Quantification of the Viscoelastic Behavior of High Molecular Weight Polymers used for Chemical Enhanced Oil Recovery

by

Oluwaseun Adedeji Magbagbeola, B.S.

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Quantification of the Viscoelastic Behavior of High Molecular Weight Polymers used for Chemical Enhanced Oil Recovery

Approved by
Supervising Committee:

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Gary Pope, Supervisor

________________________
Chun Huh, Supervisor
Dedication

To my GOD; thank you LORD.
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Abstract

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Oluwaseun Adedeji Magbagbeola, M.S.E.

The University of Texas at Austin, 2008

Supervisors: Gary A. Pope and Chun Huh.

The main objective of this study was to validate a proposed Universal Viscosity Model (UVM) for the apparent viscosity of polymer solutions flowing in permeable media and to determine the parameters of this model and how they vary with the polymer characteristics. New rheological data for several polymers of current interest for both polymer flooding and other chemical EOR processes were measured and new coreflood data over a wide range of velocities were measured for this purpose. Two types of polymer were used: a partially hydrolyzed polyacrylamide (HPAM) and a co-polymer of acrylamido-methyl-propane sulfonate (AMPS) and acrylamide. Both steady shear and oscillatory measurements were carried out to determine the viscous and elastic components of the complex viscosity and to determine the relaxation time of the polymers. Core flood experiments over a wide range of flow rates were used to measure the apparent viscosity of these same polymer solutions.
The viscosity of the polymer solutions was modeled using the Carreau model. The relaxation times of the polymer solutions were obtained by modeling the dynamic/oscillatory data using the Rouse model. The UVM parameters time constant, $\lambda_2$, shear-thickening index, $n_2$, and maximum viscosity before shear degradation, $\mu_{\text{max}}$, were determined by fitting the experimental data. All of the data could be fit with a constant value of the time constant, $\lambda_2$ of 0.01. The shear-thickening was found to have a value of about 2.3.

The most important conclusion of this study is that the UVM fits measured core flood data under a wide range of conditions for commonly used EOR polymers and can therefore be used to make predictions of apparent viscosity of these polymer solutions under certain conditions using only rheological data that are relatively inexpensive to measure compared to core flood data. This model can now be used in reservoir simulation studies of polymer flooding processes and other chemical enhanced oil recovery processes involving the use of polymers.
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Chapter 1: INTRODUCTION

With the increasing demand for oil and gas resources in recent years, enhanced oil recovery (EOR) techniques are getting renewed attention, as they would greatly increase the supply of oil and subsequently help meet the growing demand. One of these EOR techniques is polymer-flooding. It involves the addition of specific water-soluble polymers to injection water to improve sweep efficiency thereby increasing oil recovery.

Typically, about 70% of most proven oil reserves in the world remain untapped after primary drive mechanisms. Even after extensive waterflooding (secondary recovery), there remains a significant amount of the oil resource unrecovered as a result of reservoir heterogeneity and complex geology. Polymer flooding is then carried out as a tertiary measure to improve mobility control, increase reservoir sweep efficiency and ultimately enhance the oil recovery. The most common synthetic polymer used for polymer flooding is the partially hydrolyzed polyacrylamide (HPAM). For decades, polymer flooding has been applied commercially around the world and more recently at the Daqing oil field in China where about 300,000 barrels/day of oil is being attributed to polymer flooding (Wang et al., 2001).

The effect of the increase in injection water viscosity on oil recovery has been studied for decades and is a well understood phenomenon. An important characteristic of all synthetic and biopolymers used for enhanced oil recovery is that their viscosity decreases with increase in shear rate (a.k.a. shear-thinning). This behavior has been exploited in improving the injectivity of these viscous polymer solutions. It also implies that in high permeability zones in the reservoir, the viscosity of the injected solution would be low, hence not attaining the desired sweep efficiency. Another key characteristic of HPAM polymer solutions is that after a certain critical flow velocity (or
apparent shear rate), the apparent viscosity of the solution begins to increase (a.k.a. shear thickening). This shear-thickening behavior has been attributed to the viscoelastic nature of the polymers. This could be exploited for better sweep efficiency in the high permeability zones of the reservoir, since the apparent viscosity of the solution would increase with increase in flow velocity. This advantage of shear thickening fluids has been shown by Jones (1980). The viscoelastic property of HPAM has also been reported to reduce residual oil saturation (Wang et al., 2001).

Most high molecular weight HPAM polymers while flowing through a porous medium exhibit both shear thinning (for low to intermediate flow velocities) and shear thickening behaviors (above a critical flow velocity). These ‘viscoelastic’ polymers have begun to assume an important role in chemical EOR processes such as polymer, surfactant polymer (SP) and alkaline surfactant polymer (ASP) flooding. Therefore, it has become imperative to be able to understand and fully characterize the in-situ rheology of these polymers.

1.2 RESEARCH OBJECTIVES

The objective of this study is to obtain a better understanding and characterization of the in-situ rheology of high molecular weight polymers with special emphasis on the shear thickening behavior of the polymers. These lead to the development of a unified viscosity model (UVM) that accounts for the entire range of flow velocities (apparent shear rates), for both the shear thinning and shear thickening regions of the flow field. Fully characterizing the in-situ rheology of polymers requires a large number of coreflood experiments. The development of the UVM, with accounting for relevant physical mechanisms for the model, served to reduce the number of corefloods required to characterize the rheology of polymers as they transport through porous media. Being
able to completely model the flow velocity dependence of the polymers as it flows through a porous medium is also critically important in the numerical simulation of polymer flood processes.

Extensive coreflood experiments were carried out to validate the UVM. These experiments were done with a focus to delineate the dilatant behavior of the polymers. Several synthetic polymers with varying molecular weights were studied. This particular investigation has been deliberately constrained to a simplified system in order to fundamentally understand the in-situ rheology of these high molecular weight polymers and to help validate the UVM. These constraints are:

- Single phase transport of the polymer solutions with no oil in the core.
- Berea sandstone cores as the representative porous medium.
- Room temperature (23 °C) and atmospheric pressure.

A preliminary study was conducted using COMSOL Multiphysics® to obtain a better understanding of the injection allocation profile of a polymer solution along a horizontal well. Results from this study have been presented in Appendix C.

1.3 DESCRIPTION OF CHAPTERS

The review of previous investigation available in literature is discussed in Chapter 2 and the experimental methodology, are described in Chapter 3. In Chapter 4, the results of bulk rheological tests and core-flood experiments are presented. The outcome of the application of a Unified Viscosity Model is discussed in Chapter 5. Finally, Chapter 6 is a summary of the entire study and also presents conclusions to the results obtained; and recommendations for further study. The appendix includes description of a preliminary injectivity modeling work carried out using COMSOL Multiphysics® (Appendix C).
2.1 OVERVIEW

The aim of this research study is to obtain a better understanding and characterization of the in-situ rheology of high molecular weight polymers with special emphasis on the shear thickening behavior of the polymers. The proper characterization of the rheology of polymer solutions in porous media would help in the design of more robust polymer flooding and chemical enhanced oil recovery processes. This section explores previous work done on this subject and it also presents the theoretical background which served as the foundation for this research effort.

2.2 THEORY

2.2.1 Chemical Enhanced Oil Recovery

A Chemical Enhanced Oil Recovery process is one that involves the injection of certain chemicals not present in the reservoir for the purpose of increasing or enhancing the oil recovery. Chemicals utilized for this category of EOR include; polymers, surfactants and alkali. Therefore, chemical enhanced oil recovery can be further subdivided into Polymer, Surfactant-Polymer (SP) and Alkaline-Surfactant-Polymer (ASP) flooding processes. This research effort focuses on the “polymer flooding” subcategory of the chemical enhanced oil recovery techniques.

Polymer flooding has been applied commercially in oil bearing formations worldwide for over 4 decades. Successful polymer floods have been reported in the literature (Wang et al., 2002, Putz et al., 1988 and Koning and Mentzer, 1988). Wang et al. (2006) attributed approximately 27.5% of total oil production from the Daqing oil
field to polymer flooding. Koning and Mentzer (1988), in evaluating a pilot polymer flood, reported a recovery of about 0.91 – 1.23 bbl of oil/lbm of polymer. Also, Putz et al., 1988 reported 1.5 bbl of oil per pound of polymer. These results show the economic viability of a well designed polymer flooding process.

Accurate characterization and quantification of the phenomena in polymer transport in porous media would aid in the design of a robust process.

Researchers such as Kozeny, Darcy, and Ergun investigated and accurately modeled the flow of Newtonian fluids through a porous medium. Since then, additional studies on non-Newtonian fluid (i.e. polymers) transport in porous media have been done. Among the pioneering work was that of Bird, Stewart and Lightfoot in the 1960s. A lot of the earlier studies focused on the flow of Power-Law (shear-thinning) fluids through the porous media. However, as long as over four decades ago, Christopher and Middleman (1967) investigated the flow of viscoelastic fluids in porous media. Yuan and Pope (1981) at the University of Texas carefully studied the rheological behavior of polymers and microemulsion in porous media. More recently, Wang et al. (2001) reported better displacement efficiency as a result of polymer viscoelasticity.

2.2.2 EOR Polymer Overview

On the laboratory scale, numerous polymers have been considered for polymerflooding. These polymers include biopolymers such as Xanthan gum and synthetic polymers such as hydrolyzed polyacrylamide (HPAM), polyacrylamide, polyacrylic acid, copolymers of polyacrylamide (PAM) and acrylamido methyl propane sulfonate (AMPS) and copolymers of acrylamide and acrylic acid. Polyethylene oxide (PEO) and hydroxyethylcellulose (HEC) are examples of others that have been considered. However, the most commonly used polymer in the field for Enhanced Oil Recovery
purposes have been the Xanthan gum and HPAM. In contrast to the Xanthan gum, partially hydrolyzed polyacrylamide is resistant to biodegradation.

Partially hydrolyzed polyacrylamide (HPAM) is a straight chain synthetic polymer of acrylamide monomers, some of which have undergone partial hydrolysis (Figure 2.1). The degree of hydrolysis (D.H.) of the polymer affects the solubility, salinity tolerance, viscosity, shear and thermal stability of the polymer solution. For instance, the larger the D.H, the more sensitive the solution properties would be to salinity (especially divalent ions). Sorbie (1991) gave a thorough review of polymers in EOR.

![Figure 2.1: Partially Hydrolyzed Polyacrylamide (HPAM).](image)

The molecular weight (MW) of polymers is another very important characteristic of polymers. It determines the viscosifying potential of the polymer. Also, high MW polymers have larger molecule sizes and this directly affects their transport in a porous medium such that if the hydrodynamic diameter of the polymer molecule is close to the particle diameter of the porous medium, then plugging of the medium may occur. Earlier literature (Lake, 1989 and Sorbie, 1991) has noted that HPAM is strongly sensitive to salinity and hardness, however, recent studies by Levitt and Pope (2008) show that this polymer can withstand very high salinities if certain precautions are taken.
2.3 POLYMER CHARACTERIZATION

2.3.1 Bulk Rheological Properties

Rheology is the study on the flow and deformation of matter. An important subject in rheology is the study of the deformation under stress and flow behavior of non-Newtonian fluids such as polyacrylamide and its copolymers. The rheological properties: shear viscosity, intrinsic viscosity and viscoelastic properties such as the storage and loss moduli are very important for the characterization of EOR polymer solutions.

**Bulk or Shear Viscosity**

The most important property of polymer solutions used for evaluating polymer flooding processes is its viscosity. Polymers are added to injection brine in order to increase the viscosity of the water, which then reduces the mobility ratio and consequently improves reservoir sweep efficiency. The viscosity of a fluid is a measure of its resistance to shear. It can be defined as the ratio of shear stress to shear rate and is mathematically represented as:

\[ \tau = -\mu \left( \frac{dv}{dr} \right) = -\mu \dot{\gamma} \]  

(2.1)

where \( \mu \) is fluid viscosity; \( \tau \) is the shear stress and \( \dot{\gamma} \); the rate of deformation or shear rate. Equation (2.1) is valid for a Newtonian fluid where the viscosity is constant irrespective of the shear rate. For non-Newtonian fluids, the viscosity is a function of shear rate, hence the stress equation becomes:

\[ \tau = -\eta \left( \frac{dv}{dr} \right) = -\eta (\dot{\gamma}) \dot{\gamma} \]  

(2.2)

A viscometer is used to experimentally determine the viscosity of fluids. They are broadly divided into capillary, rotational and falling ball viscometers. The rotational
viscometers such as the couette or coaxial cylinders and the cone and plate are the most commonly used ones. A typical viscosity-shear rate plot is shown in Figure 2.2.

Several mathematical models have been proposed to describe the shear rate dependence of non-Newtonian fluids. The simplest of such models is the Power-Law model which is given as:

$$\eta(\dot{\gamma}) = K \dot{\gamma}^{n-1}$$

(2.3)

where K and n are empirical constants; n is also known as the Power-Law index. K is the viscosity $\mu$ and n is unity for a Newtonian fluid. This equation is only applicable in the shear thinning (pseudoplastic) region of the flow curve. It is not valid at high and low shear rates. In order to model the entire range of shear rates; other models were developed such as the Carreau Model:

$$\eta = \eta_o + (\eta_o - \eta_\infty) \left[1 + \left(\lambda \dot{\gamma}\right)^\alpha\right]^{\eta_\infty(\eta_o - \eta_\infty)}$$

(2.4)

where $\eta_o$ & $\eta_\infty$ are the zero and infinite shear rate viscosities respectively; $\lambda$ is a time constant, $\alpha$ is usually taken as 2 and n is the same as the power-law index. A similar viscosity model is the Meter model [Meter and Bird (1964)], which is given as:

$$\eta = \eta_o + \frac{\eta_o - \eta_\infty}{\left[1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{1/2}}\right)^{\eta_\infty(\eta_o - \eta_\infty)}\right]^{\eta_\infty(\eta_o - \eta_\infty)}}$$

(2.5)

where n is an empirical constant and $\dot{\gamma}_{1/2}$ is the shear rate at which $\eta$ is half the value of $\eta_o$. This model has been successfully implemented in the UTCHEM simulator.

The bulk viscosity of polymers is a steady shear measurement whereby the stress is measured at a constant shear rate. Dynamic or oscillatory tests are carried out to measure elastic properties.
**Intrinsic Viscosity**

The thickening ability of a polymer solution is a measure of its intrinsic viscosity (Lake, 1989). The intrinsic viscosity is defined as:

\[
[\eta] = \lim_{C \to 0} \left( \frac{\eta_{sp}}{C} \right) = \lim_{C \to 0} \left( \frac{\eta_{solution} - \eta_{solvent}}{\eta_{solvent} C} \right)
\]

(2.6)

where \( \eta_{sp} \) is the specific viscosity. It is also often given as:

\[
[\eta] = \lim_{C \to 0} \left( \frac{\ln \eta_r}{C} \right) = \lim_{C \to 0} \left( \frac{1}{C} \ln \left( \frac{\eta_{solution}}{\eta_{solvent}} \right) \right)
\]

(2.7)

In equation (2.7), \( \eta_r \) is the relative viscosity. \( \eta_{solution} \) and \( \eta_{solvent} \) are the solution and solvent viscosities, respectively.

The intrinsic viscosity of most polymers increases as the molecular weight increases following the Mark-Houwink equation:

\[
[\eta] = K M_w^a
\]

(2.8)

where \( K \) and “\( a \)” are empirical constants at a given temperature for a polymer in a particular solvent. The value of exponent “\( a \)” usually ranges from 0.5 to 1. Factors affecting the intrinsic viscosity of a polymer with a given molecular weight include but are not limited to the following: type of solvent, temperature, shear rate, charge, chain branching and chemical structure.

**Hydrodynamic Radius of a Polymer Molecule**

The hydrodynamic radius of a polymer molecule is also known as the radius of gyration. It is difficult to experimentally determine this parameter. However, a theoretical expression has been proposed and is known as the Flory-Fox equation (Flory, 1953). It is given as:

\[
\Omega_p = \left( \frac{[\eta] \cdot M}{\Phi} \right)^{\frac{1}{3}}
\]

(2.9)
where $\Omega_p$ is the hydrodynamic radius of polymer molecule and $\Phi$ is a universal constant of value $2.1 \times 10^{21}$ dl/g.mol.cm$^3$.

**Viscoelastic Properties**

Viscoelastic fluids are fluids in which their stress at any particular time is dependent on past strain history. These fluids generally return to their original configurations when deformed (Sorbie, 1991). The viscoelastic properties of a polymer are also known as oscillatory properties. They give the response of polymer molecules to oscillatory perturbation. Frequency $\omega$ is the independent variable in these measurements. These dynamic properties are very useful in quantifying the viscoelastic nature of the polymer.

Let the shear strain be:

$$\gamma = \gamma^o \sin \omega t$$  \hspace{1cm} (2.10)

Therefore, the shear rate is

$$\dot{\gamma} = \omega \gamma^o \sin \omega t$$

where $\gamma^o$ = maximum amplitude of the shear strain. Assuming linear viscoelasticity, the shear stress is given as:

$$\sigma(t) = \int_{0}^{\infty} G(s) \omega \gamma^o \cos[\omega(t - s)] ds$$

$$= \gamma^o \left[ \omega \int_{0}^{\infty} G(s) \sin \omega s ds \right] \sin \omega t + \gamma^o \left[ \omega \int_{0}^{\infty} G(s) \cos \omega s ds \right] \cos \omega t$$  \hspace{1cm} (2.11)

$$= \gamma^o (G' \sin \omega t + G'' \cos \omega t)$$

where $G'$ is the shear storage modulus (or elastic modulus), which is a measure of stored energy per cycle and $G''$ is the shear loss modulus (or viscous modulus), which is a measure of viscous dissipation energy given off per cycle of sinusoidal deformation. Figure 2.4 shows a typical oscillatory/dynamic measurement.
Every dynamic measurement at a given frequency gives these two dependent variables; $G'$ and $G''$. They can be expressed as a complex modulus:

$$G^* = G' + iG''$$  \hspace{1cm} (2.12)

Viscoelastic fluids are alternatively described by the complex viscosity:

$$\eta^* = \eta' + i\eta''$$  \hspace{1cm} (2.13)

where $\eta' = \frac{G''}{\omega}$ and $\eta'' = \frac{G'}{\omega}$.

### 2.3.2 Relaxation Time Models

Several relaxation models have been used to predict the relaxation time of polymer solutions. The relaxation time is defined as the time required for a property having been displaced from equilibrium to decay back to its original value. Relaxation processes are central to the rheological properties of fluids. The relaxation time is of interest because it is required in order to compute the Deborah number, which is used to quantify viscoelasticity and determine the onset of the shear thickening behavior of polymer solutions. In this section, various relaxation time models in the literature are described with the goal of finding the appropriate model for polymer flood applications.

Based on hydrodynamic interaction, the relaxation time models can be broadly divided into two:

- Those that neglect any hydrodynamic interaction between the polymer molecules in solution. It is assumed that the polymer solution is very dilute (infinite dilution); hence the forces acting on a molecule do not affect another molecule.
- Models that do not neglect the hydrodynamic interaction between the polymer molecules in solution.
Models that neglect hydrodynamic interaction between polymer molecules in solution

The models that for mathematical simplicity neglected hydrodynamic interaction between polymer molecules can be further discriminated by their dependence on polymer concentration. Hence two sub-groups are identified and are shown below:

Models that are not functions of the Polymer concentration.

1. The Bead-Spring Model with no Hydrodynamic interaction among the beads:

   This model (Ferry, 1980) has been derived using the Rouse theory for relaxation processes and it is given as:

   \[ \tau_p = \frac{6[\eta]\eta_s M}{\pi^2 \eta_s \eta \pi T} \]  

   where \( p \) = number of elements in the relaxation spectrum. Longest or terminal relaxation time is at \( p = 1 \). \( 'p' \) is the number of sub-molecules of the polymer solution which represents the ‘bead-spring’ model. In this model, a macromolecule (polymer solution) is mathematically divided into \( N \) sub-molecules which are connected end-to-end by \( N + 1 \) beads. In the above equation, \([\eta] = \) intrinsic viscosity; \( \eta_s = \) solvent viscosity; \( M = \) molecular weight of polymer; \( T = \) Absolute temperature; and \( R = \) Gas constant.

2. The Non-linear elastic dumbbell model:

   This model (Haas and Durst, 1981) combines the elastic nature of polymer molecules (represented as dumbbells) and the viscous properties of the solvent. This gives the relaxation time of the solution as:

   \[ \tau_r = \frac{[\eta]\eta_s M}{RT} \]  

   (2.15)
According to Haas and Durst (1982), the largest Zimm relaxation time is also defined as:

$$\tau_z = 0.42 \cdot \tau_r.$$

The Zimm theory is a modification of the bead-spring chain model in which the motion of the beads is strongly influenced by the viscous drag of other beads in the same chain. Thereby it attempts to account for hydrodynamic interaction between the sub-molecules that make up the polymer solution.

**Model that is a function of the Polymer concentration**

3. **The classical Rouse model:**

The data from the dynamic frequency sweep test ($G'$ and $G''$ versus frequency) is usually fit with this model in order to obtain a spectrum of relaxation times. The model (Heemskerk et al., 1984) is given as:

$$G' = \frac{cRT}{M} \sum_{p=1}^{N} \frac{\omega^2 \tau_p^2}{1 + \omega^2 \tau_p^2}$$

$$G'' = \frac{cRT}{M} \sum_{p=1}^{N} \frac{\omega \tau_p}{1 + \omega^2 \tau_p^2}$$

(2.16)

where $\tau_p =$ relaxation time. (The generalized Maxwell model consists of p elements of spring-dashpot pairs.)

Experimental dynamic test data would be fitted to Equation (2.16). The polymer molecule is represented as a chain of N beads connected together using N – 1 elastic springs. The longest time of the spectrum of relaxation times obtained is the most relevant for Deborah number calculations, and so this is used when modeling flow through cores.
Models that do not neglect hydrodynamic interaction between polymer molecules in solution

These models essentially utilize data from oscillatory measurements.

1. The $G'$ and $G''$ cross-over point model:

Munoz et al., (2003) suggested that the inverse of the frequency at which $G'$ and $G''$ intersects is the characteristic relaxation time of the polymer solution. This intersection has also been described as an indication of the onset of a phenomenon called entanglement coupling. This is a phenomenon whereby there is strong coupling of neighboring molecules to molecular motion along the chain. This phenomenon causes significant changes in the relaxation spectrum and hence affects the accuracy of relaxation time obtained using this model.

2. The rod-climbing height model:

The relaxation time is estimated using data obtained from rod-climbing experiments (Choi, 1991). Results from the experiments combined with coefficients of a second order fluid model (2nd order model that shows the effective viscosity of a solution as a function of shear rate and temperature) is correlated with the first normal stress difference coefficient. This leads to a relaxation time definition given as:

$$\tau_r = \frac{\beta}{\eta}$$

where; $\beta = 0.5\Psi_1 =$ rod-climbing constant; $\eta =$ solution viscosity, and $\Psi_1 =$ first normal stress difference coefficient.

Other relevant relationships with respect to this model available are:

$$\Psi_1 = \frac{N1}{2\dot{\gamma}^2}$$

Munoz et al., 2003
\[ N1 = 2G' \left[ 1 + \left( \frac{G'}{G''} \right)^2 \right]^{0.7}_{\omega \rightarrow 0} \]  

Xia Huifen et al., 2004

where \( N1 \) – first normal stress difference, (Pa); and accordingly,

\[ \tau_r = \frac{N1}{4\eta\gamma^2} \]  

The major limitation to applying this model is the difficulty in measuring the first normal stress difference coefficient, \( \Psi_1 \) of dilute polymer solutions. First normal stress measurements are more practical with polymer melts.

3. Other models:

Relaxation time at a fixed frequency: According to Thurston (1984), at a particular frequency of flow excitation, an effective relaxation time can be calculated. This relaxation time is based on constants of the complex viscosity of the polymer solution.

\[ \tau_r = \frac{\eta_E}{\omega \eta_v} \]  

since \( \eta^* = \eta_v - i\eta_E, \eta_E = G'/\omega, \eta_v = G''/\omega \Rightarrow G^* = \omega \eta_v, \therefore \tau = \frac{\eta_E}{G^*} \]

where; \( \eta_E \) = Imaginary part of the complex solution viscosity, \( \eta^* \)
\( \eta_v \) = Real part of the complex solution viscosity, \( \eta^* \)
\( \tau_r \) = relaxation time.

2.3.3 The Deborah Number

Sorbie (1990) suggested that if the transit time of a polymer solution through a porous medium is large compared to the relaxation time, then the elastic effects of the
polymer would not be observed. However, if the transit time is small compared to the relaxation time, then there would be an elastic effect.

The Deborah number is used to characterize the viscoelasticity of a polymer solution. It is the ratio of the characteristic time of the fluid, $\theta_i$, to the duration time of the process, $\theta_p$:

$$ N_{De} = \frac{\theta_i}{\theta_p} \quad (2.19) $$

and is often estimated as:

$$ N_{De} = \frac{\tau_r v}{D_p} $$

where $\tau_r$ is the relaxation time, $v$ is the interstitial velocity and $D_p$ is the particle diameter.

$N_{De}$ is also interpreted as the ratio of elastic forces to viscous forces. The implication is such that if $N_{De}$ is large, solid-like behavior (elastic effects dominate) results. A small Deborah number results in fluid-like behavior (viscous forces dominate).

A critical value of $N_{De}$ exists beyond which viscoelasticity affects the flow and below which the flow is mainly viscous.

However, Heemskerk et al. (1984) later indicated that the critical Deborah number can only be used to give a first estimate of the onset of dilatant behavior because of the difficulty in evaluating the stretch rates that exists in a porous matrix. Gupta and Sridhar (1984) also concluded that viscoelastic behavior cannot be predicted by $N_{De}$ alone but also by the ratio of maximum and minimum diameters.

The Deborah number has also been expressed as:

$$ N_{De} = \dot{\varepsilon} \cdot \tau_r \quad (2.20) $$

where $\dot{\varepsilon}$ = stretching rate and $\tau_r$ = fluid relaxation time.

According to Heemskerk et al. (1984); the steep increase in pressure beyond a critical flow rate is a direct consequence of viscoelasticity with respect to the
unsteadiness of the flow field in a porous medium. It was also concluded that the onset of shear thickening in terms of critical flow rate shifts towards higher values with increasing permeability, temperature and salinity and with decreasing molecular weight and polymer concentration. This implies that the higher the concentration of the polymer, the faster it exhibits shear thickening.

2.3.4 Apparent Rheological Properties

**Apparent Viscosity**

The apparent viscosity of a fluid in a porous medium is the viscosity estimated from steady-state pressure drop and flow-rate data using Darcy’s Law. The permeability used is the brine permeability. This brine should be of the same composition as that used to prepare the polymer solution.

\[
\mu_{\text{app}} = \frac{k_{\text{brine}} \Delta p}{u L}
\]

where \(\mu_{\text{app}}\) is the apparent viscosity, \(k_{\text{brine}}\) is the brine permeability, \(u\) is the volumetric flux or Darcy velocity and \(\Delta p\) is the pressure drop across the porous medium.

**Apparent or Effective Shear-rate**

The effective shear rate is usually computed using the bundle of capillary tubes model for flow of non-Newtonian fluids. Many researchers have proposed different theoretical models for calculating effective shear rate, most of which can be represented in the form:

\[
\dot{\gamma}_{\text{eff}} = C \left( \frac{3n + 1}{4n} \right)^{n-1} \frac{u}{\sqrt{k\phi}}
\]

(2.22)
where $C$ is the shear rate coefficient, $u$ is the volumetric flux or Darcy velocity, $n$ is the power-law exponent of the fluid, $k$ is the permeability and $\phi$ is the porosity. The shear rate coefficient is used to correct for the difference observed between apparent viscosity of polymer solutions in porous media and bulk viscosity measured using rheometers or viscometers. Cannella et al. (1988) used a value of 6 to match all of their experimental data. However, Wreath et al. (1990) observed that the shear rate coefficient, $C$ varies widely over a range of petrophysical and transport properties and proposed a correlation for estimating the shear rate coefficient.

The equations used to compute the effective shear rate also serve as a correlation between flow velocities of the fluid to the apparent shear rate experienced by the fluid molecules.

2.4 SHEAR THICKENING BEHAVIOR OF HPAM

Synthetic polymers such as hydrolyzed polyacrylamide (HPAM) exhibit a complex rheological behavior when flowing through porous media. The behavior of HPAM solutions undergoes transitions from Newtonian flow through shear thinning and into shear thickening as flowrate increases. Seright et al., 2008 reported no evidence of shear thinning behavior for HPAM in porous medium, but rather, a transition from Newtonian to dilatant behavior was observed. Figure 2.5 shows a schematic of the shear rate dependence of the apparent viscosity of polymers.

The increase in the apparent viscosity of the polymer solution after a certain critical shear rate is also referred to as the viscoelastic, dilatant or shear-thickening behavior of the polymer. This behavior results from the stretch-relaxation transition of the polymer molecules as they flow through the converging-diverging pore throats that exist in porous media. Magueur (1985) asserted that the onset of this viscoelastic
behavior also known as elongational behavior is when the product of the polymer molecule relaxation time and maximum stretching rate is greater than unity.

Wang et al. (2001) observed in their laboratory experiments that polymers which exhibit viscoelastic behavior displace some waterflood residual oil. This was unexpected since it has been widely accepted that polymer flooding cannot displace waterflood residual oil saturation. However, secondary recovery polymer floods have yielded lower residual oil saturation values than those from waterflooding. Huh and Pope (2008) and Wang et al., 2007 proposed explanations on the possible mechanisms governing the reduction in residual oil saturation from polymer flood used as a secondary process.

Quite a number of scientific investigators such as Hirasaki and Pope (1974), Haas and Durst (1981), Ranjbar et al. (1992), Masuda et al. (1992), Han et al. (1995) and Garrouch (2006) have proposed theoretical models to capture and describe the shear-thickening behavior of a polymer solution as it flows through a porous medium. More recently, Delshad et al. (2008) developed and proposed a unified apparent viscosity model for the entire range of flow velocity. One major advantage of this model is that the dependence of polymer viscosity on the flow velocity through the porous medium can be estimated using only the bulk rheological properties of the polymer and petrophysical features of the porous media.

### 2.4.1 The Unified apparent Viscosity Model

Delshad et al. (2008) have presented an apparent viscosity model that can be applied to the full spectrum of Newtonian, pseudoplastic or shear-thinning and dilatant or shear-thickening regimes. In this model, via the effective shear rate, the apparent viscosity can be correlated with Darcy velocity. The model was developed based on the
premise that the apparent viscosity of the polymer solution is a sum of the shear-dominating viscosity and the elongational-dominating viscosity:

\[ \mu_{\text{app}} = \mu_{\text{sh}} + \mu_{\text{el}} \quad (2.23) \]

where \( \mu_{\text{sh}} \) and \( \mu_{\text{el}} \) are the shear and elongational viscosities, respectively.

The Carreau model was used for the shear-dominating viscosity and an empirical model was used to describe the shear-thickening viscosity. Thus, the unified viscosity model is given as:

\[ \mu_{\text{app}} = \mu_{\infty} + \left( \mu^p_{\infty} - \mu_{\infty} \right) \left[ 1 + \left( \frac{\dot{\gamma}_{\text{eff}}}{\dot{\gamma}_{\text{eff}}^c} \right)^n \right]^{(1-n)/\alpha} + \mu_{\text{max}} \left[ 1 - \exp\left( -\left( \frac{\dot{\gamma}_{\text{eff}}^c}{\dot{\gamma}_{\text{eff}}^c} \right)^n \right) \right] \quad (2.24) \]

where \( \mu_{\infty}, \mu^p_{\infty}, \lambda, n \) and \( \alpha \) are empirical constants that will be obtained from the Carreau model fit to the polymer’s bulk viscosity data.

\( \mu_{\text{max}} \): A plateau value of viscosity beyond which the shear degradation will occur.

\( \lambda_2 \): A proposed ‘universal’ constant that is independent of data being matched.

\( \tau_r \): Relaxation time of injected fluid. It is obtained from the dynamic frequency sweep test.

\( n_2 \): Shear-thickening index. It indicates the extent of polymer ‘dilatancy’.
Figure 2.2: Schematic of shear rate dependence of polymer (HPAM) bulk or shear viscosity.

Figure 2.3: Typical plots for estimating intrinsic viscosity.
Figure 2.4: Typical dynamic frequency test.

Figure 2.5: Schematic of shear rate dependence of polymer (HPAM) apparent viscosity.
Chapter 3: EXPERIMENTAL APPARATUS AND METHODOLOGY

3.1 INTRODUCTION

The experimental setup and procedures employed to successfully undertake this research study are discussed in this section. Basic calculations, materials and equipment utilized are also presented. The polymers and fluid preparation, bulk rheological measurements, and core-flood description represent the major subsections in this chapter.

The equipment utilized for this research effort include: weight balance, magnetic stir plates, stirrers, air minipermeameter, pumps, tubing (Nylon and stainless steel), fraction collector, data acquisition recorder, pressure transducers, water deionizer unit, pH meter, fluid reservoir, stainless steel core-holder, filter press, couette viscometer and the rheometer. The uses of the aforementioned equipment for the purpose of this study are also discussed in this Chapter.

3.2 POLYMERS AND FLUID PREPARATION

The high molecular weight polymers primarily used for the bulk and in-situ rheological characterization are presented in this sub-section. Polymer preparation is a very crucial aspect of any rheological study; as such, the preparation procedures have been carefully outlined as well.

3.2.1 The Polymers

In this study, the polymers used were partially hydrolyzed polyacrylamide and related copolymers.

Hydrolyzed polyacrylamide (HPAM) is a straight chain synthetic polymer of acrylamide monomers, some of which have undergone partial hydrolysis as shown in
Figure 2.1. The degree of hydrolysis (D.H.) of the polymer affects its solubility, salinity tolerance, viscosity, shear and thermal stability. The molecular weight (MW) of polymers is a very important characteristic of the polymer. It determines its viscosifying potential. Also, high MW polymers have larger molecule sizes and this directly affects the transport of the polymer in a porous medium such that as the hydrodynamic diameter of the polymer molecule approaches the pore throat diameter of the porous medium, plugging of the medium begins to occur. HPAM polymers from the Flopaam® and Hengfloc® series were used for the experiments, as well as a copolymer of acrylamide and 2-acrylamido 2-methyl propane sulfonate (AMPS) referred to as AN-125 (see Table 3.1). Specifically, Flopaam® 3630S and AN-125, Hengfloc® 63020 and 63026 were studied. The Flopaam® polymers have a degree of hydrolysis of approximately 30% while the Hengfloc® polymers have a D.H. of ~ 28 – 30%. The AN-125 has a molecular weight of 8 million Daltons and the Flopaam™ 3630S, Hengfloc® 63020 and 63026 were 20 million, 20 million and 26 million Daltons respectively. These molecular weights are stated by the manufacturers and have not been independently verified, but agree qualitatively with viscosity data.

3.2.2 The Electrolytes

Sodium chloride (NaCl), calcium chloride (CaCl₂) and magnesium chloride (MgCl₂) were used as electrolytes in the polymer solutions. They were primarily prepared as synthetic reservoir field brine.

3.2.3 The Deionized Water (DI water)

In order to prepare all polymers and brine solutions, deionized water was required. A pumping unit comprising of a Millipore™ filter helps deionize supplied tap
water to a resistivity value of about 18 MΩ-cm, which is a threshold value signaling adequate removal of ions initially present.

3.2.4 Polymer Preparation Equipment

Excellent fluid preparation is a necessary precursor for accurate characterization and/or experimentation in chemical enhanced oil recovery. Equipment used to prepare polymer solutions for this study include: weighing balances, magnetic stir plates and stirrers and a filter press unit.

Weight Measurements

Accurate weight measurements are required to prepare polymer solutions of specific concentrations and salinity. The weighing balances supplied by Denver Instrument with 0.001g precision were used to measure the mass of all the components necessary for preparing the polymer and brine solutions. The chemical components required include: polymer (usually in powder form) and the various electrolyte salts such as NaCl, CaCl₂, MgCl₂·6H₂O, NaHCO₃, etc. The weight balance was also used to measure the mass of the sandstone core.

Magnetic Stir plates and Stirrers

CORNING PC-420D electrically powered magnetic stir plates were used to mix the brine and polymer solutions. Magnetic stir bars placed inside the glass beakers and plastic containers rotate as a result of the motor in the stir plates, thereby mixing the solution.
The Filter Press Unit

Injected fluids which include formation brine and polymer solutions were filtered using a FANN® 12BL filter press. It is comprised of a 90mm diameter stainless steel bell which stores the fluid to be filtered, a filter paper, a graduating cylinder used to collect the filtrate and a source of pressure. The polymer solutions and formation brine were filtered using 1.2 \( \mu \text{m} \) and 0.45 \( \mu \text{m} \) sized Millipore™ hydrophilic cellulose filter papers respectively. 10 – 15 pounds per square inch (psi) of compressed air was used to supply the differential pressure.

3.2.5 Brine and Polymer preparation

Brine Solution

The cores are usually saturated with a synthetic formulation of a typical reservoir formation brine, which we will refer to as synthetic formation brine (SFB). The polymer stock samples are also diluted to their appropriate concentrations using the SFB. Qualitative compositional analysis of the actual reservoir formation brine give data on the ions (in mg/L) present in the brine. The composition of the SFB is based on the concentration of the ions present in the actual reservoir brine (see Table 3.2). Ions present in reservoir brines usually consists of Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\) and HCO\(_3^-\). Some other ions such as Ba\(^{2+}\) could also be present in the reservoir brine; however, trace ions are not considered when preparing the synthetic brine unless they are present in significant quantities. These ions are supplied synthetically by diluting the salts, NaCl, CaCl\(_2\), and MgCl\(_2\) in de-ionized water to similar concentrations as that of the reservoir brine. The prepared SFB is then filtered with 0.45 \( \mu \text{m} \) filter paper to ensure that the solution is free of any particulate matter and that a uniform solution has been made.
**Polymer Stock Solution**

In order to prepare a polymer solution, the proven practice has been to dilute a stock solution to the desired polymer concentration. The concentration of the stock solution ranges from 4000 parts per million (ppm) to 5000 ppm depending on the molecular weight of the polymer. The two common stock solution formulations are 5000 ppm polymer in 1000 ppm NaCl and the 4000 ppm polymer in 5000 ppm NaCl. For instance, the 4000 ppm polymer stock solutions are used for high molecular weight polymers (> $2 \times 10^6$ Daltons) while the 5000 ppm polymer stock solutions are used for polymers of molecular weights in the ballpark of $8 \times 10^6$ Daltons. As an example; to prepare a 500 g stock batch of 4000 ppm polymer will require 2g of dry polymer powder, 2.5g of NaCl powder and 495.5g of de-ionized (DI) water. The 2.5g of sodium chloride (NaCl) will be added to 495.5g of DI water and mixed on the magnetic stir plate. While the salt solution is still slowly mixing, the polymer powder is gradually added in grain quantities to the side of the vortex formed by the rotating motion of the stirrers. The addition of the polymer is as fast as necessary to prevent the solution from being hydrated while the other particles are still being added and slow enough not to lead to aggregation of the hydrating particles; typically the polymer is added over the course of 3-5 minutes. In order to allow for complete hydration once the entire polymer has been added, the solution is allowed to mix for at least 30 hours.

A fully hydrated and consistent polymer solution will filter through a 1.2μm sized Millipore™ hydrophilic cellulose filter paper under 15 psi at a relatively constant rate (see Figure 3.1) and will give a filtration ratio (F.R) less than or equal to 1.2. The viability of a polymer solution is measured by its ability to pass the filtration test (i.e. a F.R $\leq 1.2$). The filtration ratio is a measure of the time taken to filter the same volume
of polymer solution at the beginning and end of the filtration process. It is expressed as:

$$F.R. = \frac{t_{200ml} - t_{180ml}}{t_{80ml} - t_{60ml}}$$ (3.1)

3.3 BULK RHEOLOGICAL MEASUREMENT

Rheometry is the measurement of fluid deformation under stress and flow behavior in well defined geometries using a viscometer or rheometer. Two viscosity measuring devices were used in this study, one of which was a rheometer that measured oscillatory properties of the solutions such as the storage and loss modulus and the other measured shear viscosities at low shear rates.

3.3.1 Viscometer

The Contraves Low-Shear 30 (LS 30) was used to accurately measure bulk viscosities at low shear rates. The LS 30 viscometer uses a bob-and-cup fixture and can measure shear rates as low as 0.0174 sec\(^{-1}\) up to a maximum of 128.5 sec\(^{-1}\). The shear rates and viscosities are calculated using correlations and conversion factors that have been developed into a spreadsheet. One major advantage of this equipment is that it requires a small sample of fluid (about 1ml). Results from the LS-30 were used to confirm the validity of the rheometer measurements.

3.3.2 The Rheometer

TA Instruments’ Advanced Rheometric Expansion System (ARES) LS-1 was used for measuring all of the bulk rheological properties (see Figure 3.2). A unique feature of this rheometer is that it utilizes independent strain and stress controls. The proprietary Force Rebalance Transducer (FRT) \(\text{TM}\) and Low Shear (LS) motor measure
the torque generated in response to a steady or oscillatory shear strain applied onto the sample. The torque measured is converted to either time-varying or steady quantities which are displayed on the data-acquisition application known as TA Orchestrator. Several geometries or fixtures can be used with this equipment. The double wall couette geometry which handles low-viscosity fluids was adequate for the fluids considered in this research study.

For a typical fluid sample, two oscillatory tests; strain and frequency sweep tests were conducted to measure dynamic properties and estimate viscoelastic properties. Also, two steady rate tests; transient and steady shear sweeps were carried out to measure the steady shear viscosity of the fluid as a function of shear rate. The details for each test are described in the following sub-sections.

3.3.3 The Dynamic Strain Sweep Test

Dynamic strain sweep test is performed to determine the range of linear viscoelasticity and torque levels at constant frequency and temperature. The sweeps were conducted over the range of strain between 1% and 200% at a fixed frequency of 10 rad/s for polymer samples used in this study. Storage modulus, loss modulus and complex viscosity are measured as a function of strain. Figure 3.3 shows a typical strain sweep plot. For this example (Figure 3.3), after a strain value of about 50%, the measurement becomes out of the range of linear viscoelasticity. A strain value within the range of linear viscoelasticity is chosen for the frequency sweep test.
3.3.4 Dynamic Frequency Sweep Test

The aim of this test is to measure the dynamic properties of the fluid sample such as the storage modulus, loss modulus and complex viscosity in the specified range of oscillatory frequencies. These measurements are carried out at a strain value that is within the range of linear viscoelasticity. The frequency sweep test was conducted over the range of frequencies between 0.1 and 100 rad/s in this study. The frequency sweep test result for a polymer sample is shown in Figure 3.4. The relaxation time of the polymer is estimated from the dynamic data obtained from this test.

3.3.5 Strain Controlled Step Rate Transient Test

At a given constant shear rate, the steady state rheological properties of the fluid sample are measured as a function of time using this test. Four separate zones can be programmed to investigate stress growth; time required to reach steady state behavior and relaxation before and after steady shear. The main purpose of the test in this study is used to determine the time it will take for the stress response of the fluid to attain steady state, which ensures that accurate viscosity measurements are made for the following steady rate sweep test. Figure 3.5 shows a typical transient test result. It can be observed from the plot that before the stress or viscosity becomes steady, it initially overshoots the steady state value before relaxing and becoming steady. This overshoot is indicative of the elastic behavior of the fluid.

3.3.6 Steady Rate Sweep Test

The rate of deformation varies and the viscosity of the fluid sample is measured at steady state. Shear rates could vary from 0.01 to 1000 s\(^{-1}\) in this study. The result of this
test gives the fluid viscosity as a function of shear rate. Figure 3.6 shows the viscosity of a typical polymer solution used for chemical enhanced oil recovery applications.

3.4 COREFLOOD EXPERIMENTAL SETUP

This section describes the details of the set-up of the coreflood experiments carried out to study the transport of polymer solutions in porous media for chemical EOR applications. Brine flooding experiments are performed to determine the core’s petrophysical properties. After which series of polymer floods are executed. A schematic of the coreflood setup is represented in Figure 3.9. It consists of a syringe pump, fluid reservoir, core-holder, pressure transducers, tubing and fraction collectors. Using the pump, the brine or polymer solution in the fluid reservoir is injected into the core which is contained in the core-holder. The pressure difference between sections of the core is measured by the transducers. Effluents are collected with the fraction collector and their viscosities measured to ensure consistency with the injected fluid.

3.4.1 Equipment/Materials

The equipment required for the proper setup of the coreflood apparatus include the stainless steel core holder, fluid reservoir which are either made of stainless steel or glass materials, pressure transducers, stainless steel tubing, effluent sample fraction collector and data acquisition tools. They are described below:

**Stainless Steel Core Holder**

The 8 inch long Berea sandstone cores used for all the experiments was secured in a stainless steel Phoenix Instruments core holder with a pressure rating of 3,000 psig and
150 °F (Figure 3.7) using a rubber sleeve. Pressure drop across sections of the core are measured via the 3 pressure taps at 2 inch intervals along the length of the core holder. Stainless steel tubing of 1/16 inch internal diameter and 1/8 inch outer diameter was used in these experiments.

**Fluid Reservoirs**

Two types of glass columns were used for these experiments. The first was rated for a maximum pressure of 50 psi at room temperature. It was 4.8 cm in diameter and 15 cm in length. Viton O-rings and washers in the end pieces prevent leakage during the experiments. The second type had a pressure rating of 30 bar (~ 435 psi) and was 6 cm in diameter and 100 cm in length.

**Pressure Transducers**

Pressure drop across sections of the core were measured using Validyne DP 15 pressure transducers. These transducers are made of a stainless steel diaphragm sandwiched between two stainless steel blocks. Having been calibrated, they measure the pressure difference between inlet and exit ports. Bleed ports located on the side of these transducers make it possible to clean the transducers. Pressure transducers that could measure 0 – 10 psi, 0 – 100 psi and 0 – 1000 psi were used so that all the expected pressure can be measured accurately.

**Data Acquisition**

A National Instruments’ (NI) data acquisition card was used to capture signals from the pressure transducers and subsequently transferred to NI’s LabView 8.0 software
on the computer. Prior to recording the pressures, the transducers are zeroed by using an offset value in LabView.

**Fraction Collectors**

A Retriever fraction collector from Instruments Specialties Company (ISCO) was used to recover effluent from the corefloods. The fraction collector was loaded with test tubes and set to a specific time duration whereby the test-tube sample will be collected.

**Pumps**

Instruments Specialties Company’s (ISCO) LC-5000 Syringe pump was used (Figure 3.8). The pump had a volumetric capacity of 260 ml and uses mineral oil to displace the brine or polymer at a constant flow rate through the cores.

**3.4.2 Experimental Procedures**

The procedure undertaken to execute a successful polymer coreflood experiment can be subdivided into the following: core preparation and the flooding processes which include: brine flooding, polymer flush, polymer flooding and brine flush after the polymer flood.

**Core Preparation**

The cores used for this experiment were made from an outcrop of Berea sandstone. The cores were 1 inch in diameter and 8 inches long. After being cut, the core was dried in an oven at about 170 °F overnight or 12hrs and then weighed using a weight balance. It was wrapped with Teflon tape and then aluminum foil to prevent any contact
with injected fluids. It was then covered with Teflon shrink sleeve to also prevent injected fluids from leaking through the sides of the core. The Teflon heat shrink sleeve was applied using a heat gun. The prepared core was placed inside the core-holder and firmly secured with an overburden pressure applied using an ENERPAC P-39 hydraulic hand pump. The pressure taps were accessed by drilling holes through the taps into the core. This allowed for the fluids to flow to the inlet ports of the pressure transducers.

The core preparation is described in more detail below:

1. The core was drilled from a block of Berea sandstone rock, dried in a convection oven overnight at 170°F and its mass recorded.

2. Air permeability measurements were made on the dried core using the air permeameter.

3. It was wrapped in Teflon tape and then with aluminum foil. The foil was tight around the core without wrinkles and then fastened with cello tape. Excess foil was cut off the ends of the core.

4. The core was placed inside a Teflon heat shrink sleeve an end pieces were put at both ends of the core. Using a heat gun, the sleeve was shrunk until it wrapped tightly around the core.

5. A vacuum pump was attached to the core using the end pieces whereby the entire the core was placed under vacuum. The shrinking of the sleeve with heat continued as the air in the core was being expelled. This ensured a complete seal around the core.

6. After about 15 minutes, the heating was stopped and the core was allowed to cool off while still under vacuum.
7. The core was then loaded into the stainless steel phoenix instruments core-holder. The end pieces were then put to ensure that the core was firmly in place.

8. A confining overburden pressure of about 1000 psig was applied on the core-holder using the ENERPAC P-39 hydraulic hand pump.

9. Holes were then drilled into the core through the pressure tap apertures using the appropriate drill bit size. Air was flowing through the core while that drilling was done. The drilling was stopped when air began to exit the pressure tap.

10. The core now firmly secured in the core-holder was placed under vacuum by attaching the exit of the core-holder to a vacuum pump. The vacuum was applied for approximately 6 hours. This was to ensure that there was absolutely no air left in the pores of the core.

11. While under vacuum, the inlet of the core-holder was connected to a burette containing the synthetic formation brine (SFB) and the present level of the brine recorded. After vacuuming, the inlet valve to the core-holder was opened and SFB was allowed to saturate the core. The core was fully saturated when the level of brine in the burette remained constant. The final level of the burette was then recorded. This brine saturation was done to establish the pore volume of the core.

The coreflood experiments began only after preparing the core and placing it in the core-holder as described above.

*Brine flood (determination of the brine permeability)*

Brine flooding was used to establish the brine permeability of the core and the effective particle diameter of the particles that make up the berea sandstone core.
Synthetic formation brine with about 2% total dissolved solids (TDS) as described in Table 1 was used. The brine was made by dissolving the salts into deionized water (DI) with the divalent ions added last. The solution was mixed on a magnetic stir plate. The prepared brine was then filtered through a 0.45μm Millipore filter paper using a vacuum operated filtration system. The filtered brine is then put into the glass column by vacuum suction; the column was vacuumed, then the brine was allowed to fill it up as a result of the pressure gradient created by the vacuum in the column. The brine in the column was then degassed; air bubbles in the valves and fittings were also purged.

The brine which is now in the fluid reservoir (i.e. glass column) was then injected into the core at a specific flow rate. The ISCO syringe pump was used to control the flowrate, which was also verified from the time duration and volume of effluent samples collected.

Pressure drops across sections of the core were measured using pressure transducers from the pressure taps located along the length of the core-holder. The pressure drop measured were recorded and displayed using NI's LabView 8.0 software on a computer monitor in real-time. The brine flood experiment was only stopped after a steady pressure was observed for about 2 pore volumes of injected fluid.

**Polymer flooding**

Several partially hydrolyzed polyacrylamide polymers were tested in this research study. Some were modified copolymers similar to HPAM. The polymers (see Table 3.1) used were:

- KYPAM-4 (A stearically modified variant of HPAM)
- FLOPAAM® 3630S (HPAM manufactured by SNF Floerger)
- AN-125 (AMPS/Acrylamide copolymer; manufactured by SNF Floerger)
- HENGFLOC® 63020 (HPAM manufactured by Hengju)
- HENGFLOC® 63026 (HPAM manufactured by Hengju)

The desired polymer solution is usually prepared by diluting a concentrated polymer stock solution. For the high molecular weight polymers used in this study, the polymer stock solution is 4,000 parts per million (ppm) of polymer in 0.5% Sodium Chloride (NaCl). The target polymer solution is obtained by pouring a predetermined amount of the polymer stock into a stirred solution of make-up brine. The composition of the make-up brine is always slightly different from that of the synthetic formation brine. Make-up brine was used so that the resultant polymer solution would have the same composition as the SFB.

For instance, to prepare a 1500 ppm polymer solution from a 4000 ppm polymer stock solution, the steps will be required:

1. Prepare the make-up brine by calculating the required composition by material balance.
2. Put 250 g of the make-up brine in a beaker and place on a magnetic stir plate then begin mixing using the stirrers.
3. Carefully pour 150 g of the polymer stock solution (4000 ppm polymer and 0.5% NaCl) into the mixing brine.
4. Use Argon gas to displace any air on the surface of the beaker and to serve as a blanket over the solution.
5. Seal the beaker and allow mixing for at least 12 hours. Because these are high molecular weight polymers, 24 hour mixing might be required in some cases.

6. Filter the solution using a 1.2 μm Millipore filter paper in a 90mm FANN® 12BL filter press under 15 psi of Argon gas or air.

7. Record the filtration times at intervals of 10ml of filtrate. Calculate the filtration ratio using equation (3.1). If the filtration ratio is less than 1.2, then a good solution has been prepared otherwise repeat steps 2 – 6.

The complete coreflood experiment follows the itemized description:

1. The core was prepared as described in the ‘core preparation’ section above.

2. The core was then saturated with SFB in order to establish the pore volume of the porous medium.

3. Brine flooding of the core was carried out at a specific flow rate and a steady pressure drop was obtained. Brine permeability was then calculated from the pressure and flow rate data. Also, the pore diameter was estimated using the brine permeability value.

4. The core was then flushed with the polymer solution at an arbitrarily selected flow rate until a steady pressure drop is obtained and the viscosity of the effluent solution is similar to that of the injected polymer solution. This was done in order to ensure that the core was completely saturated with polymer.
5. Polymer flooding was conducted and the flow rate was gradually increased from low rates to high rates. At every flow rate, the pressure drop was recorded and flooding continued until a steady pressure drop is observed for at least 2 pore volumes.

6. Effluent samples were collected and their viscosity measured to observe the occurrence of any shear degradation.
Table 3.1: Polymers used in this research study

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Type</th>
<th>M.W. (Dalton)</th>
<th>D.H</th>
<th>Manufacturer</th>
<th>Lot #</th>
</tr>
</thead>
<tbody>
<tr>
<td>KYPAM-4</td>
<td>Stearically modified HPAM</td>
<td>Unknown</td>
<td>25–27%</td>
<td>Beijing Hengju</td>
<td>SP 0307*</td>
</tr>
<tr>
<td>Flopaam™ 3630S</td>
<td>HPAM</td>
<td>$20 \times 10^6$</td>
<td>30%</td>
<td>SNF Floerger</td>
<td>UE 4353</td>
</tr>
<tr>
<td>AN-125</td>
<td>Copolymer of AM and AMPS</td>
<td>$8 \times 10^6$</td>
<td>20-30%</td>
<td>SNF Floerger</td>
<td>UB 4558</td>
</tr>
<tr>
<td>Hengfloc® 63020</td>
<td>HPAM</td>
<td>$20 \times 10^6$</td>
<td>28-30%</td>
<td>Beijing Hengju</td>
<td>SU 0508*</td>
</tr>
<tr>
<td>Hengfloc® 63026</td>
<td>HPAM</td>
<td>$26 \times 10^6$</td>
<td>28-30%</td>
<td>Beijing Hengju</td>
<td>SU 0708*</td>
</tr>
</tbody>
</table>

* - Designated lot numbers not from the manufacturers.

Table 3.2: Composition of the Synthetic Formation Brine (SFB)

<table>
<thead>
<tr>
<th>Compound (Salt) Name</th>
<th>Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>15400.0</td>
</tr>
<tr>
<td>CaCl₂.2H₂O</td>
<td>2540.0</td>
</tr>
<tr>
<td>MgCl₂.6H₂O</td>
<td>2100.0</td>
</tr>
<tr>
<td>Total TDS</td>
<td>20040.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ion</th>
<th>Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>6300</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>640</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>260</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>11500</td>
</tr>
</tbody>
</table>
Figure 3-1: The filter press unit.

Figure 3.2: TA Instruments’ Advanced Rheometric Expansion System (ARES) LS-1.
Figure 3.3: Typical dynamic strain sweep test result.

Figure 3.4: Typical frequency sweep test result.
Figure 3.5: Typical transient test result.

Figure 3.6: Typical steady shear scan result for a non-Newtonian fluid (i.e. polymer).
Figure 3.7: The stainless steel core-holder.

Figure 3.8: The ISCO LC-5000 syringe pump.
Figure 3.9: Schematic of the coreflood experimental setup.
Chapter 4: RESULTS OF BULK RHEOLOGICAL TESTS AND COREFLOOD EXPERIMENTS

4.1 INTRODUCTION

The objectives of the laboratory experiments were to estimate relaxation times of the polymer solutions and to obtain the apparent viscosities of polymers solutions flowing through porous media. The results of the rheological tests (i.e. oscillatory and steady shear tests) of all polymer solutions employed and polymer coreflood experiments are described in this chapter. After calibration/verification of our newly acquired TA Instruments’ Advanced Rheometric Expansion System (ARES LS-1), the rheological data were obtained for all the polymers to be analyzed. Data obtained from these laboratory experiments were employed to characterize the polymers with rheological models (i.e. the Carreau and Rouse models). Flow properties of several polymers were investigated using coreflood experiments. Results from the corefloods and their interpretation constitute the final sections of this chapter.

4.1.1 Rheometer Verification/Calibration

Viscosity measurements using Contraves LS-30 were employed to cross-validate the results from the ARES LS-1.

The polymers used for this research study are listed in Table 3.1. Hengju®’s KYPAM-4 was used for this experiment. A polymer stock solution was diluted into 4 different polymer concentration samples. All the diluted solutions were at 4% salinity (i.e. 4% NaCl brine). Figures 4.1(a) to 4.1(d) show the steady shear viscosity versus shear rate for the polymer concentrations of: 1000 ppm, 1500 ppm, 2000 ppm and 2500 ppm, respectively. The plots show that both rheometers gave very similar results, thereby
validating the accuracy of the new ARES LS-1. The ARES LS-1 was thus used for all subsequent rheological tests.

4.2 BULK RHEOLOGICAL RESULTS

The bulk rheological characterization of high molecular weight polymer solutions is presented in this section. The polymers are mainly variants of partially hydrolyzed polyacrylamide (HPAM). The following polymers were studied: KYPAM-4, Flopaam™ 3630S, AN-125, HENGFLOC® 63020, and HENGFLOC® 63026 (see Tables 3.1 and 4.1).

Their bulk rheological results are classified into 4 categories; the dynamic strain sweep tests, the dynamic frequency sweep, step rate transient tests and the steady rate sweep tests.

4.2.1 Dynamic Strain Sweep Test Results

The dynamic strain sweep test results for all the polymers considered are presented in this sub-section. It was done to obtain the range of strain values for which dynamic properties such as $G'$, $G''$ and $\eta^*$ are constant. The resulting value is used as an input parameter for the dynamic frequency sweep measurement. This test is also carried out in order to establish the range of linear viscoelasticity and torque with temperature and frequency held constant. Storage modulus, $G'$, loss modulus, $G''$, and complex viscosity, $\eta^*$, are measured as a function of strain. Figure 4.2 shows the strain sweep test (at a fixed frequency of 10 rad/s) result for AN-125.

The figures showing the dynamic strain sweep test results for all the polymers studied can be seen in Appendix A.
**KYPAM-4**

The dynamic strain sweep test for the KYPAM polymer samples was done at a constant frequency of 10 rad/s and room temperature. Complex viscosity, elastic and viscous modulus were measured at a strain range of 1 to 100%.

Figures A.1(a), A.1(b), A.1(c) and A.1(d) in Appendix A show the results of the strain sweep test for 1000, 1500, 2000 and 2500 ppm polymer respectively. 4% NaCl brine solution was used. From the figures A.1(a) – A.1(d), it was observed that at a strain value of 40%, the complex viscosity, elastic and viscous modulus were already constant. The elastic modulus started reducing after about 60%. However, the plots show that at a strain value of 40%, the solution was still within its range of linear viscoelasticity since both the elastic and viscous modulus remained constant at this strain value. The strain value obtained here was used in setting up the dynamic frequency test.

**Flopaam™ 3630S**

The polymer solution tested here was 1500 ppm Flopaam™ 3630S in SFB. The dynamic strain sweep test for Flopaam™ 3630S was done at a constant frequency of 10 rad/s and room temperature. Complex viscosity, elastic and viscous modulus were measured at a strain range of 1 to 200%.

Figure A.2 in Appendix A show the results of the strain sweep test for this sample. It was observed that the complex viscosity, elastic and viscous moduli were already constant at a strain value of 25%. The solution was still within its range of linear viscoelasticity since both the elastic and viscous modulus remained constant at this strain value. The elastic modulus started reducing after about 90%. The strain value obtained here was used in setting up the dynamic frequency test.
**AN-125**

1500 ppm of AN-125 polymer in SFB was tested here. The dynamic strain sweep test for AN-125 was done at a constant frequency of 10 rad/s and room temperature. Complex viscosity, elastic and viscous modulus were measured at a strain range of 1 to 200%.

Figure A.3 in Appendix A shows the results of the strain sweep test for this sample. It was observed that the complex viscosity, elastic and viscous moduli were already constant at a strain value of 25%. The solution was still within its range of linear viscoelasticity since both the elastic and viscous modulus remained constant at this strain value. The elastic modulus started reducing after about 50%. The strain value obtained here was used in setting up the dynamic frequency test.

**HENGFLOC® 63020**

At a constant frequency of 10 rad/s, room temperature and for a range of 1 to 200% strain, the dynamic strain sweep test of Hengju’s HENGFLOC® 63020 was carried out. Two samples of the polymer were considered. Both samples were made of 1500 ppm polymer but different brine composition. The first was with SFB while the second was with softened synthetic formation brine (SSFB) containing 20 ppm of Ca$^{2+}$.

Figures A.4(a) and A.4(b) show the strain sweep test results for the first and second samples. The samples were within their range of linear viscoelasticity at strain values of 25% and 20% respectively. The dynamic frequency sweep tests were done at these constant strain values.
**HENGFLOC® 63026**

The polymer solution considered here was 1500 ppm Hengju’s HENGFLOC® 63026 in containing 20 ppm of Ca\(^{2+}\). The dynamic strain sweep test for this sample was done at a constant frequency of 10 rad/s and room temperature. Complex viscosity, elastic and viscous modulus were measured at a strain range of 1 to 200%.

Figure A.5 in Appendix A show the results of the strain sweep test for this sample. The solution was within its range of linear viscoelasticity at a strain value of 25% since both the elastic and viscous modulus remained constant. The elastic modulus started reducing after about 100%. The strain value obtained here was used in setting up the dynamic frequency test.

**4.2.2 Dynamic Frequency Sweep Test Results**

The aim of this test is to measure the storage modulus, loss modulus and complex viscosity of the polymers as a function of the frequency of oscillation. Relaxation time of the polymer is estimated from the dynamic data obtained from this test. These measurements are carried out at constant temperature and at a strain value that is within the range of linear viscoelasticity obtained from the dynamic strain sweep test.

Below a certain critical frequency, the viscous modulus (G”) was higher than the elastic modulus (G’) for all of the tests. G’ and G” represent, respectively, the elastic restoration and viscous dissipation by polymer chains during oscillatory flow (Ferry, 1980). At the critical frequency, G’ and G” intersect and the inverse of this frequency is a characteristic time called the relaxation time of the polymer solution. Above the critical frequency, the flow behavior is governed more by elasticity of the polymer than by the viscous force.
**KYPAM-4**

The dynamic frequency sweep test for the KYPAM-4 polymer samples was done at a constant strain value of 40% and room temperature. Complex viscosity, elastic and viscous modulus were measured at frequencies ranging from 0.1 to 100 rad/s.

Figures 4.3(a), 4.3(b), 4.3(c) and 4.3(d) show the results of the frequency sweep test for 1000, 1500, 2000 and 2500 ppm polymer respectively. 4% NaCl brine solution was used. Figures 4.3(e) and 4.3(f) compare the elastic and viscous modulus of the polymers. It was observed that both moduli increased as the concentration of polymer in solution increases. As the concentration of polymer is increased, the viscosifying ability of the solution increases too hence the increase in the viscous modulus. Also, there are more polymer chain entanglements as the concentration or number of polymer molecules in the solution increases, therefore the more elastic the polymer solution would be and hence the elastic modulus. The elastic moduli of the polymer samples were more sensitive for slow oscillations or low frequencies thereby causing an increase in their differences at low frequencies.

**Flopaam™ 3630S, AN-125, HENGFLOC® 63020 and HENGFLOC® 63026**

The dynamic frequency sweep test for these polymers was done at a constant strain value of about 25% and room temperature. Complex viscosity, elastic and viscous modulus were measured at frequencies ranging from 0.1 to 100 rad/s.

Figures 4.4, 4.5, 4.6 and 4.7 show the dynamic frequency test results for the polymers: Flopaam™ 3630S, AN-125, HENGFLOC® 63020 and 63026 respectively. At high frequencies of about 100 rad/s, some inertia effects occur and were observed by the decrease in the elastic modulus. The elastic and viscous modulus intersected at a certain
critical frequency for all the polymers. This indicated a potential for viscoelastic behavior.

Figures 4.8(a) and 4.8(b) compared the elastic and viscous modulus of these polymers. Several factors such as molecular weight, polymer concentration, salinity and degree of hydrolysis affect the dynamic properties of polymers. All the samples were of the same polymer concentration. The higher molecular weight HENGFLOC® 63026 (26 x 10^6 Dalton) had the highest viscous and elastic modulus at any given frequency. Polymers with a higher degree of hydrolysis (> 30%) are more sensitive to the effect of divalent ions such as calcium and magnesium. That is why the HENGFLOC® 63020 (MW: 20 x 10^6 Dalton) with D.H. of ~ 28 – 30% had the least viscous and elastic modulus at all frequencies despite having a higher molecular weight than AN-125 (MW: 8 x 10^6 Dalton) which has a lower D.H.

Higher molecular weight polymers gave higher values of G’ and G” (see Figures 4.8(a) - (b)). Also, increasing the salinity or degree of hydrolysis will result in a decrease in the viscous and elastic modulus assuming all other parameters remain constant.

4.2.3 Strain Controlled Step Rate Transient Test Results

This test helps determine the time it will take for the stress response of the fluid to attain steady state. The figures showing the transient test results can be seen in appendix A. Figure 4.9 shows the step rate transient test for 1500 ppm Flopaam™ 3630S in SFB. The step change occurred after 5 s. The viscosity and torque had become steady after 10s. This implies that it would require approximately 10 s to attain steady state when measurements are being made.
From the results of the step rate transient test, 15 s was set as the time of delay before measuring the steady rate viscosity and 10 s for the actual measurement. This ensured that accurate viscosity measurements were made.

### 4.2.4 Steady Rate Sweep Test Results

The rate of shear deformation varies and the viscosity of the fluid sample is measured at steady state. Shear rates could vary from 0.01 to 1000 s\(^{-1}\) in this study. The result of this test for all the polymers considered is presented in this subsection.

**KYPAM-4**

The shear scans for the KYPAM-4 polymers are shown in Figure 4.10. The steady rate sweep test results for KYPAM-4 is separately described because these measurements were conducted primarily to cross-validate results from ARES LS-1.

**Flopaam™ 3630S, AN-125, HENGFLOC® 63020 and HENGFLOC® 63026**

The data for these polymers are typical of most shear-thinning non-Newtonian fluids. Figures 4.11, 4.12, 4.13 and 4.14 show the steady shear rate sweep test results for the polymers: Flopaam™ 3630S, AN-125, HENGFLOC® 63020 and 63026, respectively.

Figure 4.15 compares the viscosities of the aforementioned polymers (1500 ppm polymer in SFB and SSFB with 20 ppm Ca\(^{2+}\)). At the given fixed temperature (23°C) and polymer concentration (1500 ppm), the higher the molecular weight of the polymer, the higher the viscosity. HENGFLOC® 63026 (26 x 10\(^6\) Dalton) had the highest viscosity. Polymers with a higher degree of hydrolysis are more sensitive to the effect of divalent ions such as Ca\(^{2+}\) and Mg\(^{2+}\). That is why the HENGFLOC® 63020 \((MW: 20 \times 10^6)\)
Dalton) had the least viscosity despite having a higher molecular weight than AN-125 (MW: 8 x 10^6 Dalton).

Higher molecular weight polymers give higher viscosities (see Figure 4.15); this is consistent with the Mark-Houwink equation (Eq. 2.8). The polymer with the largest M.W. of 26 x 10^6 Daltons exhibited the most shear-thinning behavior which is reflected as the least power-law index of 0.662. Also, increasing the salinity or degree of hydrolysis will result in a decrease in the viscosity given that all other parameters remained constant.

4.2.5 Intrinsic Viscosities

The viscosifying potential of a polymer can be quantified via its intrinsic viscosity. The intrinsic viscosities of the polymer samples considered are listed in Table 4.1. It was obtained using equations (2.6) and (2.7). The plots generated are shown in Figures 4.16 – 4.21. Factors such as molecular weight, salinity and concentration that affect a polymer’s bulk rheological properties also affect its intrinsic viscosity. The higher molecular weight polymers have higher intrinsic viscosities. Flopaam™ 3630S and HJ 63026 polymer solution having M.W. > 20 x 10^6 Dalton had intrinsic viscosities of 2046.7 and 3455 cm^3/g, respectively. A polymer’s molecular weight also represents the size of its molecules. Using equation (2.9), the hydrodynamic radius, Ω_p, was estimated and listed in Table 4.1 as well. AN-125 had the least M.W. of 8 x 10^6 and thus had the smallest sized molecules with Ω_p of 0.418 μm compared with a hydrodynamic radius of 0.753 μm for HJ 63026.
4.2.6 Relaxation Time Estimates

The relaxation times, $\tau_r$, of the polymer solutions were obtained from data extracted from the dynamic frequency sweep test. The elastic and viscous modulus data was fitted to the Rouse model (Heemskerk et al., 1984). The longest time in the relaxation spectrum was then taken as the relaxation time of the polymer. This value was compared to a quick characteristic time estimate obtained from the $G'/G''$ crossover point. Table 4.2 is a summary of the relaxation times for the various polymers used in this study. Figures A.12 – A.16 show the model fit plots. The relaxation times for different concentrations of KYPAM-4 are shown in Figure 4.22. The samples with higher polymer concentration showed more physical elasticity during their preparation, thus suggesting that their relaxation times should be higher. The values of $\tau_r$ obtained from the Rouse model fit were consistent with the visual observation of the samples; the more concentrated samples had higher relaxation times. Therefore, for analysis and numerical calculations involving the use of $\tau_r$, the values obtained from the model fit were employed.

4.3 COREFLOOD RESULTS

The results of the coreflood experiments conducted are reported in this section. Experimental procedures described in Chapter 3 were followed for the measurements made. The corefloods were run at room temperature (23 °C). Berea sandstone cores and the same set-up were used in all cases. Properties altered were divalent ion concentration, type of polymer (i.e. HPAM and a co-polymer of acrylamide and AMPS) and degree of hydrolysis. Pressure and flow-rate data constitute the most important measurements or results extracted from these coreflood experiments.
4.3.1 Discussion of Coreflood Results

Different polymer samples and salinities were used for the coreflood experiments. The variation in coreflood conditions is shown in Table 4.3. Also, core properties for each of the experiments are summarized in Table 4.4.

Figures B.1 to B.24 in Appendix B show the pressure drop recorded during the corefloods. The pressure drop during the brine floods attained steady state before half a pore volume of fluid was injected. This was expected since SFB was a Newtonian low viscosity fluid. The pressure drop profile for the brine floods can be seen in Figures B.1, B.6, B.12, B.18 and B.21.

Steady pressure drop was attained for all corefloods at their injection flow rates. Within experimental errors, the pressure gradient across the middle sections of the core was similar to the pressure gradient across the entire core for most of the experiments conducted. This showed that the pressure transducers were working adequately. To ensure consistency in the data analysis, the overall pressure drop was employed for computations and analysis.

For the polymer floods, the pressure drop across the core did not vary linearly with flow rate of injection as shown in Figures 4.24, 4.25, 4.26, 4.27 and 4.28 for experiments BV-1, BV-2, BV-3, BV-4 and BV-5, respectively. After a certain rate, the slope of the line changes and it becomes steeper (higher). This implies that a greater pressure response would be observed for the same change in flow rate. It occurred as a result of the non-Newtonian behavior of the injected fluid (i.e. polymer). The higher the slope, the more shear-thickening the fluid will behave. For Newtonian fluids, the pressure drop will vary linearly with changes in flow rate.
Permeability reduction, which is a complex phenomenon resulting from the combined effects of polymer-rock interactions including polymer adsorption, the wall exclusion effect, and inaccessible pore volume (Chauveteau and Kohler, 1974), is also estimated.

An important property derived from results of these coreflood experiments is the apparent viscosity of the polymer as it propagates through a porous medium.

4.3.2 Apparent Viscosity

For all the polymer coreflood experiments, the apparent viscosities of the polymer solutions flowing through the cores, $\mu_{app}$, were computed using equation (2.21).

$$\mu_{app} = \frac{k_{permc} \Delta p}{u L}$$

As described in Chapter 2, $\mu_{app}$ is same as the viscosity for Newtonian fluids, $\mu_{app}$ for non-Newtonian fluids generally deviates from the bulk viscosity.

Figure 4.29 is a plot of the apparent viscosity of 1500 ppm of Flopaam™ 3630S in SFB flowing through a 647 md Berea sandstone rock (experiment BV-1). Only three data points were measured during this experiment. Nevertheless, the deviation from measured bulk viscosity was significant. Comparison of the apparent viscosity with the bulk viscosity shows that for shear rates higher than 30 s$^{-1}$, the apparent viscosity of the polymer increases as shear rate increases. This is known as shear-thickening, and under these conditions, Flopaam™ 3630S can be said to be exhibiting viscoelastic properties.

All the polymers considered in this study showed significant viscoelasticity at high flow velocity. Although the relaxation times of all polymers tested were approximately the same, Figures 4.29 to 4.33 show that the longer the relaxation time of
the polymer solution, the more the apparent viscosity will deviate from the measured bulk viscosity, thus showing increased shear thickening attributes.

Polymer flooding was conducted at flow rates low enough in Experiment BV-3 for apparent viscosity to fall into the shear-thinning region and match the bulk data. In this case, the polymer began to shear-thicken beyond a shear rate of 50 s⁻¹.

Another observation worth noting here is that the AN-125 polymer (in Experiment BV-2) showed a steep shear-thickening region (see Figure 4.30) despite its lower molecular weight compared to the other polymers. The reason for this strong viscoelastic response is not known. Also, the relaxation time for this polymer is as long as that for the high molecular weight polymers.

In order to have a better understanding of the shear thickening behavior of these polymers, the unified viscosity model (UVM) was proposed (Delshad et al., 2008) and applied to the experimental results. The findings from this particular research effort are presented in the Chapter 5.
Table 4.1: Summary of polymers’ intrinsic viscosities

<table>
<thead>
<tr>
<th>Polymer</th>
<th>M.W. (Dalton)</th>
<th>$[\eta]$, cm$^3$/g</th>
<th>$\Omega_p$, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>KYPAM-4 in 4% NaCl</td>
<td>Unknown</td>
<td>2537.3</td>
<td>0.680</td>
</tr>
<tr>
<td>Flopaam™ 3630S in SFB</td>
<td>$20 \times 10^6$</td>
<td>2046.7</td>
<td>0.580</td>
</tr>
<tr>
<td>AN-125 in SFB</td>
<td>$8 \times 10^6$</td>
<td>1913.6</td>
<td>0.418</td>
</tr>
<tr>
<td>HJ 63020 in SFB</td>
<td>$20 \times 10^6$</td>
<td>1858.6</td>
<td>0.561</td>
</tr>
<tr>
<td>HJ 63020 in SSFB w/ 20ppm Ca$^{2+}$</td>
<td>$20 \times 10^6$</td>
<td>2610.6</td>
<td>0.629</td>
</tr>
<tr>
<td>HJ 63026 in SSFB w/ 20ppm Ca$^{2+}$</td>
<td>$26 \times 10^6$</td>
<td>3455.0</td>
<td>0.753</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of relaxation time estimates

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Concentration (ppm)</th>
<th>Salinity</th>
<th>$\tau_r$, (sec) (G’/G” crossover)</th>
<th>$\tau_r$, (sec) (Rouse model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KYPAM-4</td>
<td>1000</td>
<td>4% NaCl</td>
<td>0.0523</td>
<td>0.0577</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td></td>
<td>0.0585</td>
<td>0.0770</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td></td>
<td>0.0529</td>
<td>0.1100</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td></td>
<td>0.0509</td>
<td>0.1500</td>
</tr>
<tr>
<td>Flopaam™ 3630S</td>
<td>1500</td>
<td>SFB</td>
<td>0.0626</td>
<td>0.0859</td>
</tr>
<tr>
<td>AN-125</td>
<td>1500</td>
<td>SFB</td>
<td>0.0602</td>
<td>0.0605</td>
</tr>
<tr>
<td>HJ 63020</td>
<td>1500</td>
<td>SFB</td>
<td>0.0501</td>
<td>0.0450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SFB with 20 ppm Ca$^{2+}$</td>
<td>0.0500</td>
<td>0.0671</td>
</tr>
<tr>
<td>HJ 63026</td>
<td>1500</td>
<td>SFB with 20 ppm Ca$^{2+}$</td>
<td>0.0745</td>
<td>0.1360</td>
</tr>
</tbody>
</table>
### Table 4.3: Schedule of coreflood experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BV-1</th>
<th>BV-2</th>
<th>BV-3</th>
<th>BV-4</th>
<th>BV-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>Flopaam™ 3630S</td>
<td>AN-125</td>
<td>HJ 63020</td>
<td>HJ 63020</td>
<td>HJ 63026</td>
</tr>
<tr>
<td>M.W. (Daltons)</td>
<td>$20 \times 10^6$</td>
<td>$8 \times 10^6$</td>
<td>$20 \times 10^6$</td>
<td>$20 \times 10^6$</td>
<td>$26 \times 10^6$</td>
</tr>
<tr>
<td>Brine</td>
<td>SFB</td>
<td>SFB</td>
<td>SFB</td>
<td>SSFB w/ 20 ppm Ca$^{2+}$</td>
<td>SSFB w/ 20 ppm Ca$^{2+}$</td>
</tr>
<tr>
<td>D.H</td>
<td>30%</td>
<td>20 - 30%</td>
<td>28 – 30%</td>
<td>28 – 30%</td>
<td>28 – 30%</td>
</tr>
<tr>
<td>$\tau_r$</td>
<td>0.0859</td>
<td>0.0605</td>
<td>0.045</td>
<td>0.0671</td>
<td>0.136</td>
</tr>
</tbody>
</table>

### Table 4.4: Summary of core properties

<table>
<thead>
<tr>
<th>Property</th>
<th>BV-1</th>
<th>BV-2</th>
<th>BV-3</th>
<th>BV-4</th>
<th>BV-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td>211.14</td>
<td>207.4</td>
<td>208.79</td>
<td>207.0</td>
<td>206.6</td>
</tr>
<tr>
<td>Porosity (cm$^3$/cm$^3$)</td>
<td>0.23</td>
<td>0.24</td>
<td>0.235</td>
<td>0.24</td>
<td>0.243</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>20.32</td>
<td>20.32</td>
<td>20.32</td>
<td>20.32</td>
<td>20.32</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>2.54</td>
<td>2.54</td>
<td>2.54</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td>Area (cm$^2$)</td>
<td>5.07</td>
<td>5.07</td>
<td>5.07</td>
<td>5.07</td>
<td>5.07</td>
</tr>
<tr>
<td>Pore Volume (cm$^3$/cm$^3$)</td>
<td>24.86</td>
<td>24.26</td>
<td>24.66</td>
<td>24.7</td>
<td>23.06</td>
</tr>
<tr>
<td>Brine Permeability (md)</td>
<td>647</td>
<td>578</td>
<td>552</td>
<td>372</td>
<td>260</td>
</tr>
</tbody>
</table>
Figure 4.1(a): Viscosity comparison for 1000 ppm KYPAM-4 in 4% NaCl.

Figure 4.1(b): Viscosity comparison for 1500 ppm KYPAM-4 in 4% NaCl.
Figure 4.1(c): Viscosity comparison for 2000 ppm KYPAM-4 in 4% NaCl.

Figure 4.1(d): Viscosity comparison for 2500 ppm KYPAM-4 in 4% NaCl.
Figure 4.2: Dynamic strain sweep test for 1500ppm AN-125 in SFB.

Figure 4.3(a): Dynamic frequency sweep test for 1000 ppm KYPAM-4 in 4% NaCl.
Figure 4.3(b): Dynamic frequency sweep test for 1500 ppm KYPAM-4 in 4% NaCl.

Figure 4.3(c): Dynamic frequency sweep test for 2000 ppm KYPAM-4 in 4% NaCl.
Figure 4.3(d): Dynamic frequency sweep test for 2500 ppm KYPAM-4 in 4% NaCl.

Figure 4.3(e): Comparison of elastic modulus for the KYPAM-4 polymer.
Figure 4.3(f): Comparison of viscous modulus for the KYPAM-4 polymer.

Figure 4.4: Dynamic frequency sweep test for 1500 ppm Flopaam™ 3630S in SFB.
Figure 4.5: Dynamic frequency sweep test for 1500 ppm AN-125 in SFB.

Figure 4.6(a): Dynamic frequency sweep test for 1500 ppm HJ 63020 in SFB.
Figure 4.6(b): Dynamic frequency sweep test for 1500 ppm HJ 63020 in SSFB with 20 ppm Ca$^{2+}$.

Figure 4.7: Dynamic frequency sweep test for 1500 ppm HJ 63026 in SSFB with 20 ppm Ca$^{2+}$.
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Figure 4.8(b): Comparison of viscous modulus for the polymers.
Figure 4.9: Step rate transient test for 1500 ppm Flopaam™ 3630S in SFB.

Figure 4.10: Comparison of steady shear rate sweep for the KYPAM-4 polymer.
Figure 4.11: Steady shear rate sweep test for 1500 ppm Flopaam™ 3630S in SFB.

Figure 4.12: Steady shear rate sweep test for 1500 ppm AN-125 in SFB.
Figure 4.13(a): Steady shear rate sweep test for 1500 ppm HJ 63020 in SSFB.

Figure 4.13(b): Steady shear rate sweep test for 1500 ppm HJ 63020 in SSFB with 20ppm Ca$^{2+}$. 
Figure 4.14: Steady shear rate sweep test for 1500 ppm HJ 63026 in SSFB with 20 ppm Ca$^{2+}$.

Figure 4.15: Comparison of steady shear rate sweep test for the polymers (1500 ppm).
Figure 4.16: Intrinsic viscosity plot for KYPAM-4 in 4% NaCl brine.

Figure 4.17: Intrinsic viscosity plot for Flopaam™ 3630S in SFB.
Figure 4.18: Intrinsic viscosity plot for AN-125 in SFB.

Figure 4.19: Intrinsic viscosity plot for HENGFLOC® 63020 in SFB.
Figure 4.20: Intrinsic viscosity plot for HENGFLOC® 63020 in SSFB with 20 ppm Ca$^{2+}$.

Figure 4.21: Intrinsic viscosity plot for HENGFLOC® 63026 in SSFB with 20 ppm Ca$^{2+}$.
Figure 4.22: Relaxation times for different concentrations of KYPAM-4 in 4% NaCl.

Figure 4.23: Comparison of the relaxation times obtained using the $G'/G''$ crossover method and Rouse model.
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Figure 4.25: Pressure drop versus flow rate for experiment BV-2.
Figure 4.26: Pressure drop versus flow rate for experiment BV-3.

Figure 4.27: Pressure drop versus flow rate for experiment BV-4.
Figure 4.28: Pressure drop versus flow rate for experiment BV-5.

Figure 4.29: Apparent viscosity of 1500 ppm Flopaam™ 3630S in SFB (Experiment BV-1).
Figure 4.30: Apparent viscosity of 1500 ppm AN-125 in SFB (Experiment BV-2).

Figure 4.31: Apparent viscosity of 1500 ppm HJ 63020 in SFB (Experiment BV-3).
Figure 4.32: Apparent viscosity of 1500 ppm HJ 63020 in SSFB with 20 ppm Ca^{2+} (Experiment BV-4).

Figure 4.33: Apparent viscosity of 1500 ppm HJ 63026 in SSFB with 20 ppm Ca^{2+} (Experiment BV-5).
Chapter 5: THE UNIFIED APPARENT VISCOSITY MODEL

5.1 INTRODUCTION

Much less time and effort is required to measure the viscosity of a polymer solution than the time and effort required to measure the apparent viscosity by doing a core flood. Thus, many attempts have been made over the past 40 years to develop models that use rheological measurements to predict apparent viscosity in the permeable medium as described schematically in Figure 5.1. Also, such a model is needed in reservoir simulators to model polymer flooding and other chemical enhanced oil recovery processes involving the use of polymer. Delshad et al. 2008 recently developed such a unified apparent viscosity model (UVM) for the entire range of velocity. The rheological and core flood data measured during this study have been used to test this model. The results of this effort are described in this chapter.

5.2 APPLICATION OF THE UNIFIED APPARENT VISCOSITY MODEL

5.2.1 Determination of Carreau model parameters

Many models have been developed for the bulk viscosity of a polymer solution as described in section [2.3]. For this study, the Carreau model (Equation (2.4)) was used. All the bulk viscosity measurements were fit to the Carreau model to obtain the model parameters (Table 5.1). Figures 5.2 to 5.7 show that the Carreau model fits all of the viscosity data for the polymer solutions used for experiments BV-1 to BV-5. The power-law index, n, ranged from 0.6 ~ 0.83. A lower value of index, n indicates a higher degree of shear-thinning for the fluid. The polymer solution used for BV-5 (HJ 63026 in SSFB) had the lowest power-law index (0.662) while that used for experiment BV-3 (HJ 63020 in SFB) had the largest value of (0.828). HJ 63020 in SSFB with 20ppm Ca\(^{2+}\) had the
lowest value of $\lambda$ (0.066) and can be seen to be the least non-linear amongst all the polymers (Figure 5.4 and 5.7). The Carreau model parameters, $n$ and $\lambda$ vary with factors such as polymer structure, molecular weight and salinity.

5.2.2 Fitting parameters for the Unified Apparent Viscosity model

Equation (2.24) gives the expression for UVM.

$$\mu_{\text{app}} = \mu_\infty + \left(\mu_p - \mu_\infty\right) \left[1 + \left(\frac{\lambda \dot{\gamma}_{\text{eff}}}{\mu_\infty}\right)^{(n-1)/n}\right] + \mu_\text{max} \left[1 - \exp\left(-\left(\frac{\lambda_2 \tau_r \dot{\gamma}_{\text{eff}}}{\mu_\infty}\right)^{n_2-1}\right)\right]$$

where $\mu_\infty$, $\mu_p$, $\lambda$, $n$ and $\alpha$ are empirical constants that will be obtained from the Carreau model fit to the polymer’s bulk viscosity data. The other parameters in the UVM are:

- $\mu_\text{max}$: A plateau value of viscosity beyond which shear degradation will occur.
- $\lambda_2$: A proposed ‘universal’ constant that is independent of data being matched.
- $\tau_r$: Relaxation time of injected fluid. It is obtained from the dynamic frequency sweep test.
- $n_2$: Shear-thickening index. It indicates the extent of polymer ‘dilatancy’.

These are the fitting parameters required for the application of the unified apparent viscosity model.

5.2.3 Model application to experimental data

The UVM was successfully applied to fit the experimental data obtained in this research study as well as to the data from experiments conducted by Yuan (1981). Yuan used a high permeability ($k = 4 \sim 38$ D) glass bead pack and Pusher-700 (M.W. $\sim 8 \times 10^6$ Daltons) polymer for his experiments. Yuan’s data served to complement the data from this study by expanding the range of permeability and velocity. Data from coreflood experiments PF-5b, 6d and 7b were analyzed in this study. Experiments PF-5b and 7b
were conducted using 1000 ppm Pusher-700 in a 1% NaCl brine and 4.2 and 37.9 Darcy bead packs, respectively. Experiment PF-6d was conducted using 1000 ppm Pusher-700 in 0.1% NaCl brine and a 3.6 D glass bead pack.

The UVM parameters for each of these experiments are summarized in Tables 5.2 and 5.3. Figures 5.8 to 5.12 show a comparison of the experimental data from this study with the UVM model curves and Figures 5.14, 5.15 and 5.16 show a comparison of the experimental data of Yuan (1981) with the UVM model curves using the parameters given in Tables 5.2 and 5.3, respectively. A value of 6 for constant, C and the power-law index, n, obtained from the Carreau model fit to steady shear viscosity data were substituted into equation (2.22) to calculate the apparent shear rate, \( \dot{\gamma} \), shown in these plots. Plotting the apparent viscosity as a function of Darcy velocity is another way of representing the results and those plots can be seen in Appendix B. The UVM was fit to apparent viscosity data obtained from each coreflood experiment (i.e. individual coreflood matches) and model parameters, \( n_2 \), \( \lambda_2 \) and \( \mu_{\text{max}} \) were obtained.

As expected, the apparent viscosity of the polymer began to increase after a certain critical shear rate. The onset of shear thickening behavior was approximately the same for experiments BV-1, BV-4 and BV-5 (~ 40 s\(^{-1}\)). Figure 5.13 compares all of the experiments done in this study. The slope of shear thickening as indicated by the parameter, \( n_2 \) was observed to be the same for all the experiments except for experiment BV-3. The polymer used for BV-3 had the smallest relaxation time, thereby having less elastic attributes than other polymers.

The onset of shear-thickening behavior for Yuan’s experiments was at an apparent shear rate on the order of 100 s\(^{-1}\). The permeabilities of the glass bead packs used by Yuan are much larger than the permeability of the Berea sandstone used in this study, which means the pore throats are much larger, and less deformation of the polymer
coil occurs at a given velocity. Also, the polymers used by Yuan had lower M.W (8 million Daltons) than the ones used in this study. As shown in Figures 5.13 and 5.17, lower molecular weight polymers (e.g. for AN-125 in SFB: 8 x 10^6 Daltons) have lower intrinsic viscosities (1913 cm^3/g) and hydrodynamic radii (0.418 μm), thus exhibiting less viscoelastic behavior than polymers with higher molecular weights (e.g. for HJ 63020 in SSFB: M.W. = 20 x 10^6 Daltons, [η] = 2610.6 cm^3/g and Ω_p = 0.629 μm).

The parameter μ_max in the UVM is the maximum apparent viscosity at high shear rate, quantifies the maximum degree of shear thickening in the model. Several variables such as the permeability, salinity, polymer relaxation time and molecular weight affect the value of μ_max. More elastic fluids or lower permeability gave a greater the value of μ_max. A plausible explanation for this trend is that the polymers with a higher relaxation time require more time to change shape as they flow through the pore throats and more deformation is needed to flow through the smaller pore throats, so the resistance to flow increases, which translates to a higher pressure drop and apparent viscosity at high velocity where the shear thickening behavior is greatest.

Experiment BV-2 did not follow the trend observed from the other tests. It had a high value of μ_max despite the fact that it has the lowest molecular weight. Also, its shear-thickening index (n_2 = 2.05) was different from the others. AN-125 is a co-polymer of acrylamide and 2-acrylamido 2-methyl propane sulfonate (AMPS), so its behavior might be expected to be different than the HPAM polymers since it has a different structure.

From the model fits, the shear-thickening index, n_2, was observed to have a typical value of 2.3. All of the data could be fit with a constant value of 0.01 for the parameter, λ_2, so on a provisional basis it may be considered a universal constant for similar experiments and conditions. However, more experiments will be needed to confirm its constant value of 0.01.
Figure 5.1: Schematic of advantage of deployment of a unified apparent viscosity model

Table 5.1: Summary of Carreau model fitting parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BV-1</th>
<th>BV-2</th>
<th>BV-3</th>
<th>BV-4</th>
<th>BV-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_\infty$, cp</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>$\eta_0$, cp</td>
<td>13.76</td>
<td>10.146</td>
<td>6.540</td>
<td>18.086</td>
<td>65.877</td>
</tr>
<tr>
<td>$\lambda$, s</td>
<td>0.221</td>
<td>0.250</td>
<td>0.066</td>
<td>0.175</td>
<td>1.631</td>
</tr>
<tr>
<td>n</td>
<td>0.755</td>
<td>0.802</td>
<td>0.828</td>
<td>0.720</td>
<td>0.662</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table 5.2:  Fitting parameter for the Unified apparent Viscosity Model (UVM)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BV-1</th>
<th>BV-2</th>
<th>BV-3</th>
<th>BV-4</th>
<th>BV-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{max, \text{cp}}$</td>
<td>65</td>
<td>90</td>
<td>21</td>
<td>82</td>
<td>95.52</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
</tr>
<tr>
<td>$\tau_r, \text{s}$</td>
<td>0.085</td>
<td>0.06</td>
<td>0.045</td>
<td>0.067</td>
<td>0.136</td>
</tr>
<tr>
<td>$n_2$</td>
<td><strong>2.3</strong></td>
<td><strong>2.05</strong></td>
<td><strong>2.3</strong></td>
<td><strong>2.25</strong></td>
<td><strong>2.35</strong></td>
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</tbody>
</table>

Table 5.3:  Summary of viscosity model fitting parameters for Yuan’s data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PF-5b</th>
<th>PF-6d</th>
<th>PF-7b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_\infty, \text{cp}$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\eta_0, \text{cp}$</td>
<td>8.0</td>
<td>36</td>
<td>8.4</td>
</tr>
<tr>
<td>$\lambda, \text{s}$</td>
<td>0.057</td>
<td>0.158</td>
<td>0.057</td>
</tr>
<tr>
<td>$n$</td>
<td>0.75</td>
<td>0.591</td>
<td>0.73</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu_{max, \text{cp}}$</td>
<td>50</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
</tr>
<tr>
<td>$\tau_r, \text{s}$</td>
<td>0.035</td>
<td>0.066</td>
<td>0.035</td>
</tr>
<tr>
<td>$n_2$</td>
<td><strong>2.3</strong></td>
<td><strong>1.65</strong></td>
<td><strong>2.3</strong></td>
</tr>
</tbody>
</table>
Figure 5.2: Carreau model fit for 1500 ppm Flopaam™ 3630S in SFB.

Figure 5.3: Carreau model fit for 1500 ppm AN-125 in SFB.
Figure 5.4: Carreau model fit for 1500 ppm HJ 63020 in SFB.

Figure 5.5: Carreau model fit for 1500 ppm HJ 63020 in SSFB with 20 ppm Ca\(^{2+}\).
Figure 5.6: Carreau model fit for 1500 ppm HJ 63026 in SSFB with 20 ppm Ca$^{2+}$.

Figure 5.7: Comparison of the Carreau model fit for all the polymers used.
Figure 5.8: Unified apparent viscosity model fit for BV-1.

Figure 5.9: Unified apparent viscosity model fit for BV-2.
Figure 5.10: Unified apparent viscosity model fit for BV-3.

Figure 5.11: Unified apparent viscosity model fit for BV-4.
Figure 5.12: Unified apparent viscosity model fit for BV-5.

Figure 5.13: Comparison of the Unified apparent viscosity model fit for all the polymers used.
Figure 5.14: Unified apparent viscosity model fit for PF-5b (Data from Yuan, 1981).

Figure 5.15: Unified apparent viscosity model fit for PF-6d (Data from Yuan, 1981).
Figure 5.16: Unified apparent viscosity model fit for PF-7b (Data from Yuan, 1981).

Figure 5.17: Comparison of the Unified apparent viscosity model fit for Yuan’s data.
Chapter 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Adequate understanding of in-situ polymer rheology is required in order to develop an accurate simulation model that can be used to optimize the chemical EOR processes that employ polymer for mobility control purposes. The viscoelastic behavior of high molecular weight polymers was explored and quantified. Extensive bulk and in-situ rheological measurements using high molecular weights polymers were done in order to quantitatively understand the nature and effect of the viscoelastic behavior of these polymers. Bulk measurements were carried out using a rheometer, while polymer coreflood experiments provided data to characterize in-situ rheology.

Two types of polymer were used: a partially hydrolyzed polyacrylamide (HPAM) and an acrylamido-methyl-propane sulfonate (AMPS) co-polymerized with acrylamide. The well known Carreau and Rouse models were used to fit bulk steady shear and dynamic frequency test data, respectively. Results from our coreflood experiments show that the apparent viscosity of a polymer solution can be described using a recently proposed Unified Viscosity Model (UVM). The model parameters in UVM vary with factors such as the brine salinity, calcium concentration in the brine, permeability and polymer molecular weight that affect the apparent viscosity in the permeable medium including the shear thickening behavior observed at high velocities.

The most important conclusion of this study is that the UVM fits measured core flood data under a wide range of conditions for commonly used EOR polymers and can therefore be used to make predictions of apparent viscosity of these polymer solutions under certain conditions using only rheological data that are relatively inexpensive to measure compared to core flood data. This model can now be used in reservoir
simulation studies of polymer flooding processes and other chemical enhanced oil recovery processes involving the use of polymers.

Additional conclusions are as follows:

1. A recently proposed Unified Viscosity Model (UVM) that accounts for shear thickening behavior at high velocities was validated using data obtained from this study and the experiments conducted by Yuan (1981), who did similar experiments at the University of Texas at Austin 27 years ago.

2. Factors such as permeability, polymer concentration, molecular weight and brine salinity (especially divalent ions) affect in-situ rheological properties of polymer solutions in porous media. More shear thickening is observed in experiments with low permeability cores, lower brine salinity, higher polymer concentration and higher molecular weight polymers.

3. Oscillatory measurements (dynamic frequency sweep test) were used to establish the relaxation time of the polymer molecules. Polymer flow coreflood experiments were successfully carried out for different shear rates (or flow velocities) and molecular weights to determine apparent viscosity of the polymer solutions.

4. The elastic and viscous modulus (G', G'') obtained from a dynamic frequency sweep test was fit to the Rouse model in order to obtain the longest time of the relaxation spectrum. This time is taken as the relaxation time of the polymer molecules in solution and was used to estimate the Deborah number of the flow process. The relaxation time from the Rouse model fit was similar to that corresponding to the G'-G'' cross-over point.
5. The parameter, $\lambda_2$, in the UVM was found to be 0.01 for all experiments, so provisionally it may be considered a constant parameter. The shear-thickening index, $n_2$, varied from only 2 to 2.35 with 2.3 as the most typical value.

6. The polymers: Hengfloc® 63020 and 63026 showed more sensitivity to divalent ions (Ca$^{2+}$ and Mg$^{2+}$) present in the brine than flopaam™ 3630S and AN-125. Also, Hengfloc® 63026 exhibited the most shear thickening behavior of all the polymers tested.

7. A preliminary study was done using COMSOL Multiphysics® to obtain a better understanding of the injection allocation profile of a polymer solution along a horizontal well. Uniform injection along the entire wellbore is often assumed for these long horizontal wells. However, since the pressure varies downstream the well, it becomes theoretically unlikely that the injection rates into the reservoir will be uniform through the entire length of the well. Adequate knowledge of the injection profile helps give better reservoir simulation results. It will also serve to provide accurate injected fluid breakthrough and oil recovery forecast for the polymer flooding process. Results from this study are presented in Appendix C.

6.2 RECOMMENDATION:

1. Additional laboratory measurements of the bulk and in-situ rheological properties of polymer solutions under a wide range of conditions of interest in chemical enhanced oil recovery should be done to further
validate the UVM and determine its parameters as a function of the many pertinent variables.

2. Application of the UVM in reservoir simulators such as UTCHEM should be done to evaluate the effect of shear thickening behavior under reservoir conditions. In particular, the effect of shear thickening may be important near the wellbore where the velocities are highest and may have a significant effect on injectivity that should be more carefully studied.
APPENDICES

APPENDIX A

A. POLYMER BULK RHEOLOGY

In this appendix, the bulk rheological tests of all the polymers tested are presented. Tests conducted include the dynamic strain sweep test, dynamic frequency sweep test, the step rate transient test and the steady rate sweep test.

A.1 RHEOLOGICAL TEST RESULTS

A.1.1 Dynamic Strain Sweep Test Figures

Figure A.1(a): Dynamic strain sweep test for 1000 ppm KYPAM-4 in 4% NaCl.
Figure A.1(b): Dynamic strain sweep test for 1500 ppm KYPAM-4 in 4% NaCl.

Figure A.1(c): Dynamic strain sweep test for 2000 ppm KYPAM-4 in 4% NaCl.
Figure A.1(d): Dynamic strain sweep test for 2500 ppm KYPAM-4 in 4% NaCl.

Figure A.2: Dynamic strain sweep test for 1500 ppm Flopaam™ 3630S in SFB.
Figure A.3: Dynamic strain sweep test for 1500 ppm AN-125 in SFB.

Figure A.4(a): Dynamic strain sweep test for 1500 ppm HJ 63020 in SFB.
Figure A.4(b): Dynamic strain sweep test for 1500ppm HJ 63020 in SFB with 20 ppm Ca$^{2+}$.

Figure A.5: Dynamic strain sweep test for 1500ppm HJ 63026 in SFB with 20 ppm Ca$^{2+}$.
A.1.2 Step Rate Transient Test Figures

Figure A.6(a): Step rate transient test for 1000 ppm KYPAM-4 in 4% NaCl.

Figure A.6(b): Step rate transient test for 1500 ppm KYPAM-4 in 4% NaCl.
Figure A.6(c): Step rate transient test for 2000 ppm KYPAM-4 in 4% NaCl.

Figure A.6(d): Step rate transient test for 2500 ppm KYPAM-4 in 4% NaCl.
Figure A.7: Step rate transient test for 1500 ppm Flopaam™ 3630S in SFB.

Figure A.8: Step rate transient test for 1500 ppm AN-125 in SFB.
Figure A.9(a): Step rate transient test for 1500 ppm HJ 63020 in SFB.

Figure A.9(b): Step rate transient test for 1500 ppm HJ 63020 in SSFB with 20 ppm Ca^{2+}. 
Figure A.10: Step rate transient test for 1500 ppm HJ 63026 in SSFB with 20 ppm Ca^{2+}.
A.1.3 Steady Rate Sweep Test Figures

Figure A.11(a): Steady rate sweep test for 1000 ppm KYPAM-4 in 4% NaCl.

Figure A.11(b): Steady rate sweep test for 1500 ppm KYPAM-4 in 4% NaCl.
Figure A.11(c): Steady rate sweep test for 2000 ppm KYPAM-4 in 4% NaCl.

Figure A.11(d): Steady rate sweep test for 2500 ppm KYPAM-4 in 4% NaCl.
Figure A.11(e): Comparison of steady rate sweep for the KYPAM-4 polymer.
A.2 ESTIMATING RELAXATION TIME

Rouse Model fits to dynamic frequency test results are shown in this section.

Figure A.12(a): Rouse model fit for 1000 ppm KYPAM-4 in 4% NaCl

Figure A.12(b): Rouse model fit for 1500 ppm KYPAM-4 in 4% NaCl
Figure A.12(c): Rouse model fit for 2000 ppm KYPAM-4 in 4% NaCl

Figure A.12(d): Rouse model fit for 2500 ppm KYPAM-4 in 4% NaCl
Figure A.13: Rouse model fit for 1500 ppm Flopaam™ 3630S in SFB

Figure A.14: Rouse model fit for 1500 ppm AN-125 in SFB
Figure A.15(a): Rouse model fit for 1500 ppm HJ 63020 in SFB

Figure A.15(b): Rouse model fit for 1500 ppm HJ 63020 in SSFB with 20ppm Ca$^{2+}$
Figure A.16: Rouse model fit for 1500 ppm HJ 63026 in SSFB with 20 ppm Ca$^{2+}$. 

Points: Data
Curves: Model fit
### A.3 TABLE OF VALUES FOR BULK RHEOLOGICAL TEST RESULTS

#### A.3.1 Dynamic Frequency Sweep Test

Table A.1: Dynamic frequency sweep test result for KYPAM polymer in 4% NaCl

<table>
<thead>
<tr>
<th>ω (rad/s)</th>
<th>1000ppm</th>
<th>1500ppm</th>
<th>2000ppm</th>
<th>2500ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G' (dyn/cm²)</td>
<td>G'' (dyn/cm²)</td>
<td>G' (dyn/cm²)</td>
<td>G'' (dyn/cm²)</td>
</tr>
<tr>
<td>0.1000</td>
<td>0.0047</td>
<td>0.0151</td>
<td>0.0463</td>
<td>0.0401</td>
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<tr>
<td>0.1585</td>
<td>0.0057</td>
<td>0.0250</td>
<td>0.0611</td>
<td>0.0496</td>
</tr>
<tr>
<td>0.2512</td>
<td>0.0098</td>
<td>0.0301</td>
<td>0.0644</td>
<td>0.0613</td>
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<tr>
<td>0.3981</td>
<td>0.0085</td>
<td>0.0507</td>
<td>0.0772</td>
<td>0.0912</td>
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<tr>
<td>0.6310</td>
<td>0.0119</td>
<td>0.0782</td>
<td>0.0872</td>
<td>0.1237</td>
</tr>
<tr>
<td>1.0000</td>
<td>0.0181</td>
<td>0.1225</td>
<td>0.0998</td>
<td>0.1825</td>
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<tr>
<td>1.5849</td>
<td>0.0364</td>
<td>0.1774</td>
<td>0.1271</td>
<td>0.2740</td>
</tr>
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<td>0.0698</td>
<td>0.2664</td>
<td>0.1755</td>
<td>0.4050</td>
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<tr>
<td>3.9811</td>
<td>0.1354</td>
<td>0.3835</td>
<td>0.2802</td>
<td>0.5847</td>
</tr>
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<td>0.5351</td>
<td>0.4446</td>
<td>0.8217</td>
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<td>0.4684</td>
<td>0.7102</td>
<td>0.7429</td>
<td>1.1059</td>
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<td>0.8533</td>
<td>0.8755</td>
<td>1.2837</td>
<td>1.3662</td>
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<tr>
<td>25.1189</td>
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<td>0.8462</td>
<td>2.1091</td>
<td>1.4702</td>
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<tr>
<td>39.8107</td>
<td>2.4342</td>
<td>0.0030</td>
<td>3.4599</td>
<td>0.9582</td>
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<tr>
<td>63.0957</td>
<td>2.1182</td>
<td>-1.9426</td>
<td>4.4453</td>
<td>-1.5386</td>
</tr>
<tr>
<td>100.0000</td>
<td>0.0932</td>
<td>-2.5781</td>
<td>2.1985</td>
<td>-4.8556</td>
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</tbody>
</table>
Table A.2a: Dynamic frequency sweep test result for polymers used in corefloods

<table>
<thead>
<tr>
<th>ω (rad/s)</th>
<th>Flopaam™ 3630S</th>
<th>AN-125</th>
<th>HJ 63020 in SFB</th>
<th>HJ 63026 in SSFB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G' (dyn/cm²)</td>
<td>G'' (dyn/cm²)</td>
<td>G' (dyn/cm²)</td>
<td>G'' (dyn/cm²)</td>
</tr>
<tr>
<td>100.0000</td>
<td>0.8526</td>
<td>-3.4012</td>
<td>0.4571</td>
<td>-2.5816</td>
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<td>3.0474</td>
<td>-0.1673</td>
<td>2.4030</td>
<td>-0.3202</td>
</tr>
<tr>
<td>21.5443</td>
<td>1.3764</td>
<td>1.0507</td>
<td>1.0977</td>
<td>0.8416</td>
</tr>
<tr>
<td>10.0000</td>
<td>0.5312</td>
<td>0.8123</td>
<td>0.3908</td>
<td>0.6575</td>
</tr>
<tr>
<td>4.6416</td>
<td>0.2040</td>
<td>0.4846</td>
<td>0.1245</td>
<td>0.3836</td>
</tr>
<tr>
<td>2.1544</td>
<td>0.0757</td>
<td>0.2607</td>
<td>0.0394</td>
<td>0.1966</td>
</tr>
<tr>
<td>1.0000</td>
<td>0.0311</td>
<td>0.1289</td>
<td>0.0130</td>
<td>0.0951</td>
</tr>
<tr>
<td>0.4642</td>
<td>0.0192</td>
<td>0.0614</td>
<td>0.0056</td>
<td>0.0486</td>
</tr>
<tr>
<td>0.2154</td>
<td>0.0184</td>
<td>0.0275</td>
<td>0.0006</td>
<td>0.0219</td>
</tr>
<tr>
<td>0.1000</td>
<td>0.0140</td>
<td>0.0111</td>
<td>0.0038</td>
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Table A.2b: Dynamic frequency sweep test result for HJ 63020 in SSFB with 20ppm Ca$^{2+}$

<table>
<thead>
<tr>
<th>$\omega$ (rad/s)</th>
<th>G' (dyn/cm$^2$)</th>
<th>G'' (dyn/cm$^2$)</th>
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</thead>
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<td>100.0000</td>
<td>3.7205</td>
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<tr>
<td>56.2341</td>
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<tr>
<td>31.6228</td>
<td>2.7733</td>
<td>1.7009</td>
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<tr>
<td>17.7828</td>
<td>1.3617</td>
<td>1.5451</td>
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<td>0.6498</td>
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</tr>
<tr>
<td>5.6234</td>
<td>0.2970</td>
<td>0.7629</td>
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<td>3.1623</td>
<td>0.1310</td>
<td>0.4746</td>
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<td>1.7783</td>
<td>0.0496</td>
<td>0.2892</td>
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<td>0.0224</td>
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<tr>
<td>0.3162</td>
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<tr>
<td>0.1778</td>
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<td>0.1000</td>
<td>0.0024</td>
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### A.3.2 Steady Rate Sweep Test

Table A.3: Steady rate sweep test for KYPAM polymer in 4% NaCl

<table>
<thead>
<tr>
<th>γ, s⁻¹</th>
<th>Viscosity, cp</th>
<th>Viscosity, cp</th>
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<tbody>
<tr>
<td></td>
<td>1000ppm</td>
<td>2000ppm</td>
</tr>
<tr>
<td>0.3981</td>
<td>12.0587</td>
<td>1500ppm</td>
</tr>
<tr>
<td>0.6310</td>
<td>11.7500</td>
<td>0.2154</td>
</tr>
<tr>
<td>1.0000</td>
<td>11.2363</td>
<td>0.4642</td>
</tr>
<tr>
<td>1.5849</td>
<td>11.1735</td>
<td>1.0000</td>
</tr>
<tr>
<td>2.5119</td>
<td>10.7513</td>
<td>2.1544</td>
</tr>
<tr>
<td>6.3096</td>
<td>9.7997</td>
<td>10.0000</td>
</tr>
<tr>
<td>25.1189</td>
<td>7.6549</td>
<td>100.0000</td>
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<tr>
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<td>5.5657</td>
<td>999.9999</td>
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<tr>
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<td>5.0359</td>
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<tr>
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<td>2511.1111</td>
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<tr>
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### Table A.4: Steady rate sweep test results for polymers used in corefloods

<table>
<thead>
<tr>
<th>$\gamma$, s$^{-1}$</th>
<th>Flopaam™ 3630S</th>
<th>AN-125</th>
<th>HJ 63020 in SFB</th>
<th>HJ 63020 in SSFB</th>
<th>HJ 63026 in SSFB</th>
</tr>
</thead>
<tbody>
<tr>
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<td>14.5828</td>
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<tr>
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<td>65.8643</td>
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<td>13.3036</td>
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<td>17.8425</td>
<td>66.3458</td>
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<tr>
<td>0.2154</td>
<td>14.8506</td>
<td>10.1882</td>
<td>6.8834</td>
<td>18.1270</td>
<td>64.6463</td>
</tr>
<tr>
<td>0.4642</td>
<td>13.7651</td>
<td>10.2206</td>
<td>6.6333</td>
<td>17.9758</td>
<td>60.4061</td>
</tr>
<tr>
<td>1.0000</td>
<td>13.3142</td>
<td>9.9201</td>
<td>6.4065</td>
<td>17.8501</td>
<td>53.5350</td>
</tr>
<tr>
<td>2.1544</td>
<td>13.1183</td>
<td>9.7916</td>
<td>6.5416</td>
<td>17.5071</td>
<td>44.8401</td>
</tr>
<tr>
<td>10.0000</td>
<td>11.1030</td>
<td>8.5414</td>
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<td>5.0610</td>
<td>8.6618</td>
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</table>
APPENDIX B

B. COREFLOOD RESULTS

Figure B.1: Brine viscosity.
B.1 EXPERIMENT BV-1 (1500PPM FLOPAAM™ 3630S IN SFB)

Table B.1: Core properties for experiment BV-1

<table>
<thead>
<tr>
<th>Core</th>
<th>Berea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>211.14 g</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.23</td>
</tr>
<tr>
<td>Length</td>
<td>20.32 cm</td>
</tr>
<tr>
<td>Length to Tap 1</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 2</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 3</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Outlet</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Area</td>
<td>5.07 cm²</td>
</tr>
<tr>
<td>Brine permeability</td>
<td>647 md</td>
</tr>
<tr>
<td>PV</td>
<td>24.86 ml</td>
</tr>
</tbody>
</table>

Operating Temperature: 23 °C.

Table B.2: Apparent viscosity of Flopaam™ 3630S in experiment BV-1

<table>
<thead>
<tr>
<th>Flowrate, (ml/min)</th>
<th>Pressure drop, (psi)</th>
<th>γ, (s⁻¹)</th>
<th>Apparent viscosity, (cp)</th>
<th>Darcy Velocity, (ft/day)</th>
<th>N_Dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>10.60</td>
<td>254.14</td>
<td>15.86</td>
<td>4.1370</td>
<td>0.7842</td>
</tr>
<tr>
<td>0.94</td>
<td>27.50</td>
<td>542.94</td>
<td>19.27</td>
<td>8.8381</td>
<td>1.6752</td>
</tr>
<tr>
<td>2.00</td>
<td>144.07</td>
<td>1155.20</td>
<td>47.44</td>
<td>18.8046</td>
<td>3.5643</td>
</tr>
</tbody>
</table>

Hydrodynamic radius of the polymer molecule is:

\[
\Omega_p = \left[ \frac{[\eta] \cdot M}{\Phi} \right]^{\frac{1}{2}}
\]

\[
= \left[ \frac{2046.7 \text{ cm}^3/\text{g} \times 20 \times 10^6 \text{ g/mol}}{2.1 \times 10^{23} \text{ g/mol}^{-1}} \right]^{\frac{1}{2}}
\]

\[
= 0.5798 \mu m
\]
The equivalent radius of a pore:

\[ R_{eq} = \sqrt{\frac{8r^2k}{\phi}} \]

\[ = \sqrt{\frac{8 \times 2.5^2 \times 647 \times 10^{-15}}{0.23}} \text{ m} \]

\[ = 11.9 \mu m \]

\[ \frac{\Omega_p}{R_{eq}} = \frac{0.5798 \mu m}{11.9 \mu m} = 0.0487 \]

This shows that the polymer may be capable of going through the core without plugging.
Figure B.2: Pressure profile for BV-1 Brine Flood.

Figure B.3: Pressure profile for BV-1 Polymer Flood at 0.44 ml/min.
Figure B.4: Pressure profile for BV-1 Polymer Flood at 0.94 ml/min.

Figure B.5: Pressure profile for BV-1 Polymer Flood at 2.0 ml/min.
Figure B.6: Unified apparent viscosity as a function of Darcy Velocity for BV-1
B.2 EXPERIMENT BV-2 (1500PPM AN-125 IN SFB)

Table B.3: Core properties for experiment BV-2

<table>
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</tr>
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<tbody>
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<tr>
<td>Porosity</td>
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<tr>
<td>Length</td>
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<tr>
<td>Length to Tap 1</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 2</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 3</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Outlet</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Area</td>
<td>5.07 cm²</td>
</tr>
<tr>
<td>Brine permeability</td>
<td>578 md</td>
</tr>
<tr>
<td>PV</td>
<td>24.26 ml</td>
</tr>
</tbody>
</table>

Operating Temperature: 23 °C.

Table B.4: Apparent viscosity of AN-125 in experiment BV-2

<table>
<thead>
<tr>
<th>Flowrate, (ml/min)</th>
<th>Pressure drop, (psi)</th>
<th>$\gamma$, (s⁻¹)</th>
<th>Apparent viscosity, (cp)</th>
<th>Darcy Velocity, (ft/day)</th>
<th>$N_{De}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>1.04</td>
<td>29.26</td>
<td>8.74</td>
<td>0.6528</td>
<td>0.0097</td>
</tr>
<tr>
<td>0.11</td>
<td>2.07</td>
<td>45.98</td>
<td>11.07</td>
<td>1.0259</td>
<td>0.0153</td>
</tr>
<tr>
<td>0.21</td>
<td>4.65</td>
<td>87.78</td>
<td>13.03</td>
<td>1.9585</td>
<td>0.0292</td>
</tr>
<tr>
<td>0.50</td>
<td>16.21</td>
<td>209.00</td>
<td>19.07</td>
<td>4.6630</td>
<td>0.0695</td>
</tr>
<tr>
<td>0.80</td>
<td>33.65</td>
<td>334.39</td>
<td>24.75</td>
<td>7.4609</td>
<td>0.1113</td>
</tr>
<tr>
<td>1.50</td>
<td>93.53</td>
<td>626.99</td>
<td>36.68</td>
<td>13.9891</td>
<td>0.2086</td>
</tr>
<tr>
<td>2.40</td>
<td>231.54</td>
<td>1003.18</td>
<td>56.76</td>
<td>22.3826</td>
<td>0.3338</td>
</tr>
</tbody>
</table>
Hydrodynamic radius of the polymer molecule is:

\[
\Omega_p = \left[ \frac{[\eta]}{\Phi} \cdot \frac{M}{\eta} \right]^{\frac{1}{2}}
\]

\[
= \left[ \frac{1913.6 \text{ cm}^3/\text{g} \times 8 \times 10^6 \text{ g/mol}}{2.1 \times 10^{23} \text{ gmol}^{-1}} \right]^{\frac{1}{2}}
\]

\[= 0.418 \mu m\]

The equivalent radius of a pore:

\[
R_{eq} = \sqrt{\frac{8 \pi^2 k}{\phi}}
\]

\[
= \sqrt{\frac{8 \times 2.5^2 \times 578 \times 10^{-15}}{0.24}} \text{ m}
\]

\[= 10.97 \mu m\]

\[
\frac{\Omega_p}{R_{eq}} = \frac{0.418 \mu m}{10.97 \mu m} = 0.0381
\]

This shows that the polymer may be capable of going through the core without plugging.
Figure B.7: Pressure profile for BV-2 Brine Flood at 3.2 ml/min.

Figure B.8: Pressure profile for BV-2 Polymer Flood at 0.07 ml/min.
Figure B.9: Pressure profile for BV-2 Polymer Flood at 0.11 ml/min.

Figure B.10: Pressure profile for BV-2 Polymer Flood at 0.21 ml/min.
Figure B.11: Pressure profile for BV-2 Polymer Flood at 0.5 and 0.8 ml/min.

Figure B.12: Pressure profile for BV-2 Polymer Flood at 1.5 ml/min.
Figure B.13: Pressure profile for BV-2 Polymer Flood at 2.4 ml/min.

Figure B.14: Unified apparent viscosity as a function of Darcy Velocity for BV-2
**B.3 EXPERIMENT BV-3 (1500PPM HJ 63020 IN SFB)**

Table B.5: Core properties for experiment BV-3

<table>
<thead>
<tr>
<th>Core</th>
<th>Berea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>208.79 g</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.239</td>
</tr>
<tr>
<td>Length</td>
<td>20.32 cm</td>
</tr>
<tr>
<td>Length to Tap 1</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 2</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 3</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Outlet</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Area</td>
<td>5.07 cm²</td>
</tr>
<tr>
<td>Brine permeability</td>
<td>552 md</td>
</tr>
<tr>
<td>PV</td>
<td>24.66 ml</td>
</tr>
</tbody>
</table>

Operating Temperature: 23 °C.

Table B.6: Apparent viscosity of HJ 63020 in experiment BV-3

<table>
<thead>
<tr>
<th>Flowrate, (ml/min)</th>
<th>Pressure drop, (psi)</th>
<th>γ, (s⁻¹)</th>
<th>Apparent viscosity, (cp)</th>
<th>Darcy Velocity, (ft/day)</th>
<th>NDe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.00</td>
<td>61.09</td>
<td>5.62</td>
<td>0.9228</td>
<td>0.0140</td>
</tr>
<tr>
<td>0.25</td>
<td>2.50</td>
<td>152.74</td>
<td>5.62</td>
<td>2.3071</td>
<td>0.0350</td>
</tr>
<tr>
<td>0.5</td>
<td>5.63</td>
<td>305.47</td>
<td>6.33</td>
<td>4.6141</td>
<td>0.0699</td>
</tr>
<tr>
<td>1</td>
<td>13.07</td>
<td>610.94</td>
<td>7.34</td>
<td>9.2282</td>
<td>0.1399</td>
</tr>
<tr>
<td>1.5</td>
<td>24.37</td>
<td>916.41</td>
<td>9.13</td>
<td>13.8423</td>
<td>0.2098</td>
</tr>
<tr>
<td>2.13</td>
<td>39.6</td>
<td>1301.31</td>
<td>10.45</td>
<td>19.6561</td>
<td>0.2979</td>
</tr>
</tbody>
</table>
Hydrodynamic radius of the polymer molecule is:

$$\Omega_p = \left[ \frac{[\eta] \cdot M}{\Phi} \right]^{\frac{1}{3}}$$

$$= \left[ \frac{1858.6 \, cm^3/g \times 2 \times 10^6 \, g/mol}{2.1 \times 10^{23} \, g/mol^{-1}} \right]^{\frac{1}{3}}$$

$$= 0.561 \, \mu m$$

The equivalent radius of a pore:

$$R_{eq} = \sqrt[3]{\frac{8\pi^2 k}{\phi}}$$

$$= \sqrt[3]{\frac{8 \times 2.5^2 \times 552 \times 10^{-15}}{0.24}} \, m$$

$$= 10.72 \, \mu m$$

$$\frac{\Omega_p}{R_{eq}} = \frac{0.561 \, \mu m}{10.72 \, \mu m} = 0.052$$

This shows that the polymer may be capable of going through the core without plugging.
Figure B.15: Pressure profile for BV-3 Brine Flood at 3.2 ml/min.

Figure B.16: Pressure profile for BV-3 Polymer Flood at 0.1 and 0.25 ml/min.
BV-3 Polymer Flood
Flow rate = 0.5 ml/min

Figure B.17: Pressure profile for BV-3 Polymer Flood at 0.5 ml/min.

BV-3 Polymer Flood
Flow rate = 1.0 ml/min

Figure B.18: Pressure profile for BV-3 Polymer Flood at 1.0 ml/min.
Figure B.19: Pressure profile for BV-3 Polymer Flood at 1.5 ml/min.

Figure B.20: Pressure profile for BV-3 Polymer Flood at 2.13 ml/min.
Figure B.21: Unified apparent viscosity as a function of Darcy Velocity for BV-3
B.4 EXPERIMENT BV-4 (1500PPM HJ 63020 IN SSFB W/ 20 PPM CALCULUM ION)

Table B.7: Core properties for experiment BV-4

<table>
<thead>
<tr>
<th>Core</th>
<th>Berea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>207 g</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.24</td>
</tr>
<tr>
<td>Length</td>
<td>20.32 cm</td>
</tr>
<tr>
<td>Length to Tap 1</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 2</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 3</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Outlet</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Area</td>
<td>5.07 cm²</td>
</tr>
<tr>
<td>Brine permeability</td>
<td>372 md</td>
</tr>
<tr>
<td>PV</td>
<td>24.7 ml</td>
</tr>
</tbody>
</table>

Operating Temperature: 23 °C.

Table B.8: Apparent viscosity of HJ 63020 in experiment BV-4

<table>
<thead>
<tr>
<th>Flowrate, (ml/min)</th>
<th>Pressure drop, (psi)</th>
<th>γ, (s⁻¹)</th>
<th>Apparent viscosity, (cp)</th>
<th>Darcy Velocity, (ft/day)</th>
<th>N_Dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>10.30</td>
<td>191.78</td>
<td>15.00</td>
<td>2.4174</td>
<td>0.0453</td>
</tr>
<tr>
<td>0.585</td>
<td>32.35</td>
<td>431.50</td>
<td>20.94</td>
<td>5.4392</td>
<td>0.1019</td>
</tr>
<tr>
<td>1.17</td>
<td>115.62</td>
<td>863.00</td>
<td>37.42</td>
<td>10.8783</td>
<td>0.2038</td>
</tr>
<tr>
<td>2.6</td>
<td>408.35</td>
<td>1917.78</td>
<td>59.47</td>
<td>24.1740</td>
<td>0.4530</td>
</tr>
</tbody>
</table>
Hydrodynamic radius of the polymer molecule is:

\[
\Omega_p = \left[ \frac{[\eta] \cdot M}{\Phi} \right]^{\frac{1}{2}}
\]

\[
= \left[ \frac{2610.6 \text{ cm}^3/\text{g} \times 20 \times 10^6 \text{ g/mol}}{2.1 \times 10^{23} \text{ gmol}^{-1}} \right]^{\frac{1}{2}}
\]

= 0.629 \mu m

The equivalent radius of a pore:

\[
R_{eq} = \sqrt{\frac{8 \tau^2 k}{\phi}}
\]

\[
= \sqrt{\frac{8 \times 2.5^2 \times 372 \times 10^{-15}}{0.24}} \text{ m}
\]

= 8.803 \mu m

\[
\frac{\Omega_p}{R_{eq}} = \frac{0.629 \mu m}{8.803 \mu m} = 0.071
\]

This shows that the polymer may be capable of going through the core without plugging.
Figure B.22: Pressure profile for BV-4 Brine Flood at 3.12 ml/min.

Figure B.23: Pressure profile for BV-4 Polymer Flood at 0.26, 0.585 and 1.17 ml/min.
Figure B.24: Pressure profile for BV-4 Polymer Flood at 2.6 ml/min.

Figure B.25: Unified apparent viscosity as a function of Darcy Velocity for BV-4
B.5 EXPERIMENT BV-5 (1500ppm HJ 63026 in SSFB w/ 20 PPM CALCIUM ION)

Table B.9: Core properties for experiment BV-5

<table>
<thead>
<tr>
<th>Core</th>
<th>Berea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>206.6 g</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.224</td>
</tr>
<tr>
<td>Length</td>
<td>20.32 cm</td>
</tr>
<tr>
<td>Length to Tap 1</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 2</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Tap 3</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Length to Outlet</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Area</td>
<td>5.07 cm²</td>
</tr>
<tr>
<td>Brine permeability</td>
<td>260 md</td>
</tr>
<tr>
<td>PV</td>
<td>23.06 ml</td>
</tr>
</tbody>
</table>

Operating Temperature: 23 °C.

Table B.10: Apparent viscosity of HJ 63026 in experiment BV-5

<table>
<thead>
<tr>
<th>Flowrate, (ml/min)</th>
<th>Pressure drop, (psi)</th>
<th>γ, (s⁻¹)</th>
<th>Apparent viscosity, (cp)</th>
<th>Darcy Velocity, (ft/day)</th>
<th>NDe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.208</td>
<td>19.54</td>
<td>182.22</td>
<td>24.86</td>
<td>1.8313</td>
<td>0.0436</td>
</tr>
<tr>
<td>0.585</td>
<td>113.01</td>
<td>512.48</td>
<td>51.12</td>
<td>5.1506</td>
<td>0.1225</td>
</tr>
<tr>
<td>0.875</td>
<td>218.18</td>
<td>766.53</td>
<td>65.99</td>
<td>7.7039</td>
<td>0.1833</td>
</tr>
</tbody>
</table>

Hydrodynamic radius of the polymer molecule is:

\[
\Omega_p = \left[ \frac{[\eta] \cdot M}{\Phi} \right]^{1/2}
\]

\[
= \left[ \frac{3455 \text{cm}^3/\text{g} \times 26 \times 10^4 \text{g/mol}}{2.1 \times 10^{23} \text{g/mol}^{-1}} \right]^{1/2}
\]

\[
= 0.753 \mu m
\]
The equivalent radius of a pore:

\[ R_{eq} = \sqrt{\frac{8\tau^2 k}{\phi}} \]

\[ = \sqrt{\frac{8 \times 2.5^2 \times 260 \times 10^{-15}}{0.22}} \text{ m} \]

\[ = 7.687 \text{ \(\mu\)m} \]

\[ \frac{\Omega_p}{R_{eq}} = \frac{0.753 \text{ \(\mu\)m}}{7.687 \text{ \(\mu\)m}} = 0.098 \]

This shows that the polymer may be capable of going through the core without plugging.
Figure B.26: Pressure profile for BV-5 Brine Flood at 3.9 ml/min.

Figure B.27: Pressure profile for BV-5 Polymer Flood at 0.208 ml/min.
Figure B.28: Pressure profile for BV-5 Polymer Flood at 0.585 ml/min.

Figure B.29: Pressure profile for BV-5 Polymer Flood at 0.875 ml/min.
Figure B.30: Unified apparent viscosity as a function of Darcy Velocity for BV-5
B.6 SUMMARY OF PLOTS

Figure B.31: Pressure drop versus Flow rate for the coreflood experiments.

Figure B.32: Unified Apparent Viscosity.
APPENDIX C

C. PRELIMINARY STUDIES FOR FLUID INJECTION ALLOCATION ALONG A HORIZONTAL WELL

C.1 MOTIVATION

The aim of this preliminary research study was to obtain a better understanding of the injection allocation profile of a polymer along a horizontal well. Uniform injection along the entire wellbore is often assumed for these long horizontal wells. However, since the pressure varies downstream the well, it becomes theoretically unlikely that the injection rates into the reservoir will be uniform through the entire length of the well. Adequate knowledge of the injection profile helps give better reservoir simulation results. It also serves to provide accurate injected fluid breakthrough and oil recovery forecast for the polymer flooding process.

C.2 GOVERNING EQUATIONS FOR FLOW IN WELL AND POROUS MEDIA

C.2.1 Newtonian Fluid Flow in Wellbore and Reservoir

The Wellbore Subdomain

The wellbore is modeled as a pipe of infinite permeability. Fluid flow through the wellbore can be adequately and accurately described using the Navier-Stokes equations for fluid flow. The Navier-Stokes equations have been derived from expressions describing the conservation of momentum. It also includes the mass continuity equation.

The generalized Navier-Stokes equation is given as:

\[ \text{Equation} \]
\[
\rho \left[ \frac{\partial v}{\partial t} + v \cdot \nabla v \right] + \nabla p - \nabla \cdot \left[ \eta \left( \nabla v + (\nabla v)^T \right) \right] = F \quad \text{(C.1)}
\]

And
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad \text{(C.2)}
\]

where \( v \) is the velocity field; \( u, v, w \) (Cartesian) or \( v_r, v_z \) and \( v_0 \) (Cylindrical) [m/s],
\( p \) is the pressure [Pa],
\( \eta \) is the viscosity [Pa-s],
\( \rho \) is the density [kg/m^3], and
\( F \) describes other body forces such as gravity or centrifugal forces.

The Navier-Stokes (N-S) equations for incompressible fluid can be expanded into a 3-
Dimensional coordinate system as:
\[
\begin{align*}
\rho \left[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right] &+ \frac{\partial p}{\partial x} - \eta \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] = F \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &+ \frac{\partial p}{\partial y} - \eta \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] = F \\
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &+ \frac{\partial p}{\partial z} - \eta \left[ \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] = F
\end{align*}
\]

And
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad \text{(C.4)}
\]

In this case, the cylindrical coordinate system has been used in order to exploit the
advantages of symmetry. Therefore, the two-dimensional cylindrical system will be
sufficient in describing the wellbore. Hence the N-S equations used are:
\[
\begin{align*}
\rho \left[ \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} \right] &+ \frac{\partial p}{\partial r} - \eta \left[ \frac{1}{r} \frac{\partial v_r}{\partial r} + \frac{\partial^2 v_r}{\partial z^2} - \frac{v_r}{r^2} \right] = F \\
\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} &+ \frac{\partial p}{\partial z} - \eta \left[ \frac{1}{r} \frac{\partial v_z}{\partial r} + \frac{\partial^2 v_z}{\partial z^2} \right] = F
\end{align*}
\]

And
\[ \frac{1}{r} \frac{\partial}{\partial r} (rv_r) + \frac{\partial}{\partial z} v_z = 0 \quad \text{(C.6)} \]

**The Reservoir Subdomain**

The reservoir subdomain is a typical layer of porous medium bounded by impervious rock. Most hydrocarbon resources are trapped in these types of geological formations. Being a porous medium where laminar fluid flow is predominant; the flow dynamics is governed by Darcy’s law; the experimentally determined constitutive equation that models laminar fluid flow through porous media. It is given in as:

\[ \nu = -\frac{\kappa}{\eta} \nabla \Phi \quad \text{(C.7)} \]

Where \( \nu \) is the flow velocity field [m/s],
\( \kappa \) is the permeability field of the porous medium [m\(^2\)]. Isotropy of the permeability tensor is assumed.
\( \eta \) is the viscosity [Pa-s] while \( \nabla \Phi \) is the force gradient (pressure and hydrostatic forces).

By substituting Darcy’s law as expressed in equation (C.7) (COMSOL Modeling guide, 2004) into the continuity equation gives:

\[ S \frac{\partial p}{\partial t} + \nabla \left[ \frac{-\kappa}{\eta} \nabla (p + \rho g D) \right] = Q \quad \text{(C.8)} \]

Where \( S \) is a storage term [1/Pa], \( \rho g D \) is the force due to gravity [Pa] while \( Q \) represents a source term [1/s].

**C.2.2 Non-Newtonian Fluid Flow in Wellbore and Reservoir**

A modified form of the Navier-Stokes equations will be used to describe the flow through the wellbore. This modification accounts for the Non-Newtonian nature of the
fluid. Hence, the change in viscosity with shear rate (or flow rate) will be included in the expressions. Therefore, equation (C.5) becomes:

\[
\rho \left[ \frac{\partial v_x}{\partial t} + v_r \frac{\partial v_x}{\partial r} + v_z \frac{\partial v_x}{\partial z} \right] + \left[ \frac{\partial p}{\partial r} \right] + \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \eta \frac{\partial v_x}{\partial r} \right) + \frac{\partial}{\partial z} \left( \eta \frac{\partial v_x}{\partial z} \right) - \eta \frac{v_z}{r} \right] = F \]  

(C.9)

Coupled with equation (C.6), these become the Navier-Stokes equations for a Non-Newtonian fluid. The viscosity in this case will be represented by the Carreau Model; equation (2.4) as:

\[
\eta = \eta_\infty + \left( \eta_0 - \eta_\infty \right) \left[ 1 + \left( \frac{\dot{\gamma}}{\lambda} \right)^\eta \right]^{(\eta-1)/\eta}
\]

Where \( \eta_0 \) & \( \eta_\infty \) are the zero and infinite shear rate viscosities [Pa-s], respectively, \( \lambda \) is a time constant [s] and \( \eta \) is the power-law index. \( \dot{\gamma} \) is the shear rate [1/s]

A modified Darcy’s law is also used to describe the flow of the polymer through the porous media. Here, the viscosity term is substituted with the Unified apparent Viscosity Model (UVM). The more general equation (C.8) becomes:

\[
S \frac{\partial p}{\partial t} + \nabla \cdot \left( \frac{-k}{\mu_{\text{app}}} \nabla (p + \rho gD) \right) = Q
\]

(C.10)

where the apparent viscosity \( \mu_{\text{app}} \) is given by equation (2.24):

\[
\mu_{\text{app}} = \mu_\infty + \left( \mu_p^0 - \mu_\infty \right) \left[ 1 + \left( \frac{\lambda_\gamma}{\lambda_\gamma} \right)^\eta \right]^{(\eta-1)/\eta} + \mu_{\text{max}} \left[ 1 - \exp\left( -\left( \frac{\lambda_\gamma}{\lambda_\gamma} \right)^\eta \right) \right]^\eta
\]
C.3 PRELIMINARY SIMULATION STUDIES

C.3.1 Injection Allocation of a Simple Newtonian Fluid into the Reservoir

Schematic of the Wellbore and Reservoir

The following cartoon represents a schematic of the horizontal injection open completion well:

![Schematic of horizontal well system](image)

Figure C.1: Schematic of horizontal well system

Injection Allocation of a simple Newtonian fluid flow into the Reservoir

In COMSOL Multiphysics®, the wellbore and reservoir are represented with the geometry:
Figure C.2: Schematic of system subdomains

The grid layout is shown below. It consists of 867 elements: 51 x 17.
Verification Case Study: This case study utilizes very simple and hypothetical boundary conditions. The B.Cs can be easily viewed using the simple figure:
The results obtained can be summarized via the following figures:

**Figure C.4:** Diagram showing Boundary Conditions for simple case

The results obtained can be summarized via the following figures:
Figure C.5: Velocity surface plot (m/s), streamline and arrow plots.
Figure C.6: Pressure (in Pa) surface plot
The injection allocation is taken to be the velocity along the reservoir-wellbore boundary. In this case, it is:

![Injection Allocation Graph](image)

Figure C.7: Injection allocation along the reservoir-wellbore boundary

As anticipated, most of the flow into the reservoir occurs at the heel of the horizontal well and not uniformly along the entire length of the well. However, after about half-way along the length of the wellbore, the injection into the reservoir becomes somewhat uniform.

The effect of parameters such as the viscosity, inlet pressure and boundary conditions will be thoroughly investigated to ascertain the full range of possible injection allocation profiles.
Using the current boundary conditions, the sensitivity studies’ results can be summarized using the following plots:

Effect of Injection Pressure

Figure C.8(a): Effect of pressure on Injection allocation

Using a logarithm scale on the y-axis gives a better visual illustration:
As the pressure at the wellhead decreases (or. the pressure gradient), the more non-uniform the injection allocation along the entire length of the wellbore becomes as shown in the plot above. Also, the velocity of the injected fluid increased with an increase in the wellhead pressure.
Effect of Injected fluid viscosity

At an injection pressure of $1.17 \times 10^7$ Pa (1696.94 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:

Figure C.9: Effect of fluid viscosity on Injection allocation at an injection pressure of $1.17 \times 10^7$ Pa

Higher injected fluid viscosities lead to more uniform fluid injection into the reservoir along the entire length of the well. The flow of fluids into the reservoir increased with a decrease in the viscosity of the injected fluid. The injection pressure also influenced the initial fluid allocation at the heel of the wheel. The lower the injection
pressure, the more uniform the injection allocation of the fluid along the entire length of the well.

At an injection pressure of $2.0 \times 10^7$ Pa (2900.8 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:

![Graph showing injection allocation profile at an injection pressure of $2.0 \times 10^7$ Pa](image)

Figure C.10: Effect of fluid viscosity on Injection allocation at an injection pressure of $2.0 \times 10^7$ Pa

At an injection pressure of $5.0 \times 10^7$ Pa (2900.8 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:
The same conclusion that higher injected fluid viscosities lead to more uniform fluid injection into the reservoir along the entire length of the well can be reached with higher wellhead pressures. As expected, the non-uniformity of the injection allocation for low viscosity fluids is more pronounced at higher injection pressures.
Effect of Boundary Conditions

More practical boundary conditions have been applied. In reality, the right boundary of the reservoir subdomain should not be a no-flow boundary; hence, a linearly decreasing pressure profile was assumed at that boundary.

![Diagram showing Boundary Conditions for case II](image)

Figure C.12: Diagram showing Boundary Conditions for case II
Keeping other variables such as viscosity and permeability constant and solving to obtain the injection allocation into the reservoir formation. The results are:

Figure C.13: Velocity surface plot (m/s), streamline and arrow plots for case II.
Figure C.14: Pressure (in Pa) surface plot for case II
The injection allocation is taken to be the velocity along the reservoir-wellbore boundary. In this case, it is:

![Injection Allocation Graph](image)

Figure C.15: Injection allocation along the reservoir-wellbore boundary for case II

In this case, most of the flow into the reservoir also occurs at the heel of the horizontal well and not uniformly along the entire length of the well. However, the injection profile remained non-uniform throughout the entire length of the well.
The study on the effect of variables such as the viscosity and injection pressure is underway. The outcome is expected to be similar to the previous case (no flow boundary condition at the foot of the wellbore and at the right boundary of the reservoir subdomain).

Using the current boundary conditions, the sensitivity studies’ results can be summarized using the following plots:

**Effect of Injection Pressure**

![Effect of Injection Pressure](image)

Figure C.16(a): Effect of pressure on Injection allocation for case II

Using a logarithm scale on the y-axis gives a better visual illustration:
Unlike the previous boundary condition case, the pressure at the wellhead (or the pressure gradient) did not significantly affect extent of non-uniformity of the injection allocation along the entire length of the wellbore as shown in the plot above. Also, the velocity of the injected fluid increased with an increase in the wellhead pressure.
Effect of Injected fluid viscosity

At an injection pressure of $1.5 \times 10^7$ Pa (2175.57 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:

![Graph showing injection allocation against normalized length of well for different viscosities](image)

Figure C.17: Effect of fluid viscosity on Injection allocation at an injection pressure of $1.5 \times 10^7$ Pa for case II

The injected fluid viscosities also did not affect the non-uniformity of fluid injection into the reservoir along the entire length of the well. The flow of fluids into the reservoir increased with a decrease in the viscosity of the injected fluid. The injection pressure also influenced the initial fluid allocation at the heel of the wheel but not the uniformity of allocation.
At an injection pressure of $2.0 \times 10^7$ Pa (2900.8 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:

![Plot showing the effect of fluid viscosity on injection allocation at an injection pressure of $2.0 \times 10^7$ Pa for case II](image)

Figure C.18: Effect of fluid viscosity on Injection allocation at an injection pressure of $2.0 \times 10^7$ Pa for case II
At an injection pressure of $5.0 \times 10^7$ Pa (2900.8 psi), the effect of the fluid viscosity on the injection allocation profile is illustrated by the plot:

Figure C.17: Effect of fluid viscosity on Injection allocation at an injection pressure of $5.0 \times 10^7$ Pa for case II
## Nomenclature/Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Exponent of Mark-Houwink equation</td>
</tr>
<tr>
<td>AMPS</td>
<td>Acrylamido-Methyl Propane Sulfonate</td>
</tr>
<tr>
<td>ARES</td>
<td>Advanced Rheometric Expansion System</td>
</tr>
<tr>
<td>ASP</td>
<td>Alkaline-Surfactant-Polymer</td>
</tr>
<tr>
<td>BV-#</td>
<td>Berea coreflood test – no. of experiment</td>
</tr>
<tr>
<td>C, c</td>
<td>Concentration</td>
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<tr>
<td>D.H.</td>
<td>Degree of Hydrolysis</td>
</tr>
<tr>
<td>D_p</td>
<td>Particle Diameter</td>
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<tr>
<td>EOR</td>
<td>Enhanced Oil Recovery</td>
</tr>
<tr>
<td>G*</td>
<td>Complex modulus</td>
</tr>
<tr>
<td>G'</td>
<td>Storage or elastic modulus</td>
</tr>
<tr>
<td>G”</td>
<td>Loss or viscous modulus</td>
</tr>
<tr>
<td>HEC</td>
<td>Hydroxyethylcellulose</td>
</tr>
<tr>
<td>HJ</td>
<td>Hengju’s Hengfloc</td>
</tr>
<tr>
<td>HPAM</td>
<td>Hydrolyzed Polyacrylamide</td>
</tr>
<tr>
<td>K</td>
<td>Empirical constant for Power-law and Mark-Houwink equation.</td>
</tr>
<tr>
<td>kbrine</td>
<td>Brine Permeability</td>
</tr>
<tr>
<td>LS</td>
<td>Low Shear</td>
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<tr>
<td>M, MW</td>
<td>Molecular Weight</td>
</tr>
<tr>
<td>n</td>
<td>Power-law index</td>
</tr>
<tr>
<td>N1</td>
<td>First Normal Stress Difference</td>
</tr>
<tr>
<td>n_1</td>
<td>Shear-thinning index</td>
</tr>
<tr>
<td>n_2</td>
<td>Shear-thickening index</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>$N_{De}$</td>
<td>Deborah number</td>
</tr>
<tr>
<td>PEO</td>
<td>Polyethylene Oxide</td>
</tr>
<tr>
<td>$q$</td>
<td>Flow rate</td>
</tr>
<tr>
<td>$R$</td>
<td>Gas constant</td>
</tr>
<tr>
<td>SFB</td>
<td>Synthetic Formation Brine</td>
</tr>
<tr>
<td>SP</td>
<td>Surfactant-Polymer</td>
</tr>
<tr>
<td>SSFB</td>
<td>Softened Synthetic Formation Brine</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>UTCHEM</td>
<td>UT’s proprietary reservoir simulator</td>
</tr>
<tr>
<td>UVM</td>
<td>Unified apparent Viscosity Model</td>
</tr>
</tbody>
</table>

Symbols and Greek Characters

- $\tau$: Shear stress
- $\gamma$: Shear strain
- $\dot{\gamma}$: Shear rate
- $\dot{\gamma}_{eff}$: Effective Shear rate
- $\dot{\gamma}_{1/2}$: Shear rate at which $\eta$ is half of $\eta_o$
- $\mu$: Viscosity of Newtonian fluid
- $v$: Darcy velocity
- $\eta$: Viscosity of non-Newtonian fluid
- $\eta_o$: Viscosity of non-Newtonian fluid at zero shear rate
- $\eta_\infty$: Viscosity of non-Newtonian fluid at infinite shear rate
- $[\eta]$: Intrinsic viscosity of fluid
- $\eta_{sp}$: Specific viscosity
\( \eta_r \)  Relative Viscosity
\( \eta_{\text{solution}} \)  Viscosity of solution
\( \eta_{\text{solvent}} \)  Viscosity of solvent
\( \eta^* \)  Complex Viscosity
\( \eta' \)  Real part of complex viscosity
\( \eta'' \)  Imaginary part of complex viscosity
\( \tau_r, \tau_p \)  Relaxation time of polymer solution
\( \beta \)  Rod climbing constant
\( \Psi_1 \)  First Normal Stress Difference coefficient
\( \dot{\varepsilon} \)  Stretching rate
\( \mu_{\text{app}} \)  Apparent viscosity
\( \mu_{\infty} \)  Apparent viscosity at infinite shear rate
\( \mu_p^o \)  Apparent viscosity at zero shear rate
\( \mu_{\text{max}} \)  Maximum apparent viscosity before shear degradation
\( \mu_{\text{el}} \)  Viscosity for elastic contribution
\( \mu_{\text{sh}} \)  Viscosity for viscous contribution
\( \lambda \)  Time constant in seconds for the Carreau model
\( \lambda_2 \)  Universal constant for Unified apparent Viscosity Model (0.01)
\( \phi \)  Porosity
\( \Omega_p \)  Hydrodynamic radius of polymer
\( \Phi \)  Constant \( (2.1 \times 10^{21} \text{ dl/g.mol.cm}^3) \)
\( \omega \)  Frequency
\( \sigma(t) \)  Shear stress
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