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DILUTE POLYMER SOLUTION EXTENSIONAL FLOW IN POROUS MEDIA

Introduction

Table I lists the polymer systems that have been studied and the solution extensional flow model parameters associated with each polymer system. The working equation developed for the polymer extension model has been explained previously\(^1\) and was used to calculate the coil modulus and coil viscosity for each polymer system. Recall that the extensional model for very dilute polymer solutions can be expressed in dimensionless format using the relationship

\[
NSFR = 4\pi^2 S_h^2 \frac{PHDe}{1 + 4\pi^2 De^2} + 1
\]

The dimensionless geometry, \( P = (\psi \phi / \kappa)^2 \), for all porous media used in this study has a value of 0.792. The dimensionless coil viscosity, \( H = (\rho \mu_o \eta_{intr}) / \eta \), will vary depending upon the polymer coil dashpot viscosity, \( \eta \), solvent viscosity, \( \mu_o \), and monomer density, \( \rho \). The coil shielding factor, \( S_h \), is set equal to unity. The experimentally determined dimensionless coil viscosity, \( H \), together with the maximum in the normalized solution flow resistance (NSFR), are listed in Table I for each polymer system studied.

Note from Table I that the solutions of the polyacrylamide (PAM), hydrolyzed polyacrylamide (HPAM) and polacrylamide copolymers (AM/AMBA) have coil parameters that are desirable for enhanced oil recovery. Each of these polymer systems have a large dimensionless coil viscosity, \( H \), and this produces a large maximum in the NSFR. In contrast, all the poly(ethylene oxide) solutions have coil parameters that do not greatly increase the NSFR. These high molecular weight polymers are not suitable for polymer flooding an oil reservoir.

Application To Polymer Flooding in a Sandstone Reservoir

As previously discussed\(^2\), the porosity, \( \phi \), and effective sand diameter, \( d \), of a Woodbrine sandstone can be approximated from a knowledge of the reservoir's permeability, \( k \).

\[
\phi = a + b \log(k) \quad d = \frac{1 - \phi}{\phi} \sqrt{\frac{180k}{\phi}}
\]

In the above relationship the permeability is expressed in cm\(^2\) and \( a \) and \( b \) have values of 0.466 and 0.025, respectively.

The Deborah number used in the polymer extensional model can be determined from the average fluid velocity, \( v \), and the sandstone parameters \( d \) and \( \phi \).
Usually at large distances away from the injection wellhead, fluid velocities in the reservoir are very low, about 1.0 ft/day. If we use this average fluid velocity, a typical sandstone permeability of 10 md (10\(^{-10}\) cm\(^2\)), and a polymer coil dashpot viscosity and spring modulus of 1.4 poise and 1,000 dyne/cm\(^2\), respectively, then the porosity, effective sand diameter, and Deborah number can be calculated to have values of 0.215, 1.1 \times 10^{-3} cm, and 5.3 \times 10^{-5}, respectively. These fluid flow conditions are laminar (a porous media Reynolds number of 3.8 \times 10^{-5}).

Under these low fluid flow conditions, \(1 + 4\pi^2 De^2 \approx 1\), and the extensional model in dimensionless format simplifies to

\[
NSFR = 1 + 4\pi^2 S_h^2 P H De
\]

We can use this relationship and the conditions given (\(S_h = 1, P = 0.272, H= 33, De = 5.3 \times 10^{-5}\)) to find a NSFR value of 2.9. For a polymer flooding solution concentration, \(c\), of 5.0 \times 10^{-5} g/ml (50 ppm) and a polymer intrinsic viscosity of 4600 ml/g the dimensionless concentration, \(c \eta_{intrinsic}\), equals to 0.23. Therefore for this example

\[
NSFR = \frac{\Delta P_s - \Delta P_{so}}{\Delta P_{so} \eta_{intrinsic} c} = 2.9 \quad \text{or} \quad \frac{\Delta P_s}{\Delta P_{so}} = 1.67
\]

Thus the solution is 67% more resistant to flow through the sandstone than the solvent alone. The polymer has reduced the mobility of the displacing fluid within the sandstone and would improve the flooding sweep efficiency.

The above example can be modified to determine the mobility of any polymer solutions in a sandstone reservoir if the polymer coil dashpot viscosity, spring modulus and intrinsic viscosity are determined from laboratory experiments. Figure 1 shows the model prediction of fluid resistance for three polymer systems that are listed in Table I and three sandstone reservoirs having permeabilities of 0.1, 1.0 and 10 md. As expected the curves are linear at low average fluid velocities but curve upward at higher fluid velocities. Solution resistance is greatest for the AM/AMBA and PAM polymer systems with larger intrinsic and coil dashpot viscosities and a lower coil spring modulus. The HPAM solution has low resistance to fluid flow and would not be an acceptable polymer for flooding.

**General Flow Behavior of All Polymer Solutions**

All polymer solutions have the same dimensionless flow behavior. At Deborah numbers less than about 0.01, the normalized solution flow resistance is very low which indicates that a low degree of coil extension and recovery is occurring under these conditions. At Deborah numbers between 0.01

\[
De = \frac{v \psi \eta}{G \phi \kappa \delta}
\]
and 0.15, the normalized solution flow resistance increases to a maximum and then slowly decreases as the Deborah number increases to higher values. This suggests that the degree of polymer coil expansion and recovery is at first increasing under these conditions, then reaches a limit at a Deborah number of about 0.15. Above this Deborah number the polymer coils are probably not able to completely recover all of the large extensional strains developed during initial extension-recovery cycles. Thus they have less potential to extend in subsequent extension-recovery cycles. Therefore, at higher Deborah numbers the coils travel through the bed in a more extended state. They will have less and less recoverable extension as they travel from cavity to cavity. At very high Deborah Numbers the polymers travel through the bed in a highly extended state and thus less fluid kinetic energy is converted to heat. If laminar flow conditions are maintained, the normalized solution flow resistance should eventually decrease to zero in the limit of very high Deborah numbers.

The reduction in the normalized solution flow resistance at higher Deborah numbers is due to the diminished ability of polymer coils to convert kinetic energy to heat as they are extended and recover at faster rates. At greater fluid flow conditions the polymer coils are not able to follow in concert with the rapidly changing local fluid velocities. At high flow rates insufficient time is available for coil extension during fluid acceleration and coil recovery during fluid deceleration. As a consequence, less total coil deformation is experienced each cycle and thus less energy is converted into heat by the macromolecules. Therefore the solution will have less resistance to flow through the porous medium at higher Deborah numbers.

Conclusions

Of all the polymer systems examined in this laboratory, the NaAMB/AM 20/80 copolymer solutions had the greatest flow resistance in a porous media. This is because the polymer coils of these macromolecular structures are greatly expanded (have large hydrodynamic diameters) and can elongate and recover in extensional flow fields having low average fluid velocities.

The use of high molecular weight, highly expanded copolymers versus lower molecular weight polymers that are not greatly expanded has a dual advantage in reservoir flooding. Solutions of larger molecular weight macromolecules with large polymer coils not only require less polymer mass for a given fluid flow resistance but this resistance is also experienced at lower flow rates through the porous media. Thus they are effective flooding agents even at low concentrations and have a significant economic advantage.

References


Table I. Packed bed extensional results for polymer solutions using 0.5 m NaCl solvent.

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Mol. Wt. g/mole x 10^6</th>
<th>Intrinsic Viscosity cm^3/g</th>
<th>Solution Conc. g/cm^3 x 10^6</th>
<th>Packing Sphere Size cm x 10^3</th>
<th>Coil Dashpot Viscosity poise</th>
<th>Coil Spring Modulus dyne/cm^2 x 10^3</th>
<th>Coil Response Time msec</th>
<th>Dimensionless Coil Viscosity</th>
<th>Dimensionless Conc.</th>
<th>Maximum in NSFR</th>
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a) Acrylamide and 3-acrylamido-3-methylbutanoic acid copolymers b) Polyacrylamide c) Hydrolyzed polyacrylamide, 3% hydrolysis d) Hydrolyzed polyacrylamide, 13% hydrolysis e) Poly(ethylene oxide) from Polysciences, Inc.
Figure 1. Model prediction of solution flow resistance to solvent flow resistance for AM/AMBA copolymer (solid lines), polyacrylamide homopolymer (doted lines) and 13% hydrolyzed polyacrylamide (dashed lines) in sandstone reservoirs. See the 2nd, 7th, and 12th listing in Table I. All solutions have a polymer concentration of 50 ppm.