

Flow of Mixtures of Poly(ethylene oxide) and Hydrolyzed Polyacrylamide Solutions through Opposed Jets

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ABSTRACT: The flow of solutions of poly(ethylene oxide) (PEO), hydrolyzed polyacrylamide (HPAA), and their blends through opposed jets is investigated. Measurements of pressure drop across the jets as a function of strain rate were used to characterize the elongational flow behavior. In deionized water, solutions of PEO/HPAA mixtures exhibit a synergistic increase in flow resistance with respect to the parent polymer solutions. The addition of amounts of HPAA as low as 2 ppm to a 500 ppm PEO solution cause sizeable increases in pressure drops. Such increases have been interpreted as arising from the formation of interpolymer transient entanglement networks that become mechanically active at time scales equivalent to the lowest strain rates available. In the case of excess salt environment, the flow resistance of the mixtures seems to be dominated by the PEO in the concentration range explored. © 2000 John Wiley & Sons, Inc. *J Appl Polym Sci* 76: 1910–1919, 2000

Key words: opposed jets flow; poly(ethylene oxide); hydrolyzed polyacrylamide; mixtures; transient networks

INTRODUCTION

Solutions of polymer blends have been studied in shear and elongational flows mainly to ascertain the effect of the flow on the miscibility of the system. However, drag reduction experiments in turbulent flows through pipes^{1,2} have shown that mixtures of high molecular weight polymers have drag reducing capabilities that exceed that of solutions of each of the individual polymers, especially when at least one of the polymers has a semirigid structure. Because turbulent flows have a strong local elongational component, one might

wonder if the synergy observed in drag reduction can be extrapolated to the extension thickening capabilities that polymer solutions exhibit in laminar elongational flows. Porous media flows have important elongational components due to the successive expansions and contractions experienced by a typical fluid element, and to the presence of stagnation points. This motivated our previous studies of the flow of solutions of polymer blends through porous media.^{3,4}

It is well known that aqueous solutions of flexible polymers exhibit critical extension thickening when they flow through porous media.⁵ On the other hand, semiflexible polymers might exhibit a gradual extension thickening or even shear thinning at high concentrations.^{6,7} Results obtained with blends of a flexible polymer, poly(ethylene oxide) (PEO), and a semiflexible polymer, hy-

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droxypropyl guar (HPG) in porous media flows³ showed that the extension thickening induced by the PEO became less critical with increasing flow rate as the concentration of HPG in the blend was increased. At high concentrations of HPG, the presence of PEO merely inhibits the shear-thinning behavior exhibited by pure HPG solutions.

In a more recent work,⁴ we investigated the behavior of mixtures of hydrolyzed polyacrylamide (HPAA) and PEO in porous media flows. HPAA solutions exhibit critical extension thickening in excess salt environments, but their behavior changes to a more gradual extension thickening when dissolved in deionized water. The mixtures of solutions of HPAA and PEO, therefore, vary its porous media flow behavior, depending on the ionic environment. In deionized water, a critical extension thickening similar to that obtained with PEO is still observed when the HPAA is mixed in at concentrations low enough so that its apparent viscosity does not mask the influence of the PEO. In the presence of salt, only a critical extension thickening is observed, which is attributed to transient network formation of both PEO and HPAA molecules. The mixtures generally exhibit a less critical behavior, and display a lower than expected sensitivity of the onset Reynolds number for extension thickening with concentration.

Our previous results⁴ indicate that interspecies molecular interactions through transient network formation, and the associated flow modification, play a major role in determining the complex non-Newtonian flow behavior of these polymer solutions when they flow through porous media. In view of the fact that the flow field at the pore level is not an ideal extensional flow due to the relatively large lateral velocity gradients that occur close to the walls of the pores, which impose an important degree of shear and rotation, we decided to study the flow of the same polymer mixtures through opposed jets, in which the flow is close to idealized uniaxial extension.

The merits and limitations of elongational flow techniques, and in particular opposed jets flow, have been the subject of extensive reviews over the past decade.^{8–12} For this reason, only a brief recapitulation will be given here.

Basic Principles: Chain Stretching in Dilute Solutions

Elongational flow theories^{8,13,14} predict that isolated flexible polymer coils can be fully stretched

in dilute solutions if such a solution is subjected to uniaxial elongational flow (such as opposed jets flow) at a high enough elongational rate and for a time long enough so that it can accumulate the required molecular strain.

In previous works, the predicted coil–stretch transition has been experimentally verified for a number of high molecular weight flexible polymers such as PEO and atactic polystyrene using near-ideal extensional flow fields like opposed jets, cross-slots and four-roll mills.^{8,15} The molecular extension has usually been assessed from optical retardation measurements of the solution through crossed polarizers. In dilute solutions of high molecular weight flexible polymers, as the strain rate is increased, a localized narrow birefringent line is observed around the stagnation point, signaling that the molecules are only being extended where large strains are available. Even though chain stretching and orientation in the direction of flow is undisputed, the actual sharpness of the transition and the attainment of full chain extension have been the subject of recent controversies that are outside the scope of the present article.^{5,10,12,16–18}

Semidilute Solutions and Extensional Rheometry with the Opposed Jets

When the solution concentration is increased beyond a critical concentration (C^+), the elongational flow behavior changes dramatically, depending on the applied strain rate compared to the dilute solution case.¹⁹ At low strain rates (long time scales) the semidilute solutions behave as if they were dilute: a localized birefringent line can still be seen beyond a critical strain rate $\dot{\epsilon}_c$. The polymer coils can be stretched as if in isolation as long as they have enough time to disentangle from one another. At higher strain rates, the molecules go from the stretched state to a regime called “pipe” in which significant flow modification occurs between the jets due to the presence of polymer molecules.^{20,21} At even higher strain rates (very short time scales), the molecules do not have enough time to slip past each other and form a transient network. The presence of such transient networks causes a flow instability that leads to the delocalization of the birefringent line, with regions of relatively high birefringent intensity that exhibit spatial fluctuations that follow a pattern resembling a flame in motion or flare.^{20,22}

The University of Bristol group developed a technique to enable the simultaneous assessment of macroscopic flow resistance and visual observations of molecular strains and flow fields.^{9,19,20,22,23} The flow resistance is determined by measuring the pressure drop across the jets as the strain rate is increased.²³ For the dilute PEO solutions, after the macromolecules undergo a coil-stretch transition, the solution exhibits only small departures in flow resistance with respect to the solvent. On the other hand, for semidilute PEO solutions, a small increase in flow resistance with respect to the solvent after the coil-stretch transition is usually observed at low strain rates, but beyond a critical strain rate, strong extension thickening is evident. This only occurs when transient networks of polymer molecules are formed in the flow. Furthermore, such critical transient network formation increases the elongational viscosity of the system to such a degree that the ΔP vs. $\dot{\epsilon}$ curve beyond the transient network onset strain rate ($\dot{\epsilon}_n$) is highly unstable, and the volumetric flow rates fluctuates as the entangled chains try to comply with the flow field. In fact, extensive flow visualization has demonstrated that after flare formation the flow field breaks down, losing its symmetry and its stagnation point.²⁰

The effect of the ionic environment on opposed jets flow of polyelectrolyte solutions like hydrolyzed polyacrylamide (HPAA) in water–NaCl mixtures has been previously studied by Odell et al.²³ As the NaCl concentration is increased, thereby increasing the ionic strength of the solution, the behavior changes from that of an expanded free-draining coil to the one of a more compact nonfree draining coil, because the HPAA molecule tends to adopt a coiled conformation as a result of the complete screening of its anionic groups by the sodium cations.²³ In the absence of salt, HPAA solutions tend to behave as semidilute solutions at much smaller concentrations than in ionic environments, because coil–coil interpenetration is now favored by the expanded chain macroconformation.

In this work, we study the opposed jets flow of aqueous solutions of blends of PEO and HPAA. In this case we can vary the molecular equilibrium conformation of the latter by changing the ionic strength of the solvent with the addition of NaCl. In excess salt, the blend will be of flexible–flexible polymer coils, whereas in deionized water they will contain flexible and semiflexible polymer coils.

EXPERIMENTAL

The experimental setup employed has been described elsewhere.^{7,9,22} Sucking the solution simultaneously into both jets generates a closely uniaxial extensional flow. It has been assumed that the nominal strain rate corresponding to a volumetric flow rate Q is given by:

$$\dot{\epsilon} = \frac{Q}{Ad} \quad (1)$$

where A is the cross-sectional area of each jet, and d is the jet separation. The jets were formed by opposed cylindrical glass capillaries with dimensions: 0.9 mm internal diameter, 1.5 mm external diameter and $d = 1.2$ mm. The whole assembly was placed at the geometric center of a cell with dimensions $4 \times 5 \times 15$ cm. The flow was established by decreasing the pressure inside the capillaries by means of a vacuum pump. The vacuum was regulated with two receiving reservoirs and a solenoid valve controlled by a microcomputer. Once steady flow through the jets was achieved, both the flow rate and the pressure drop across the jets were recorded by using two differential piezoelectric pressure transducers.

The HPAA employed was a high molecular weight hydrolyzed polyacrylamide (ALCO-FLOOD 1175A, supplied by Allied Colloids Inc.) with $\bar{M}_w = 18 \times 10^6$ and a degree of hydrolysis between 35 and 40%. The ionic environment of the aqueous solutions was varied by adding NaCl. We have determined that solutions with salt yield different results, depending on the point at which the salt is added.⁷ To ensure reproducibility of the results, all solutions with salt were prepared by dissolving the polymer in powder form in a 0.5M NaCl solution. The PEO employed was supplied by Polysciences, and its average viscometric molecular weight was determined by capillary viscometry to be $\bar{M}_v = 3 \times 10^6$.

All polymer solutions were prepared by carefully dissolving in deionized and distilled water (or the corresponding NaCl solution) the required quantity of polymer in powder form with minimum agitation (to avoid mechanical degradation) for 24 h. This time was needed to ensure complete dissolution of the polymer. For the preparation of the blends, the solution of each polymer was prepared using the procedure mentioned previously, and then they were mixed (after the 24-h disso-

lution period) and left to stand for 1 h before starting the flow experiments. All the solutions prepared were optically transparent, and no apparent signs of gel formation or phase segregation were detected. Therefore, we consider that all the HPAA/PEO/water mixtures were a single phase after preparation. Furthermore, during the flow of the polymer solutions through the opposed jets, because the flow cell was made of glass, we examined the flowing solution optically, and it always looked transparent at all points in the flow system, including between the jets.

RESULTS AND DISCUSSION

Opposed Jets Flow Behavior of PEO and HPAA Solutions

Figure 1 presents the behavior of the aqueous PEO solutions used in this work as they flow through the opposed jets. The PEO behaves as a typical high molecular weight flexible polymer, as has been reported previously in a wider concentration range.^{9,22} The 50-ppm PEO solution is a dilute solution whose shear viscosity is identical to that of water. After the coil-stretch transition, only very modest increases in the apparent elongational viscosity of the solution (as reflected by increases in pressure drop with respect to water) are achieved because the chain stretching region within the flow field is confined to a small volume that encompasses those streamlines that pass very close to the stagnation point.^{18,20} Therefore, the

50 ppm solution can hardly be distinguished from the water curve at low strain rates (Fig. 1). However, at high strain rates, turbulence is suppressed. We have previously shown that the addition of small amounts of high molecular weight polymers delays the onset of turbulence in opposed jets flow.^{24,25} When turbulence sets in, the rate of increase of the pressure drop with the strain rate is significantly reduced. This can be observed in the water curve in Figure 1 at about 3000 s^{-1} . Turbulence suppression occurs regardless of the equilibrium conformation of the polymer in solution, because this behavior is exhibited by both flexible and semirigid polymers, as long as they have long enough contour lengths to be stretched by the applied elongational flow.²⁴⁻²⁶

The 200-ppm solution can be still considered to be dilute, because only modest increases in apparent viscosity with respect to the solvent are observed (as reflected by the ΔP data in Fig. 1). At 500 ppm, the PEO solution can be considered to be semidilute in view of its flow resistance behavior. Figure 1 shows how the 500-ppm PEO curve departs from the water curve at low strain rates (around 700 s^{-1}), and exhibits a greater flow resistance than water until $\dot{\epsilon}_n = 3000 \text{ s}^{-1}$, where transient entanglement networks are formed. Therefore, in this case, C^+ must be between 200 and 500 ppm. As was mentioned in the introduction, the formation of a transient entanglement network increases the apparent elongational viscosity of the system, inducing a breakdown of the flow field and highly non-Newtonian elastic flow instabilities. The increase in apparent elongational viscosity is so large at the moment of flare formation in PEO solutions that the flow rate decreases while the pressure drop largely increases with major fluctuations at the same applied vacuum pressure. This is why the ΔP vs. $\dot{\epsilon}$ curve increases monotonically until at approximately 3000 s^{-1} , where the strain rate is reduced to about 2600 s^{-1} while the ΔP increases abruptly.

As shown in Figure 1, flare formation is highly dependent on concentration. Therefore, $\dot{\epsilon}_n$ decreases very rapidly upon increasing concentration. Figure 1 shows how the dramatic increase in flow resistance brought about by network formation in PEO solutions occurs at progressively lower strain rates as the concentration is further increased beyond 500 ppm.

As argued above, because HPAA has a polyelectrolytic nature, its flow behavior should be

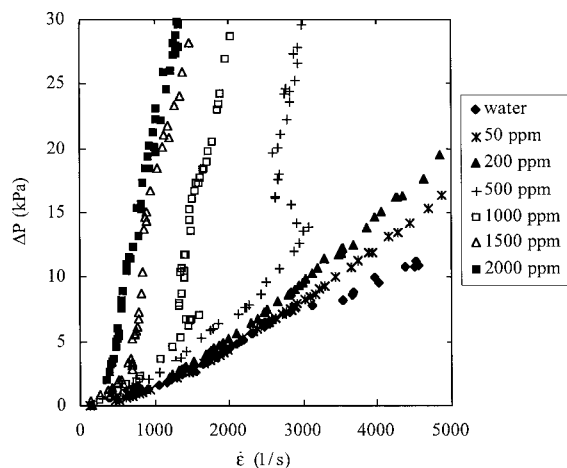


Figure 1 Effect of PEO concentration on the pressure drop across the jets for aqueous PEO solutions.

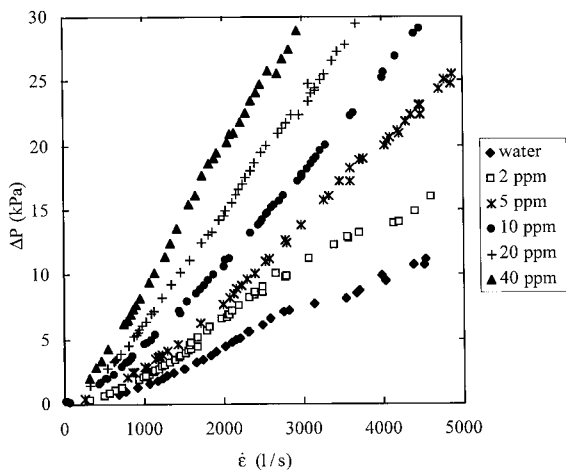


Figure 2 Effects of HPAA concentration on the pressure drop across the jets for solutions of HPAA in deionized water.

highly dependent on the ionic environment. Figure 2 shows ΔP vs. $\dot{\epsilon}$ curves for HPAA solutions in deionized water. It can be seen that the flow resistance of the HPAA solutions is higher than that of water even for concentrations as low as 2 ppm, and almost from the lowest strain rates. This behavior would correspond to transient entanglement network formation from very low strain rates, and is consistent with previous results on HPAA dissolved in deionized water, where flow modifications were identified from the lowest possible flow rates, as well as flare birefringent patterns.²³ Such behavior, as already mentioned in the introduction, is characteristic of very high molecular weight polymers that exhibit an expanded coil conformation in solution.²³ In the present case, even at 2 ppm, the solution behaves as a semidilute solution, because the expanded coil conformation provides connectivity of the chains at such low concentrations.

In the presence of NaCl, the HPAA adopts a coiled conformation, due to the screening of charges along the chain (COO^- groups) by the sodium cations. In this work, we will present results obtained with a salt concentration that exceeds the saturation value (0.5M NaCl) to ensure that the equilibrium conformation of the HPAA is at its most coiled state. The behavior of HPAA in excess NaCl solution exhibits the typical features of high molecular weight flexible polymers, like PEO in water. Such behavior can be seen in Figure 3 for four different HPAA concentrations in 0.5M NaCl solutions. However, because the

HPAA has a much higher molecular weight than the PEO, their behavior has notable differences. The HPAA solutions of 5 and 10 ppm are clearly dilute, exhibiting only small departures from the water curve beyond the coil–stretch transitions. The critical concentration C^+ seems to be between 10 and 20 ppm. The 20-ppm solution forms transient entanglement networks beyond a strain rate of about 1200 s^{-1} , as judged by fluctuations observed in the ΔP values beyond that strain rate. Note that the flare formation in this case does not involve the extreme instabilities observed in the PEO case. This might be a consequence of the low HPAA concentrations required to produce the networks. Another indication that the 20-ppm HPAA/salt solution is already semidilute is its relatively high level of viscosification compared to 5- and 10-ppm solutions. The 40-ppm HPAA/salt solution is highly viscous, and behaves as an entangled system from the lowest achievable strain rates.

The effect of the ionic environment on the flow properties of HPAA through opposed jets is further exemplified in Figures 4 and 5 by a direct comparison of ΔP vs. $\dot{\epsilon}$ curves at selected concentrations, with and without the addition of NaCl. Figure 4 shows how the 5-ppm HPAA in excess salt environment behaves as a dilute solution of a flexible polymer, exhibiting an almost nondetectable increase in flow resistance compared to water, but a clear suppression of turbulence. On the other hand, when the same HPAA is dissolved in deionized water, the intramolecular repulsion of

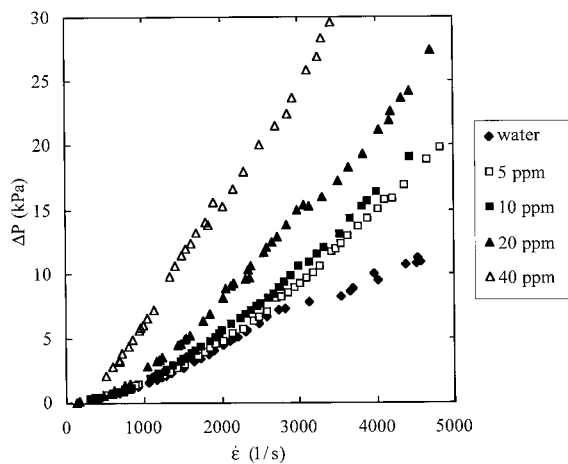


Figure 3 Effects of HPAA concentration on the pressure drop across the jets for solutions of HPAA in 0.5M NaCl.

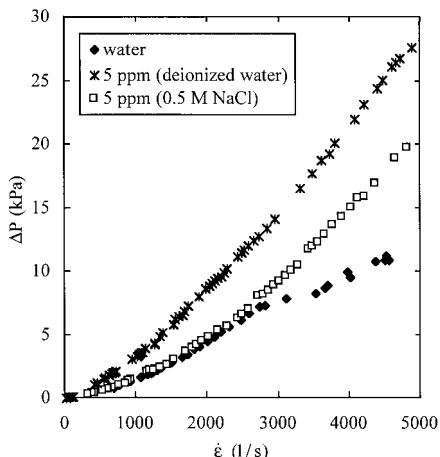


Figure 4 Effect of ionic environment on the pressure drop across the jets for 5-ppm HPAA solutions.

its anionic groups expand the polymeric coils in such a way that allows dynamic interaction between them at short time scales. Therefore, at strain rates greater than about 400 s^{-1} , the expanded HPAA coils can not disentangle from one another, thereby creating a transient network of polymer molecules. Figure 5 parallels the same situation for a more concentrated HPAA solution. In this case, the 20-ppm HPAA solution in excess salt environment is already semidilute, exhibiting transient network formation beyond a strain rate of about 800 s^{-1} . When the same quantity of HPAA is dissolved in deionized water, the transient network is formed at very low strain rates, undetectable in the scale of Figure 5.

If we take into account the behavior of the polymer solutions to be mixed, we can envisage

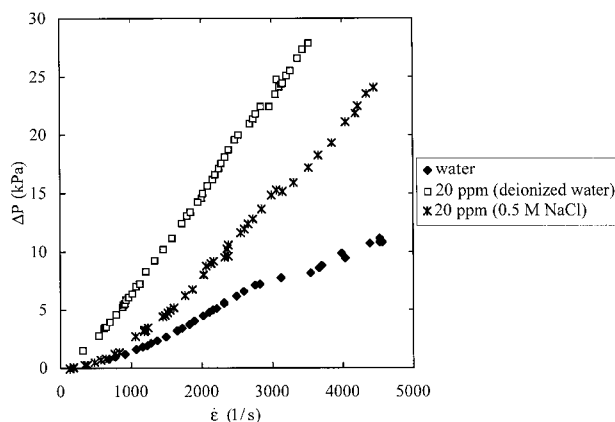


Figure 5 Effect of ionic environment on the pressure drop across the jets for 20-ppm HPAA solutions.

that their blends at both extreme ionic strengths will be equivalent to solutions of blends of highly compact nonfree draining (PEO)–nonfree draining (HPAA) polymer coils (in excess salt solutions) or nonfree draining (PEO) and freedraining (HPAA) polymer coils (in deionized water solutions). The possible interactions between the polymer coils are expected to affect the flow behavior of the solutions through the opposed jets.

Opposed Jets Flow of Solutions of HPAA/PEO Mixtures

HPAA/PEO Blends in Deionized Water

Figures 6 and 7 show results obtained with solutions of HPAA/PEO mixtures in deionized water. Figure 6 shows the effect of increasing the amount of HPAA added to a 500-ppm PEO solution. The change experienced by the ΔP vs. $\dot{\epsilon}$ curve upon the addition of only 2 ppm of HPAA is remarkable: between strain rates of 100 and 2500 s^{-1} , the pressure drop increases up to a factor of 3. From this result we conclude that the two polymers must be interacting in solution, because the strain rate for network formation has been dramatically lowered from around 3000 s^{-1} , for the 500-ppm PEO solution, to a value of the order of 100 s^{-1} for the HPAA/PEO 2/500 blend. The solutions of the mixtures could not be made to flow through the opposed jets at the lowest available strain rates in our equipment without exhibiting transient network formation with an appreciable

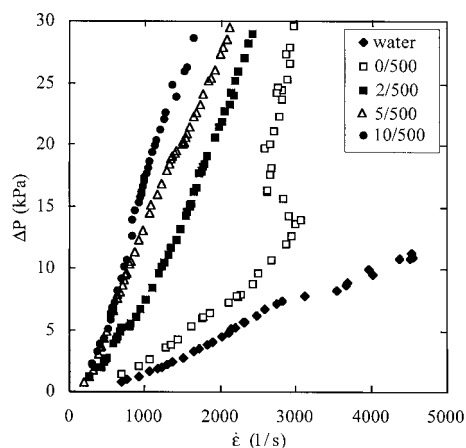


Figure 6 Pressure drops across the jets for solutions of HPAA/PEO mixtures in deionized water at a fixed PEO concentration of 500 ppm. Legend shows the HPAA/PEO concentrations in ppm.

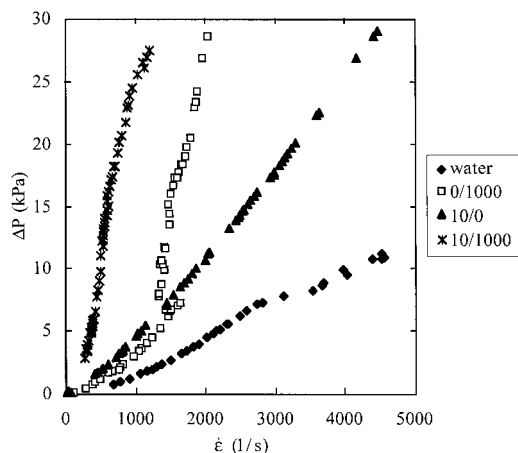


Figure 7 Comparison of flow behavior of solutions of PEO, HPAA, and their mixture in deionized water.

increase in apparent elongational viscosity, as reflected by the departure of the pressure drops from the water curve. This result evidences a highly synergistic behavior of the mixture, because it is clear that the level of viscosification attained by the mixture is much higher than the sum of the contributions of the apparent viscosity of each solution. When polymer–polymer blends in the melt are studied, such positive deviations in viscosity are usually taken as evidence of intermolecular interactions between the blend components.²⁷

Further increases in HPAA concentration beyond 2 ppm (Fig. 6) lead to a progressively more viscous behavior, which qualitatively follows the pattern of solutions of pure HPAA in deionized water (Fig. 2).

The critical nature of network formation is less pronounced in the blends of Figure 6 than in the pure PEO/water case, in the sense that the virtual “plugging” effect that forced the pure PEO curve to go back on itself and exhibit decreases in strain rates at higher ΔP was not observed. This may be a consequence of the fact that the flow field is in the flare state from the lowest attainable strain rates, and the PEO molecules are participating in the entanglements from strain rates much lower than those necessary to induce networks with pure PEO.

Figure 7 presents comparative results for opposed jets flow of solutions of PEO (1000 ppm), HPAA (10 ppm) and their blend. Note how the onset of transient network formation of the 0/1000 curve induces a higher instability (the

curve goes back on itself) than that of the 10/1000 curve. The synergistic behavior of the blend is evident. Note that, for a strain rate of 1000 s^{-1} , the pressure drop of the HPAA solutions is only slightly higher than that of the PEO solution, but the 10/1000 HPAA/PEO mixture has a pressure drop that is five times higher than the solutions of the pure polymers.

The molecular picture that can be derived by the above results indicates that molecular interactions between the two types of macromolecular coils are responsible for the formation of intermolecular transient entanglement networks. The nature of the interaction between the two polymers in solution is unknown, but it is most likely caused by topological entanglements formed by coil–coil interpenetration. These results also confirm the assumption that the solution of the mixture was a homogeneous single phase, which is consistent with the transparent optical appearance of the solution before, during, and after the flow through the opposed jets.

HPAA/PEO Blends in NaCl Solutions

Figure 8 shows ΔP vs. $\dot{\epsilon}$ curves for flow through opposed jets of a mixture of HPAA and PEO in $0.5M$ NaCl, along with the results corresponding to solutions of the pure polymers. It should be noted that the presence of salt does not alter the flow behavior of PEO, because this polymer is nonionic.⁷

In the presence of NaCl, the flow resistance of the HPAA/PEO mixtures is much less sensitive to

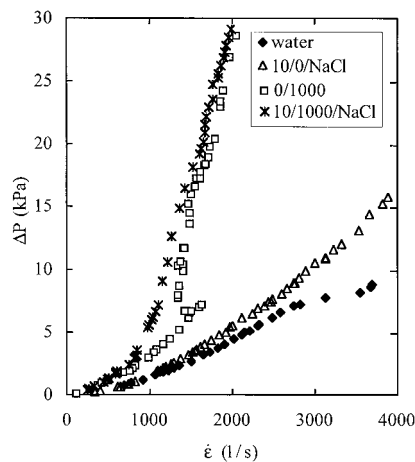


Figure 8 Comparison of flow behavior of solutions of PEO, HPAA, and their mixture in $0.5M$ NaCl.

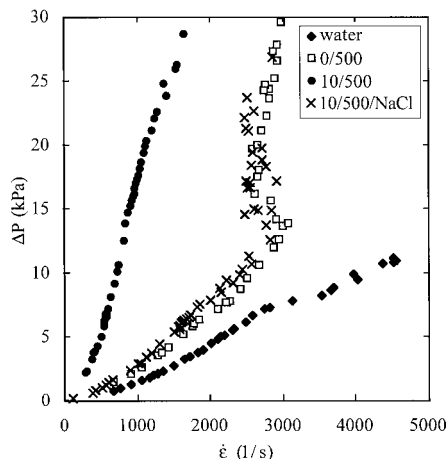


Figure 9 Comparison of flow behavior of a solution of 500 ppm PEO, and its mixture with 10 ppm HPAA in deionized water and 0.5M NaCl.

HPAA concentration than without salt. This is a consequence of the fact that, at low Reynolds numbers, the HPAA adopts a coiled conformation and, therefore, transient network formation occurs at a specific strain rate, as is characteristic of flexible polymers. Nevertheless, in the solution of the mixture in the excess ionic environment, there are still some interactions between the two types of macromolecules because the strain rate for network formation is lower than that of the pure PEO solution. However, the PEO controls the extension thickening behavior of the mixture in Figure 8.

Notice that the addition of HPAA, in the HPAA/PEO mixture with salt, decreases the onset strain rate for extension thickening, while making the effect somewhat less critical, the transition to the transient network state does not cause the curve to go back on itself as in the pure PEO case. The less critical extension thickening effect may be related to the interactions between the HPAA and PEO molecules when the transient entanglements are formed.

From the standpoint of the increase in the apparent viscosity of the mixtures, the results presented above indicate that it is more effective to add HPAA to a PEO solution in the absence of NaCl. A comparison between some solution mixtures with and without NaCl is shown in Figure 9. In this case, a concentration of PEO of 500 ppm was used in the mixture, and virtually no effect was observed upon addition of the 10 ppm HPAA in the presence of salt. A more effective viscosifi-

cation at low strain rates is always achieved in the blends without salt, as shown in Figure 9.

Comparison between Opposed Jets Flow and Porous Media Flow

The solutions studied in this work were previously examined in porous media flow.⁴ The results obtained here are qualitatively similar to those obtained in the more complex porous media flow situation, where also the elongational component of the deformation rate tensor plays a determining role on the macroscopic flow resistance of the solution. The porous media were made up of disordered packings of spheres with diameter $d = 1$ mm in a cylinder with a diameter of 1.9 cm and a length of 30 cm. The porosity of the packing was $\phi = 0.37$. The relation between pressure drop and superficial velocity in flow through porous media made up of sphere packings is commonly represented in dimensionless form in terms of the resistance coefficient, which is a dimensionless ratio between pressure drop and superficial velocity, defined by

$$\Lambda = \frac{d^2 \phi^3 \Delta P}{L \mu v (1 - \phi)^2} \quad (2)$$

In this equation, ΔP is the pressure drop over a length L of porous medium, μ is the viscosity of the solvent, and v is the superficial velocity. The Reynolds number is defined as

$$Re = \frac{\rho v d}{\mu (1 - \phi)} \quad (3)$$

where ρ is the density of the fluid.

Figure 10 presents a comparison between porous media flow [Fig. 10(a)] and opposed jets flow [Fig. 10(b)] for the same solutions. The qualitative trends of the resistance coefficient in the porous medium and the ratio between pressure drop and strain rate in the jets are very similar. In this case, the solution of the mixture exhibits an apparent viscosity that is appreciably higher than those of the solutions of the pure polymers. The solution of the 10/1000 (HPAA/PEO) mixture exhibits a more critical behavior in the opposed jets, as it is the case for the 1000-ppm PEO solution. These results are consistent with our previous results on HPG/PEO blends³ where the addition

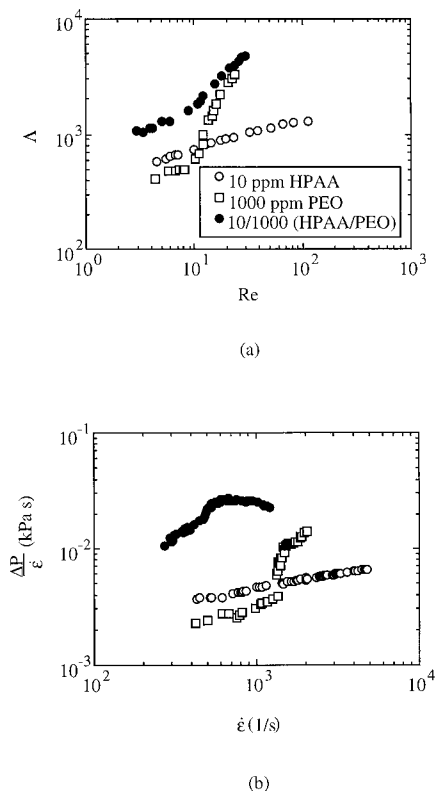


Figure 10 Comparison between porous media and opposed jets flow for solutions of PEO, HPAA, and their mixture; (a) porous media flow, (b) opposed jets flow.

of HPG (a semirigid polymer) turned the extension thickening of the PEO less critical.

The close similarity between the porous medium and opposed jets result highlights the importance of elongational components in porous media flows with regard to the extension thickening behavior of solutions of pure and mixed polymers.⁷

CONCLUSIONS

The results obtained in this work corroborate previous findings that reported the formation of transient entanglement networks of polymer molecules in opposed jet flow beyond a specific concentration (C^+) and a critical strain rate $\dot{\epsilon}_n$. The elongational flow behavior of mixtures of HPAA and PEO is determined by the ionic environment of the solution because of the polyelectrolytic nature of HPAA. In deionized water, the mixtures exhibit a synergistic increase in flow resistance with respect to the parent polymer solutions.

Even adding 2 ppm HPAA to a 500-ppm PEO solution causes a remarkable increase in flow resistance. Such increases have been interpreted as arising from the formation of intermolecular transient entanglement networks that become mechanically active at time scales equivalent to the lowest strain rates available in the opposed jets. In the case of excess salt environment, the opposed flow behavior is less critical in the mixtures, and seems to be dominated by the PEO in the concentration range explored here. From the standpoint of the increase in the apparent viscosity of the mixtures, our results indicate that it is more effective to add HPAA to a PEO solution in the absence of NaCl. The results obtained indicate that intermolecular interactions and associated transient network formation determine the complex non-Newtonian flow behavior of the mixed solutions.

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