Analysis of Polymer Injectivity in Porous Media: Experiments and Modelling

16th July 2012
Sanjay Surya Yerramilli

Delft University of Technology
Title : Analysis of Polymer Injectivity in Porous Media: Experiments and Modelling

Author(s) : Sanjay Surya Yerramilli

Date : July 2012
Professor(s) : Prof. Dr. P.L.J. Zitha
Supervisor(s) : Prof. Dr. P.L.J. Zitha
TA Report number : AES/PE/12-16

Postal Address : Section for Petroleum Engineering
                Department of Applied Earth Sciences
                Delft University of Technology
                P.O. Box 5028
                The Netherlands

Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189

Copyright ©2012  Section for Petroleum Engineering

All rights reserved.
No parts of this publication may be reproduced,
Stored in a retrieval system, or transmitted,
In any form or by any means, electronic,
Mechanical, photocopying, recording, or otherwise,
Without the prior written permission of the
Section for Petroleum Engineering
Abstract

A considerable portion of world’s reserves are located in mature and viscous oil reservoirs having thickness less than 15 m. Polymer flooding is a mature technology and still is the most important EOR method based on full field case histories. Accurate assessment of injectibility of viscous polymer solutions into these reservoirs without induced fractures is a major challenge. Therefore, the objective of this study is to experimentally investigate and model the polymer injectivity in porous media using unfiltered partially hydrolysed polyacrylamide (HPAM) solutions for wide range of polymer concentrations (125-5000 ppm) and salinities (5-20 g/L) in high permeability sandstones. Data from rheological measurements and single phase linear core flood studies carried out as a part of this study were utilised for understanding the key microscopic (pore level) mechanisms and for quantifying the injectivity.

Based on the experimental analyses, it was found that viscous nature of polymer solutions and their retention in porous media were the main mechanisms for loss in injectivity. Data obtained from the experiments were used to validate and fine tune the model. Subsequently, with the help of the Langmuir adsorption isotherm, filtration theory, permeability reduction model, Non-Newtonian viscosity and Darcy laws numerical modelling was performed for predicting the injectivity losses during polymer injection. A good quality match was obtained with experimental data. Finally, sensitivity of various parameters (polymer concentration, salinity etc.) on injectivity was studied. Further, the results from this study, will serve as an auxiliary input for field scale simulations, will help operators in the selection, design and execution of the field projects and will stand as guidelines for extending the polymer flooding technology for heavy oil reservoirs.

**Keywords:** Polymers, Porous Media, Injectivity, Adsorption, Polymer Filtration
Acknowledgements

Without the grace of almighty and support of the kind people around me, it would not have been possible to complete my master’s degree. I take this opportunity to thank all the people who have contributed to this success.

First and foremost, I would like to express my sincere gratitude to Prof. Dr. P.L.J. Zitha, for his patience, encouragement and valuable guidance throughout my graduate study. During the course of this thesis, he always encouraged me to pursue new thoughts and ideas, and provided me with necessary feedback and scope for further research. In spite of his busy schedule, he always provided me with necessary feedback on this work.

I would also like to express my sincere gratitude to Prof. Dr. William R. Rossen, for his valuable advice and guidance throughout my graduate study. In spite of his busy schedule, he was always available for discussion and help, whenever I stopped by his office. It would not have been possible for me to win prestigious scholarships, without his constant encouragement and support.

During my stay at TU Delft, I had the privilege to learn many new concepts from all my professors. Special thanks to all the professors of the Department of Geotechnology, for their constant support and guidance. I would like to especially thank, Dr. Martin van Gijzen and Dr. Cas Berentsen for their lectures on the concepts of numerical modelling in petroleum engineering. The concepts behind these lectures helped me to complete the modeling part of this thesis work successfully. I would also like to sincerely thank the committee members, Prof. Dr. William R. Rossen, Dr. D.E.A. van Odyck and Dr. M. Simjoo for their comments on my work and for accommodating me amidst their busy schedule. In addition, I am very much thankful to the technicians (Marc, Ellen, Dik and Henk) and the other staff and students (M. Simjoo) of Dietz laboratory for their assistance in setting up and carrying out the experiments safely and accurately. I am also indebted to the staff of TU Delft, who helped me with the administrative issues.

I am grateful to my parents, brother (Ramesh) and relatives, for their extraordinary support and love since my childhood. All these achievements would not have been possible without their constant motivation and encouragement for me, to pursue higher studies. No words can express my parents love and confidence on me. I immensely value their support and blessings.

Thanks to all my classmates for the support and the comfort provided to me throughout my graduate study at TU Delft. I should once again thank all the faculty, staff and students of the Department of Geotechnology for making my time at TU Delft, such a memorable experience.

Sanjay
Nomenclature

\( a_1, a_2, a_3 \)  Fitting constants for viscosity relation [-]
\( A_s \)  Specific surface area of rock per unit mass \([cm^2/g]\)
\( A_b \)  Absorbance [-]
\( a_s \)  Specific surface area per unit bulk volume \([1/cm]\)
\( A \)  Cross sectional area of core \([cm^2]\)
\( b \)  Constant in viscosity relation [-]
\( c_p^* \)  Critical overlap concentration \([g/cm^3, ppm, vol. frac]\)
\( c_p \)  Polymer concentration \([g/cm^3, ppm, vol. frac]\)
\( c_{p,in} \)  Injected Polymer concentration \([g/cm^3, ppm, vol. frac]\)
\( C \)  Constant by Canella [-]
\( D \)  Dispersion \([cm^2/hr]\)
\( dV \)  Volume of infinitesimal element \([cm^3]\)
\( D_x, D_r, D_\theta \)  Dispersion coefficients in axial, radial and angular directions \([cm^2/hr]\)
\( d_g \)  Average grain diameter \([cm]\)
\( I_p \)  Polymer injectivity [-]
\( I_o \)  Intensity of incident light [-]
\( I \)  Intensity of transmitted light [-]
\( J_x, J_r, J_\theta \)  Total flux in axial, radial and angular directions \([g/hr]\)
\( k \)  Permeability \([cm^2, Darcy]\)
\( k_e \)  Equilibrium rate constant \([cm^3/g]\)
\( k_H \)  Huggins coefficient [-]
\( L \)  Length of core \([cm]\)
\( M_w \)  Molecular weight of polymer \([g/mol]\)
\( M_{pl} \)  Mass of polymer entrained by the liquid \([g]\)
\( M_{pa} \)  Mass of polymer retained due to adsorption to rock \([g]\)
\( m_v \)  Exponent for viscosity model [-]
\( n \)  Exponent for porous medium [-]
\( N_x \)  Number of grid blocks [-]
\( N_t \)  Number of time steps [-]
\( N_{De} \)  Deborah number [-]
\( q \)  Flow rate \([cc/min]\)
\( r \)  Radial coordinate \([cm]\)
\( R_G \)  Radius of Gyration \([cm]\)
\( r_p \)  Average pore throat radius \([cm]\)
\[ R_m \quad \text{Mobility reduction [-]} \]
\[ R_k \quad \text{Permeability Reduction [-]} \]
\[ S_s \quad \text{Salinity of solvent [vol.frac, g/cc]} \]
\[ SF \quad \text{Scaling Factor [-]} \]
\[ T \quad \text{Temperature [°C, °K]} \]
\[ t \quad \text{Time [hr]} \]
\[ u \quad \text{Darcy velocity [cm/hr]} \]
\[ u_x, u_r, u_\theta \quad \text{Darcy velocity in axial, radial and angular directions [cm/hr]} \]
\[ v_x, v_r, v_\theta \quad \text{Interstitial velocity in axial, radial and angular directions [cm/hr]} \]
\[ v \quad \text{Interstitial velocity [cm/hr]} \]
\[ x \quad \text{Axial coordinate [cm]} \]
\[ \Phi \quad \text{Universal constant [}4.2\times10^{24}\text{mol}^{-1}\text{]} \]
\[ \Gamma_p \quad \text{Polymer adsorption [g/cm}^2\text{, g/g]} \]
\[ \Gamma_\infty \quad \text{Maximum adsorbent capacity [g/cm}^2\text{, g/g]} \]
\[ \varphi \quad \text{Porosity [fraction]} \]
\[ \gamma_{eq} \quad \text{Equivalent shear rate in porous media [s}^{-1}\text{]} \]
\[ \alpha_l \quad \text{Longitudinal dispersivity [cm]} \]
\[ \gamma_c \quad \text{Critical shear rate [s}^{-1}\text{]} \]
\[ \gamma_{ref} \quad \text{Reference shear rate [s}^{-1}\text{]} \]
\[ \gamma \quad \text{Shear rate [s}^{-1}\text{]} \]
\[ \rho_s \quad \text{Density of rock [g/cm}^3\text{]} \]
\[ \theta \quad \text{Axial coordinate [Deg°]} \]
\[ \Delta P/q \quad \text{Slope of Pressure Drop vs. Flowrate plot from experiments [Pa.min/cm}^3\text{]} \]
\[ \Delta P \quad \text{Pressure drop from experiments [Pa]} \]
\[ \mu_b \quad \text{Viscosity of brine [Pa.s]} \]
\[ \mu_{p,app} \quad \text{Apparent viscosity of polymer [Pa.s]} \]
\[ \mu_{p,sh} \quad \text{Polymer viscosity after correction for shear rate effect [Pa.s]} \]
\[ \mu_{p,sh,rel} \quad \text{Polymer relative viscosity after correction for shear rate effect [-]} \]
\[ \mu_p \quad \text{Polymer viscosity [Pa.s]} \]
\[ \mu_{p,0} \quad \text{Polymer viscosity at zero shear rate [Pa.s]} \]
\[ [\mu] \quad \text{Intrinsic viscosity [cm}^3\text{/g]} \]
\[ \mu_{sp} \quad \text{Specific viscosity [-]} \]
\[ \tau \quad \text{Relaxation time [s]} \]
\[ \tau_r \quad \text{Liquid relaxation time [s]} \]
\[ \tau_s \quad \text{Characteristic time for fluid flow [s]} \]
\[ \lambda_f \quad \text{Filtration coefficient [1/cm]} \]
\( \beta \)  Maximum damage factor [-]
\( \Delta t \)  Time step size [hr]
\( \Delta x \)  Grid size [cm]
\( \varepsilon_H \)  Effective hydrodynamic thickness [cm]
\( \Delta P_p \)  Pressure drop during polymer injection [Bar]
\( \Delta P_b^p \)  Pressure drop for brine prior to polymer injection [Bar]
\( \delta_d \)  Depletion layer thickness [cm]
\( \delta_r \)  Radial dimension of infinitesimal element
\( \delta_\theta \)  Angular dimension of infinitesimal element
\( \delta_x \)  Axial dimension of infinitesimal element
\( O(\Delta x) \)  Truncation error of first order in space
\( O(\Delta t) \)  Truncation error of first order in time
\( O(\Delta x^2) \)  Truncation error of second order in space

**Abbreviations**

*EOR*  Enhanced Oil Recovery
*IOR*  Improved Oil Recovery
*Wt\%*  Weight percent
*R^2*  Regression coefficient
*NaCl*  Sodium Chloride
*KI*  Potassium Iodide
*HPAM*  Hydrolyzed Polyacrylamide
*PAM*  Polyacrylamide
*UV – VIS*  Ultraviolet visible
*TOC*  Total Organic Carbon
*PV*  Pore Volume
*SSE*  Sum of Squares Error
*CO_2*  Carbon Dioxide
*PEEK*  Poly-Ether Ether-Ketone
*N_2*  Nitrogen
*O*  Oxygen
*H*  Hydrogen
*K^+*  Potassium ion
*Na^+*  Sodium ion
*MgCl_2*  Magnesium chloride
*CaCl_2*  Calcium chloride
*CONH_2*  Amide group
*COO –*  Carboxyl group
*SiC*  Silicon Carbide
**System of Units**

- $m$: Meter
- $mBar$: Millibar
- $cc$: Centimeter cube
- $mD$: Millidarcy
- $L$: Liter
- $cm$: Centimeter
- $hr$: Hour
- $kg$: Kilogram
- $g$: Gram
- $Pa$: Pascal
- $Deg^\circ$: Degree
- $s$: Second
- $^\circ C$: Degree centigrade
- $^\circ K$: Degree kelvin
- $ppm$: Parts per million
- $mol$: Moles
- $g / l$: Gram per liter
Contents

Nomenclature .......................................................................................................................... 1
List of Tables ............................................................................................................................ 8
List of Figures .......................................................................................................................... 10
1 Introduction .......................................................................................................................... 15
2 Statement of Problem .......................................................................................................... 16
3 Research Objectives ........................................................................................................... 16
4 Background .......................................................................................................................... 17
  4.1 Properties of Polymers in Solution .................................................................................. 17
    4.1.1 Structural Characteristics ....................................................................................... 17
    4.1.2 Conformation in Solution ...................................................................................... 18
    4.1.3 Concentration Regimes ......................................................................................... 18
  4.2 Polymer Rheology ........................................................................................................... 19
    4.2.1 Non-Newtonian Effects ......................................................................................... 20
    4.2.2 Viscosity Relation ................................................................................................. 20
    4.2.3 Intrinsic Viscosity ................................................................................................. 21
    4.2.4 Radius of Gyration ............................................................................................... 21
  4.3 Polymer Flow behavior in Porous Media ....................................................................... 21
    4.3.1 Polymer Rheology in Porous Media ....................................................................... 21
    4.3.2 Polymer Retention ................................................................................................. 23
    4.3.3 Mechanical Stability of Polymers ......................................................................... 25
5 Modelling of Polymer Flow in Porous Media .................................................................... 26
  5.1 Problem Formulation and Assumptions ........................................................................ 26
  5.2 Governing Equations ....................................................................................................... 26
  5.3 Initial and Boundary Conditions ..................................................................................... 27
    5.3.1 Initial Conditions .................................................................................................. 27
    5.3.2 Boundary Conditions ............................................................................................ 27
  5.4 Constitutive and Auxiliary Relations ............................................................................. 27
    5.4.1 Polymer Adsorption Kinetics ................................................................................. 28
    5.4.2 Permeability Reduction ......................................................................................... 28
    5.4.3 Polymer Velocity Enhancement ............................................................................. 29
    5.4.4 Apparent Viscosity ............................................................................................... 29
    5.4.5 Darcy Law ............................................................................................................ 30
    5.4.6 Mobility Reduction ............................................................................................... 30
    5.4.7 Polymer Injectivity ............................................................................................... 30
  5.5 Numerical Solution .......................................................................................................... 31
6

Experiments

6.1 Materials

6.2 Solution Preparation

6.3 Porous Medium

6.4 Experimental Setup

6.5 Procedure

7

Results and Discussion

7.1 Polymer Characterisation

7.1.1 Effect of Shear Rate

7.1.2 Effect of Polymer Concentration

7.1.3 Effect of Salinity

7.1.4 Polymer Solution Viscosity

7.1.5 Polymer Intrinsic Viscosity

7.1.6 Hydrodynamic Radius

7.2 Core flood Experiments

7.2.1 Analysis of Transport Properties

7.2.2 Analysis of Effluents

7.2.3 Polymer Retention

7.2.4 Mechanical Degradation of Polymer

8

Effect of Physical and Numerical Parameters

8.1 Effect of Polymer Concentration

8.2 Effect of Salinity

8.3 Effect of Number of Grid Blocks

8.4 Effect of Number of Time Steps

9

Model Testing

10

Limitations of the Model

11

Conclusions and Recommendations

Appendices

A Derivation of Conservation Law in Three Dimensions

B Modelling of Polymer/Tracer Flow and Polymer Retention in Porous Media

C Non-Linear Least Square Analysis for Modelling of Rheological Data

D Filtering Pressure Data using Butterworth Filter

E Total Organic Carbon (TOC) analysis of Effluents

F Tracer Potassium Iodide (KI) analysis of Effluents

G Calculation of Experimental and Model Parameters

G.1 Porosity

G.2 Permeability
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.3 Dead Volume</td>
<td>79</td>
</tr>
<tr>
<td>G.4 Average Pore Throat Radius</td>
<td>79</td>
</tr>
<tr>
<td>H Experimental and Modelled Results</td>
<td>80</td>
</tr>
<tr>
<td>H.1 Experiment – 1</td>
<td>80</td>
</tr>
<tr>
<td>H.2 Experiment - 2</td>
<td>82</td>
</tr>
<tr>
<td>H.3 Experiment - 3</td>
<td>84</td>
</tr>
<tr>
<td>H.4 Experiment - 4</td>
<td>87</td>
</tr>
<tr>
<td>H.5 Experiment - 5</td>
<td>89</td>
</tr>
<tr>
<td>H.6 Experiment - 6</td>
<td>92</td>
</tr>
<tr>
<td>H.7 Experiment - 7</td>
<td>95</td>
</tr>
<tr>
<td>H.8 Experiment - 8</td>
<td>97</td>
</tr>
<tr>
<td>H.9 Experiment - 9</td>
<td>99</td>
</tr>
<tr>
<td>References</td>
<td>102</td>
</tr>
</tbody>
</table>
List of Tables

Table.7.1  P-36  Parameters of Carreau model Eq. (4.1), obtained from non-linear regression analysis of rheological measurements at (T = 20 ± 1°C) for various salinities.

Table.7.2  P-40  Parameters for the Flory’s equation Eq. (4.2), obtained from non-linear regression analysis of rheological measurements.

Table.7.3  P-41  Parameters obtained from non-linear regression analysis of viscosity measurements at a shear rate of (1s⁻¹) and error associated with modelling.

Table.7.4  P-42  Parameters obtained from linear regression analysis of viscosity measurements at a shear rate of (1s⁻¹).

Table.7.5  P-43  Hydrodynamic radius (radius of gyration) of polymer molecule at 20 g/L solvent salinity.

Table.7.6  P-43  Experimental and model parameters for all the experiments.

Table.7.7  P-47  Values of the key parameters obtained from experiments and modeling and the error associated with the modeling of experimental data (250 pm).

Table.8.1  P-50  Adsorption and permeability reduction for various polymer concentrations.

Table.8.2  P-58  Adsorption values for 500 ppm polymer concentration and at different salinities.

Table.C.1  P-74  Sum of Squares Error (SSE) obtained from modelling of rheological measurements with the Carreau viscosity model.

Table.G.1  P-79  Dead volume measurements of the experimental setup.

Table.H.1  P-80  Solution and petrophysical parameters of the core flood experiment-1 (125 ppm).

Table.H.2  P-80  Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (125 ppm).

Table.H.3  P-82  Solution and petrophysical parameters of the core flood experiment-2 (250 ppm).

Table.H.4  P-82  Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (250 ppm).

Table.H.5  P-84  Solution and petrophysical parameters of the core flood experiment-3 (500 ppm).

Table.H.6  P-85  Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (500 ppm).

Table.H.7  P-87  Solution and petrophysical parameters of the core flood experiment-4 (1000 ppm).
Table.H.8
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (1000 ppm).
Table.H.9
Table.H.10
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (2000 ppm).
Table.H.11
Solution and petrophysical parameters of the core flood experiment-6 (3000 ppm).
Table.H.12
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (3000 ppm).
Table.H.13
Solution and petrophysical parameters of the core flood experiment-7 (5000 ppm).
Table.H.14
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (5000 ppm).
Table.H.15
Solution and petrophysical parameters of the core flood experiment-8 (500-10 ppm).
Table.H.16
Solution and petrophysical parameters of the core flood experiment-9 (500-5 ppm).
List of Figures

**Fig.4.1**  
Structure of polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (HPAM).

**Fig.4.2**  
Concentration regimes for polymers.

**Fig.4.3**  
Viscosity vs. shear rate for injection of 0.37 g/L PAM solution in high permeability (3.2 Darcy) permeability SiC pack. The onset of shear thinning and shear thickening behavior were marked by red and blue lines (110 s⁻¹) respectively.

**Fig.4.4**  
Schematic of polymer retention mechanisms in porous media for concentrations below and above critical overlap concentration.

**Fig.4.5**  
Three main mechanisms during polymer injection in different permeable media, Case (a) \( r_p > 50R_G \), Case (b) \( 3R_G < r_p < 50R_G \), Case (c) \( r_p < 3R_G \).

**Fig.6.1**  
Photograph of polymer core flood setup.

**Fig.6.2**  
Schematic of experimental setup used for polymer flood experiments.

**Fig.7.1**  
Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 5 g/L salinity.

**Fig.7.2**  
Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 10 g/L salinity.

**Fig.7.3**  
Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 20 g/L salinity.

**Fig.7.4**  
Rheological measurements (markers) modelled with Carreau viscosity model (lines) for different salinities at 5000 ppm polymer concentration.

**Fig.7.5**  
Plot of specific viscosity vs. salinity for a polymer concentration of 3000 ppm and pH of 5.8 for obtaining the exponent (b) for Flory’s viscosity relation.

**Fig.7.6**  
Rheological measurements fitted with Flory model Eq. (4.2) for a salinity of 20 g/L NaCl.

**Fig.7.7**  
Rheological measurements (markers) fitted with linear equations for determining \( (c_p^*) \), \( (k_H) \) and \( ([\eta]) \) at 20 g/L NaCl.

**Fig.7.8**  
Pressure drop across the core with number of pore volumes injected for a polymer concentration of 250 ppm.

**Fig.7.9**  
Mobility reduction with pore volumes injected for a polymer concentration of 250 ppm.
Fig.7.10  P-46
Polymer injectivity with number of pore volumes injected for a polymer concentration of 250 ppm.

Fig.7.11  P-46
Effluent concentration profiles of polymer and tracer with number of pore volumes injected for a polymer concentration of 250 ppm.

Fig.7.12  P-48
Retardation factor obtained from core flood effluent data for various polymer concentrations.

Fig.7.13  P-48
The rate of change of adsorption with concentration for various polymer concentrations.

Fig.7.14  P-49
Experimental adsorption values for various polymer concentrations obtained from the curve fitting exercise.

Fig.8.1  P-52
Effluent concentration profiles of tracer and polymer for various injected polymer concentrations.

Fig.8.2  P-53
Mobility reduction vs. number of pore volumes injected for various polymer concentrations.

Fig.8.3  P-54
Pressure drop for polymer (normalised to 2 Darcy) vs. number of pore volumes injected for various polymer concentrations.

Fig.8.4  P-55
Polymer injectivity vs. pore volumes injected for various polymer concentrations.

Fig.8.5  P-56
Pressure drop for polymer (normalised to 2 Darcy) vs. number of pore volumes for 500 ppm polymer concentration and at different salinities.

Fig.8.6  P-57
Mobility reduction vs. number of pore volumes injected for 500 ppm polymer concentration and at different salinities.

Fig.8.7  P-57
Polymer injectivity vs. number of pore volumes injected for 500 ppm polymer concentration and at different salinities.

Fig.8.8  P-58
Tracer effluent profile vs. number of pore volumes injected for various number of spatial grid points.

Fig.8.9  P-59
Effluent profiles vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).

Fig.8.10  P-59
Pressure drop for polymer vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).

Fig.8.11  P-60
Mobility reduction vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).

Fig.8.12  P-60
Polymer injectivity vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).
Fig.8.13  Tracer effluent profile vs. number of pore volumes injected for various number of temporal grid points.

Fig.8.14  Effluent profiles vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig.8.15  Pressure drop for polymer vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig.8.16  Mobility reduction vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig.8.17  Polymer injectivity vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig.A.1  Porous medium and infinitesimal element in cylindrical coordinate system.

Fig.B.1  Spatial computational domain showing the fictitious and real grid blocks.

Fig.B.2  Discretization of spatial-temporal computational domain and the grid system.

Fig.B.3  MATLAB workflow for modelling polymer injectivity.

Fig.D.1  Original pressure data (Blue) and filtered data (Red).

Fig.E.1  Photograph of DC-190 Dohrmann High Temperature TOC Apparatus.

Fig.F.1  Photograph of UV Spectrophotometer (UV Mini Schimadzu).

Fig.G.1  Plot of pressure drop at different flow rates for determination of liquid permeability.

Fig.H.1  Raw and filtered pressure drop vs. PV injected (125 ppm).

Fig.H.2  Pressure drop for polymer vs. PV injected (125 ppm).

Fig.H.3  Mobility reduction vs. PV injected (125 ppm).

Fig.H.4  Polymer injectivity vs. PV injected (125 ppm).

Fig.H.5  Effluent concentration vs. PV injected (125 ppm).

Fig.H.6  Raw and filtered pressure drop vs. PV injected (250 ppm).

Fig.H.7  Pressure drop for polymer vs. PV injected (250 ppm).

Fig.H.8  Mobility reduction vs. PV injected (250 ppm).
Fig.H.9  Polymer injectivity vs. PV injected (250 ppm).
Fig.H.10  Effluent concentration vs. PV injected (250 ppm).
Fig.H.11  Raw and filtered pressure drop vs. PV injected (500 ppm).
Fig.H.12  Pressure drop for polymer vs. PV injected (500 ppm).
Fig.H.13  Mobility reduction vs. PV injected (500 ppm).
Fig.H.14  Polymer injectivity vs. PV injected (500 ppm).
Fig.H.15  Effluent concentration vs. PV injected (500 ppm).
Fig.H.16  Raw and filtered pressure drop vs. PV injected (1000 ppm).
Fig.H.17  Pressure drop for polymer vs. PV injected (1000 ppm).
Fig.H.18  Mobility reduction vs. PV injected (1000 ppm).
Fig.H.19  Polymer injectivity vs. PV injected (1000 ppm).
Fig.H.20  Effluent concentration vs. PV injected (1000 ppm).
Fig.H.21  Scaling factor vs. polymer concentration (1000 ppm).
Fig.H.22  Raw and filtered pressure drop vs. PV injected (2000 ppm).
Fig.H.23  Pressure drop for polymer vs. PV injected (2000 ppm).
Fig.H.24  Mobility reduction vs. PV injected (2000 ppm).
Fig.H.25  Polymer injectivity vs. PV injected (2000 ppm).
Fig.H.26  Effluent concentration vs. PV injected (2000 ppm).
Fig.H.27  Scaling factor vs. polymer concentration (2000 ppm).
Fig.H.28  Raw and filtered pressure drop vs. PV injected (3000 ppm).
Fig.H.29  Pressure drop for polymer vs. PV injected (3000 ppm).
Fig.H.30  Mobility reduction vs. PV injected (3000 ppm).
Fig.H.31  Polymer injectivity vs. PV injected (3000 ppm).
Fig.H.32  Effluent concentration vs. PV injected (3000 ppm).
Fig. H.33  
Scaling factor vs. polymer concentration (3000 ppm).

Fig. H.34  
Raw and filtered pressure drop vs. PV injected (5000 ppm).

Fig. H.35  
Pressure drop for polymer vs. PV injected (5000 ppm).

Fig. H.36  
Mobility reduction vs. PV injected (5000 ppm).

Fig. H.37  
Polymer injectivity vs. PV injected (5000 ppm).

Fig. H.38  
Effluent concentration vs. PV injected (5000 ppm).

Fig. H.39  
Scaling factor vs. polymer concentration (5000 ppm).

Fig. H.40  
Raw and filtered pressure drop vs. PV injected (500-10 ppm).

Fig. H.41  
Pressure drop for polymer vs. PV injected (500-10 ppm).

Fig. H.42  
Mobility reduction vs. PV injected (500-10 ppm).

Fig. H.43  
Polymer injectivity vs. PV injected (500-10 ppm).

Fig. H.44  
Effluent concentration vs. PV injected (500-10 ppm).

Fig. H.45  
Raw and filtered pressure drop vs. PV injected (500-5 ppm).

Fig. H.46  
Pressure drop for polymer vs. PV injected (500-5 ppm).

Fig. H.47  
Mobility reduction vs. PV injected (500-5 ppm).

Fig. H.48  
Polymer injectivity vs. PV injected (500-5 ppm).

Fig. H.49  
Effluent concentration vs. PV injected (500-5 ppm).
1 Introduction

Polymer flooding is a mature technique with over 40 years of commercial application. Polymers are used in several improved/enhanced oil recovery (EOR) processes for maintaining the mobility control of the injected fluid front and for increasing the recovery (Sorbie, 1991). Recently, there has been a growing interest for the application of this technique to heavy oil reservoirs. Based on the EOR survey (Gao, 2011), there are five case studies (Bohai Bay, Offshore China; East Bodo and Pelican Lake, Canada; Tambaredjo, Suriname; Bati Raman, Turkey; Marmul, Oman) on the application of polymer flooding for heavy oil recovery. Water soluble polymers are well suited for increasing the injectant viscosity and thus the ultimate recovery (Sorbie, 1991). According to our knowledge, most of the previous core flood studies on polymer flow through porous media tested the polymer concentrations up to a maximum of 1500 ppm. Asghari and Nakutnyy (2008); stressed the importance of high polymer concentrations for increasing the oil recovery. They also showed that recovery improves steadily with increase in polymer concentrations from 500 ppm to 5000 ppm.

Viscosity is a strong function of polymer concentration (Szabo, 1979). Above critical overlap concentration the polymer solution viscosity increases drastically with increase in concentration. The viscous nature of these polymer solutions reduces the injectivity and delay oil production. Apart from the viscosity, polymer retention in porous media due to various mechanisms such as adsorption onto rock surface, mechanical entrapment and hydrodynamic retention (Dominquez and Willhite, 1977; Chun Huh, 1990; Sorbie, 1991) were found to be potential causes for reduction in injectivity. Seright (2009), conducted experiments on Berea core samples with wide variety of EOR polymers to assess their injectivity characteristics. He emphasised three main properties that affect polymer injectivity: (1) Debris in the polymer, (2) Rheology in porous media, (3) Mechanical degradation. He found that in the absence of face plugging the viscous nature of polymer solutions cause injectivity losses.

Ineffective hydration, microgels and debris in the polymer can cause face plugging at the inlet of the core. Seright (2009) developed a modified filter test for higher solution throughputs in 100-600 mD Berea sandstones with porosity of 21%. The effect of face-plugging was also observed in the Coalinga field test in a sandstone formation with permeability around 50-480 mD (Duane, 1983). It was also found that extensive filtration of polymer prior to laboratory experiments without the loss of polymer solution viscosity can retain the injectivity to some extent. It was also observed that this varies with the permeability of the formation. Castagno (1987) also found face plugging in core floods having a permeability of 200-400 mD with unfiltered polymer solutions. Hove (1990), conducted experiments with unfiltered Xanthan polymer solutions with concentrations around 400 to 1000 ppm. These are polymer/brine displacement studies in stratified cores with permeabilities in between 450-1000 mD. From the study it was found that unfiltered Xanthan solutions do not cause permanent plugging of the porous medium especially in high permeability layers.
2 Statement of Problem

HPAM is one of the polymers that are widely used for mobility control applications due to its low cost and for its ability to produce high injectant viscosity. It was found that injectibility of HPAM into porous media is much better than micro gels even at neutral pH conditions due to less retention and less mechanical filtration. The use of high HPAM concentrations is required for increasing the recovery from viscous oil reservoirs (Asghari and Nakutnyy, 2008). This poses a question on the injectibility of polymer solutions into porous media at high concentrations (> 1500 ppm). To answer the above question two main aspects (rheology and retention in porous media) of HPAM were exploited in this study. Many previous studies used extensively filtered polymer solutions for laboratory evaluations. However, the economics of field projects is likely to improve when the expensive equipment like filters are eliminated (Castagno, 1987). The next question to be answered is whether the injectibility of unfiltered HPAM solutions in to porous media is plausible without any sign of mechanical entrapment. To answer these questions unfiltered HPAM solutions were selected for evaluation in high permeability Bentheim cores. Further, a mathematical model capable of simulating the injectivity phenomena is required for extending the laboratory results to field scale.

3 Research Objectives

The objective of this research is to investigate and model the relation between polymer rheology, injectivity and retention in porous media. The tasks of this research are to,

3.1 Model and interpret the rheological behaviour of HPAM solutions.
Model and interpret the rheological properties of HPAM solutions for wide range of polymer concentrations (125-5000 ppm) and salinities (5-20 g/L) at shear rates in the range of (1 to 1000 s⁻¹), so that the temporal variations of viscosity during polymer flow in porous media could be accurately described.

3.2 Quantification and modelling of the injectivity and transport properties of polymer solutions in porous media.
Quantify and model the injectivity and transport properties (mobility reduction and adsorption) of unfiltered polymer solutions in highly permeable and homogenous Bentheim sandstone for wide range of polymer concentrations (125 - 5000 ppm) for 20 g/L salinity. Investigate the effect of injectivity for different salinities (5 and 10 g/L) at a polymer concentration of 500 ppm through two additional core flood experiments.

3.3 Model validation and study the effect of the main physical and numerical parameters on injectivity.
Validate the formulated model with the experimental data for the given operating conditions and perform a sensitivity analysis to study the effect of various parameters on injectivity and transport properties.
4 Background

In order to investigate the relation between polymer injectivity, rheology and retention in porous medium, it is essential to understand the three main aspects of polymer technology. (1) Properties of Polymers in Solution, (2) Polymer Rheology and (3) Polymer Flow Behavior in Porous Media.

4.1 Properties of Polymers in Solution

Structural characteristics, Polymer solvent interactions and Concentration regimes are three key factors that determine the extent of injectivity of polymer and its transport in the porous medium. These aspects are briefly reviewed below.

4.1.1 Structural Characteristics

Polymers are long molecules (macromolecules) comprised of several sub-units called monomers. The most common polymers used for polymer flooding are anionic and partially hydrolyzed poly acrylamides HPAM (Ait-Kadi.et.al, 1987; Lake, 1989) with typical degree of hydrolysis around 5% to 30%. The HPAM molecule shown in Fig.4.1 is negatively charged due to the presence of carboxyl groups on its ethylene backbone chain. This is an important property which controls the physical properties of polymer as will be discussed below.

Fig.4.1: Structure of polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (HPAM).
4.1.2 Conformation in Solution

Although polymer molecules are rather long chains in solution they adopt a coil conformation. Radius of gyration (Fig.4.2a) is a property to characterize the size of polymer molecule in solution (Lake, 1989). The radius of gyration \( R_G \) is much smaller than the contour length of the chain. It is defined as the average squared distance from the center of mass of coil to its monomer units. In good solvents the attraction between solvent molecules and polymer segments is larger than the attraction between the polymer segments. As a result the coil will be swollen. In case of poor solvents the attractions between polymer segments dominate over other attractions between polymer and solvent molecules. As a result, the coil gets collapsed and its size decreases. Whereas, in case of theta solvent the attraction between solvent molecules and polymer segments cancel out the attraction between the polymer segments and the molecule attains its original conformation. As mentioned above the structural properties of polyelectrolytes, i.e. polymers containing a certain fraction of charged groups, depends on salt content. In pure water the electrostatic repulsion of the anionic groups causes the molecule to expand and to adopt an elongated semi-rod like conformation. In presence of salt, the charges along the polymer chain are screened which causes the molecule to coil up. The coil size diminishes with increase in salt concentration resulting in a decrease in viscosity.

4.1.3 Concentration Regimes

Three main concentration regimes for polymer exist (Macosko, 1994; Teraoka, 2002). In general each linear polymer chain occupies the space of a sphere or linear dimension of \( R_G \) as illustrated in Fig.4.2.

a) At low polymer concentrations (Fig.4.2a), these polymer molecules behave independently in the solution and hardly interact with each other. The polymer chain mainly interacts with the solvent molecules.

![Concentration regimes for polymers.](image)
b) When the polymer concentration in the solvent increases, the average distance between coils diminishes and interactions between the coils increases. At certain critical concentration ($c_p^*$) the chains overlap with each other (Fig.4.2b). At this concentration the whole volume of solution is packed with these polymer molecules. This marks the onset of semi-dilute regime.

c) Beyond the critical overlap concentration, i.e. for $c_p > c_p^*$ (Fig.4.2c), the chains are overlapped and entangled. In this regime the mobility of individual chains is greatly reduced as compared with chains in dilute regime. Thus with increased number of molecules per unit volume causes the viscosity to be higher in this regime as compared to the dilute regime. Also elastic effects play a significant role.

### 4.2 Polymer Rheology

Polymers are complex non-Newtonian fluids and the study of their flow behavior is known as rheology. Viscosity is an important property to characterize the flow of HPAM solutions through porous media and for increasing the sweep efficiency and recovery. The viscosity of HPAM solutions depends on the molecular weight, degree of hydrolysis, concentration, solvent quality, pH and temperature. The presence of salt and divalent ions in the solvent screens the charges along the polymer chain resulting in the coiling of the polymer chain with a consequence of viscosity reduction. Large numbers of laboratory studies on the rheology of polymer solutions have been reported in literature. Mungan (1972) carried out experiments on ionic polyacrylamide solutions with molecular weights in the range of 7-9 million Daltons in the presence of NaCl, MgCl$_2$ and CaCl$_2$. They have shown that viscosity and pseudo plasticity (shear thinning behavior) of polymer solutions were more strongly affected by the presence of divalent cations than by monovalent cations. The effect of salt on the viscoelastic properties of partially hydrolyzed polyacrylamide solutions was extensively studied experimentally by Ait-Kadi.et.al (1987). Similar to (Mungan, 1972), these authors also found that the shear thickening behavior decreases as salt concentration increases. They also noticed the shear thickening behavior at very high shear rates. From their analyses it was concluded that lower the value of Huggins coefficient better the solvent quality.

Szabo (1979) conducted experiments using three different concentrations of polymer solutions under three different salinity conditions (0.1, 2 and 10% NaCl) for a given range of shear rates (0 to 79 s$^{-1}$). In addition, the effect of pH on the viscosity of polymer solutions was also studied. From this study he found that the effect of pH on viscosity was minor for the pH range normally encountered in most reservoirs. As seen from previous studies (Ait-Kadi.et.al, 1987; Szabo, 1979; Sorbie, 1991), for a given polymer concentration, the viscosity changes as a function of both shear rate and salinity for most of the polymers used in IOR/EOR applications. Hence, it is essential to understand and model the polymer rheology in bulk.
4.2.1 Non-Newtonian Effects

Most of the EOR polymers display pure shear thinning, Non-Newtonian behavior (decrease in viscosity with increasing shear rate) in a viscometer. This phenomenon is attributed to the structural characteristics of polymer chains, which are aligned along the flow streamlines with respect to the variation in shear rate. Shear thinning behavior is more pronounced at intermediate (in between low and high) shear rates. The polymer solutions display Newtonian behavior at low shear rates, where the structural characteristics of the polymer chains no longer affect the viscosity. The well-known Carreau model (Ait Kadi et al., 1987) presented below accounts for the variation of HPAM viscosity for full range of shear rates including the Newtonian plateau at low shear rates.

\[
\mu_p = \mu_b + (\mu_{p,0} - \mu_b)\left[1 + \left(\frac{\tau \gamma}{2}\right)^{m_i-1}\right]^{\frac{1}{2}}
\]

(4.1)

where, \(\mu_p\) and \(\mu_b\) are the polymer and brine viscosities, \(\mu_{p,0}\) is the polymer viscosity at zero shear rate, \(\tau\) the relaxation time, \(\gamma\) the shear rate, \(m_i\) is an exponent.

4.2.2 Viscosity Relation

Increase in viscosity with concentration and loss of viscosity in brines of high ionic strength are the major factors in assessing the permeability reduction and in-turn polymer injectivity. HPAM contains Amide (CONH2) and Carboxyl (COO-) groups attached to the ethylene backbone chain. The HPAM molecule is therefore negatively charged, i.e. it is anionic, which accounts for its many physical properties. The reduction in viscosity of polymer solutions by salt is caused by the association of cations with the negative charges (Carboxyl groups) along the polymer chain. Hence the variation of polymer solution viscosity with concentration and salinity at a specific shear rate was modeled using modified Flory-Huggins equation (Lake, 1989; Farajzadeh, 2011) as shown below.

\[
\mu_p = \mu_b \left[1 + \left(a_1 c_p + a_2 c_p^2 + a_3 c_p^3\right) S_s^b\right]
\]

(4.2)

where, \(a_1\), \(a_2\) and \(a_3\) are fitting parameters and vary with salinity of the solvent \(S_s, vol.\frac{frac}{frac}\), \(c_p\) is the concentration of polymer \(vol.\frac{frac}{frac}\), \(\mu_p\) and \(\mu_b\) are the viscosities of polymer and brine respectively. The constant ‘\(b\)’ is the slope of \(\frac{\mu_p - \mu_b}{\mu_b}\) vs. \(S_s\) on a log-log plot at zero shear rate and for a given concentration. The linear term \(1 + a_1 c_p S_s^b\) with respect to \(c_p\) in Eq. (4.2), accounts for the behavior of polymer in dilute regime in the absence of entanglements.
4.2.3 Intrinsic Viscosity

It is the viscosity at infinite dilution. Intrinsic viscosity (Lake, 1989) is a measure of the thickening power of the polymer. It is defined as,

\[ [\mu] = \lim_{c_p \to 0} \frac{\mu_{sp}}{c_p}; \quad \text{where, } \mu_{sp} = \frac{\mu_p - \mu_b}{\mu_b} \]

where, \([\mu] \) is the intrinsic viscosity, \(c_p\) is the concentration of polymer and \(\mu_{sp}\) is specific viscosity. The intercept of the initial linear part of \(\frac{\mu_{sp}}{c_p}\) vs. \(c_p\) on a Cartesian plot gives the value of \([\mu]\). The slope gives the value of Huggins coefficient \((k_H)\).

4.2.4 Radius of Gyration

This is the size of polymer molecules in solution (Ait Kadi.et.al, 1987). This is a measure of polymer size and is useful in understanding how these molecules propagate through the porous medium. It can be written as,

\[ R_G = \left( \frac{[\mu]M_w}{\Phi} \right)^{1/3} \]

where, \([\mu] \) is the intrinsic viscosity, \(M_w\) is the molecular weight of the polymer and \(\Phi\) is a universal constant with a value of \(4.2 \times 10^{24} \text{ mol}^{-1}\).

4.3 Polymer Flow behavior in Porous Media

Polymer flow behavior in porous media is dependent on three main factors, (1) Polymer Rheology in Porous Media, (2) Polymer Retention and (3) Mechanical Stability of Polymers

4.3.1 Polymer Rheology in Porous Media

Polymer rheology in porous media affects both injectivity and sweep efficiency in most of the chemical EOR projects. Most of the polymers used for EOR/IOR applications are viscoelastic in nature. Zitha (1995), conducted experiments on PAM/brine solution in high permeability (3.2 Darcy) grain packs of 110 µm diameter SiC grains. He observed three different regimes. Newtonian flow behavior at low shear rates (no coil deformation), shear thinning behavior at high shear rates (coil deformation) and shear thickening behavior (coil stretching) at very high shear rates, i.e. above a critical shear rate of 110 s\(^{-1}\) as illustrated in Fig.4.3.
Stahl (1988) found that HPAM solutions are strongly shear dependent and display shear thinning behavior at shear rates normally encountered at the injection wells. In-situ viscosity of these solutions in porous media at a particular shear rate is not directly measured. Instead, it is calculated from the Darcy’s law using the pressure drop obtained from core floods. If we consider the bulk measured viscosity to describe the flow behavior in porous media, the first task is to calculate the shear rate in porous media which is equivalent to that in a bulk viscometer. The equivalent shear rate in porous media was given by (Cannella, 1988) as,

$$\gamma_{eq} = C \left( \frac{3m_v + 1}{4m_v} \right)^{m_v} \frac{u}{\sqrt{k\phi}}$$

Where, $\gamma_{eq}$ is the equivalent shear rate in porous medium, $m_v$ is an exponent from Carreau model for a particular polymer concentration, $u$ is Darcy velocity, $C$ is a constant accounting for porous medium structure (Cannella, 1988; Sorbie, 1991). The polymer apparent viscosity in porous medium can then be found for a specific polymer concentration using the Carreau viscosity model Eq. (4.1) taking into account the equivalent shear rate calculated using Eq. (4.5).

Chauveteau (1984) found that the calculated apparent solution viscosities in porous medium are less than those predicted by Carreau model for a given equivalent shear rate. Based on this observation, a concept of depletion layer was proposed. Stavland (2010) suggested a modified model for change in polymer apparent viscosity as a result of depletion layer, taking into account the polymer concentration balance.
4.3.2 Polymer Retention

Injectivity of polymer solutions into porous media is a function of polymer solution properties, rheology and the nature of the porous medium under consideration. Szabo (1975) conducted numerous single phase flow experiments on low permeability Berea sandstones and found that mechanical entrapment of polymer plays a dominant role in polymer retention. Following the previous works, (Dominguez and Willhite, 1977; Chun Huh, 1990) conducted experiments to study the retention and flow characteristics of polymer in porous media using HPAM in Berea sandstone. They reported adsorption, mechanical entrapment and a rate dependent retention of polymer in porous media (hydrodynamic retention) to be the main causes for permeability reduction (Fig.4.4). Kolodziej (1988) carried out series of single phase core flood experiments with and without the presence of residual oil to show the combined effects of polymer adsorption, inaccessible pore volume (IPV) and dispersion in porous media for a range of polymer concentrations (100 to 1500 ppm). It was known that, at low gradients and for concentrations above critical overlap concentration ($c^*_p$), the entangled polymer chains are retained close to the inlet as a result of filtration (Chun Huh, 1990) as shown in Fig.4.4. It was noted that the degree of filtration of the polymer chains increases with decreasing permeability and increasing molecular weight. This mechanism was found to be more severe at low permeabilities ($r_p < 3R_c$).

![Fig.4.4: Schematic of polymer retention mechanisms in porous media for concentrations below and above critical overlap concentration.](image-url)
Sorbie (1991) indicated that adsorption and mechanical entrapment play a dominant role for polymer retention in porous media as compared to hydrodynamic retention. Zitha (2001) carried out experiments to investigate the unsteady flow of polymers in porous media. In his work a new mechanism for polymer retention i.e. bridging adsorption of polymers in porous media at high gradients was proposed. They found three main ideal conditions for this phenomenon to take place: (1) Velocity is high enough to induce the coil to stretch to its transition, (2) Polymer adsorption on the rock surface, (3) When the length of stretched macromolecules is larger than the average pore throat radius. We have seen earlier in Sec.4.2.4 that hydrodynamic radius of polymer molecule plays an important role in retention of polymer within the porous medium. Similar to the polymer solution, the porous medium is also also characterized by a specific pore throat size distribution with average pore throat radius ($r_p$). Depending on the type of polymer and porous medium, three possible scenarios were identified based on the experimental data from the literature (Denys, 2003). The three different scenarios ($r_p < 3R_g$, $3R_g < r_p < 50R_g$, and $r_p > 50R_g$) for polymer flow through porous media are shown schematically in Fig.4.5.

![Fig.4.5: Three main mechanisms during polymer injection in different permeable media, Case (a) $r_p > 50R_g$, Case (b) $3R_g < r_p < 50R_g$, Case (c) $r_p < 3R_g$.](image)

Case (a): In the case of high permeable media ($r_p > 50R_g$) the average pore throat diameter is large as compared to the polymer coil size in solution and thus the major mechanism for retention of polymer is adsorption onto rock surface. Mechanical entrapment of polymer at pore throats is negligible. Zitha (1995) found that at high gradients mobility reduction increased with shear rate above critical value due to strong coil stretching, but the value of permeability reduction was the same at different shear rates. Also, depending on the concentration regime, filtration of polymer at the face of the core can take place as discussed earlier.

Case (b): In intermediate permeability media ($3R_g < r_p < 50R_g$) the retention of polymer occurs due to both mechanical entrapment and adsorption. At low gradients
the plugging rate increases with increase in polymer concentration/molecular weight and most of the polymer molecules retain near to the core inlet. Zitha (1995) found that at high shear rates a continuous increase in permeability reduction was observed indicating the presence of bridging adsorption at the pore throats.

**Case (c):** In low permeability porous media \( r_p < 3R_g \), the main retention mechanism is by mechanical entrapment, where the polymer molecules are filtered at the pore throats while passing through the porous medium. Sorbie (1991) found that the retention was high near the core inlet and the retention rate increased with increase in the flow rate.

The above studies were carried out with filtered polymer solutions in the laboratory. For unfiltered polymer solutions some sign of filtration at inlet face of the core could be observed (Castagno, 1987). This is in agreement with the observations from the core flood results obtained in this study.

**4.3.3 Mechanical Stability of Polymers**

Sorbie (1984) indicated that, in porous media due to the difference in radii between the pore throats and pore bodies (expansions and contractions), polymers show shear thickening effect at very high shear rates and over longer flow distances due to strong chain stretching which may lead to mechanical degradation. Like other linear flexible polymers, HPAM can be degraded during flow through tortuous paths in porous media at very high velocities near the injection wells. Mechanical degradation is mainly associated with large apparent shear thickening behaviour as a result of high elongational stresses on the polymer molecule during flow through porous media. The onset of this shear thickening behaviour of HPAM solutions in porous media occurs when Deborah number \( N_D \) exceeds a critical value of 0.5 (Sorbie, 1991).

\[
N_D = \frac{\text{Liquid relaxation time} (\tau_L)}{\text{Characteristic time for fluid flow} (\tau_f)} = t_c \dot{\varepsilon} \tag{4.6}
\]

where, \( t_c = \frac{[\mu]M_w e}{RT} \) and \( \dot{\varepsilon} = \frac{v}{d_g} \); \( d_g \) is the average grain diameter \( \frac{6(1-\phi)}{a_s} \); \( v \) is interstitial velocity, \( R \) is universal gas constant and \( T \) is absolute temperature.
5 Modelling of Polymer Flow in Porous Media

5.1 Problem Formulation and Assumptions

The purpose of this work is to understand the loss in injectivity during polymer propagation in porous media. Conceptually, this problem can be addressed, by formulating and solving system of equations describing polymer flow in porous media. Let us consider a homogenous and isotropic porous medium of length $L$ and cross sectional area $A$ having porosity $\varphi$ and permeability $k$, with well-rounded sand grains of diameter $d_g$. The core is initially saturated with single fluid (brine) and then the polymer solution (density same as saturated brine) of concentration $c_{p,in}$ is injected into the porous medium at constant velocity $u$ (interstitial velocity $v = u / \varphi$). The analysis is restricted to in-compressible, non-inertial and isothermal flows. For the remainder of the work the following assumptions will be considered.

1. Polymer degradation by chemical, mechanical, thermal and bacterial means is not considered and chromatographic separation in porous medium is neglected.
2. No chemical reactions between polymer, rock and formation brine.
3. No mass transfer between the stagnant and flowing regions of the fluid.
4. The polymer adsorption onto the rock surface is instantaneous and mixing zone between the water and polymer fronts is negligible.
5. The density of aqueous phase is constant, i.e. polymer does not change the density of aqueous phase.

5.2 Governing Equations

We are interested in the spatial and temporal variation of polymer concentration $c_p$ and adsorption $\Gamma_p$. For this purpose, a transport equation for single phase polymer flow in porous media was formulated in Appendix. A. The mass conservation of polymer in one dimension (axial) described by the Eq. (A.15), and can be rewritten as,

$$-v \frac{\partial c_p}{\partial x} + D \frac{\partial^2 c_p}{\partial x^2} - \lambda_f v c_p = \rho_s A_s \frac{(1-\varphi)}{\varphi} \frac{\partial \Gamma_p}{\partial t} + \frac{\partial \hat{c}_p}{\partial t}$$

(5.1)

where, $c_p$ is the polymer concentration, $v$ is the interstitial velocity, $\lambda_f$ is the filtration coefficient, $\rho_s$ and $A_s$ are the density of rock and surface area per unit mass of the porous medium respectively. The term $\frac{\partial \Gamma_p}{\partial t}$ accounts for polymer adsorption in porous medium Eq. (5.8), defined using a kinetic equation that resembles the Langmuir adsorption and $D$ describes dispersion for most of the porous media flows.
For the current experimental conditions, \( Pe > 6 \) the longitudinal dispersion coefficient (Perkins, 1963; Genuchten, 1986) is defined as,

\[
D = \alpha_l v^n \tag{5.2}
\]

where, \( D \) is longitudinal dispersion coefficient, \( v \) is the interstitial velocity, \( \alpha_l \) is longitudinal dispersivity and \( n \) is an exponent which varies with the porous medium. The diffusion coefficient and Peclet number are \( 4.64 \times 10^{-5} \text{ cm}^2 / \text{hr} \) and 7744 respectively.

5.3 Initial and Boundary Conditions

5.3.1 Initial Conditions

Prior to injection the polymer concentration and adsorption are zero. Therefore the initial conditions are given by,

\[
c_p(x, t = 0) = 0 \tag{5.3}
\]

\[
\Gamma_p(x, t = 0) = 0 \tag{5.4}
\]

5.3.2 Boundary Conditions

At the injection face of the core, the solution is injected continuously with time. So the mass flux conservation can be applied at the inlet of the transport domain. This can be written as,

\[
v c_p(x = 0, t) = v c_{p,in} + D \left( \frac{\partial c_p}{\partial x} \right)_{x=0} \tag{5.5}
\]

At the outlet the change in concentration with distance is zero which is described for the finite domain using the boundary condition as shown below.

\[
\frac{\partial c_p}{\partial x}(x = L, t) = 0 \tag{5.6}
\]

5.4 Constitutive and Auxiliary Relations

These form the basis for solving the overall conservation equation described in Sec.5.2. The additional relations include Langmuir adsorption isotherm, permeability reduction model, polymer velocity enhancement, depletion layer effect, viscosity and Darcy’s law. Since the focus of this work is to predict the injectivity during polymer injection, the following relations/models have been utilised.
5.4.1 Polymer Adsorption Kinetics

In permeable media, polymers experience adsorption onto rock surface mainly due to van der Waals forces and Hydrogen bonding. Polymer adsorption onto rock surface follows Langmuir adsorption isotherm (Zitha, 2001) defined as,

\[ \Gamma_p = \Gamma_\infty \frac{c_p k_e}{1 + k_e c_p} \] .................................(5.7)

The rate of change of adsorption with time is defined below as,

\[ \frac{\partial \Gamma_p}{\partial t} = \frac{d \Gamma_p}{dc_p} \frac{\partial c_p}{\partial t} \] .................................(5.8)

\[ \frac{d \Gamma_p}{dc_p} = \frac{k_e \Gamma_\infty}{(1 + k_e c_p)^2} \] .................................(5.9)

where, \( k_e \) is the equilibrium rate constant, \( \Gamma_\infty \) is the total adsorbent capacity, \( c_p \) is the polymer concentration.

5.4.2 Permeability Reduction

As a result of adsorption of the polymer within the porous medium, the permeability declines with distance and time. The function mentioned below, derived from the concept of plugging and non-plugging pathways model (Saripalli, 1999) takes into account the formation damage due to polymer retention.

\[ R_e(t) = 1 + (\beta - 1) \frac{\Gamma_p(t)}{\Gamma_\infty} \] .................................(5.10)

where, ‘\( \beta \)’ is a factor accounting for the maximum damage as a result of polymer retention and can be expressed as follows.

\[ \beta = \left( 1 - \frac{e_H}{r_p} \right)^4 \] .................................(5.11)

where, \( e_H = 2R_G \) is the hydrodynamic thickness (Chauveteau, 1984) of the adsorbed polymer layer is assumed to be equal to twice the radius of gyration (Sec.4.2.4) and \( r_p \) is average pore throat radius Eq. (G.2).
5.4.3 Polymer Velocity Enhancement

The velocity enhancement that polymer shows in porous media was incorporated using a velocity enhancement factor defined by (Sorbie, 1991) and (Stavland, 2010) as,

\[ f = \frac{\phi_p}{\phi} = \frac{1}{\sqrt[3]{\xi}} \] .................................(5.12)

where, \( f \) is the fraction of pore space available for polymer flow and \( \xi \) is given as,

\[ \xi = \left(1 - \frac{\delta_d}{r_p - c_H}\right)^4 \] .................................(5.13)

where, \( \delta_d \) is the thickness of depleted layer and is assumed to be equal to twice the radius of gyration of polymer molecule (Chauveteau, 1984).

5.4.4 Apparent Viscosity

The polymer solution viscosity for various concentrations predicted using Eq. (4.2); needs to be corrected to account for shear rate and depletion layer effects in the porous medium. The scaling factor (SF) is defined as the polymer viscosity at equivalent shear rate to polymer viscosity at a reference shear rate for the range of polymer concentrations. This can be written as,

\[ SF(c_p, \gamma_{eq}) = \frac{\mu_p(c_p, \gamma_{eq})}{\mu_p(c_p, \gamma_{ref})} \] .................................(5.14)

where, \( \mu_p \) is the polymer solution viscosity, \( \gamma_{eq} \) is the equivalent shear rate within the porous medium and \( \gamma_{ref} \) is the reference shear rate.

Polymer solution viscosity corrected for shear rate effects in porous media with an appropriate scaling factor can be written as,

\[ \mu_{p,sh} = \mu_p(c_p, \gamma_{ref}) \times SF(c_p, \gamma_{eq}) \] .................................(5.15)

where, \( \mu_{p,sh} \) is the polymer solution viscosity corrected for shear rate effects in porous media and \( SF \) is the scaling factor.

A concept and model to account for viscosity reduction due to the presence of depletion layer within the porous medium was proposed by Chauveteau (1984). Later Stavland
Sanjay Surya Yerramilli / Polymer Injectivity: Experiments and Modelling

(2010) and his co-authors; suggested a modified model taking into account the polymer concentration balance which is given as,

\[ \mu_{p, \text{app}} = \frac{\mu_{p, \text{rel}}(1 + \xi)}{1 + \xi \sqrt{\mu_{p, \text{rel}}}} \] ..............................(5.16)

where, \( \mu_{p, \text{app}} \) is the polymer solution apparent viscosity corrected for depletion and shear rate effects in porous media and \( \mu_{p, \text{rel}} \) shear rate corrected relative viscosity within the porous medium.

5.4.5 Darcy Law

Combining the equations, (5.10) and (5.16) with the Darcy law enable us to calculate the pressure drop during polymer injection. The Darcy’s law is given as,

\[ q = -\frac{kA}{\mu} \frac{\partial P}{\partial x} \] ..............................(5.17)

where, \( \mu \) is the viscosity in porous media, \( k \) is permeability, \( A \) and is the cross sectional area of the porous medium.

5.4.6 Mobility Reduction

Mobility reduction is an indication of loss of injectivity during polymer flooding. It takes into account the pressure drop due to viscosity and adsorption of polymer to the rock. It is defined as,

\[ R_m = \frac{\Delta P_p}{\Delta P_b} \] ..............................(5.18)

5.4.7 Polymer Injectivity

Polymer injectivity is defined as the pressure drop to brine divided by the pressure drop to polymer.

\[ I_p = \frac{\Delta P_b^0}{\Delta P_p} \] ..............................(5.19)

where, \( I_p \) is polymer injectivity, \( \Delta P_p \) is pressure drop for polymer and where, \( \Delta P_b^0 \) is pressure drop for brine before polymer injection.
5.5 Numerical Solution

Numerical modeling in one dimension was carried out to solve the time dependent mass conservation equation for polymer flow in porous media. The governing equation Eq. (5.1) was solved with the aid boundary conditions Eq. (5.3) to Eq. (5.6) and auxiliary equations Eq. (5.8) and Eq. (5.9) for the polymer concentration and adsorption. All the equations were discretized using finite difference approximations as shown in Appendix B. The spatial domain was discretized using central difference approximation for the diffusion term and using upwind approximation for the advection term. The spatial domain was divided into equal number of grid blocks that remains constant during the course of each simulation. In temporal domain the equations were discretized using implicit ‘Euler backward’ method. The primary dependent variables in the model such as the polymer concentration and adsorption were calculated at each time step and at every spatial point.

Polymer concentration is calculated implicitly at each time step throughout the simulation using the discretized equation as shown below. In addition, the equations incorporating boundary conditions at inlet and outlet were shown in Appendix B.

\[
\frac{c^{t+1}_{p,j} \Delta x}{\Delta x} + c^{t+1}_{p,i} \left( \frac{D}{(\Delta x)^2} - \frac{v}{\Delta x} \right) + c^{t+1}_{p,j+1} \left( \frac{D}{(\Delta x)^2} \right) = R \left( c^{t+1}_{p,j} - c^{t+1}_{p,j-1} \right) \] ........................(5.20)

The retardation factor ‘R’ in Eq. (5.20) was treated explicitly at each time step as shown by Eq. (B.19). The polymer adsorption for all the grid blocks and at each time step throughout the simulation was calculated numerically using the equation (5.21) as shown below.

\[
\Gamma^{t+1}_{p} = k_c \Gamma \Gamma_{c_{p,j}} c^{t+1}_{p,j} \] ........................(5.21)

The concentration and adsorption obtained from the numerical solution were then coupled with Eq. (5.10) and Eq. (4.2) to obtain the permeability reduction and polymer solution viscosity. Consequently, the equations were integrated over the spatial domain for obtaining permeability reduction and polymer solution viscosity with time. The polymer solution viscosity was then scaled with appropriate scaling factors to account for the effects of shear rates and depletion layer with in the porous medium using Eq. (5.14) and Eq. (5.16). Finally, pressure drop for polymer Eq. (5.17), mobility reduction Eq. (5.18) and polymer injectivity Eq. (5.19) were calculated. The approach followed for calculation of each of these parameters is summarised in the form of a flow diagram in Appendix B.
6 Experiments

This section provides the details of single phase core flooding experiments using Hydrolysed Polyacrylamide (HPAM) for evaluation of its injectibility and transport through porous media. The injection and transport characteristics of the polymer were evaluated in terms of permeability reduction, mobility reduction and polymer injectivity. Adsorption under dynamic conditions was quantified with the help of tracer and polymer effluent profiles. Finally, the effects of concentration and salinity on the transport characteristics of polymer solutions through porous media were investigated.

6.1 Materials

The commercial polymer (AN 905 Lot E 2686) used in this study was partially hydrolysed polyacrylamide (HPAM) provided in powder form by SNF Floerger. The polymer had an approximate molecular weight of 8-9 million Daltons (g/mol) [Barany, 2010]. Potassium iodide (KI) and sodium chloride (NaCl) Potassium iodide were provided by Sigma-Aldrich and J. T. Baker respectively. Potassium iodide (KI) was used as a tracer. Sodium chloride (NaCl) was used for preparing synthetic brine.

6.2 Solution Preparation

Brine was prepared by dissolving required weight of sodium chloride (NaCl) in demineralised water on mass-balance basis and was stirred using a magnetic stirrer for 15 minutes. The brine was stirred until the creation of a vortex. At the same time, 10.0±0.1 g/L of potassium iodide (KI) tracer was added to the vortex. The polymer was then added gently to the vortex to avoid agglomeration of polymer particles. The mouth of the beaker was then covered with an aluminium foil to prevent contact with air. After 30 minutes, the speed was reduced to medium and was further stirred for at least one day to obtain homogenous polymer solution in equilibrium and to guarantee complete hydration. Once the sample is ready the pH of the sample was measured using a pH meter. The same procedure was repeated for different polymer concentrations and salinities used for the experiments.

6.3 Porous Medium

The experiments were conducted on Bentheim sandstone core samples. The use of glass beads was discarded as they poorly represent the natural sandstone geometrical structure. The glass beads also contain soluble ions such as bore or calcium that may modify the adsorption properties (Zitha, 2001). Bentheim sandstone is a Lower Cretaceous, homogeneous, yellow Aeolian sandstone, containing 95% quartz, 3% feldspar, and 2% kaolinite (Stanchits, 2009). The core samples were drilled from a cubical block and then sawn using a water cooled diamond saw to desired dimensions of 40±1 mm in diameter and 170±1 mm in length. Next, the cores were dried in an oven up
to 48 hours at 60±1 °C. The cores were then placed in molds and encased in self-hardening glue (Araldite) to ensure that the O-rings make the annular space between the core and core holder completely independent from the inlet and outlet. After hardening, the outer surface of the glue is machined, for the core to fit exactly into the core holder. The machined samples were dried in oven for 48 hours at 30±1 °C. The penetration depth of the glue into the core is approximately 1 mm. The effective diameter (3.8±0.1 cm) and length (17.0±0.1 cm) was used for experimental and modelling calculations. The permeability of the core was determined using Darcy’s law Eq. (G.1), by flowing brine at different rates through the core and by noting the pressure drop and with known fluid viscosity. The density of the Bentheim sandstone was taken as 2.65±0.1 g/cc (Bansal, 2008). The petrophysical properties of all the core samples used for the experiments were summarised in Appendix. H.

6.4 Experimental Setup

The (Fig.6.1) shows photograph of the polymer core flood setup, used for carrying out the experiments.

Fig.6.1: Photograph of polymer core flood setup.
Fig.6.2: Schematic of experimental setup used for polymer flood experiments.
Fig. 6.2 above shows the schematic of the experimental setup used for performing core flooding experiments. The core sample is placed in a Poly-Ether Ether-Ketone (PEEK) core holder with O-rings on both ends. The two open ends of the core are covered by caps with ports for inlet and outlet. A displacement pump (GE P-903 in Fig. 6.2) injects brine and polymer solutions. The pump has a flowrate accuracy of ± 2% about the set point. The pump flowrate ranges from 0.01±2E-5 to 10.00±0.02 cc/min. Two differential pressure transducers (KEMA 03 ATEX 1561) were employed to measure the pressure drop within the core sample. The pressure transducers has a rating of -3 to 3 bar and 0–40 bar respectively. They had an offset of ± 0.001 bar about the set point. The valves (Swagelok) at their respective locations are used to control the flow. A back-pressure regulator coupled with N₂ cylinder (100 bars) was employed to apply required back pressure and confining pressure. CO₂ cylinder at 100 bars was also kept in place for saturating the core at a back pressure of 25±1 bars. A fraction collector (GE Frac 920) enables to collect the sample at different times for measurement of effluent concentration. A weighing machine (Sartorius CP 3202S) measures the weight of the outlet fractions. The pressure drop and injection flow rate are recorded with time by a data acquisition system (National Instruments). All the experiments were carried out at atmospheric pressure (1 Bar) and ambient temperature (20±1 °C).

6.5 Procedure

1. In order to ensure that the core and the injection lines are devoid of any air before saturation with brine, CO₂ is injected into the core followed by the injection lines at a flow rate of 1.00±0.02 cc/min for 30±2 to 45±2 minutes. The back pressure was raised to 25 bars slowly in steps of 3 bars before injection of brine.

2. Around 25.00±0.04 to 30.00±0.04 PV’s of brine (salinity equivalent to that of the injected polymer solution) was injected from below under the gravity stable condition at a flow rate of 1.00±0.02 cc/min to displace the CO₂ with the aid of dissolution and displacement to guarantee complete saturation of the core.

3. The permeability to brine Eq. (G.1) was determined by injecting brine at various flow rates with and without back pressure to ensure accuracy.

4. A specified concentration of polymer solution was then injected up to 10.00±0.04 PV at constant flow rate of 1.00±0.02 cc/min through the core sample until a steady flow condition was achieved i.e. stabilisation of the pressure drop across the core. During polymer injection, the pressure drop over the core length was recorded continuously as a function of time. The pressure drop of polymer with time was used to obtain the mobility reduction Eq. (5.18) and polymer injectivity Eq. (5.19).

5. From the start of polymer injection, effluents were collected at the outlet in plastic tubes at 5 minute intervals. The effluents were analysed for total-organic-carbon (TOC), using a Dhormann 80 apparatus (Appendix. E). Potassium iodide tracer was analysed by the use of UV-VIS Spectrophotometer (Appendix. F) UV Mini 1240 (Shimadzu).

6. The above procedure was repeated for different polymer concentrations and salinities.
7 Results and Discussion

7.1 Polymer Characterisation

The viscosity measurements were used to validate the proposed model and to evaluate injectivity that can guide the design, execution and evaluation of field treatments.

This section reports polymer rheological measurement data obtained by (Zhou, 2010) on brine, and on (AN 905 Lot E 2686) polymer solutions of varying concentrations. The data were utilised in this section for modelling purposes. Concentrated polymer solutions (5000 ppm) in various brine concentrations 5.0±0.1, 10.0±0.1 and 20.0±0.1 g/L NaCl were prepared. They were diluted into lower concentrations (250, 500, 1000, 2000, 3000 and 4000 ppm) and the viscosity was measured as a function of shear rate (1 to 1000 s⁻¹) using an AR-G2 Rheometer.

Measurements were conducted at atmospheric pressure (1 bar) and at ambient temperature (20±1 °C). The viscosity of brine (5g/L) was found to be 0.001 Pa.s. Figs. 7.1-7.3, shows a shear thinning behaviour with an increase in the shear rate [Lake, 1989] for all the salinities investigated in the study. The markers in Figs 7.1-7.3, below indicate the data obtained from the experiments, while the lines indicate the results obtained from Carreau viscosity model as dealt in Sec. 4.2.1. Table.7.1 below shows the results obtained from modelling and Table.C-1 in Appendix. C shows the Sum of Squares Error (SSE) associated with the modelling of rheological measurements.

Table.7.1
Parameters of Carreau model Eq. (4.1), obtained from non-linear regression analysis of rheological measurements at (T = 20 ± 1°C) for various salinities.

<table>
<thead>
<tr>
<th>Salinity 5 g/L</th>
<th>Salinity 10 g/L</th>
<th>Salinity 20 g/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_p, ppm</td>
<td>τ , s</td>
<td>m_v</td>
</tr>
<tr>
<td>Brine</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>0.098</td>
<td>0.884</td>
</tr>
<tr>
<td>1000</td>
<td>0.139</td>
<td>0.830</td>
</tr>
<tr>
<td>2000</td>
<td>0.272</td>
<td>0.779</td>
</tr>
<tr>
<td>3000</td>
<td>0.334</td>
<td>0.721</td>
</tr>
<tr>
<td>4000</td>
<td>0.390</td>
<td>0.640</td>
</tr>
<tr>
<td>5000</td>
<td>0.517</td>
<td>0.602</td>
</tr>
</tbody>
</table>
Fig. 7.1: Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 5 g/L salinity.

Fig. 7.2: Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 10 g/L salinity.
Fig. 7.3: Experimental rheological measurements (markers) modelled with Carreau viscosity model (lines) for 20 g/L salinity.

Fig. 7.4: Rheological measurements (markers) modelled with Carreau viscosity model (lines) for different salinities at 5000 ppm polymer concentration.
7.1.1 Effect of Shear Rate

The variation of viscosity in shear rate range (1 to 1000 s\(^{-1}\)) was tested for all the concentrations and salinities used in this study. From Figs.7.1-7.3, we observed that the viscosity shows Newtonian behaviour at low shear rates and from some critical rate (\(\gamma_c\)) viscosity decreases with increase in shear rate. As discussed in Sec.4.2.1, this phenomenon is attributed to the structural characteristics of polymer chains, which are aligned along the flow streamlines with respect to the increase in shear rate. Shear thinning behavior is more pronounced at intermediate (in between low and high) shear rates. It was found that the polymer solutions display Newtonian behavior at low shear rates, where the structural characteristics of the polymer chains no longer affect the viscosity.

7.1.2 Effect of Polymer Concentration

Polymer viscosity at various polymer concentrations shown in Table.7.1 was tested for given shear rates while maintaining all the other variables constant. It can be observed from Figs.7.1-7.3, that for a given shear rate and salinity, the viscosity increases with increase in polymer concentration. This is due to the fact that, with increase in concentration the number of polymer chains in a given volume increases, which further strongly interact with each other resulting in more frictional effects which increases the viscosity. From Table.7.1, it can be seen that irrespective of the salinity the relaxation time increases with increase in polymer concentration. Thus, due to pronounced viscous effects with increasing concentration, once the polymer molecule gets deformed by shear forces, it takes long time before it comes back to its original conformation. Hence, the Newtonian plateau is less pronounced at higher polymer concentrations. It can be seen from Fig.7.6 below, that at a constant shear rate, the viscosity dependence on polymer concentration shows an exponential behaviour. This is because at concentrations above the critical overlap concentration (\(c^*_\mu\)) as indicated in Fig.4.2 (c), the polymer chains overlap extensively and almost behave like weak gels. So, there is a steep increase in viscosity after the critical overlap concentration.

7.1.3 Effect of Salinity

Three different salinities were chosen to see the effect on rheology of polymer solutions. In accordance with the previous studies (Lake, 1989), a decrease in the polymer solution viscosity was observed for full range of polymer concentrations with increase in salinity as seen from Figs.7.1-7.3. This is due to the screening of the charges along the polymer chain by salt cations as discussed earlier in Sec.4.2.2. It can be observed that the shear thinning behaviour is less pronounced at higher salinities. Also it can be seen that, as the viscosity is higher at lower salinities, the relaxation time (Table.7.1) for the polymer molecule to come to its original conformation is also larger. Hence, polymer solution undergoes continuous deformation with increasing shear rates.
at lower salinities. Also as seen from Fig.7.4, at a particular concentration (in this case 5000 ppm), the shear thinning behaviour is less pronounced at higher salinities. This is because, the smaller size macromolecules are less sensitive to orientation and deformation by shear forces leading to less pronounced shear thinning properties. Moreover, with increasing salinity the intrinsic viscosity decreases (Ait Kadi.et.al, 1987) which further results in a decrease in the size of macromolecule (due to screening of charges along the polymer backbone chain).

7.1.4 Polymer Solution Viscosity

The polymer viscosity measurements at zero shear rates and at a salinity of 20 g/L were modelled using the Flory-Huggins equation as described in Sec.4.2.2. From the rheology measurements at different salinities the value of ‘b’ was obtained initially and with the help of the Flory’s model the viscosity dependence of concentration was modelled.

Table 7.2
Parameters for the Flory’s equation Eq. (4.2), obtained from non-linear regression analysis of rheological measurements.

<table>
<thead>
<tr>
<th>Salinity ($S_s$), g/L</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>126.60</td>
<td>15545.18</td>
<td>14105109.79</td>
<td>-0.639</td>
</tr>
</tbody>
</table>

![Plot of specific viscosity vs. salinity for a polymer concentration of 3000 ppm and pH of 5.8 for obtaining the exponent (b) for Flory’s viscosity relation.](image)

Fig.7.5: Plot of specific viscosity vs. salinity for a polymer concentration of 3000 ppm and pH of 5.8 for obtaining the exponent (b) for Flory’s viscosity relation.
Fig. 7.6: Rheological measurements fitted with Flory model Eq. (4.2) for a salinity of 20 g/L NaCl.

The viscosity measurements were modelled with the Flory’s equation for different concentrations from 500 to 5000 ppm. The values of the viscosity at 125 and 250 ppm concentrations were found by parameters obtained from modelling. There will be always some error associated with the modelling of experimental data. Table 7.3 below shows the viscosity values and absolute error associated with modelling. From the data it can be observed the highest error was observed with the viscosity at 1000 ppm polymer concentration followed by 2000 and 3000 ppm.

**Table 7.3**
Parameters obtained from non-linear regression analysis of viscosity measurements at a shear rate of (1s⁻¹) and error associated with modelling.

<table>
<thead>
<tr>
<th>$c_p$ [g/cc]</th>
<th>Viscosity, μ_p (Pa.s) Experiments</th>
<th>Viscosity, μ_p (Pa.s) Modelling</th>
<th>Abs. Error (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000125</td>
<td>-</td>
<td>0.00119</td>
<td>-</td>
</tr>
<tr>
<td>0.00025</td>
<td>-</td>
<td>0.00140</td>
<td>-</td>
</tr>
<tr>
<td>0.0005</td>
<td>0.00186</td>
<td>0.00184</td>
<td>2E-5</td>
</tr>
<tr>
<td>0.001</td>
<td>0.00327</td>
<td>0.00290</td>
<td>0.0298</td>
</tr>
<tr>
<td>0.002</td>
<td>0.00641</td>
<td>0.00621</td>
<td>2E-4</td>
</tr>
<tr>
<td>0.003</td>
<td>0.01173</td>
<td>0.01196</td>
<td>2.3E-4</td>
</tr>
<tr>
<td>0.004</td>
<td>0.02122</td>
<td>0.02119</td>
<td>3E-5</td>
</tr>
<tr>
<td>0.005</td>
<td>0.03494</td>
<td>0.03491</td>
<td>3E-5</td>
</tr>
</tbody>
</table>
7.1.5 Polymer Intrinsic Viscosity

The intrinsic viscosity of a polymer is a property related to the hydrodynamic radius of the molecules in solution. As discussed earlier in Sec.4.2.3, the ratio of specific viscosity to concentration was plotted against polymer concentration for determination of the intrinsic viscosity at salinity of 20 g/L.

**Table.7.4**

Parameters obtained from linear regression analysis of viscosity measurements at a shear rate of (1s⁻¹).

<table>
<thead>
<tr>
<th>Salinity ($S_s$), g/L</th>
<th>$[\eta]$, cc/g</th>
<th>$c^*_p$ (ppm)</th>
<th>$K_H$</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1542 ± 20</td>
<td>2750 ± 30</td>
<td>0.25 ± 0.01</td>
<td>5.8</td>
</tr>
</tbody>
</table>

As seen from Fig.7.7, that the experimental data (blue markers) can be approximated with two linear equations, at low and high polymer concentrations. The intersection point of both the lines gives an indication of the critical overlap concentration ($c^*_p$). As discussed earlier in Sec.4.2.3, the intrinsic viscosity is the viscosity of polymer at infinite dilution, i.e. ($c_p \rightarrow 0$) on a plot of specific viscosity divided by concentration vs. concentration.

![Fig.7.7: Rheological measurements (markers) fitted with linear equations for determining ($c^*_p$), ($k_H$) and ($[\eta]$) at 20 g/L NaCl.](image-url)
The slope and intercept of the first linear part gives the values of the Huggins coefficient and intrinsic viscosity for that particular salinity. Lower the values of Huggins coefficient better the solvent quality (Tanaka, 2011; Ait Kadi.et.al, 1987). The value of Huggins coefficient (0.25) obtained from the calculations indicates that the solvent is of good quality.

### 7.1.6 Hydrodynamic Radius

For the current experimental conditions (pH = 5.8) hydrodynamic radius was calculated using Eq. (4.4), for a solvent salinity of 20 g/L and the value is shown in Table.7.5.

<table>
<thead>
<tr>
<th>Salinity ($S_s$), g/L</th>
<th>$[\eta]$, cc/g</th>
<th>$M_w$, g/mol</th>
<th>$\Phi$, 1/mol</th>
<th>$R_G$, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1542 ± 20</td>
<td>$9 \times 10^6$</td>
<td>$4.2 \times 10^{24}$</td>
<td>$(1.66 \pm 0.01) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

With decreasing salinity the intrinsic viscosity increases (Ait Kadi.et.al, 1987) which further results in an increase in size of the macromolecule and thus higher viscosity.

### 7.2 Core flood Experiments

In total nine core flood experiments were conducted as a part of this study. The key parameters of all these experiments are shown in Table.7.6.

<table>
<thead>
<tr>
<th>Exp. No</th>
<th>$c_p$, (ppm)</th>
<th>$S_s$, g/L</th>
<th>$k$, mD</th>
<th>$\phi$, %</th>
<th>$R_m$</th>
<th>$I_p$</th>
<th>$\Gamma_p$, g/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125</td>
<td>20</td>
<td>2.450</td>
<td>0.23</td>
<td>1.200</td>
<td>0.83</td>
<td>3.82E-5</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>20</td>
<td>2.314</td>
<td>0.21</td>
<td>1.410</td>
<td>0.74</td>
<td>5.71E-5</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>20</td>
<td>2.499</td>
<td>0.22</td>
<td>1.673</td>
<td>0.59</td>
<td>8.84E-5</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>20</td>
<td>2.659</td>
<td>0.22</td>
<td>3.000</td>
<td>0.33</td>
<td>1.14E-4</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>20</td>
<td>2.450</td>
<td>0.21</td>
<td>4.400</td>
<td>0.22</td>
<td>1.329E-4</td>
</tr>
<tr>
<td>6</td>
<td>3000</td>
<td>20</td>
<td>2.272</td>
<td>0.22</td>
<td>8.360</td>
<td>0.11</td>
<td>1.585E-4</td>
</tr>
<tr>
<td>7</td>
<td>5000</td>
<td>20</td>
<td>2.014</td>
<td>0.21</td>
<td>17.61</td>
<td>0.05</td>
<td>1.664E-4</td>
</tr>
<tr>
<td>8</td>
<td>500</td>
<td>10</td>
<td>2.314</td>
<td>0.21</td>
<td>1.860</td>
<td>0.53</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>5</td>
<td>2.211</td>
<td>0.21</td>
<td>1.980</td>
<td>0.48</td>
<td>-</td>
</tr>
</tbody>
</table>

The error associated with each of these parameters is summarised in Appendix. H. Seven experiments were conducted at different polymer concentrations (125, 250, 500, 1000, 2000, 3000, and 5000 ppm) for 20.0±0.1 g/L salinity of brine to study the effect of concentration on polymer flow through porous media and injectivity. Additionally
experiments with a polymer concentration of 500 ppm and at two different salinities (5.0±0.1 and 10.0±0.1 g/L) were performed to study the effect of salinity on polymer injectivity and transport through porous media. The experiment done with 250 ppm polymer concentration and 20.0±0.1 g/L salinity was considered as the base case and will be discussed in detail below. Later all experiments will be compared and discussed in the sensitivity analysis. The modelled results can be found in Appendix. H.

The sections below present the effluent data, adsorption, pressure drop, mobility reduction and injectivity obtained from core flood study on AN 905 Lot E 2686 polymer with concentration of 250 ppm at a salinity of 20.0±0.1 g/L. The intrinsic viscosity and hydrodynamic radius were calculated from the rheological measurements prior to the study and are summarised in Tables 7.4 and 7.5 respectively.

7.2.1 Analysis of Transport Properties

The core flood results obtained from the study were the pressure drop and the effluent concentration profiles for the tracer and polymer. The mobility reduction and injectivity were calculated using Eq. (5.18) and Eq. (5.19) respectively. The permeability reduction was determined by matching the experimental data with the model. Fig.7.8 shows the pressure drop (mBar) response across the core with the number of pore volumes injected for 250 ppm polymer concentration. The markers on the plot indicate the experimental data and the lines indicate the results obtained from modelling.

It can be observed that initially, there exists a flat part approximately up to 0.34±0.04 PV, which corresponds to the displacement of brine by polymer within the dead volume, before the polymer enters the core. The duration of the flat part observed in the pressure data is in good agreement with the calculated inlet dead volume as shown in Table.G.1 in Appendix. G. After 0.34±0.04 PV, the pressure drop rises; this marks the entry of the polymer into the core sample. From this point onwards, the pressure drop rose continuously with pore volumes injected. This is due to the presence of adsorbed layer and movement of both polymer and brine in the core.

After certain pore volumes (in between 2.50±0.04 and 3.50±0.04) the pressure drop reaches a flat profile. This marks the point of breakthrough of the polymer at the outlet of the core. The flat trend in the pressure drop data after the breakthrough point also indicates the absence of mechanical entrapment within the core. Figs 7.9 and 7.10 show the mobility reduction and polymer injectivity with the number of pore volumes injected. As seen from the figures below (7.8 - 7.10), an excellent fit of the model to the experimental data was obtained. Similarly, it can be observed that with increase in pore volume injected the mobility reduction increases and attains a flat profile as observed in Fig.7.9. The polymer injectivity decreases initially and after breakthrough it levels off to a plateau.
**Fig. 7.8:** Pressure drop across the core with number of pore volumes injected for a polymer concentration of 250 ppm.

- $c_p$ = 250 (ppm)
- $S_i$ = 20 ± 0.1 (g / L)
- $\phi$ = 20 ± 0.1
- $k$ = 2.314 ± 0.11 (Darcy)
- $q$ = 1 ± 0.02 (cc / min)
- $\text{Exp. Error}$ = ± 1.2 mBar

**Fig. 7.9:** Mobility reduction with pore volumes injected for a polymer concentration of 250 ppm.

- $c_p$ = 250 (ppm)
- $S_i$ = 20 ± 0.1 (g / L)
- $\phi$ = 20 ± 0.1
- $k$ = 2.314 ± 0.11 (Darcy)
- $q$ = 1 ± 0.02 (cc / min)
Fig. 7.10: Polymer injectivity with number of pore volumes injected for a polymer concentration of 250 ppm.

Fig. 7.11: Effluent concentration profiles of polymer and tracer with number of pore volumes injected for a polymer concentration of 250 ppm.
7.2.2 Analysis of Effluents

Effluent samples were collected at the outlet of the core at 5 minute time intervals. They were then analysed for the tracer and polymer concentrations, and the results are shown in Fig.7.11. It can be observed that the tracer curve passes through the 0.50±0.05 normalised concentrations at 1.00±0.04 PV, whereas, the retardation in the polymer effluent profile indicates the presence of adsorption in the core. Also it can be seen that the normalised effluent concentration for polymer does not reach unity till the end of the experiment and a tailing in the normalised concentration of polymer could be observed. This is a composite effect of filtration, dispersion (Kolodziej, 1988) and mass transfer between the stagnant and flowing polymer chains (Sorbie, 1991). As discussed earlier, unfiltered polymer solutions were used for this study. So, some effect of filtration at the inlet was also observed at the end of the experiment. This was equally reflected in the effluent data as seen from Fig.7.11. The values of parameters obtained from both experiments and modelling for this case are summarised in Table.7.7 below.

Table.7.7
Values of the key parameters obtained from experiments and modeling and the error associated with the modeling of experimental data (250 pm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>15.27</td>
<td>14.96</td>
<td>0.49</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>1.41</td>
<td>1.38</td>
<td>0.03</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.039</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.74</td>
<td>0.72</td>
<td>0.02</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>5.71E-5</td>
<td>5.60E-5</td>
<td>1.3E-6</td>
</tr>
<tr>
<td>$f$ (fraction)</td>
<td>-</td>
<td>0.94</td>
<td>-</td>
</tr>
</tbody>
</table>

7.2.3 Polymer Retention

The amount of polymer adsorption within the porous medium was calculated from the retardation factor i.e. from the separation between tracer and polymer effluent profiles (Fig.7.11) obtained from the core flood effluent data for various injected polymer concentrations (Fig.7.12). As seen earlier on the basis of Langmuir adsorption isotherm and with the assumption of instantaneous equilibrium, the retardation factor was defined by using constant (R) Eq. (B.10) in the current model. The rate of change in adsorption with concentration ($d\Gamma_p / dc_p$) can be determined from the measured retardation factor (R) from core flood effluents and other input parameters. The values of ($d\Gamma_p / dc_p$) for various polymer concentrations were then curve fitted (Fig.7.13) for obtaining the values of equilibrium rate constant ($k_e$) and maximum adsorbent capacity ($\Gamma_\infty$). From the values obtained, polymer adsorption for various concentrations was calculated (Fig.7.14).
Fig. 7.12: Retardation factor obtained from core flood effluent data for various polymer concentrations.

Fig. 7.13: The rate of change of adsorption with concentration for various polymer concentrations.
It can be seen from Fig.7.14 above, that the adsorption values the Langmuir adsorption isotherm indicative of monolayer adsorption. Also, it can be observed that the error in adsorption measurements, increase with increasing concentration. From the analyses it was found that the error in retardation factor showed decreasing trend with increasing concentration. The same decreasing trend with concentration was also observed for change in adsorption with change in concentration \((d\Gamma_p / dc_p)\). A separate curve fitting was carried out for the maximum and minimum values of \(d\Gamma_p / dc_p\). From the fits it was found that the difference in the values of \(k_z\) and \(\Gamma_\infty\) from the mean value was around ± 500 and ± 0.3\times10^{-6} respectively. This is the reason why the error in adsorption increases with increasing concentration.

### 7.2.4 Mechanical Degradation of Polymer

For the current experimental conditions the Deborah number was found to be around 6.25\times10^{-4} indicating the absence of shear thickening behavior in porous media and possibly no mechanical degradation of polymer as discussed previously in Sec.4.3.3.
8 Effect of Physical and Numerical Parameters

8.1 Effect of Polymer Concentration

Two main aspects that control the shape of the effluent concentration profile for polymer could be observed from Figs. 8.1 and 7.11. They are frontal delay and gradual approach to injection concentration. The frontal delay is mainly due to adsorption of the chains on the surface of the rock that have radius less than the average pore throat radius of porous medium. For a given salinity and flow rate, the retardation factor (separation between the tracer and polymer effluent profiles) decreases with increasing concentration. This is due to the fact that, with increase in polymer concentration the rate of change of adsorption with polymer concentration (Eq.B.19) decreases (Fig.7.13). The second aspect is related to the filtration of high molecular weight components near the inlet face of the core. It can be observed from Figs. 8.1 and 7.11 that with increasing concentration the polymer effluent profiles gradually approach injected concentration. This is because the filtration coefficient (probability of trapping of the larger polymer molecules) decreases at higher concentrations. Two main forces (hydrodynamic forces exerted by the fluid and attractive force between the polymer and rock surface) control the probability of trapping of polymer. At high polymer concentrations the surface area available for adsorption is smaller and thus the hydrodynamic forces dominate over the attractive forces with respect to the trapping of polymer molecules.

Further it can be seen from the effluent profiles that the dispersion is larger for the polymer as compared to the tracer. This can be attributed mainly to three reasons. 1) The molecular diffusion coefficient for polymer is much lower as compared to that of the tracer. For the current experimental conditions the molecular diffusion coefficient for polymer is of the order of $10^{-5} \text{ cm}^2 / \text{hr}$, whereas for the tracer it is of the order of $[10^{-3} \text{ cm}^2 / \text{hr}]$ (Sorbie, 1991). This translates to a factor $10^2$ difference in the Peclet number of polymer and tracer. 2) Velocity enhancement of polymer molecules as a result of depletion layer. 3) Adsorption of polymer i.e. retardation factor (R>1).

The retardation factor causes the motion of the polymer molecules to deviate from the average motion of the fluid. This is due to a chemico-physical effect: the adsorption of polymer to the rock, which retains the polymer molecules and does not allow them to progress further until the quantity corresponding to the chemical adsorption equilibrium has been adsorbed. The retardation factor changes the global average velocity of the polymer molecules, so that it can be slower than that of the solvent. Also it can be observed that with increasing concentration the polymer front rises more steeply. This is because with increasing concentration the viscosity of the polymer solution increases and thus a sharper front gets established. As seen at the pore scale with increase in polymer concentration the viscosity increases and the flow of polymer solutions becomes more non-Newtonian which yields a more uniform velocity profile as opposed to the parabolic velocity profile.
It can be observed from Table.8.1, that adsorption, permeability reduction and mobility reduction (Fig.8.2) increase with polymer concentration. This can be explained as follows: with increase in polymer concentration the number of chains per unit volume of porous medium increases. Thereby the polymer-polymer and rock polymer interactions are enhanced, resulting in increased solution viscosity and polymer adsorption onto the rock surface. However, the increase in pressure drop for polymer (Fig.8.3) and mobility reduction (Fig.8.2) are much more pronounced as compared to permeability reduction because the effect of polymer viscosity is dominant. It can be observed from Fig.8.3, that for 1000 and 2000 ppm the pressure drop profiles obtained from the modelling do not perfectly match the experimental pressure drop profiles. This is because for 1000 ppm polymer concentration, a significant error between the experimental and modelled values of polymer solution viscosity was observed as shown in Sec.7.1.4.

For 2000 ppm polymer concentration, it is believed to be an experimental artefact. Indeed, a fracture was observed at both the inlet and outlet of the core sample at the end of the experiment. We suspect that the fracture might have propagated slowly from the inlet to the outlet with the injection of polymer into the core. The polymer injectivity (which is defined as the inverse of mobility reduction) was shown in Fig.8.4. It can be observed that the mobility reduction increases and polymer injectivity decreases with increasing polymer concentration. From Table.8.1, it can be seen that increase in permeability reduction is not that pronounced. This confirms that permeability reduction plays a minor role on injectivity losses especially in high permeability porous media.

Table.8.1
Adsorption and permeability reduction for various polymer concentrations.

<table>
<thead>
<tr>
<th>$c_p$, [ppm]</th>
<th>Adsorption (g/g)</th>
<th>Permeability Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>3.67E-5</td>
<td>1.02</td>
</tr>
<tr>
<td>250</td>
<td>5.60E-5</td>
<td>1.04</td>
</tr>
<tr>
<td>500</td>
<td>8.73E-5</td>
<td>1.06</td>
</tr>
<tr>
<td>1000</td>
<td>1.13E-4</td>
<td>1.08</td>
</tr>
<tr>
<td>2000</td>
<td>1.326E-4</td>
<td>1.10</td>
</tr>
<tr>
<td>3000</td>
<td>1.583E-4</td>
<td>1.11</td>
</tr>
<tr>
<td>5000</td>
<td>1.664E-4</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Fig. 8.1: Effluent concentration profiles of tracer and polymer for various injected polymer concentrations.
Fig. 8.2: Mobility reduction vs. number of pore volumes injected for various polymer concentrations.

- $S_i$: $20 \pm 0.1 \, (g/L)$
- $pH$: $5.8 \pm 0.1$
- $k$: $2 \pm 0.1 \, (Darcy)$
- $q$: $1 \pm 0.02 \, (cc/\text{min})$
Fig. 8.3: Pressure drop for polymer (normalised to 2 Darcy) vs. number of pore volumes injected for various polymer concentrations.
Fig.8.4: Polymer injectivity vs. pore volumes injected for various polymer concentrations.
8.2 Effect of Salinity

The retardation factor (indicative of adsorption), polymer injectivity and mobility reduction were tested for three different salinity values (5.0±0.1, 10.0±0.1 and 20.0±0.1 g/L NaCl) at a polymer concentration of 500 ppm. It can be observed from Table 8.2, that for a given concentration (500 ppm) and flow rate, the retardation factor (indicative of adsorption) increases with increasing salinity. This is due to the fact that the presence of salts screens the charges on the polymer chain which enhances the attractive interactions of the polymer molecules with the rock surface and thus higher retardation factor and in-turn adsorption. Pressure drop for polymer and mobility reduction decreases with increasing salinity as shown in Fig.8.5 and Fig.8.6. This is because at higher salinities, the charges on the polymer chain are screened by the salt cations resulting in a reduction in viscosity. Although adsorption and permeability reduction increases with increasing salinity, its effect is negligible compared to the viscous effects. It is also interesting to note that, the curves of pressure drop for polymer (Fig.8.5) and mobility reduction (Fig.8.6) for all the three salinities are close to each other. This is because at an experimental flow rate of 1.00 ± 0.02 cc/min and for calculated values of shear rates around 25-30 s⁻¹, the viscosities of these solutions are rather close to each other. The polymer injectivity investigated at the three different salinities is shown in Fig.8.7. The dotted lines on the plots do not indicate any model and are displayed only for better viewing of the experimental results.

Fig.8.5: Pressure drop for polymer (normalised to 2 Darcy) vs. number of pore volumes for 500 ppm polymer concentration and at different salinities.
Fig. 8.6: Mobility reduction vs. number of pore volumes injected for 500 ppm polymer concentration and at different salinities.

Fig. 8.7: Polymer injectivity vs. number of pore volumes injected for 500 ppm polymer concentration and at different salinities.
Table 8.2
Retardation factor for 500 ppm polymer concentration and at different salinities.

<table>
<thead>
<tr>
<th>Salinity ($S_s$), g/L</th>
<th>Retardation, $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.65</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>1.8</td>
</tr>
</tbody>
</table>

8.3 **Effect of Number of Grid Blocks**

In this study, the transport problem for polymer flow in porous media was solved numerically. It is essential to study the effect of number of grid-blocks on the computed pressure drops and concentrations. Three runs were carried out with different number of grid points (10, 100 and 1000) while maintaining all the other variables constant. It can be observed from effluent data (Fig.8.8 and Fig.8.9), pressure drop (Fig.8.10), mobility reduction (Fig.8.11) and injectivity (Fig.8.12), that with decrease in the number of grid points the numerical error increases. This is because; since the order of global discretisation error for the spatial domain is one. Use of higher order spatial discretisation schemes with higher order of global discretisation error can give accurate results, which is out of the scope of this work. Also it can be observed that more smoothening effects than actual dispersion could be observed for less number of grids (Fig.8.8 and Fig.8.9).

![Fig.8.8: Tracer effluent profile vs. number of pore volumes injected for various number of spatial grid points.](image)
Fig. 8.9: Effluent profiles vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).

Fig. 8.10: Pressure drop for polymer vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).
Fig. 8.11: Mobility reduction vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).

Fig. 8.12: Polymer injectivity vs. number of pore volumes injected for various number of spatial grid points (polymer concentration 5000 ppm).
Also, it is interesting to note that the difference in error between 100 and 1000 grid points is smaller compared to the difference between 10 and 100 grid points. To make the work computationally efficient, 100 grid points could be used instead of 1000.

### 8.4 Effect of Number of Time Steps

In the temporal domain the problem was solved implicitly. So, it does not restrict the size of the time step to be used for the simulation and is unconditionally stable. Three runs were carried out with different number of time steps (10, 100 and 1000) to study the time step sensitivity while maintaining all the other variables constant. It can be observed from effluent data (Fig.8.13 and Fig.8.14), pressure drop (Fig.8.15), mobility reduction (Fig.8.16) and injectivity (Fig.8.17), that the numerical error increases with decrease in number of time steps used for simulation. This is because of the truncation error introduced from the numerical discretization. A major change in the final result was observed for different number of time steps, as compared to the spatial domain. Although some numerical dispersion is always present, use of 1000 time steps for simulation seems to produce accurate match with the experimental data. So, it is advisable to use 1000 time steps for the numerical simulation to mimic the experimental results with less amount of error. Alternatively, higher order temporal discretization schemes such as ‘Runge-Kutta method’ can be used for decreasing the numerical error in the approximations.

Fig.8.13: Tracer effluent profile vs. number of pore volumes injected for various number of temporal grid points.
Fig. 8.14: Effluent profiles vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig. 8.15: Pressure drop for polymer vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).
Fig. 8.16: Mobility reduction vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).

Fig. 8.17: Polymer injectivity vs. number of pore volumes injected for various number of temporal grid points (polymer concentration 5000 ppm).
9 Model Testing

Testing of the numerical model is required for assessing the accuracy of the results obtained. This is done to check the accuracy of the numerical algorithms used for solving the governing equations and to make sure that the code is fully functional without any errors. Sensitivity analysis of three different parameters was carried out in the above section to identify the possible errors in the model. From the results obtained and the assumptions considered for this study, no potential errors in the numerical code were observed. Also the efficiency of the model was tested by calculating the simulation time for various numbers of grid blocks and time steps. It was observed that the computational time for less number of grid blocks and time steps was small as compared to high number of grid blocks and time steps at the cost of accuracy. So one limitation of the present model with respect to the performance of the algorithm was identified and is summarised below.

10 Limitations of the Model

Numerical modelling is based on specific set of assumptions and is an approximation to real problems. Understanding the limitations of the model will prevent its misuse. The following limitations have been identified based on the validation and sensitivity.

1. Error in numerical approximation restricts the use of number of spatial and temporal grid points less than those used for current modelling purposes (1000×1000 or 100×1000).
2. This model is only valid in shear thinning regime and may not give accurate results if applied at very high shear rates, where the apparent viscosity of polymer behaves to be shear thickening.
11 Conclusions and Recommendations

1. A numerical model for predicting the injectivity during single phase flow of polymer solutions in porous media was successfully formulated and validated with the experimental data.
2. Rheology measurements were modeled with Carreau viscosity model with good accuracy for predicting the temporal variation of viscosity during polymer flow in porous media.
3. The pressure drop results for all the experiments revealed that, similar to filtered polymer solutions, unfiltered polymer solutions also do not cause mechanical entrapment especially in high permeability porous media.
4. Some sign of polymer filtration at the inlet face of the core was observed. Tests with much higher pore volumes should be carried out to find if the filtration of the polymer at the core face would turn to be detrimental to injectivity in long run.
5. The effects of shear rate and depletion layer on the polymer solution apparent viscosity in porous media were successfully incorporated into the model for prediction of polymer injectivity.
6. Adsorption was found to be the dominant mechanism for polymer retention and the polymer was found to be mechanically stable under the given experimental conditions.
7. The effect of polymer concentration and salinity on polymer injectivity in porous media was tested. Irrespective of the concentration and salinity, it was observed that viscosity of polymer solutions was the main reason for decline in injectivity especially in high permeability porous media.
8. Finally, the numerical model was validated with the experimental data. It was found that the model could mimic the observed phenomenon very well under the given set of assumptions. Two main limitations of the model, one with respect to the performance of the numerical algorithm and other regarding the behavior of polymer were identified.

Recommendations for future work

1. Based on the single phase equations derived in this work, polymer injectivity and transport in presence of multiple phases in porous media could be modeled.
2. Finite difference technique was applied to solve the equations numerically. Finite volume and finite element methods can be applied. Higher order temporal schemes could be used for minimizing the error.
3. Extension of this work to long cores, with multiple pressure taps will help in better quantification and modelling of retention and transport properties along the spatial domain.
Appendices

A Derivation of Conservation Law in Three Dimensions

In this section, the basic equation for describing the flow of polymer through porous media will be derived. Consider a porous medium element of porosity ‘φ’ with volume ‘dV’ which contains a mass of retained polymer due to adsorption to the rock ‘\(M_{pa}\)’ and ‘\(M_{pl}\)’, mass of polymer entrained by the incompressible liquid flowing with constant velocity. Fig.A-1 shows the region described by cylindrical coordinates in which the flow of total flux through the element is three dimensional.

\[ dV = \varphi \delta r \delta \theta \delta x \]  

(A.1)

Where, \(\delta r, \delta \theta, \delta x\) are the dimensions in radial, angular and axial directions and \(\varphi\) is the porosity of porous medium.

Applying the law of conservation of mass to the infinitesimal element with volume ‘dV’, we have,

\[ \text{Mass In} - \text{Mass Out} = \text{Rate of Accumulation of Mass} \]  

(A.2)
Advection and Dispersion are additive quantities and are clearly independent of each other. Thus the total flux ‘\(J_x\)’ in the axial direction is given as,

\[ J_x = u_x c_p - \varphi D_x \frac{\partial c_p}{\partial x} \]  

(A.3)

For ‘\(r\)’ and ‘\(\theta\)’ directions they are similar but with ‘\(u_r\)’ and ‘\(u_\theta\)’ for the velocity components and with ‘\(D_r\)’ and ‘\(D_\theta\)’ for the dispersion components, giving,

\[ J_r = u_r c_p - \varphi D_r \frac{\partial c_p}{\partial r} \]  

(A.4)

\[ J_\theta = u_\theta c_p - \varphi \frac{D_\theta}{r} \frac{\partial c_p}{\partial \theta} \]  

(A.5)

From the law of conservation of mass, the net flux through the element of volume ‘\(dV\)’ is given by the equation,

\[ \frac{\partial}{\partial t} (M_{pl} + M_{pa}) = \sum J_{\text{in}} - \sum J_{\text{out}} \]  

(A.6)

Where, ‘\(M_{pl}\)’ is the mass of polymer entrained in the liquid in the core and ‘\(M_{pa}\)’ is the mass of polymer adsorbed to the rock. The mass of polymer adsorbed to the rock per unit time within the porous element Eq. (A.7) and the mass of polymer entrained in the liquid within the control volume per unit time Eq. (A.8) are defined as,

\[ \frac{\partial M_{pa}}{\partial t} = \rho_s A_x (1-\varphi) r r \delta \theta \delta x \frac{\partial \Gamma_p}{\partial t} \]  

(A.7)

\[ \frac{\partial M_{pl}}{\partial t} = \varphi r r \delta \theta \delta x \frac{\partial c_p}{\partial t} \]  

(A.8)

The mass balance in the radial ‘\(r\)’ direction \((J_{\text{in}} - J_{\text{out}})\) can be defined as,

\[ \left( u_r c_p - \varphi D_r \frac{\partial c_p}{\partial r} \right) r \delta \theta \delta x + \left[ u_r c_p + u_r \frac{\partial c_p}{\partial r} \right] r \delta \theta \delta x - \left[ \varphi D_r \frac{\partial c_p}{\partial r} r \delta \theta \delta x + \varphi D_r \left( \frac{\partial c_p}{\partial r} \right) r \delta \theta \delta x \right] \delta \theta \delta x \]  

(A.9)

Solving the Eq. (A.9) results in,

\[ \left( -u_r \frac{\partial c_p}{\partial r} r \delta r \delta \theta \delta x + \varphi D_r \frac{\partial}{\partial r} \left( r \frac{\partial c_p}{\partial r} \right) \delta r \delta \theta \delta x \right) \]  

(A.10)
Similarly, the mass balance in the axial ‘x’ and the angular ‘θ’ directions 

\((J_{in} - J_{out})_x\) and \((J_{in} - J_{out})_\theta\) becomes,

\[-u_x \frac{\partial c_p}{\partial x} r \delta r \delta \theta \delta x + D_x \frac{\partial^2 c_p}{\partial x^2} \varphi r \delta r \delta \theta \delta x \] \hspace{1cm} \text{(A.11)}

\[-u_\theta \frac{\partial c_p}{\partial \theta} \delta r \delta \theta \delta x + \frac{D_\theta}{r} \frac{\partial^2 c_p}{\partial \theta^2} \varphi r \delta r \delta \theta \delta x \] \hspace{1cm} \text{(A.12)}

Substituting Eqns. (A.10), (A.11) and (A.12) in Eq. (A.6), gives,

\[-u_x \frac{\partial c_p}{\partial x} r \delta r \delta \theta \delta z + D_x \frac{\partial^2 c_p}{\partial x^2} \varphi r \delta r \delta \theta \delta x - u_r \frac{\partial c_p}{\partial r} r \delta r \delta \theta \delta x + \varphi D_r \left( \frac{\partial}{\partial r} \frac{\partial c_p}{\partial r} \right) \delta r \delta \theta \delta x \]

\[-u_\theta \frac{\partial c_p}{\partial \theta} \delta r \delta \theta \delta x + \frac{D_\theta}{r} \frac{\partial^2 c_p}{\partial \theta^2} \varphi r \delta r \delta \theta \delta x = \rho_s A_s (1-\varphi) r \delta r \delta \theta \delta x \frac{\partial \Gamma_p}{\partial t} + \varphi r \delta r \delta \theta \delta x \frac{\partial c_p}{\partial t} \] \hspace{1cm} \text{(A.13)}

Upon simplifying the Eq. (A.13), the convection-dispersion equation in three dimensions is obtained, which is given by,

\[-v_x \frac{\partial c_p}{\partial x} + D_x \frac{\partial^2 c_p}{\partial x^2} - v_r \frac{\partial c_p}{\partial r} + D_r \left( \frac{\partial}{\partial r} \frac{\partial c_p}{\partial r} \right) - v_\theta \frac{\partial c_p}{\partial \theta} + \frac{D_\theta}{r} \frac{\partial^2 c_p}{\partial \theta^2} = \rho_s A_s \frac{(1-\varphi)}{\varphi} \frac{\partial \Gamma_p}{\partial t} + \frac{\partial c_p}{\partial t} \] \hspace{1cm} \text{(A.14)}

Where, ‘\(v_x\)’, ‘\(v_\theta\)’ and ‘\(v_r\)’ are the interstitial velocities in axial, angular and radial directions respectively.

In one dimension i.e. in axial direction for core flood experiments, and with the introduction of filtration theory from deep bed filtration to account for the filtration of polymer at the inlet face of the core, Eq. (A.14) gets modified to,

\[-v_x \frac{\partial c_p}{\partial x} + D_x \frac{\partial^2 c_p}{\partial x^2} - \lambda_f c_p = \rho_s A_s \frac{(1-\varphi)}{\varphi} \frac{\partial \Gamma_p}{\partial t} + \frac{\partial c_p}{\partial t} \] \hspace{1cm} \text{(A.15)}

Where,

\[-v_x \frac{\partial c_p}{\partial x}\] is the advection term, 
\[D_x \frac{\partial^2 c_p}{\partial x^2}\] is the dispersion term, 
\[\rho_s A_s \frac{(1-\varphi)}{\varphi} \frac{\partial \Gamma_p}{\partial t}\] is the adsorption term, and 
\[\lambda_f c_p\] is the constant rate filtration term.
B Modelling of Polymer/Tracer Flow and Polymer Retention in Porous Media

The mass conservation equation for polymer flow in porous media in one dimension Eq. (5.1) with the assumption of instantaneous equilibrium can be rewritten as,

$$\nabla \frac{\partial c_p}{\partial x} + D \frac{\partial^2 c_p}{\partial x^2} - \lambda_j v_p c_p = \left(1 + \rho_s A_s \frac{1-\varphi}{\varphi} \frac{d\Gamma_p}{dc_p}\right) \frac{\partial c_p}{\partial t} \quad \text{..................................................(B.1)}$$

The boundary and initial conditions given by equations (5.3-5.6) were utilized for arriving at the final system of equations. They can be written as,

$$v_p(x = 0, t) = v_p, \text{in} + D \left(\frac{\partial c_p}{\partial x}\right)_{x=0} \quad \text{..................................................(B.2)}$$

$$\frac{\partial c_p}{\partial x}(x = L, t) = 0 \quad \text{..................................................(B.3)}$$

$$c_p(x, t = 0) = 0 \quad \text{..................................................(B.4)}$$

$$\Gamma_p(x, t = 0) = 0 \quad \text{..................................................(B.5)}$$

For solving the problem numerically, the spatial and temporal domain is discretized as shown in Fig.B-1 and Fig.B-2.

![Spatial computational domain showing the fictitious and real grid blocks.](image)

The spatial domain was divided into equally spaced points with distance ($\Delta x$). The temporal domain was divided into equally spaced time increments of ($\Delta t$). For this
discretization to be efficient, either the values of \((\Delta x)\) or \((\Delta t)\) or both should be very small (or) the order of global discretization error should be more than one.

**Fig B.2:** Discretization of spatial-temporal computational domain and the grid system.

The advection term in the equation *(B.1)* was discretized using the backward finite difference approximation and the dispersion term was discretized using the central finite difference approximation. The spatial grid points \((i = 0, 1, 2, \ldots, N_x - 2, N_x, N_x + 1)\) were placed at the center of the grid blocks. The points denoted by \(i = 0\) and \(i = N_x + 1\) are outside the inlet and outlet boundaries and are called fictitious points. The points denoted by \((i = 1, 2, \ldots, N_x - 2, N_x)\) are the real points and are the interior grid points. The temporal grid points are denoted by \((t = 1, 2, 3, \ldots, N_t - 2, N_t - 1, N_t)\) with \(t = 0\) as the initial condition. Using the Taylor series expansion for the advection term, the finite backward difference approximation in spatial domain can be written as,

\[
\frac{\partial c_p}{\partial x} = \frac{c_{p,j} - c_{p,j-1}}{\Delta x} + \Theta(\Delta x) \tag{B.6}
\]

The numerical approximation of the above equation can be written as,

\[
\frac{\hat{c}_p}{\Delta x} = \frac{c_{p,j} - c_{p,j-1}}{\Delta x} \tag{B.7}
\]

Similarly, the dispersion term and its numerical approximations can be written using the finite central difference approximation as,
\[
\frac{\partial^2 c_p}{\partial x^2} = \frac{c_{p,i-1} - 2c_{p,i} + c_{p,i+1}}{(\Delta x)^2} + O(\Delta x^2) \tag{B.8}
\]
\[
\frac{\partial^2 c_p}{\partial x^2} = \frac{c_{p,i-1} - 2c_{p,i} + c_{p,i+1}}{(\Delta x)^2} \tag{B.9}
\]

Substituting equations (B.7) and (B.9) in equation (B.1) and the application of Euler backward implicit method for time discretization with first order error in time (\(\Theta(\Delta t)\)), yields,
\[
-v\left(\frac{c^{i+1}_{p,j} - c^{i+1}_{p,j-1}}{\Delta x}\right) + D\left(\frac{c^{i+1}_{p,j-1} - 2c^{i+1}_{p,j} + c^{i+1}_{p,j+1}}{(\Delta x)^2}\right) - \lambda_j \nu c^{i+1}_{p,j} = \left[1 + \rho_s A_x \frac{(1-\varphi)}{\varphi} \left(\frac{d\Gamma_p}{dc_p}\right)\right]\left(\frac{c^{i+1}_{p,j} - c^{i}_{p,j}}{\Delta t}\right)
\]
\[
\left(\frac{d\Gamma_p}{dc_p}\right)^t \tag{B.10}
\]

For simplifying the equation (B.10), we say \(R = \left[1 + \rho_s A_x \frac{(1-\varphi)}{\varphi} \left(\frac{d\Gamma_p}{dc_p}\right)^t\right]\). The term \(\left(\frac{d\Gamma_p}{dc_p}\right)^t\) in retardation factor (R), will be treated explicitly all throughout the simulation and will be discussed later. The formulation of equation at the first grid block i.e. at \((i = 1)\) starts with the discretization of the inlet boundary condition on the basis of the fictitious grid point \((i = 0)\). At \((i = 1/2)\) we have,
\[
v_{1/2} c_{p, 1/2} = \nu c_{p,in} + D\left(\frac{c_{p,1} - c_{p,0}}{\Delta x}\right) \tag{B.11}
\]
\[
c_{p, 1/2} = \frac{c_{p,1} + c_{p,0}}{2} \tag{B.12}
\]

Substituting equation (B.12) into equation (B.11) and solving for the fictitious point yields,
\[
c_{p,0} = \left(\frac{\nu c_{p,in} - c_{p,1} \left(\frac{v}{2} - D \frac{\Delta x}{\Delta x}\right)}{\nu \left(\frac{v}{2} + D \frac{\Delta x}{\Delta x}\right)}\right) \tag{B.13}
\]

The outlet boundary condition is discretized and the fictitious point value at the outlet \((i = Nx + 1)\) is obtained as,
\[
\left( \frac{c_{p,Nx+1} - c_{p,Nx}}{\Delta x} \right) = 0 \quad \text{(B.14)}
\]
\[
c_{p,Nx+1} = c_{p,Nx} \quad \text{(B.15)}
\]

For convenience, we arrange the terms in the equation \((B.10)\) and represent the numerical solution for grid blocks \((i = 1, 2 \ldots \ldots Nx - 2, Nx)\) as,

\[
c_{p,i+1}^t \left( \frac{v}{\Delta x} + \frac{D}{(\Delta x)^2} \right) + c_{p,i}^t \left( -\frac{2D}{(\Delta x)^2} - \frac{v}{\Delta x} - \lambda_f v \right) + c_{p,i+1}^t \left( \frac{D}{(\Delta x)^2} \right) = R \left( \frac{c_{p,i+1}^t - c_{p,i}^t}{\Delta t} \right) \quad \text{(B.16)}
\]

We incorporate the fictitious point values at the inlet and at the outlet in the equation \((B.16)\) by substituting \((i = 1)\) and \((i = Nx)\) respectively. The equation at the inlet for \((i = 1)\) becomes,

\[
-c_{p,1}^t \left( \left[ 2 + \left( \frac{v}{2} \right) \right] - \frac{D}{(\Delta x)^2} \right) + \left[ \left( \frac{v}{2} \right) \right] \frac{D}{(\Delta x)^2} + \left( \frac{v}{2} \right) \frac{\lambda_f v}{\Delta x} + c_{p,1}^t \left( \frac{D}{(\Delta x)^2} \right) = R \left( \frac{c_{p,1}^t - c_{p,1}^t}{\Delta t} \right)
\]

\[
-\frac{vc_{p,in}}{\left( \frac{v}{2} + \frac{D}{\Delta x} \right)} \left( \frac{D}{(\Delta x)^2} + \frac{v}{\Delta x} \right) \quad \text{(B.17)}
\]

The equation at the outlet for \((i = Nx)\) can be written as,

\[
c_{p,Nx-1}^t \left( \frac{v}{\Delta x} + \frac{D}{(\Delta x)^2} \right) - c_{p,Nx}^t \left( \frac{D}{(\Delta x)^2} + \frac{v}{\Delta x} + \lambda_f v \right) = R \left( \frac{c_{p,Nx-1}^t - c_{p,Nx}^t}{\Delta t} \right) \quad \text{(B.18)}
\]

According to the assumption of instantaneous equilibrium,

\[
\left( \frac{d\Gamma_p}{dc_p} \right) = \left( \frac{k_1 \Gamma_x}{(1 + k_2 c_{p,i}^t)^2} \right) \quad \text{(B.19)}
\]

The linear system of equations \((B.17)\) for \((i = 1)\) and \((B.16)\) for \((i = 1, 2 \ldots \ldots Nx - 2, Nx)\) and \((B.18)\) for \((i = Nx)\) and \((B.19)\) were compiled in the form of a matrix and was solved implicitly for polymer concentration and polymer adsorption. The tracer concentration can be obtained by solving the same system of equations with \(R = 1\).
Fig.B.3: MATLAB workflow for modelling polymer injectivity.
C Non-Linear Least Square Analysis for Modelling of Rheological Data

The polymer rheological measurements exhibit non-linear behavior, both in viscometer and porous media. So, non-linear least square analysis was adopted for modeling the rheological measurements with the Carreau viscosity model. Non-linear least squares method (Kemmer, 2010) is a form of least squares analysis which is used to fit a set of ‘x’ observations with a model that is non-linear in ‘y’ unknown parameters (x > y). The basis of the method is to approximate the model by a linear one and to refine the parameters by successive iterations. The objective of non-linear regression is to adjust the parameters of a model function under a given set of constraints to best fit a data set.

The sum of residuals (defined as the difference between actual and calculated value) (or) Sum of Squares Error (SSE) is given by,

\[ SSE = \sum_{i=1}^{x} r_i^2 \; ; \; Where, \; r_i = b_i - f(x_i, \delta) \] ..........................(C.1)

Where, \( r_i \) is the residual at point ‘i’, \( b_i \) is the original value and \( f(x_i, \delta) \) is the calculated value at point ‘i’.

Table.C.1
Sum of Squares Error (SSE) obtained from modelling of rheological measurements with the Carreau viscosity model.

<table>
<thead>
<tr>
<th>Salinity</th>
<th>5 g/L</th>
<th>10 g/L</th>
<th>20 g/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_p ), [g/L]</td>
<td>SSE</td>
<td>( c_p ), [g/L]</td>
<td>SSE</td>
</tr>
<tr>
<td>Brine</td>
<td>1.348E-08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.25</td>
<td>2.110E-08</td>
<td>0.25</td>
<td>1.360E-08</td>
</tr>
<tr>
<td>0.50</td>
<td>3.228E-08</td>
<td>0.50</td>
<td>1.040E-07</td>
</tr>
<tr>
<td>1</td>
<td>1.156E-07</td>
<td>1</td>
<td>1.110E-06</td>
</tr>
<tr>
<td>2</td>
<td>1.290E-07</td>
<td>2</td>
<td>6.280E-08</td>
</tr>
<tr>
<td>3</td>
<td>6.984E-07</td>
<td>3</td>
<td>4.010E-07</td>
</tr>
<tr>
<td>4</td>
<td>4.897E-06</td>
<td>4</td>
<td>7.463E-07</td>
</tr>
<tr>
<td>5</td>
<td>9.139E-06</td>
<td>5</td>
<td>4.148E-06</td>
</tr>
</tbody>
</table>
D Filtering Pressure Data using Butterworth Filter

Butterworth filter is often used in many engineering analyses for filtering and smoothing the data (Winter, 2005). Briefly, this filter produces a weighted average of data from several time points. The weighted average includes the point of interest as well as the two preceding time points. This process of averaging time points prior to the time of interest causes the filtered data to “lag” behind the raw data with respect to time. To correct for this lag, data are filtered once in forward time order, then again in reverse time order to produce filtered data that are properly aligned in time. In addition to correcting for lag, the second filtering in the reverse direction creates a sharper cutoff and this is referred to as a fourth-order zero-phase shift (or zero-lag) filter.

Let us consider ‘n’ samples in time with their corresponding data values denoted as \(x_1, x_2, \ldots, x_{n-2}, x_{n-1}, x_n\). The filtered value at point ‘n’ is denoted as,

\[x'(n) = a_0 x(n) + a_1 x(n-1) + a_2 x(n-2) + b_1 x'(n-1) + b_2 x'(n-2)\] ..........................(D.1)

Where, \(x'\) is the filtered output data, \(x\) is unfiltered (raw) input data, \(n\) is \(n^{th}\) sample, \(n-1\) is one sample before ‘n’ and \(n-2\) is two samples before ‘n’. \(a_0, a_1, a_2, b_1\) and \(b_2\) are filter coefficients which can be determined as follows,

\[
\begin{align*}
\tan \left( \frac{\omega_c \pi}{f_s} \right) &= \frac{C_r}{\omega_c} \\
k_1 &= \sqrt{2} \omega_c \\
k_2 &= (\omega_c)^2 \\
\omega_c &= \frac{k_2}{(1 + k_2 + k_2)} \\
a_0 &= \frac{k_2}{1 + k_2 + k_2} \\
a_1 &= 2a_0 \\
a_2 &= a_0 \\
k_1 &= \frac{2a_0}{k_2} \\
b_1 &= -2a_0 + k_3 \\
b_2 &= 1 - 2a_0 - k_3 \\
a_0 + a_1 + a_2 + b_1 + b_2 &= 1
\end{align*}
\]

Where, \(C_r\) is a constant (0.802), \(\omega_c\) is the angular frequency, ‘\(f_c\)’ is the cutoff frequency, ‘\(f_s\)’ is the sampling frequency. \(k_1, k_2\) and \(k_3\) are filter coefficients.

Fig.D.1: Original pressure data (Blue) and filtered data (Red).
Various polymer concentrations (125, 250, 500, 1000, 2000, 3000 and 5000 ppm) used as a part of the project. The effluents collected at the outlet at specified time intervals were analyzed for the Total Organic Carbon (TOC) using DC-190 Dohrmann High Temperature TOC Apparatus (Fig.E-1).

1. The DC-190 apparatus consists of vertical quartz combustion tube packed with platinum catalyst at 680°C, which receives the continuous flow of oxygen at 200 cc/min.
2. A sample volume of 100 μL is introduced manually into the combustion tube via air actuated injection port.
3. Catalytic oxidation of the sample is complete after injection into the furnace, turning oxidizable material in the sample into gaseous form (CO₂) and H₂O.
4. A carbon-free carrier gas transports the CO₂ containing steam out of the combustion tube and into the IC reactor.
5. Then it passes through a condenser, a gas liquid separator and the moisture trap. The H₂O removal is accomplished by the permeation dryer.
6. The dried CO₂ gas is then passed through the non-dispersive infrared detector (NDIR) for the detection of the total carbon content.

Initially, the TOC content in the original polymer solution of specified polymer concentration was measured. This value was then used as a reference for converting the TOC content in the other effluent samples into the polymer concentration.

Fig.E.1: Photograph of DC-190 Dohrmann High Temperature TOC Apparatus.
**F Tracer Potassium Iodide (KI) analysis of Effluents**

Potassium Iodide (KI) tracer with a concentration of 10,000 ppm was used for all the core flood experiments carried out as a part of this project. The tracer concentration in the effluent samples was measured with the help of a UV Spectrophotometer (Fig.F-1). The UV Spectrophotometer is widely used to determine the concentration of chemical species that transmit (or) reflect light in the visible region (400 - 700 nm) of the electromagnetic spectrum. It measures the ratio of intensity of transmitted light ($I$) to the intensity of incident light ($I_o$). The ratio of ($\frac{I}{I_o}$) is referred to as the transmittance.

The spectrophotometer then displays absorbance (the amount of light absorbed relative to the initial substance) which is given by the formula as shown below.

$$A_b = \log\left(\frac{I}{I_o}\right)$$

Prior to the analysis using a UV Spectrophotometer the effluent samples were diluted 900 times. For each single measurement the UV transparent measurement cell was filled with a 1.5 ml liquid sample and is attached to the optical transparent cell holder. In this spectrometer the intensity of incident beam is recorded prior to entering the sample. The detector measures the transmitted light intensity from which the absorbance can be calculated using the above formula. Similar to the TOC analysis, initially the absorbance of the sample containing the injected tracer concentration was calculated, which was then used as a reference for obtaining the tracer concentration (using the linear calibration plot) of all the effluent samples.

![Fig.F.1: Photograph of UV Spectrophotometer (UV Mini Schimadzu).](image-url)
G Calculation of Experimental and Model Parameters

G.1 Porosity

The core samples used for the experiments were Bentheim sandstone. The porosity of each sample was found from the tracer breakthrough profile after subtracting the dead volume of the experimental setup. The values summarized with the results of each experiment in Appendix. H.

G.2 Permeability

Brine was flown through the core at different flow rates and the associated pressure drop was measured. A best fit linear regression line was used for finding the slope \( \frac{\Delta P}{q} \) for calculating the permeability as shown in Fig.G-1 (125 ppm). With the help of slope and Darcy’s law (Eq. G.1), the permeability values were calculated. The results were summarized with the results of each experiment in Appendix. H.

\[
k = \frac{q\mu_b L}{\Delta P} = \frac{\mu_b L}{A(Slope)} \quad (G.1)
\]

![Fig.G.1: Plot of pressure drop at different flow rates for determination of liquid permeability.](image-url)
G.3 Dead Volume

Dead volume is the volume of the entire experimental setup excluding the core. The setup was flushed with brine to remove any traces of air if present. CO2 was then flushed and the brine from the setup was collected at the outlet. Also, an alternative method of flowing brine through the setup and noting the time for the breakthrough was also performed for accurate results. The total dead volume, inlet and outlet dead volumes were calculated separately.

Table.G.1
Dead volume measurements of the experimental setup.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Total Dead Volume (cc)</th>
<th>Inlet Dead Volume (cc)</th>
<th>Outlet Dead Volume (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.9 ± 1</td>
<td>14.4 ± 0.5</td>
<td>11.5 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>24.6 ± 1</td>
<td>14.2 ± 0.5</td>
<td>10.4 ± 0.5</td>
</tr>
<tr>
<td>3</td>
<td>25.9 ± 1</td>
<td>14.8 ± 0.5</td>
<td>11.1 ± 0.5</td>
</tr>
<tr>
<td>Final</td>
<td>25.4 ± 1</td>
<td>14.4 ± 0.5</td>
<td>11.0 ± 0.5</td>
</tr>
</tbody>
</table>

G.4 Average Pore Throat Radius

Average pore throat radius is also an important parameter controlling the flow of polymer solutions in porous media. The equivalent capillary radius of the porous medium can be expressed as (Zitha, 2001),

\[ r_p = \alpha \sqrt[8]{\frac{k}{\phi}} \]  \hspace{1cm} (G.2)

Where, \( k \) is the permeability and \( \alpha = 1.2 \) is a geometric factor for porous medium structure (Denys, 2003).
H  Experimental and Modelled Results

H.1 Experiment – 1

Table.H.1
Solution and petrophysical parameters of the core flood experiment-1 (125 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>125</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.23 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.450 \pm 0.08$</td>
</tr>
</tbody>
</table>

Table.H.2
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (125 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>11.46</td>
<td>11.98</td>
<td>0.4</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>1.2</td>
<td>1.173</td>
<td>0.04</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.02</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.83</td>
<td>0.85</td>
<td>0.03</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>3.82E-5</td>
<td>3.67E-5</td>
<td>0.15E-5</td>
</tr>
<tr>
<td>$f$ (fraction)</td>
<td>-</td>
<td>0.938</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig.H.1: Raw and filtered pressure drop vs. PV injected (125 ppm).
Fig.H.2: Pressure drop for polymer vs. PV injected (125 ppm).

Fig.H.3: Mobility reduction vs. PV injected (125 ppm).

Fig.H.4: Polymer injectivity vs. PV injected (125 ppm).
**H.2 Experiment - 2**

**Table H.3**
Solution and petrophysical parameters of the core flood experiment-2 (250 ppm).

<table>
<thead>
<tr>
<th><strong>Solution Parameters</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>250</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.21 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.314 \pm 0.11$</td>
</tr>
</tbody>
</table>

**Table H.4**
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (250 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>15.27</td>
<td>14.96</td>
<td>0.49</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>1.41</td>
<td>1.38</td>
<td>0.03</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.039</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.74</td>
<td>0.72</td>
<td>0.02</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>5.71E-5</td>
<td>5.60E-5</td>
<td>0.11E-5</td>
</tr>
<tr>
<td>$f$ (fraction)</td>
<td>-</td>
<td>0.94</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. H.6: Raw and filtered pressure drop vs. PV injected (250 ppm).

Fig. H.7: Pressure drop for polymer vs. PV injected (250 ppm).

Fig. H.8: Mobility reduction vs. PV injected (250 ppm).
Fig.H.9: Polymer injectivity vs. PV injected (250 ppm).

Fig.H.10: Effluent concentration vs. PV injected (250 ppm).

H.3 Experiment - 3

Table.H.5
Solution and petrophysical parameters of the core flood experiment-3 (500 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>500</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.22 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.499 \pm 0.08$</td>
</tr>
</tbody>
</table>
Table H.6
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (500 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>16.73</td>
<td>18.02</td>
<td>1.01</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>1.673</td>
<td>1.801</td>
<td>0.1</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.06</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.59</td>
<td>0.55</td>
<td>0.04</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.008</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>8.84E-5</td>
<td>8.73E-5</td>
<td>2E-6</td>
</tr>
<tr>
<td>$f$ (fraction)</td>
<td>-</td>
<td>0.94</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. H.11: Raw and filtered pressure drop vs. PV injected (500 ppm).

Fig. H.12: Pressure drop for polymer vs. PV injected (500 ppm).
Fig.H.13: Mobility reduction vs. PV injected (500 ppm).

Fig.H.14: Polymer injectivity vs. PV injected (500 ppm).

Fig.H.15: Effluent concentration vs. PV injected (500 ppm).
H.4 Experiment - 4

Table H.7
Solution and petrophysical parameters of the core flood experiment-4 (1000 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>1000</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.22 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.659 \pm 0.10$</td>
</tr>
</tbody>
</table>

Table H.8
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (1000 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>28.6</td>
<td>25.42</td>
<td>3.11</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>3</td>
<td>2.704</td>
<td>0.34</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.079</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.33</td>
<td>0.36</td>
<td>0.06</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>1.14E-4</td>
<td>1.13E-4</td>
<td>0.01E-4</td>
</tr>
<tr>
<td>f (fraction)</td>
<td>-</td>
<td>0.942</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. H.16: Raw and filtered pressure drop vs. PV injected (1000 ppm).
Fig.H.17: Pressure drop for polymer vs. PV injected (1000 ppm).

Fig.H.18: Mobility reduction vs. PV injected (1000 ppm).

Fig.H.19: Polymer injectivity vs. PV injected (1000 ppm).
Fig.H.20: Effluent concentration vs. PV injected (1000 ppm).

Fig.H.21: Scaling factor vs. polymer concentration (1000 ppm).

H.5 Experiment - 5

Table.H.9

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>2000</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.21 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.450 \pm 0.09$</td>
</tr>
</tbody>
</table>
Table.H.10
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (2000 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>45.69</td>
<td>51.6</td>
<td>5.97</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>4.40</td>
<td>5.05</td>
<td>0.60</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.098</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.22</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.004</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>1.329E-4</td>
<td>1.326E-4</td>
<td>3E-7</td>
</tr>
<tr>
<td>( f ) (fraction)</td>
<td>-</td>
<td>0.941</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig.H.22: Raw and filtered pressure drop vs. PV injected (2000 ppm).

Fig.H.23: Pressure drop for polymer vs. PV injected (2000 ppm).
Fig. H.24: Mobility reduction vs. PV injected (2000 ppm).

Fig. H.25: Polymer injectivity vs. PV injected (2000 ppm).

Fig. H.26: Effluent concentration vs. PV injected (2000 ppm).
**Fig.H.27:** Scaling factor vs. polymer concentration (2000 ppm).

**H.6 Experiment - 6**

**Table.H.11**
Solution and petrophysical parameters of the core flood experiment-6 (3000 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^5$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>3000</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.22 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.272 \pm 0.09$</td>
</tr>
</tbody>
</table>

**Table.H.12**
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (3000 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>92.03</td>
<td>93.8</td>
<td>4.66</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>8.36</td>
<td>8.52</td>
<td>0.44</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.112</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.11</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.003</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>$1.585E-4$</td>
<td>$1.583E-4$</td>
<td>2E-7</td>
</tr>
<tr>
<td>$f^*$ (fraction)</td>
<td>-</td>
<td>0.938</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig.H.28: Raw and filtered pressure drop vs. PV injected (3000 ppm).

Fig.H.29: Pressure drop for polymer vs. PV injected (3000 ppm).

Fig.H.30: Mobility reduction vs. PV injected (3000 ppm).
Fig.H.31: Polymer injectivity vs. PV injected (3000 ppm).

Fig.H.32: Effluent concentration vs. PV injected (3000 ppm).

Fig.H.33: Scaling factor vs. polymer concentration (3000 ppm).
H.7 Experiment - 7

Table.H.13
Solution and petrophysical parameters of the core flood experiment-7 (5000 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>5000</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$20 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.21 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.014 \pm 0.03$</td>
</tr>
</tbody>
</table>

Table.H.14
Values of the key parameters obtained from experiments and modeling and the absolute error associated with the modeling of experimental data (5000 ppm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experiments</th>
<th>Modelling</th>
<th>Mean. Abs. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (mBar)</td>
<td>218</td>
<td>218</td>
<td>5.25</td>
</tr>
<tr>
<td>Mobility Reduction (-)</td>
<td>17.61</td>
<td>17.61</td>
<td>0.42</td>
</tr>
<tr>
<td>Permeability Reduction (-)</td>
<td>-</td>
<td>1.12</td>
<td>-</td>
</tr>
<tr>
<td>Injectivity (-)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0025</td>
</tr>
<tr>
<td>Lambda (1/cm)</td>
<td>-</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption (g/g)</td>
<td>1.664E-4</td>
<td>1.664E-4</td>
<td>-</td>
</tr>
<tr>
<td>$f$ (fraction)</td>
<td>-</td>
<td>0.935</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig.H.34: Raw and filtered pressure drop vs. PV injected (5000 ppm).
Fig. H.35: Pressure drop for polymer vs. PV injected (5000 ppm).

Fig. H.36: Mobility reduction vs. PV injected (5000 ppm).

Fig. H.37: Polymer injectivity vs. PV injected (5000 ppm).
Fig.H.38: Effluent concentration vs. PV injected (5000 ppm).

Fig.H.39: Scaling factor vs. polymer concentration (5000 ppm).

H.8 Experiment - 8

Table.H.15
Solution and petrophysical parameters of the core flood experiment-8 (500-10 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^5$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>500</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$10 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.21 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.314 \pm 0.07$</td>
</tr>
</tbody>
</table>
Fig.H.40: Raw and filtered pressure drop vs. PV injected (500-10 ppm).

Fig.H.41: Pressure drop for polymer vs. PV injected (500-10 ppm).

Fig.H.42: Mobility reduction vs. PV injected (500-10 ppm).
Fig. H.43: Polymer injectivity vs. PV injected (500-10 ppm).

Fig. H.44: Effluent concentration vs. PV injected (500-10 ppm).

H.9 Experiment - 9

Table H.16
Solution and petrophysical parameters of the core flood experiment-9 (500-5 ppm).

<table>
<thead>
<tr>
<th>Solution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>AN905 Lot E 2686</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>Degree of Hydrolysis (%)</td>
<td>5</td>
</tr>
<tr>
<td>Concentration (ppm)</td>
<td>500</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$5 \pm 0.1$</td>
</tr>
<tr>
<td>pH</td>
<td>$5.8 \pm 0.1$</td>
</tr>
<tr>
<td>Flow rate (cc/min)</td>
<td>$1 \pm 0.02$</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>$0.21 \pm 0.01$</td>
</tr>
<tr>
<td>Permeability (Darcy)</td>
<td>$2.211 \pm 0.06$</td>
</tr>
</tbody>
</table>
Fig.H.45: Raw and filtered pressure drop vs. PV injected (500-5 ppm).

Fig.H.46: Pressure drop for polymer vs. PV injected (500-5 ppm).

Fig.H.47: Mobility reduction vs. PV injected (500-5 ppm).
Fig.H.48: Polymer injectivity vs. PV injected (500-5 ppm).

Fig.H.49: Effluent concentration vs. PV injected (500-5 ppm).
References