×10^4 . Measurements of the mean velocity and turbulence characteristics for the same average concentrations with and without such polymer structures reveal that the presence of the polymer structures alter the properties of the fluid turbulence and increase the levels of drag reduction achieved considerably.

The purpose of the present work is to compare the resistance to degradation of polymer solutions of both

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PAM and HPAM with and without the presence of macro-molecular polymer structures. As such, samples with the same concentration corresponding to homogeneous solutions are compared to samples drawn from the test section of a channel filled with structured polymer. These samples are run through a pipe several times and the corresponding levels of drag reduction recorded and compared. The study was performed for a wide range of Reynolds numbers to ascertain, to the extent possible, the generality of the conclusions regarding the role played by the presence of polymer structures in drag reduction.

The formation of macro-molecular polymer structures can be tied up with the process followed to prepare the polymer solutions, or with the effects of the polymer delivery system or they could even be induced by the flow to which the polymer solution is added if the shear rates are large enough. If indeed polymer structures are better drag reduction agents than polymer molecules, more attention needs to be brought to optimize the design of the polymer injection system as well as to the procedure followed to prepare the polymer solutions.

Experiments are performed in a rectangular water channel. The facility is a one-pass system meaning that polymer is injected continuously upstream at the entrance to the test section. In this experiment solutions of Hyperfloc NF301, a non-ionic polyacrylamide (PAM) manufactured by Hychem Inc. and an ionic polyacrylamide (HPAM), Superfloc A-110 Flocculant purchased from Cytec are used as drag reduction agents and their performances are compared. Samples obtained from the channel test section are then tested after systematic degradation in the so-called polymer consistency apparatus and their drag reduction abilities compared to those corresponding to samples of the same concentration but where structures are either not present or if so they are not induced by the polymer injection system.

The presence of polymer structures was characterized in past papers [4,5] via flow visualization as well as turbidity and birefringence measurements for the PAM solutions in the same channel used in this study. Different injection concentrations $1,000\text{ppm} \leq C_i \leq 10,000\text{ppm}$ were tested with the corresponding injection rates to translate onto the same overall concentration at the test section, 14ppm. A thorough study of the measurements corresponding to the mean velocity and turbulence characteristics corresponding to some of the polymer flows presented herein for PAM solutions were reported in Kim et al. [4] and Shen et al. [5]. Those measurements were taken with a three-component Laser Doppler Velocimeter (LDV) system. Comparisons of the mean velocity and turbulence characteristics corresponding to structured and non-structured polymer solutions were done in the mentioned studies.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

II.1 Water Channel

The experiments reported in this study were conducted at the Marine Hydrodynamics Laboratory of the University of Michigan. A recirculating water channel where the flow is driven by a 1,200 gallons per minute centrifugal pump into the 5.99 cm wide by 59.94 cm high and 6.35m long channel test section is used. The bulk velocity in the test section can be up to 2.11 m/s, leading to Reynolds numbers based on the channel's width up to 1.26×10^5 . Settling chambers are located at each end of the test section and connected to it through a one-dimensional planar contraction/expansion. The flow is conditioned in the upstream settling chamber by two stainless steel screens. A schematic of the channel is shown in Figure 1.

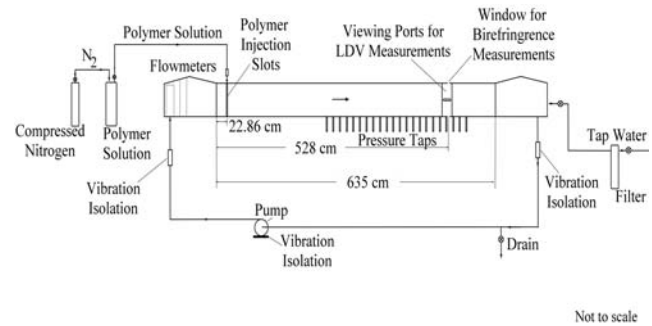


Figure 1. Schematic of the recirculating water channel

The test section is made of 0.75in clear acrylic. The measurement station is located 5.28 m downstream of the test section entrance. Twenty-one equally spaced pressure taps are located on one of the test section walls to monitor the pressure gradient. The test section has an aspect ratio of 10 and the measurement station is located 88.5 channel widths downstream the test section entrance. The test section geometry was chosen so that the flow would approximate that between two infinite parallel plates and be fully developed at the measurement station. The polymer injection slots are located on both sides of the channel at 22.86 cm downstream of the test section entrance. They are 0.25cm wide, 59.94cm high and are inclined at an angle of 25° to the wall. A pneumatic system drives the polymer solution from storage tanks to the injection slots.

The channel reference velocity is monitored continuously with a GF-Signet 5100 flowmeter. The pressure taps are connected to a W0602/IP-24T Scanivalve and a Digi-Key 287-1027-ND temperature compensated pressure sensor, with ± 4 in H_2O range. A Pentium II PC is used to collect and process the signals. During the experiments the temperature is held constant at $22 \pm 1^\circ\text{C}$.

II.2 Polymer Consistency Apparatus

The degradation tests performed in the samples drawn from the channel test section were conducted in a different experimental set-up, referred to as the "polymer consistency apparatus". It consists of a copper pipe of 1.6cm in diameter to which the polymer is gravity fed. The pressure drop and flow rate measurements in this pipe give a quick measurement of the wall shear stress and consequently of the drag reduction induced by the polymer. The measurements involve the use of a U-tube manometer with 1mm resolution and an Omega Engineering Model FTB791 flowmeter with a linear range of 1-10gpm with 2% resolution. A schematic of this apparatus is shown in Figure 2.

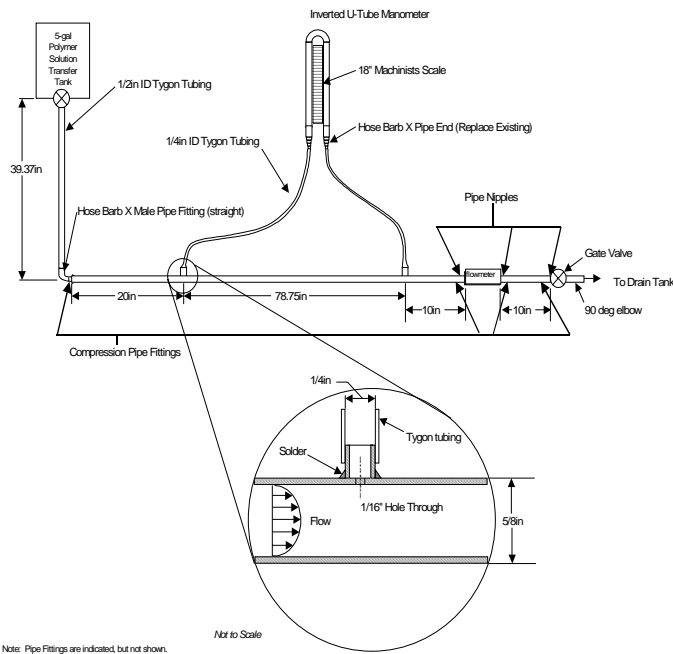


Figure 2. Schematic of the Polymer Consistency Apparatus

II.3 Polymer Solution Preparation and Experimental Procedures

In this study two polymers were used. The first one is a nonionic polyacrylamide (Hyperfloc NF301) purchased from Hychem Inc. (Tampa, FL). The study of Kim et al. [4] reports on the results of multi-angle laser light scattering used to characterize this polymer. The corresponding molar mass moments are also reported there and summarized herein. The weight average molecular weight is 7.5×10^6 g/mole and the z-average radius of gyration is 170nm. The second polymer used in this study is an ionic polyacrylamide (Superfloc A-110) Flocculant purchased from Cytec (West Paterson, NJ). No polymer characterization was done and consequently the number average molecular weight reported by the

manufacturer as 15×10^6 g/mole is the only information available.

The preparation of the aqueous solution follows a similar procedure to that of Koskie and Tiederman [11]. After combining the granular polymer, isopropyl alcohol and water, the solution requires both long-term hydration and gentle mixing. The process needs to provide enough agitation to avoid clumping without causing shear degradation of the polymer solution. The mixing is done with a Nuova magnetic stirrer for the first ten minutes and then rolled by a Bellco Cell Production Roll Apparatus. The polymer solution is stored at ambient conditions in the laboratory at 22°C. A comprehensive study to assess consistency of the polymer solution preparation procedures was performed and detailed information can be found in Sun-Chee-Fore et al. [12]. The latter study reports on the adequate hydration times required for the preparation of polymer solutions using the polymers reported herein for various concentrations. It also reports on the corresponding shelf lives of the prepared polymer solutions. It was shown that to determine the hydration time needed to produce a fully mixed, homogeneous and hence consistent polymer solution is critical, and that such time is dependent on the polymer type and concentration. At least twelve hours of hydration time were required for consistent results, within $\pm 4\%$, of the prepared PAM solutions. The prepared HPAM solutions showed consistent results after four hours with the same accuracy. The shelf lives of all polymer solutions used in this study were shown to be at least fifteen days.

The polymer solution is injected through the slots in the channel walls for a short period of time. The time during which injection is maintained, is determined by ensuring that no build up on the concentration of effective polymers in the circulating solution takes place, that is, that the pressure drop along the channel remains constant. After that time the polymer injection is stopped and the circulating solution is run through the channel until the polymers are completely degraded. At that time injection and measurements are re-started. The samples drawn from the channel test section are taken right after the constant pressure drop is first established.

II.4 Flow Visualization

The laser induced fluorescence technique (LIF) is used to visualize the channel flow to demonstrate whether or not polymer structures are present. Fluorescein disodium salt, a water-soluble fluorescent dye, is mixed with the polymer solution. The dye concentration was well below one part per million. A two-watt Lexar Argon-ion laser is the source for a planar laser sheet produced by means of a cylindrical lens. Pictures are taken with a black and white 1000x1000 pixels Kodak Megaplug ES 1.0 CCD camera, captured by a Matrox frame-grabber board and stored in a PC.

III. RESULTS AND DISCUSSION

The ability of polymer structures to be more effective drag reduction additives than individual polymer molecules, has been argued in the past. This conclusion has been confirmed for different types of polymers. It is however argued herein that the strength of the bonds holding the polymer structures together might be larger if they are primarily chemical bonds, such as in the case of ionic polyacrylamides, than if they are mechanical bonds, such as those most likely to be found in non-ionic polyacrylamides. The experiment reported herein was devised to test the endurance to degradation of structured and non-structured polymer solutions of HPAM and PAM.

Injection of homogeneous highly concentrated polymer solutions into shear flows can result into the formation of macro-molecular polymer structures [2,7]. The study of Kim et al. [4] established the injection concentration threshold needed for PAM polymer structures to be present in the channel apparatus used in this study for a given Reynolds number. Consequently the solution with polymer structures was induced by injecting a homogeneous polymer solution of 10,000ppm in the channel described in Section II. The injection was done at both channel walls well upstream the test section at a flow rate corresponding to an average 14ppm concentration at the test section, for a Reynolds number of 5×10^4 based on the centerline velocity at the test section and the channel width. The injected PAM solution was categorized as homogeneous by conducting turbidity tests in the quiescent prepared polymer solution. Such results are reported in Kim et al. [4]. The non-structured polymer solution was extracted from the channel test section while injecting a homogenous solution of a concentration below the aforementioned threshold. Injection of a 1000ppm homogeneous polymer solution was used to establish a test section concentration of 14ppm. No traces of structured solutions were found at the test section by Kim et al. [4] via turbidity and birefringence measurements for the 1,000ppm injection concentration.

For the ionic polyacrylamide visual inspection of the 10,000ppm prepared polymer solution immediately revealed the presence of polymer structures despite the duration of the hydration/rolling period allowed during the process of the polymer solution preparation. In this case it is expected, though, that differences between a degradation test conducted on a prepared sample of HPAM, and that conducted on a sample of the same concentration obtained from the channel test section after injecting the polymer solution, should also be significantly different if indeed the injection system is contributing to the process of polymer structure formation.

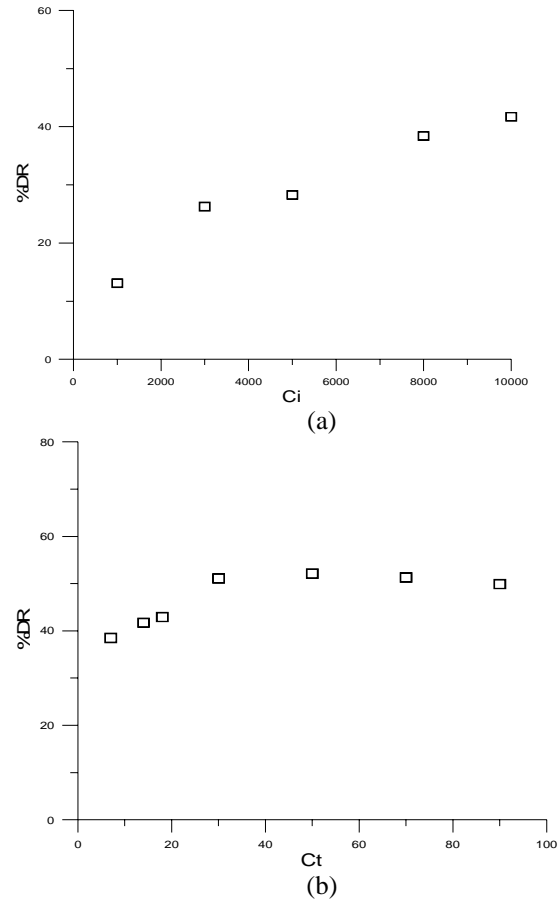


Figure 3. (a) Percentage Drag reduction versus Injection concentration (C_i) for PAM and an average test section concentration (C_t) of 14ppm; (b) %DR versus C_t for PAM and $C_i=10000$ ppm

The overall performance of both PAM and HPAM polymer solutions for different injection concentrations and corresponding concentrations at the test section are shown in Figures 3 and 4 for the same channel Reynolds number of 5×10^4 . Figure 3 shows the percentage of drag reduction versus the average concentration at the test section for injection concentrations in the range $1,000\text{ppm} \leq C_i \leq 10,000\text{ppm}$ of PAM polymer solutions. The range of concentrations at the test section is $0\text{ppm} \leq C_t \leq 100\text{ppm}$. Similar results are shown for HPAM polymer solutions in Figure 4. The results indicate the ionic HPAM yields higher levels of drag reduction than the PAM for equivalent average test section concentrations. This comparison is not entirely correct due to the different molecular characteristics of both polymers.

The drag reduction percentage is defined as:

$$\%DR = 100 \frac{(\tau_{wN} - \tau_w)}{\tau_{wN}} \quad (1)$$

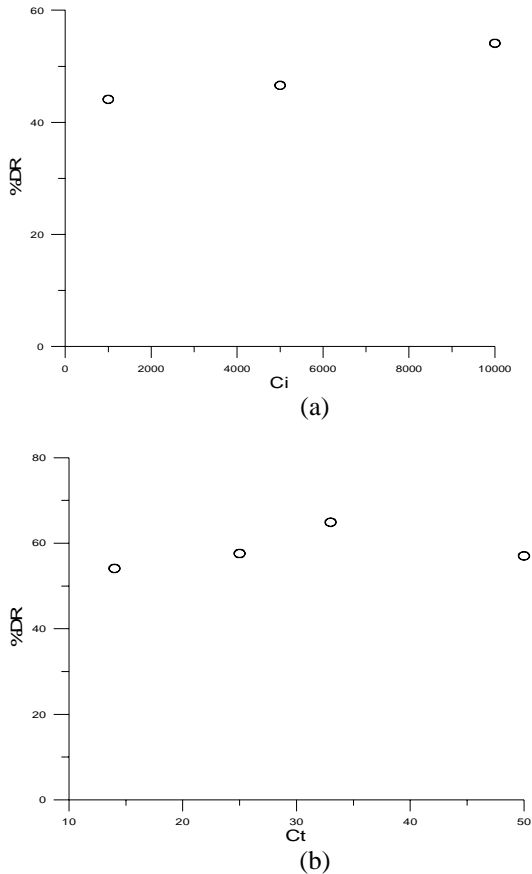


Figure 4. (a) Percentage Drag reduction versus Injection concentration (C_i) for HPAM and an average test section concentration (C_t) of 14ppm; (b) %DR versus C_t for HPAM and $C_i=10000$ ppm

where τ_{wN} represents the wall shear stress for the Newtonian flow.

III.1 Flow Visualization

The study of Kim et al. [4] reported on a flow visualization and birefringence study done in the same channel apparatus used in this study for an injection concentration of 10,000ppm and a test section concentration of 14ppm with a polyacrylamide. It was shown there that indeed macro-molecular polymer structures could be easily seen at the test section. Furthermore it was shown that the concentration of such structures is larger in the neighborhood of the channel's centerline.

The presence of such polymer structures when injecting polymer solutions of HPAM is characterized in this study by mixing the polymer solution with fluorescent dye and illuminating it with a planar laser sheet. The camera is located 76 channel widths downstream from the injection slot. The size of the window is set at $7.62 \times 10^{-2} \text{m} \times 7.62 \times 10^{-2} \text{m}$ (1,000 pixels x

1,000 pixels) with a corresponding resolution of 76.2 $\mu\text{m}/\text{pixel}$.

The laser sheet is vertical and located half-width in the channel and also at around $y^+=80$ from the wall. All visualizations are performed for an injection concentration of 10,000ppm and a test section concentration of 14ppm. Figures 5 and 6 show the results corresponding to the two cases mentioned above. The flow direction in the pictures is from left to right and each picture shows two consecutive frames from top to bottom (1000 pixels x 1000 pixels, each). The time between the two frames is fixed to 33 milliseconds and the exposure time is 10 milliseconds.

Both figures clearly indicate the presence of macro-molecular polymer structures. They also reveal that indeed as seen in the previous studies, mentioned earlier, for PAM the concentration of such polymer structures is larger in the neighborhood of the channel centerline than it is close to the wall.

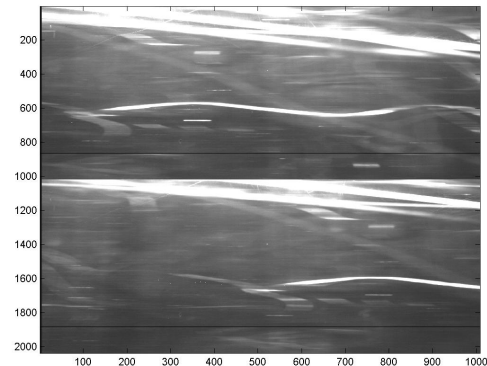


Figure 5. Visualization of Turbulent channel flow with laser sheet located at half-width, for $C_i=10000$ ppm and $C_t=14$ ppm for HPAM.

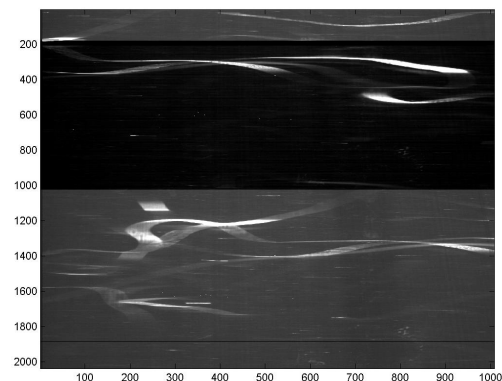


Figure 6. Visualization of Turbulent channel flow with laser sheet located at $y^+=80$ for $C_i=10000$ ppm and $C_t=14$ ppm for HPAM.

III.2 Degradation tests for the non-ionic polyacrylamide polymer solution

Degradation can take place due to mechanical or chemical effects. Chemical degradation implies a change in the polymer structure due to chemical reactions. Mechanical degradation on the other hand implies the break up of the polymer as a consequence of mechanical actions working on it with the consequent reduction in molecular weight and drag-reducing abilities. The endurance to degradation of structured versus non-structured polymer solutions is of practical interest.

The study of Kim et al. [4] showed via turbidity measurements that homogeneous PAM solutions of up to 10,000ppm could be prepared by following the same preparation procedure explained in the previous section. The PAM used in this study is the same as that used by Kim et al. [4]. To further demonstrate the homogeneity of these highly concentrated polymer solutions a degradation test was conducted on two 14ppm samples obtained by diluting both a 10,000ppm and a 1,000ppm PAM polymer solution. Both samples were tested in the polymer consistency apparatus. Flow rates and pressure drops were measured for each case and the results from several passes through the pipe recorded and compared. The percentage of drag reduction corresponding to each of the 14ppm samples versus Reynolds number (based on the pipe diameter and the bulk velocity) is shown for up to five passes through the pipe in Figure 7, plotted using Prandtl-Karman coordinates (i.e. $1/\sqrt{f}$ versus $Re\sqrt{f}$) where f is the Fanning friction factor defined as:

$$f = \frac{d\Delta p}{2\rho LV^2} \quad (2)$$

where d is the pipe diameter, Δp is the pressure drop, L is the pipe length, ρ is the fluid density, and V is the bulk velocity. Figure 7 also shows the drag reduction interval as that between the Prandtl-Karman curve for water ($1/\sqrt{f}=4 \log(Re\sqrt{f})-0.4$) and the Virk's Maximum Drag Reduction Asymptote (MDRA: $1/\sqrt{f}=19 \log(Re\sqrt{f})-32.4$).

The results shown in Figure 7 indicate that as expected the degradation history of both samples gives almost the same results for all pipe Reynolds numbers tested ($5,000 < Re < 14,000$), regardless of the number of passes through the pipe, except pass three that shows larger discrepancies between both results. Even in that case the differences are within 10% DR. These results indeed corroborate the findings reported by Kim et al. [4] regarding the homogeneity of the highly concentrated prepared solutions of PAM. It should be noted, though, that these solutions may indeed consist of small polymer structures. However, their size should be much smaller than the wavelength of light as explained by Kim et al. [4] and consequently their effectiveness as drag reduction agents might be comparable to that of single molecules.

The ability of a structured and non-structured non-ionic polyacrylamide polymer solution to endure

degradation was tested by running samples from both polymer solutions in the polymer consistency apparatus. The corresponding samples were extracted from the channel test section as explained earlier in Section III. In both cases the test section concentration was 14ppm.

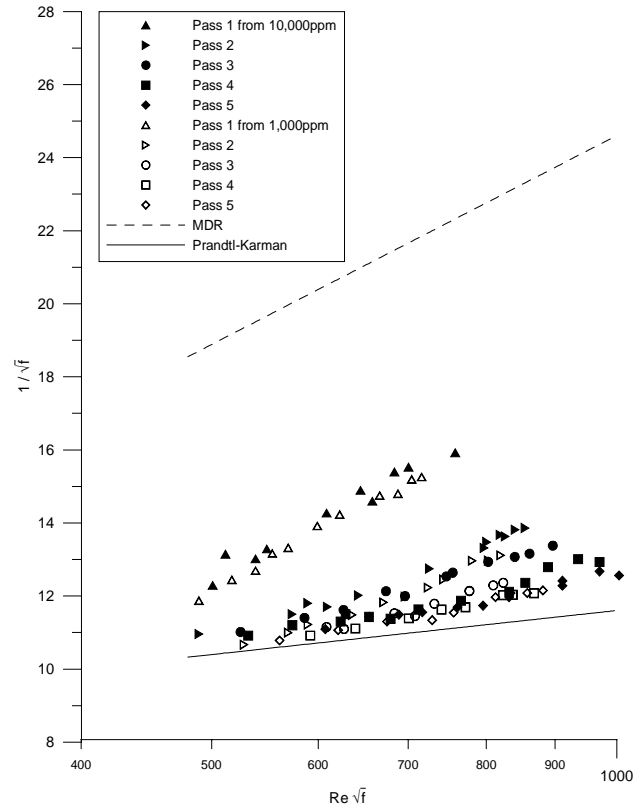


Figure 7. Degradation Test for 14ppm PAM solutions obtained by diluting 10,000ppm and 1,000ppm batches.

A degradation test was conducted on both samples by running them through the polymer consistency apparatus for up to ten passes. The corresponding percentages of drag reduction versus the pipe Reynolds numbers tested are presented in Prandtl-Karman coordinates in Figure 8. The results indicate that the initial drag reduction is higher with the structured solution compared to the unstructured solution. The trend of higher drag reduction for the structured solution holds for all Reynolds numbers. The larger the Reynolds number the more effective polymer structures are as drag reduction agents versus non-structured polymer solutions. The performance of the polymer structures as drag reduction agents is consequently also better when compared to the non-structured polymer. Ten passes through the pipe of the structured polymer solution are required to achieve similar levels of drag reduction, for all Reynolds numbers tested in this experiment, to those obtained by the non-structured polymer sample after five passes. At larger Reynolds numbers ($Re > 12,000$) five passes through the pipe are required for the structured

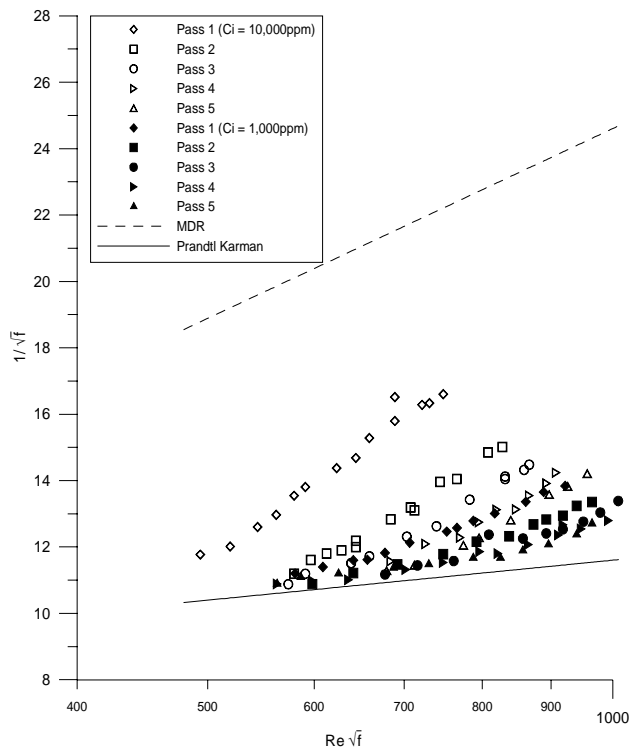


Figure 8. Comparison of degradation for 14ppm PAM samples obtained by injecting 10,000ppm and 1,000ppm solutions into the channel.

polymer solution to resemble the levels of drag reduction obtained with the non-structured polymer solution after only one pass.

Figure 9 shows comparisons of the data presented in Figure 8 with the results corresponding to the degradation test of the prepared solutions from both 10,000ppm and 1,000ppm. The latter solutions are not subjected to injection in the channel, and degradation along the channel until the sample reaches the test section. It is remarkable that the level of drag reduction obtained from the prepared samples after the first pass through the polymer consistency apparatus is practically the same as that attained by the structured channel sample. This again is an indication of the endurance of such polymer structures to degradation. On the other hand the results corresponding to the non-structured channel sample after one pass are not matched by the prepared solutions after three passes through the pipe. The level of degradation of the prepared solutions and the non-structured channel sample become consistent over the range of Reynolds numbers tested after five passes. As mentioned earlier and shown in Figure 8, the structured polymer sample will require ten passes to match the latter results.

III.3 Degradation tests for the ionic polyacrylamide polymer solution

The preparation of highly concentrated

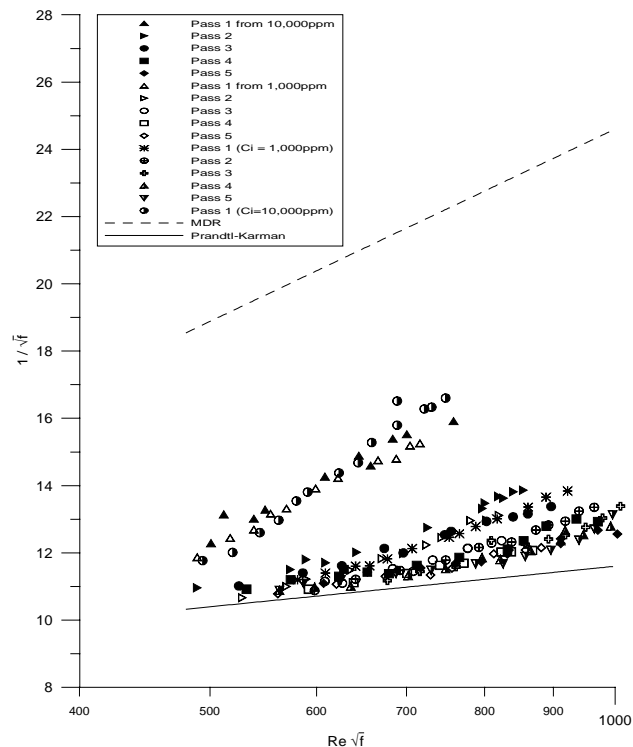


Figure 9. Comparison of degradation for 14ppm PAM solutions obtained by injecting 10,000ppm and 1,000ppm solutions into the channel versus diluted solutions prepared directly from 10,000ppm and 1,000ppm.

homogeneous polymer solutions could not be accomplished with the ionic polyacrylamide. Visual inspection of the prepared solutions immediately revealed the formation of polymer structures. To further emphasize this conclusion, degradation tests were performed on two 14ppm samples obtained by diluting both a 10,000ppm and a 1,000ppm HPAM polymer solutions. The results are shown in Figure 10 for a range of Reynolds numbers $5,000 < Re < 12,000$. The results corresponding to the first pass show almost identical results. Important differences between the two samples are found for subsequent passes through the polymer consistency apparatus. The results seem to indicate that the initial concentration of the sample does play a role on the endurance to degradation attained by them. Essentially the less concentrated the initial solution is, the less resistant the structured polymer solution becomes to degradation. As seen in Figure 10, ten passes of the sample obtained from the 10,000ppm polymer solution are required to match five passes of the sample obtained from the 1,000ppm solution over the whole range of Reynolds numbers tested. It should be mentioned that the trends of the drag reduction versus Reynolds number curves shown in Figure 10 for HPAM are different than those shown in Figures 7-9 for PAM. Most curves in the case of HPAM seem to reach a maximum within the range of Reynolds numbers tested.

Comparisons of the performance to degradation of a 14ppm sample extracted from the channel versus a 14ppm sample obtained by diluting a 10,000ppm batch are shown in Figure 11. The injection concentration of the HPAM polymer solution was 10,000ppm. Similar injection and sample extraction procedures as those mentioned earlier were used.

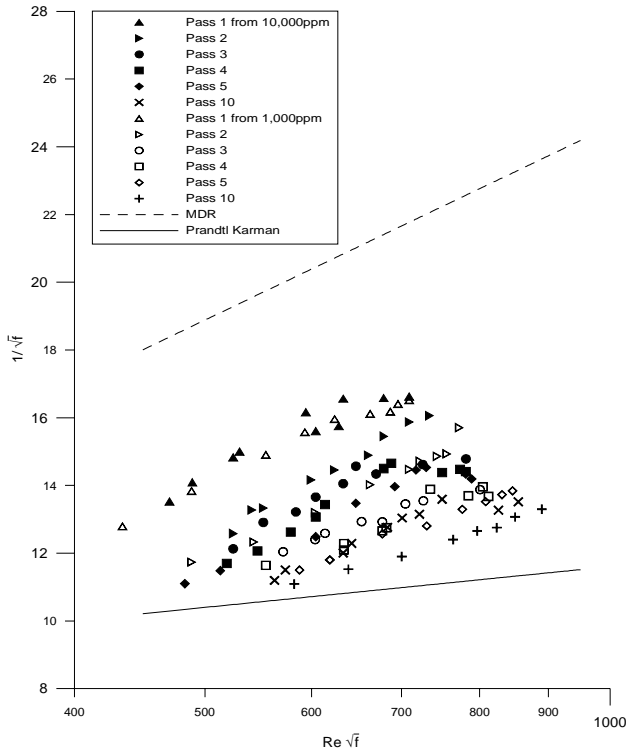


Figure 10. Comparison of degradation for 14ppm HPAM solutions prepared by dilution of 10,000ppm and 1,000ppm solutions.

The data shown in Figure 11 indicates that after the first pass the results from both samples are very comparable. However the data corresponding to the channel sample for passes 2-5 seems to almost completely overlap those corresponding to the first pass and especially so for Reynolds numbers larger than roughly 8,000. For $5,000 < Re < 8,000$ the results for up to 5 passes are within a 7%DR of those corresponding to the first pass. Ten passes through the pipe seem to be required by the channel sample to match the results corresponding to the second pass of the prepared polymer solution. As mentioned earlier in Figure 10, the trends of the curves corresponding to the prepared sample show a maximum roughly around $Re = 10,000$ for all curves after the third pass. On the other hand, the curves corresponding to the channel sample do not display a maximum in the range of Reynolds numbers tested which indicates a continuous increase of drag reduction with Reynolds number regardless of the number of passes

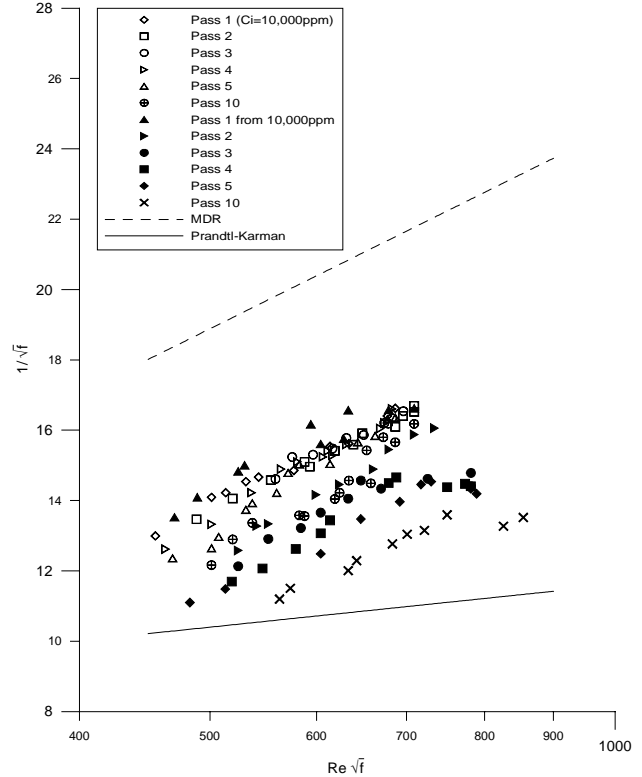


Figure 11. Comparison of degradation for 14ppm HPAM solutions obtained by injecting 10,000ppm solutions into the channel with a 14ppm solution prepared directly by diluting a 10,000ppm solution.

through the pipe. Essentially the drag reduction abilities of the solution are enhanced by injecting it into the flow and possibly also by the action induced by the channel flow itself. It is remarkable that after ten passes through the pipe the differences in drag reduction between both samples are roughly a 20%. These results are especially important when designing or optimizing polymer delivery systems.

To further emphasize the similarities and differences with regards to degradation endurance of both polymers, a comparison of the percentage of drag reduction versus number of passes is shown for both PAM and HPAM polymers for Reynolds numbers of 6810 ± 1370 and 10000 ± 790 in Tables 1 and 2 respectively. The results in Table 1 indicate a connection between effectiveness of the polymer structure and the strain it undergoes. From the results corresponding to the large Reynolds number it is clear that the structured solution ($C_i = 10,000\text{ppm}$) maintains its drag reduction abilities better than the non-structured sample. However the decay in drag reduction per pass is comparable, within $\pm 3\%$, for both structured and non-structured solutions. At the lower Reynolds number, corresponding to a lower strain rate, the advantages over the non-structured sample with regards to degradation are negligible after the first

few passes, when both results become comparable. The results corresponding to the ionic polymer (HPAM) show overall higher levels of drag reduction in comparison with PAM. However they do not display as large an increase in effectiveness with Reynolds number as shown by PAM. Note that both injected HPAM solutions contain aggregates formed chemically during preparation. The ability of the HPAM polymer structures to endure degradation (shown in Table 2) is remarkable when compared to the results shown in Table 1 for PAM. One order of magnitude difference in the injection concentration and lower strain rates do not seem to affect substantially that conclusion for HPAM.

Ci	Pass	Re	% DR	Re	% DR
10,000ppm	1	6.24E+03	22.1	1.01E+04	45.8
	2	6.92E+03	14.4	1.04E+04	34.5
	3	6.62E+03	9.0	1.05E+04	29.0
	4	7.36E+03	5.9	1.08E+04	25.2
	5	6.49E+03	2.4	1.08E+04	21.5
1,000ppm	1	6.51E+03	9.5	1.01E+04	22.5
	2	7.19E+03	7.4	1.11E+04	19.3
	3	7.57E+03	5.6	1.00E+04	17.4
	4	6.13E+03	5.6	1.04E+04	12.3
	5	6.13E+03	5.6	1.02E+04	10.1

Table 1. Injected 14ppm PAM solutions.

Ci	Pass	Re	% DR	Re	% DR
10,000ppm	1	7.06E+03	41.6	1.11E+04	51.8
	2	7.31E+03	40.8	1.14E+04	51.5
	3	8.17E+03	43.7	1.09E+04	50.8
	4	5.85E+03	30.6	1.07E+04	50.0
	5	6.34E+03	29.5	1.10E+04	51.3
	10	6.10E+03	24.5	1.15E+04	50.0
1,000ppm	1	6.54E+03	40.1	1.03E+04	52.6
	2	7.03E+03	39.7	1.09E+04	55.0
	3	7.12E+03	33.9	1.07E+04	51.0
	4	7.18E+03	33.4	1.01E+04	45.8
	5	6.11E+03	22.9	1.12E+04	46.3
	10	7.79E+03	39.7	1.07E+04	45.4

Table 2. Injected 14ppm HPAM solutions.

IV. CONCLUSIONS

The effect of macro-molecular polymer structures has been shown in the past to enhance the drag reducing abilities of polymer solutions when compared to non-structured solutions. Such polymer formations could be due most possibly to either the entanglement of polymer molecules or the ionic character of the polymer. A comparison of the performance of an ionic and a non-ionic polymer as drag reduction agents in structured and non-structured polymer solutions has been presented in this study. The ability of structured non-ionic polymer solutions to endure degradation is compared to that of a homogeneous solution and the benefits of structuring are shown for large Reynolds numbers. On the other hand, structured ionic polymer solutions show very similar drag reduction abilities for most strain rates studied. The initial drag reduction and degradation results

corresponding to 1,000ppm and 10,000ppm injection concentrations are very similar for HPAM.

The influence of the polymer delivery system and the flow-induced structures is also proven to play a significant role in polymer flows. Injection of homogeneous polymer solutions can induce the formation of polymer structures. Injection of structured polymer solutions can enhance even further the drag reduction abilities of the polymer as it was shown herein for the non-ionic polyacrylamide.

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