

## EXTENSION THICKENING EFFECTS IN THE FLOW OF POLYMER SOLUTIONS THROUGH POROUS MEDIA

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### Abstract

The rheology of polymer solutions in porous media is relevant to a wide variety of applications, including the use of polymer flooding in petroleum recovery from underground reservoirs. When solutions of flexible polymers flow through porous media, the elongational nature of the flow at the pore scale leads to extension thickening, an effect that is characterized by a sudden increase in flow resistance after a critical local strain rate. In this work we present recent results in which the effects of various independent parameters on the extension thickening behaviour of polymer solutions in porous media flows are analyzed. The analysis emphasizes the basic mechanisms that cause the extension thickening.

### I. INTRODUCTION

The rheology of polymer solutions in porous media flows is commonly characterized in terms of the relation between pressure drop and flow rate. This relation is represented in dimensionless form in terms of the resistance coefficient, which is a dimensionless ratio between pressure drop and superficial velocity. For a porous medium consisting of disordered packings of spheres the resistance coefficient is defined by

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

In this equation,  $\Delta P$  is the pressure drop over a length  $L$  of porous medium,  $\phi$  is the porosity of the medium,  $d$  is the particle diameter,  $\mu$  is the viscosity of the fluid and  $v$  is the superficial velocity. The Reynolds number is defined as

$$Re = \frac{\rho v d}{\mu (1 - \phi)} \quad (2)$$

where  $\rho$  is the density of the fluid. It has been empirically established that Newtonian fluids follow the Ergun equation,

$$\Lambda = A + B Re \quad (3)$$

According to equation (3), the resistance coefficient is a linear function of Reynolds number. For low values of this parameter (typically  $Re < 1$ ), the constant term dominates ( $A$ ). This is the Darcian regime. At higher Reynolds number, when inertial effects at the pore level become important, the

second term ( $B Re$ ) becomes appreciable. An illustration of this behaviour is shown in figure 1 for water in two packed beds with monodisperse spheres of different sizes. The curve obtained is correlated by equation (3) with  $A=134$  and  $B=1.7$ . The results show that the effect of particle diameter on pressure drop for disordered monodisperse sphere packings is well represented by the empirical Ergun equation.

In the macroscopic representation of Newtonian flows, a relation such as that described above is enough for a characterization of the hydrodynamics of the process, since the main interest is the description of pressure drop and total flow rate. In non-Newtonian flows, however, features of the local flow field that are not reflected on superficial velocity and average pressure gradients might be important. In the flow of solutions of flexible polymers there occur changes in macromolecular conformation which are induced by the local flow field. As it will be discussed below, the macroconformation changes are primarily induced by the elongational nature of the flow field at the pore level, which is a consequence of the existence of periodic contractions and expansions in the flow, and the presence of stagnation points.

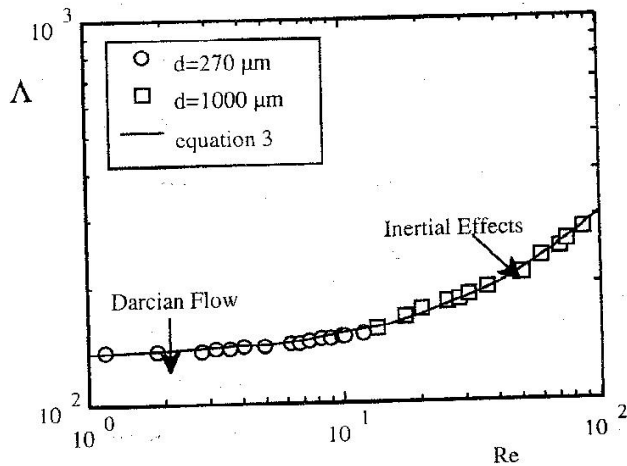


Figure 1. Resistance coefficients for water flowing through disordered monodisperse sphere packings.

The nature of the non-Newtonian behavior exhibited by polymer solutions in porous media flows is dramatically affected by parameters such as chain conformation, polymer concentration and molecular weight. In terms of resistance coefficient vs. Reynolds number, solutions of high molecular weight flexible polymers exhibit the behavior illustrated in figure 2. The values of  $\Delta$  and  $Re$  are evaluated using the viscosity of the solvent. At low Reynolds number, the solution behaves as a Newtonian fluid. There is a sudden increase in flow resistance beyond a critical Reynolds number, denoted onset Reynolds number ( $Re_0$ ). At even higher Reynolds numbers, the value of the resistance coefficient becomes practically constant, reaching a pseudo-Newtonian plateau. This behavior has been extensively studied in the literature. Some polymer solutions that exhibit this behaviour are: aqueous poly(ethylene oxide) (PEO) (1-9), aqueous solutions of polyacrylamide (PAA) and hydrolyzed polyacrylamide (HPAA) in ionic environments (2,4,10-17), polyisobutylene (PIB) in various organic solvents (2,10), and atactic polystyrene (aPS) in various organic solvents (16,18).

In this work we present results that lead to a comprehensive characterization of the extension thickening behavior of solutions of flexible polymers in porous media flows. First we consider the fundamental problem of explaining the mechanisms that cause the extension thickening, and then we analyze the effects that independent variables and operating conditions have on the extension thickening behavior. All the porous media employed to obtain the experimental data consisted

of disordered packings of monodisperse spheres.

## II. MECHANISMS PROPOSED TO EXPLAIN EXTENSION THICKENING

The increase in flow resistance with Reynolds number in porous media flows is a consequence of the extensional nature of the flow field at the pore level. The first attempts to interpret the increase in flow resistance did not recognize this fact explicitly, but approached the analysis from a macroscopic standpoint. Marshall and Metzner (10) argued that these viscoelastic effects were produced by increased elasticity as the Deborah number increases: when this parameter reaches and exceeds values of  $O(1)$ , elastic effects set in and they lead to a large increase in the pressure drop. A similar interpretation was followed by Michele (13) to analyze experimental results on the flow of HPAA solutions through sphere packings.

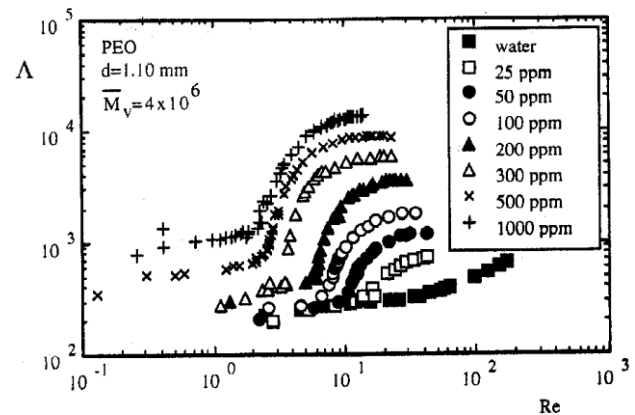


Figure 2. Extension thickening in the flow of polymer solutions through disordered sphere packings. Aqueous solutions of PEO (9).

Dauben and Menzie (1) explained the extension thickening effect in terms of macromolecular conformation changes. They argued that the macromolecules passed from a spherical coil conformation to an ellipsoid due to the application of stresses in the flow. The flow generates normal stresses that, according to them, lead to higher pressure drops. This interpretation was later proved to be inadequate by James and McLaren (3) who, based on a detailed analysis of the flow field at the pore level, inferred that normal stresses due to shear would result in negligible changes in the pressure drop. They concluded that the extensional nature of the flow field at the pore level was crucial in explaining the increase in flow resistance.

Jones and Maddock (19) associated extension thickening in porous media flows to a destabilization of the flow, attributed to the existence of stretched chains in the flow field. They argue that partial stretching of the macromolecules is enough to produce the onset of extension thickening. Even though this explanation has not been pursued further, their work is the first to invoke chain stretching and kinetic theory arguments to explain extension thickening.

Maerker (20) recognized the role of macromolecular deformation induced by the elongational nature of the flow in the pores. Maerker pictures the randomly coiled flexible molecules in solution as being entangled with one another or with themselves; when these molecules are made to flow through a constriction Maerker postulates that they stretch. Furthermore, Maerker considers that very large stresses will only build up at sufficiently large strain rates when the time scale of deformation is short and the molecules do not have time to disentangle. These arguments only seem appropriate when the solution is in the semi-dilute regime at equilibrium but they bear a similarity to more recent hypotheses used to explain the extension thickening behavior.

Theoretical considerations by de Gennes (21) and Hinch (22) predict that high molecular weight flexible molecules should undergo a coil-stretch transition in elongational flow fields when the applied strain rate exceeds a critical value which is of the order of the inverse of the longest relaxation time of the coil. According to de Gennes, a sudden transition is expected because of the hysteresis of molecular relaxation time with chain extension that arises due to the change of the draining characteristics of the stretching molecules. In other words, sudden extension implies a sudden conformational change with the random coils greatly aligned in the elongational flow direction, changing their draining characteristics and causing the frictional contact between inner chain segments and the solvent to increase. It is therefore expected that a coil-stretch transition will lead to an increase in the elongational viscosity of the solution, a fact that has been experimentally verified in ideal elongational flow situations, such as in the flow through opposed jets (23).

Elata et al (5) invoked the coil-stretch transition theory to explain the sudden increase in flow resistance observed for PEO solutions in porous

media. The authors acknowledged, however, that the coil-stretch theory could not explain the observed dependence of onset strain rates for extension thickening on polymer concentration. If the solution were truly dilute the critical strain rate for coil-stretch transition would be independent of polymer concentration. The experimental data obtained by Elata et al showed that the onset strain rate decreased with an increase in polymer concentration. Naudascher and Killen (6) performed porous media flow experiments with PEO solutions which they interpreted by means of an analysis which closely followed a suggestion presented previously by Batchelor (24). Batchelor argued that the large stress levels that had been commonly observed for polymer solutions in elongational flows were too large to be ascribed to the stretching of isolated macromolecules. He proposed that hydrodynamic interactions between stretched macromolecules could account for the observations. In the same publication, Batchelor developed a model to calculate stresses in fiber suspensions subjected to ideal extensional flow, including fiber-fiber interactions. The model shows that substantial increases in elongational viscosities can be obtained at very low fiber concentrations, provided that the fibers are aligned in the stretching direction, and that their length is much larger than the mean lateral separation distance between fibers. Naudascher and Killen (6) proposed that the extension thickening in porous media flows of solutions of flexible polymers was a consequence of the hydrodynamic interactions among stretched and aligned macromolecules in the manner described by Batchelor's model for fiber suspension. Even though this theory could predict the scaling between onset strain rates and polymer concentration, it predicts an extension thickening behaviour that is more gradual with respect to changes in strain rates than what is observed experimentally.

After the first attempts to characterize the mechanisms behind extension thickening described above, a series of works invoked the coil-stretch theory as the preferred explanation for this behavior. This explanation was adopted by making the analogy that the flow at the pore level could be treated in the same manner as idealized elongational flow. Durst and Haas (25) performed experiments with polyacrylamides in flow through porous media in a wide concentration range. They report that a representation of the results in terms of an effective

extensional viscosity (proportional to resistance coefficient) as a function of the Deborah number led to curves with an onset point which they claim to be approximately the same.

Odell et al (26) proposed an alternative explanation for the extension thickening behavior of flexible polymers in porous media flows. In experimental results obtained in opposed-jets now with HPAA at concentrations within the typical ranges used in porous media flows, they determined that after the macromolecules underwent a coil-stretch transition, the solution exhibited only small departures in flow resistance with respect to the solvent. On the other hand, beyond a critical strain rate, strong extension thickening effects were observed. These effects only occurred when transient networks of polymer molecules were formed in the flow, arising from entanglements becoming mechanically effective at time scales shorter than the network disentanglement time. Odell et al proposed that the degree of extension thickening observed in porous media flows was more consistent with the formation of transient entanglement networks than with the occurrence of only a coil-stretch transition.

Evidence that confirmed the transient network hypothesis was later found by Rodriguez et al (9) and Suez et al (18). The main aspects of the analysis rely on the dependence of the onset of extension thickening on polymer concentration, and its criticality with respect to strain rate. These results are presented in detail below.

### III. THE NATURE OF EXTENSION THICKENING IN POROUS MEDIA FLOWS

The effect of polymer concentration on the resistance coefficient versus Reynolds number curves is illustrated in figure 2 for aqueous solutions of PEO flowing through a disordered sphere packing (9). The resistance coefficient and Reynolds number are expressed in terms of the solvent viscosity. At low concentrations and low Reynolds numbers, the polymer solution behaves exactly as water. As the Reynolds number is increased, an increase in flow resistance appears. At higher concentrations (50 ppm and higher) the increase in flow resistance occurs abruptly until a plateau value is reached. Notice that increases in resistance coefficient of an order of magnitude and more are present at concentrations over 100 ppm. At the largest concentrations (500 and 1000 ppm) the curves

corresponding to the solutions do not coincide with the water curves at low Reynolds number. However, the resistance coefficient approaches a constant value as Re decreases, indicating a Newtonian behavior. The higher values of  $\Lambda$  at low Re for high concentrations reflect an increase in the shear viscosity of the solution. If the shear viscosity of the solution were used to evaluate the resistance coefficient, then the values of  $\Lambda$  would be the same for all the solutions as Re becomes small.

It should be noted that in the data presented in figure 2 the onset Reynolds number at which the extension thickening suddenly appears decreases as concentration increases. Such an effect cannot be accounted for by the increase in shear viscosity with solution concentration (18, 28). The decrease of  $Re_0$  with concentration for PEO solutions was noticed by James and McLaren (3) who did not expect this result given the low level of concentrations employed which were thought by the authors to be in the dilute regime. James and McLaren proposed that this result could be due to the wide molecular weight distribution of the polymer. Similar results led Elata et al (5) to propose an empirical correlation to fit all concentration curves by plotting  $\Lambda$  versus a dimensionless factor of the form:  $De C^{1/2}[\eta]^{1/2}$ , where  $[\eta]$  denotes the intrinsic viscosity, and De the Deborah number. Using such plots their data on PEO solutions flowing through porous media was almost independent on concentration. This means that the onset strain rate for extension thickening effects is proportional to  $C^{-1/2}$ . Müller et al (28) later found, for PEO solutions, that  $Re_0$  was proportional to  $C^{-0.6}$ , which is a behavior similar to that reported by Elata et al.

The concentration dependence of onset Reynolds number discussed above is not consistent with the trends observed for the coil-stretch transition in ideal elongational flows. The flow between opposed jets can be considered close to an ideal elongational flow in the sense that there are no appreciable rotational components in the velocity gradient, since the flow approximates a uniaxial extension field. It is well known that the strain rate at which molecules undergo a coil-stretch transition is a weak function of polymer concentration. The reason for this is that the coil-stretch transition is a process that pertains to isolated, non-interacting molecules, when the concentration of polymer is within the dilute limit. 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. At still higher strain rates a different regime is attained, termed 'flare' because of the particular form of birefringence observations, at which the formation of transient networks of molecules is evident. The transition to the flare regime is characterized by a strong interaction among polymer molecules that have been stretched in the flow field. For this reason, these transitions are very sensitive to polymer concentration: a larger concentration implies an increased probability of molecular interaction and, therefore, it leads to greater interaction at lower strain rates. In the flare regime, the polymer exerts strong flow modification, leading to unstable velocity profiles and the loss of the stagnation point (23).

Critical strain rates for flow regime transitions in opposed jets are shown in figure 3. The onset strain rate for coil-stretch transition is practically constant with concentration at low concentrations (dashed lines, where the solution viscosity is nearly identical to that of the solvent). At higher concentrations, the critical strain rate for the coil-stretch transition varies with concentration due to changes in the viscosity of the solution. The transition to the flare state decreases more rapidly as polymer concentration increases. The solid line represents the variations of Reynolds onset in porous media flows. Notice that, even though the -0.5 slope seems to be lower than the variations observed for the pipe-flare transitions, the flow in porous media is more complex than in the opposed jets, and facts such as strain rate distributions and presence of shear might smooth changes in the onset of transient entanglements, as compared with purely elongational flows. This indicates that the onset of extension thickening in porous media flows resembles the transition to the 'flare' state in opposed jets, which is when transient entanglements occur in the flow.

Sáez et al (18) have explored the origin of the increase in flow resistance observed in the flow of polymer solutions through porous media by studying the behavior of closely monodisperse atactic polystyrene. The effect of polymer concentration on the resistance coefficient can be seen in figure 4. The values of  $\Lambda$  are very high, even at low Re (in the Newtonian limit). This is a consequence of the fact that the shear viscosity of the solution is higher than that of the solvent, and

that the flow distribution is not uniform. The flow is not uniform due to the limited size of the cell used. The fact that entrances and exits have a cross section that is smaller than the cross section of the cell implies that the average velocity field in the porous medium is not completely one dimensional and this has been proven to lead to higher resistance coefficients and lower onset Reynolds numbers as compared with uniform flow (9, 29). In view of these previous results, we can treat the data presented in figure 4 as qualitatively similar to uniform flow data (for instance, the solvent behavior is accurately described by equation 3 but with different values of the constants A and B).

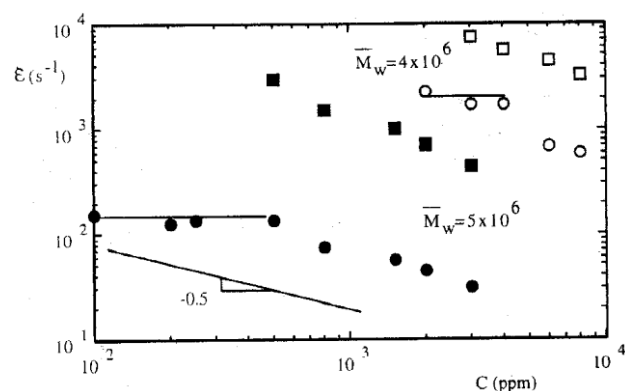


Figure 3. Effect of concentration on development of molecular connectivity in opposed jets flow for PEO solutions; m, l - coil-stretch transition; o, n-pipe-flare transition. Data obtained from Keller et al (27) and Chow et al (30).

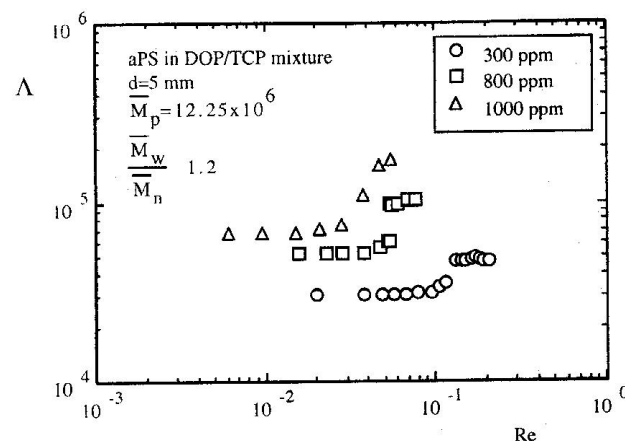
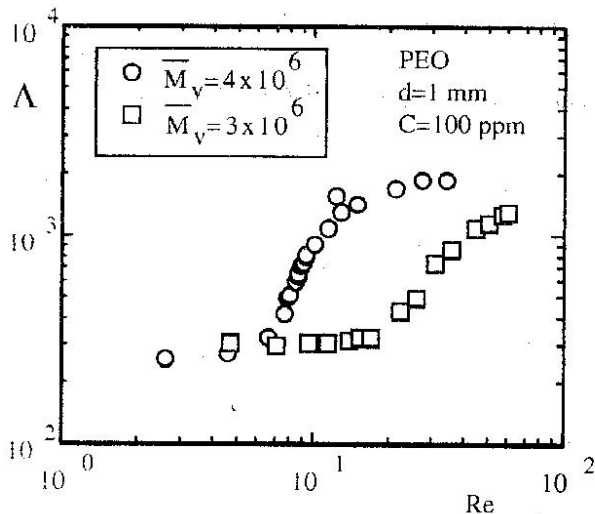


Figure 4. Resistance coefficients for solutions of a PS in a viscous solvent (80.5% dioctyl phthalate/19.5% tricresyl phosphate v/v) at various concentrations (18).

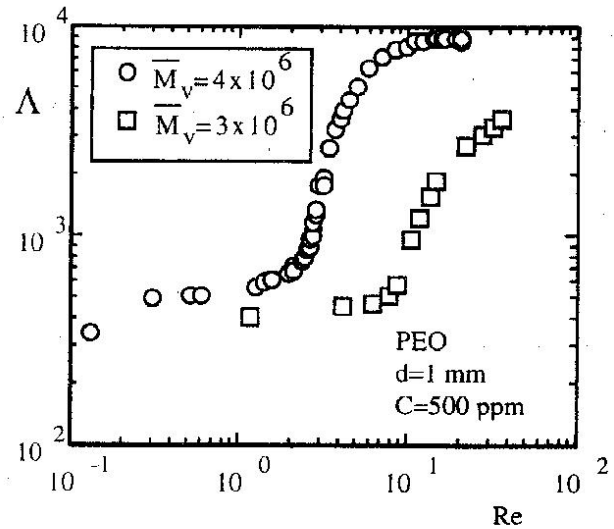
The general trend in the changes of  $\Lambda$  with concentration observed in figure 4 is similar to that

reported for other flexible polymer solutions. However, the curves exhibit a more critical thickening behavior than any other curve previously reported using polydisperse polymers, a fact that is clearly related to the narrow molecular weight distributions of the samples of aPS used. It should be pointed out that the behavior of solutions of 300 and 800 ppm was reported to be perfectly critical within the sensitivity range of the measuring devices employed; that is, there was a sudden jump in pressure drop at the onset Reynolds number and that is the reason why there is a discrete step in the  $\Lambda$  values at that point, with no intermediate values recorded.

When the concentration of 1000 ppm was used, Sáez et al were able to record a data point in the middle of the range where the pressure drop increases, thus indicating a somewhat less critical behavior, which they attributed to flow-induced degradation. As already pointed out, it can be seen in figure 4 that the onset Reynolds number decreases with increasing concentration. Such an effect is again not merely due to an increase in shear viscosity. It can be seen that the  $Re_0$  decreases by a factor of two upon changing the concentration from 300 ppm to 800 ppm. The shear viscosity, however, only changed by a factor of 1.3 as indicated by the change in  $\Lambda$  values at low  $Re$ . The formation of transient entanglement networks, as pointed out above, would explain this trend since it is expected that the strain rate for the onset of such an effect change very rapidly with varying concentration (27, 29).



(a) C=100 ppm



(b) C=500 ppm

Figure 5. Resistance coefficients for aqueous solutions of PEO (23). a) C= 100 ppm, b) C=500 ppm.

The effect of polymer molecular weight was recognized early in the literature as one of the most important aspects that affect extension thickening, since it is well known that the higher the molecular weight the lower the onset Reynolds number and the higher the resulting resistance coefficient for the same polymer concentrations (1,3,15,18,23). This effect was investigated by Müller et al (23) using two different PEOs. Figure 5 shows that the porous media flow behavior of these polymers is substantially different even at low concentrations. The onset Reynolds number is higher for the lower molecular weight polymer. It should be noted that the two 100 ppm solutions used in figure 5a had identical shear viscosities; this is indicated by the fact that the two values of resistance coefficients at very low Reynolds numbers are the same. When higher concentrations are used, the curves corresponding to the two polymers differ from the lowest  $Re$  numbers (figure 5b). The difference in the plateau value of resistance coefficient at high  $Re$  is evident even for the lowest concentrations: the lower molecular weight polymer causes a lower increase in flow resistance. This plateau value should be influenced by two opposing effects: the shear viscosity of the solution might decrease with increasing shear rate (PEO/water solutions are known to be shear thinning, and this effect is more noticeable at moderate concentrations, and it also depends on the molecular weight of the polymer)

and the elongational viscosity increases with increasing strain rate. It is clear by the shape of the curves in figure 5b that the increase in shear viscosity upon increasing solution concentration is responsible for the differences observed in the  $\Lambda$  values at low Reynolds number (Newtonian regime), while the elongational viscosity is dominating the behaviour of the resistance coefficient at Reynolds numbers larger than the onset value.

If the increase in flow resistance were due to the coil-stretch transition of the polymer molecules, then the strain rates at which this happens (which are proportional to  $Re_0$ ) should be inversely proportional to the longest relaxation time of the coil. For flexible molecules, the longest relaxation time is found to be proportional to  $Ma$ , where "a" has a value that ranges from 1.5 to 1.8 depending on the polymer-solvent interactions (30, 31). This relaxation time is inversely proportional to the critical strain rate for the coil-stretch transition. Sáez et al (18) studied the molecular weight dependence of the onset Reynolds number for extension thickening in porous media flows using three different closely monodisperse aPS Samples of molecular weights  $9.8 \times 10^6$ ,  $12.25 \times 10^6$ , and  $20 \times 10^6$  (Mw/Mn 1.2 for all samples). If the coil-stretch transition is the mechanism responsible for the non-Newtonian behavior, then  $Re_0$  should scale with  $M^{-a}$  with "a" between 1.5 and 1.8. The available data of Sáez et al followed a much greater exponent (of the order of 3.0 to 4.0), even allowing for a shear viscosity correction. On the other hand, Müller et al (23) worked with polydisperse PEO samples (figure 5). The onset Reynolds number data on these two polymers yields  $a=3.5$ . An exponent greater than 2 is not compatible with the coil-stretch hypothesis and would probably indicate that molecular interactions are taking place, a fact that gives support to the transient network hypothesis.

It has been argued (26) that the observed criticality of the extension thickening effect in porous media flows would not be expected in the context of coil-stretch transition since the polymers typically used are polydisperse PEO and HPAA. A polymer with a wide distribution of molecular weight will have a wide spectrum of relaxation times and therefore should have a gradual extension thickening behavior. This fact was recognized by early investigators who could not offer an explanation for the observed criticality (5, 16). Recently, Rodriguez

et al (9) have studied the flow of polydisperse PEO (Mw/Mn>5) solutions through non-consolidated porous media. They calculated that a polydispersity of less than 1.04 would have to be used in order to explain the observed criticality of the thickening effect in terms of only coil-stretch transitions of macromolecules. This result also supports the transient network hypothesis.

Further evidence that supports the hypothesis of the formation of transient networks is provided by figure 6 (18). It shows simultaneous results on the measured transmitted intensity due to flow induced birefringence through crossed polars, and resistance coefficient of a solution of a closely monodisperse aPS solution flowing through porous media. The intensity that is reported in figure 6 is an average value of the optical retardation through several pores. The refractive index of the glass beads that constituted the porous medium was matched to that of the solvent. Perhaps the most striking feature of figure 6 is the almost perfect criticality of both the increase in  $\Lambda$  and the simultaneous increase in the intensity. This demonstrates that when a major increase in flow resistance occurs, a major change in the molecular orientation is also occurring. However, the criticality of the effect is such that it resembles a step function; a perfectly monodisperse polymer would be required to rationalize these results in terms of the stretching of isolated molecules. Even though the polymer standard used here is closely monodisperse, its residual polydispersity (Mw/Mn= 1.2) is enough to invalidate this explanation (9). Again it is found that the formation of transient entanglement networks could explain better the criticality of the effect.

The results presented previously encourage a comparison between flow in porous media and flow in ideal elongational flows. For instance, the  $\Lambda$  vs.  $Re$  curve in figure 6 shows a small continuous rise in  $\Lambda$  at low  $Re$  (between 0.04 and 0.05), then at  $Re=0.053$  a sharp increase in  $\Lambda$  occurs. It is tempting to interpret the first small rise in  $\Lambda$  as the contribution of the coil-stretch transition, and the large rise as caused by the formation of transient networks. Such an explanation would parallel the experimental results found measuring pressure drops through opposed jets. A direct comparison between opposed jets flow and porous media flow is presented in figure 7, which shows results obtained when PEO solutions of the same concentrations are passed through a disordered sphere packing and an

opposed jets device. Notice that  $P/\epsilon$  is a parameter similar to  $\Lambda$ , since, for a given set of results, both represent the ratio between pressure drop and average velocity. The similarity between the porous media flow results and the opposed jets case is remarkable. Both sets of curves have the same overall behavior, except at low strain rates where the opposed-jets results do not achieve a plateau, a fact that is caused by inertial effects in the region between the jets. The sudden increase in  $P/\epsilon$  in the opposed jets is a result of transient network formation. This represents further evidence linking the extension thickening in porous media flows to transient network formation due to the elongational flow at the pore level.

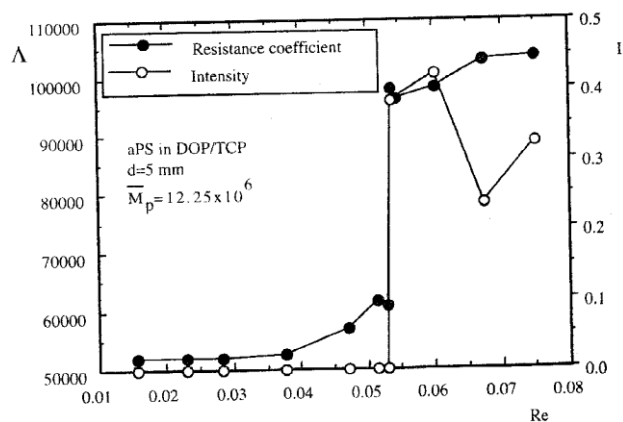


Figure 6. Resistance coefficient and intensity of optical retardation as a function of Reynolds number for a 800 ppm aPS solution in a viscous solvent (80.5% DOP/19.5% TCP v/v) (18).

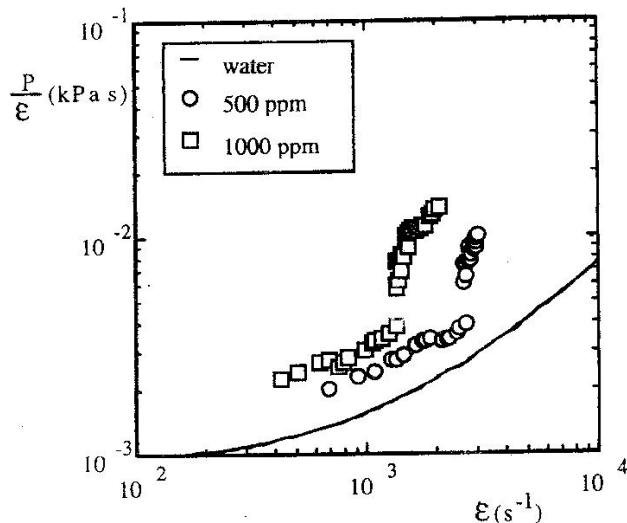
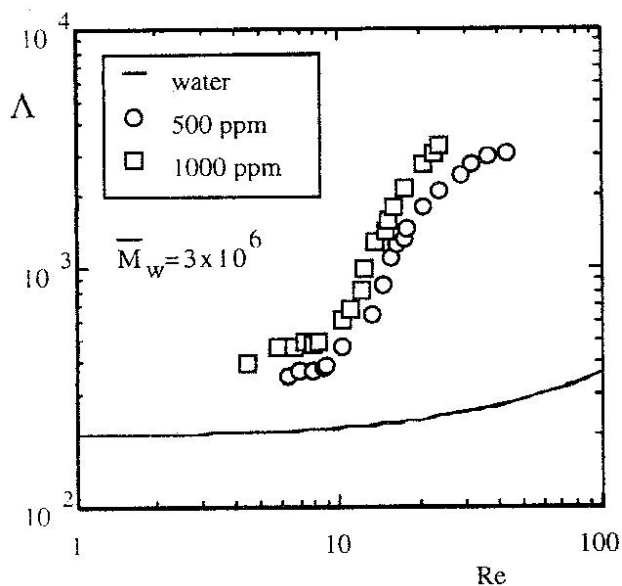


Figure 7. Comparison between porous media ( $d=1.1$  mm) and opposed jets flow for PEO solutions. (a) Porous media flow, (b) Opposed jets flow

An interesting observation from the results in figure 7 is the difference in the criticality of the extension thickening between opposed jets and porous media flows. Although the extension thickening in the porous medium is more critical than what would be expected from coil-stretch transition theory (as argued above), the behavior in opposed jets flow is even more critical. The smoothing of the resistance coefficient changes in porous media flow is a consequence of the existence of a wide range of strain rates and local geometries.

#### IV. CONCLUDING REMARKS

Solutions of flexible polymers exhibit extension thickening in flow through porous media. In the range of independent parameters in which this effect is commonly encountered, the extension thickening seems to be a consequence of the formation of transient entanglement networks of polymer molecules, even at concentrations below the equilibrium coil overlap concentration. This conclusion stems from a variety of facts that cannot be solely explained the basis of the coil-stretch transition theory. These facts include: the criticality of the extension thickening effect and its scaling with concentration and molecular weight. Furthermore, we have shown that there exist a remarkable similarity between the extension thickening in porous media flow and results obtained in closely ideal extensional flows where the existence of transient networks can be



ascertained by means of optical and mechanical measurements. This similarity indicates that extensional flow at the pore level is the dominating feature of the porous media flow of solutions of flexible polymers.

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