Pressure Drop Separation during Aqueous Polymer Flow in Porous Media

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Abstract: This paper investigates the non-Newtonian behavior of aqueous polymers solutions while flowing through porous media with the support of COMSOL Multiphysics. The single phase Darcy Law interface was used to solve Darcy's equation in order to calculate the pressure drop that occurred during the core flooding experiment. Furthermore, an equation proposed by some of the authors was utilized as an input to the simulator. The results are validated by quantitatively comparing the results from the simulation with those obtained from the laboratory experiment. Results obtained from the simulation showed to be in good agreement with the experimental results, indicating a successful implementation of the proposed equation in the simulator. Due to its capabilities and flexible framework to integrate physical and chemical mechanisms during polymer flow in the porous media or enhanced oil recovery (EOR) processes, COMSOL provides an alternative for current reservoir simulators used in the oil and gas industries.

Keywords: Enhanced Oil Recovery, Non-Newtonian, Porous Media, Numerical Simulation.

1. Introduction

Enhanced oil recovery (EOR) can be defined as a method to recover the remaining oil from the porous subsurface reservoir by using a material which is not normally present in the reservoir. The method may use steam, miscible gas or chemical substances such as the surfactant or aqueous polymer solution. One of the most widely used EOR methods is polymer flooding. The polymer solution is mixed with the injected water thereby increasing its viscosity and as results improving the sweep efficiency of the reservoir. This can significantly increase the oil recovery factor. However, detailed understanding of physical and chemical processes occurred during polymer flow in porous media is essential while designing the polymer EOR project.

Different researchers have been investigating the polymer flow behavior in porous media since last decades. There remain however several mechanisms, for instance, non-Newtonian flow behavior and polymer retention that are not fully understood and require a further study due to the complexities of the polymer solutions [1].

Due to its nature as a complex fluid, aqueous polymers used in enhanced oil recovery (EOR) can exhibit both Newtonian and non-Newtonian flow behavior. It depends on the interstitial velocity or the stress magnitude that is applied during the flooding process. This behavior results in different pressure drops while flowing through the porous media which are termed as shear pressure drop and elongation pressure drop [2].

Shear pressure drop is defined as a differential pressure occurred due to shear thinning behavior. This exists in particular in the low or medium shear rate region. Meanwhile, elongation pressure drop is defined as a differential pressure occurred due to shear thickening behavior. This normally exists in the high shear rate region. Both pressure drop contributes to the total pressure drop occurred during the flow of aqueous polymer in the porous media [2].

Commercial reservoir simulator used in the oil and gas industry often calculate the pressure drop by assuming shear thinning and thickening behavior. However, it cannot separate both flow behaviors of aqueous polymers. Therefore, the main objective of this papers is COMSOL implementation to numerically solve the pressure drop calculation by separating and taking into account the shear and elongation contribution to the total pressure drop.

2. Experimental Design and Polymer Flow Behavior in Porous Media

Different experiments were performed in order to obtain the required data [3]. Experimental evaluations include flooding the polymer solutions through different porous structures such as Bentheimer core plug flooding, sand pack flooding and micromodel flooding. Rheological evaluations were performed with a rotational rheometer and by using an extensional-viscometer- rheometer-on-a-chip (eVROC^{TM}). The polymer used for the evaluations here presented was Flopaam 1500 ppm non-sheared 0.4 g/l brine. Further details on the preparation process can be found in the work presented by Hincapie and Ganzer [4]. The discussions on this paper are however based on the core plugs flooding and eVROC^{TM} experiments.

2.1 Core Flooding

The core flooding experiment was performed by using a Bentheimer core samples. The core sample was placed inside the core holder made from steel. The confining pressure was applied surrounding the core sample to generate the radial flow through the core during the flooding process. The pressure drop was recorded and measured by using the computer attached to the pressure transducer. The figure (1) can illustrate the core flooding experiment performed at the Institute of Petroleum Engineering (ITE).

2.2 eVROC^{TM} experiment

The extensional-viscometer-rheometer-on-a-chip (eVROC^{TM}) has been utilized to characterize the complex fluid [1]. The results from this experiment can be used to describe the role of shear deformation and elongation deformation to the total pressure drop during the polymer flow in the porous media. The eVROC^{TM} also enables us to illustrate the contraction flow path due to pore geometry and distribution. The figure (2) shows us the eVROC^{TM} used in the experiment.

2.3 Bulk Viscosity of Aqueous Polymers

Bulk viscosity of aqueous polymers was measured using a rotational rheometer. The results can be used to describe the shear thinning behavior of the polymer solution. It cannot, however, be directly used to calculate the shear pressure drop occurred in the porous media since the rheometer does not have a porous media characteristic. Therefore, the conversion process should be performed in order to be able to utilize the results.

Results obtained from the rheometer were described in the form of Power Law model proposed by *Bird et al* [5]:

$$\mu_{eff} = H\left(\frac{\partial u}{\partial y}\right)^{(n-1)} \qquad (1)$$

where $\mu_{\boldsymbol{eff}}$ is the apparent viscosity measured from the rheometer, H is the flow consistency index, $\left(\frac{\boldsymbol{\partial u}}{\boldsymbol{\partial y}}\right)$ is the shear rate and n is the flow behavior index

However, this model is not able to fully describe the viscosity at the low shear rate region, thus we used Carreau-Yasuda (1979) model [6][7]:

$$\mu_{sh} = \mu_{\infty} + \left(\mu_p^0 - \mu_{\infty}\right) \left[1 + (\lambda\dot{\gamma})^{\alpha}\right]^{\frac{(n-1)}{\alpha}} \qquad (2)$$

where μ_{sh} is the shear viscosity, μ_{∞} is the viscosity of polymer at very high or infinite shear rate region, μ_p^0 is the viscosity of polymer at very low or zero shear rate region $\dot{\gamma}$ is the equivalent shear rate, λ is the relaxation time and n is the empirical parameter constant.

2.4 Equivalent Shear Rate

The shear rate measured in the rheometer is not directly comparable with the shear rate in porous media, thus an adjustment was required. The correlation derived from Hagen-Poiseuille was applied to calculate the equivalent shear rate in porous media by taking into account the permeability and the porosity. The correlation is written as:

$$\dot{\gamma}_{eq} = \left(\frac{3n+1}{4n}\right)\alpha\frac{u}{\sqrt{8k\Phi}} \qquad (3)$$

where $\dot{\gamma}_{eq}$, n, α, u, k, Φ is equivalent shear rate, the power law exponent obtained from the rheometer, correction factor, Darcy velocity, permeability, and porosity, respectively

2.5 Apparent Viscosity in Porous Media

The viscosity of the polymer solution during core flooding experiment is calculated by using a Carreau-Yasuda equation. This equation takes into account the equivalent shear rate calculated from the correlation (3). The equation is written as:

$$\mu_{app} = H\dot{\gamma}_{eq}{}^{n-1} \qquad (4)$$

2.6 Shear and Elongation Pressure Drop in Porous Media

We can calculate the shear pressure drop in porous media by using a Darcy correlation. However, the pressure drop resulted from Darcy calculation is considered as shear pressure drop in this case:

$$\Delta P_{sh} = \frac{Q\mu_{app}L}{KA} \qquad (5)$$

where ΔP_{sh} is shear pressure drop, Q is injection rate, L is the length of the porous media and A is the area.

Elongation pressure drop is meanwhile calculated by using the following equation [2]:

$$\Delta P_t = \Delta P_{sh} + \Delta P_{el} \qquad (6)$$

Where ΔP_t is the total pressure drop and ΔP_{el} is the elongation pressure drop.

2.7 CR_P Ratio

In this work, we obtained elongation pressure drop by using eVROC^{TM} or extensional-viscometer-rheometer-on-a-chip. However, the results from eVROC^{TM} are not directly comparable to the results from the core plug flooding experiment due to different porous media characteristics. Therefore, Hincapie and Gaol [8] from ITE proposed a new correlation to establish the relationship between results obtained from eVROC^{TM} and results obtained from core flooding experiment. The correlation relates the structural characteristics (geometrical characteristics) of both porous media: eVROC^{TM} device and Bentheimer core plug. The correlation introduces pressure ratio between elongation pressure drop and shear pressure drop as a comparison term and is written as:

$$CRp = \frac{\Delta P_{el}}{\Delta P_{sh}} \qquad (7)$$

and

$$CRp_{(c)} = CRp_{(e)} 0.0038c[\eta]^2 - 0.0053c[\eta] + 0.1482 \qquad (8)$$

Equation (8) takes into account polymer concentration (c) and intrinsic viscosity (η) in the calculation. $CRp_{(c)}$ is defined as the pressure ratio from the core flooding experiment and $CRp_{(e)}$ is defined as the pressure ratio from the eVROC^{TM} experiment.

3. Simulation Model and Set-Up

A three dimensional cylinder was set up as a simulation model to represent the core flooding experiment and is illustrated in figure (3). Here, several assumptions were made in the simulation:

- No oleic phase or single phase.
- Flow in one direction.
- Fluid is incompressible.
- Gravity forces is neglected.
- Atmospheric pressure at the outlet.
- Homogeneous rock properties.
- Adsorption is neglected.
- Steady state flow.

The input parameters for the simulation are listed on the table 1

Table 1: Input parameters used in simulation

Parameter	Value	Unit
Radius, r	1.5	cm
Length, l	6	cm
Initial Pressure, P_i	1	bar
Porosity, Φ	0.264	-
Permeability, $\boldsymbol{k}$	1	D
Water Saturation, S_w	1	-
Rock density, ρ_r	2650	Kg/m^3

Outlet Pressure, P_o	1	Bar
Max. element size, Δx	1	cm
Min. element size, Δx	0.15	cm
Time step, Δt	1	Min

The model was calibrated for fluid dynamics. Multiple injection rates were applied in the simulator. Moreover, free tetrahedral was selected as the simulation grid with extra coarse element size to reduce the simulation time. This is shown in figure (4).

4. COMSOL Implementation

In COMSOL, a single phase Darcy Law interface was selected to solve the pressure drop problem. COMSOL implementation requires several adjustments to illustrate the core flooding experiment.

COMSOL uses a Darcy equation that is written as:

$$u = -\frac{k}{\mu}\nabla P \qquad (9)$$

where ∇P is the pressure divergent or pressure in x, y, z direction.

The confining pressure in the laboratory experiment was replaced by the no flow boundary condition:

$$-n.\rho u = 0 \qquad (10)$$

The use of no flow boundary condition is to create the one-dimensional flow direction. We also used the inflow and outflow velocity as the simulation constraint which assumes steady state flow condition Both equations are written as:

For Inlet:

$$-n.\rho u = \rho U_0 \qquad (11)$$

For Outlet

$$-n.\rho u = -\rho U_0 \qquad (12)$$

where n is the normal vector, $\boldsymbol{\rho}$ is the fluid density, and $\mathbf{U_0}$ is the flow velocity.

5. Simulation Results

Simulation results are presented in figure (5). Results were plotted in the form of differential pressure versus interstitial velocity. The interstitial velocity can be calculated by using below equation:

$$\dot{v} = \frac{q}{A\varphi} \qquad (9)$$

Simulation results from shear pressure drop are in a very good agreement with those obtained from the experimental evaluations. Meanwhile, the simulation result from elongation pressure drop shows an acceptable match. Overall, both simulation results indicate a successful implementation of COMSOL to simulate and separate two different pressure drop that occurred during polymer flow in porous media.

5.1 CR_P Ratio Simulation

With the purpose of validation, we simulated the CR_P ratio in COMSOL. CR_P ratio was used as an input variable in the simulator. It can be defined in the component section and has different values for each injection rate and pressure drop. Results can be seen in figure (6).

Firstly, CR_P calculated values were obtained from the experimental data, as it was previously explained. Secondly, CR_P core from the proposed equation was used to validate the experimental results. Finally, we implemented CR_P equation in COMSOL to obtain the simulation results. Simulation results are in a good agreement with the experimental results indicating also a successful implementation of CR_P equation in the simulator.

6. Conclusion

COMSOL is able to solve the pressure drop problem during polymer flow in porous media by taking into account the non-Newtonian flow behavior of aqueous polymers. Furthermore, we were able to separate shear and elongation pressure drop contribution by using COMSOL. The presented results of pressure drop simulation and CR_P ratio simulation show, in general, a good agreement with the experimental results. Overall, the results provide us with the new insight of the polymer flow behavior in porous media.

7. Outlook

Due to its Multiphysics capabilities, COMSOL provides a flexible framework to simulate the polymer flooding process by taking into account chemical and physical phenomenon relevant to the chemical EOR process. Current reservoir simulators are able to simulate the chemical EOR process, but they lack of those flexible frameworks offered by COMSOL. For future work, the research may be extended to simulate two-phase conditions where the oleic phase is added. The results also provide us with the new insight in designing a polymer flooding project. In addition, a comparison with other simulators is also suggested to validate the results from COMSOL.

8. Acknowledgments

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9. References

1. Gaol, C.L, Investigation of Non-Newtonian Flow Behavior of Commercial EOR Polymers in Sand Packs and Cores, Master Thesis TU-Clausthal, Clausthal-Zellerfeld (2015).
2. Sheng, J., Modern Chemical Enhanced Oil Recovery: Theory and Practice, Elsevier Inc. Burlington, USA (2011).
3. Hincapie, R. E., Duffy, J., O'Grady, C., & Ganzer, L. An Approach to Determine Polymer Viscoelasticity Under Flow Through Porous Media by Combining Complementary Rheological Techniques. SPE – 174689 SPE Asia Pacific Enhanced Oil Recovery Conference. 11-13 August, Kuala Lumpur, Malaysia. (2015).
4. Hincapie, R., Ganzer, L., Assessment of Polymer Injectivity with Regards to Viscoelasticity: Lab Evaluations towards Better Field Operations, in EUROPEC 2015. 2015, Society of Petroleum Engineers, SPE-174346-MS: Madrid, Spain (2015).
5. Bird, R. B.; Armstrong R. C. and Hassager, O. Dynamics of Polymeric Liquids, Fluid Mechanics, Volume1, Wiley Interscience, New York (1987).
6. Carreau, P.J., Rheological Equations from Molecular Network Theories, *Trans. Soc. Rheol*, 16 (1), (1972).
7. Yasuda, K., Investigation of the Analogies between Viscometric and Linear Viscoelastic Properties of Polystyrene Fluids. PhD thesis, Massachusetts Institute of Technology. Dept. of Chemical Engineering, USA (1979).
8. Hincapie, R.E. Pore-Scale Investigation of the Viscoelastic Phenomenon during Enhanced Oil Recovery (EOR) Polymer Flooding through Porous Media. Doctoral Dissertation. PapierFlieger Verlag GmbH. 2016
9. Ober, T. J., Haward, S. J., Pipe, C. J., Soulages, J. & McKinley, G. H, Microfluidic Extensional Rheometry using a Hyperbolic Contraction Geometry, *Rheologica Acta*, 52, 529–546. (2013)
10. D. M Jones and K. Walter, The Behaviour of Polymer Solutions in Extension-Dominated Flows, with Applications to Enhanced Oil Recovery, *Rheology Acta*, Vol. 28 (6), p. 482 (1989)

10. Appendix A. Figures

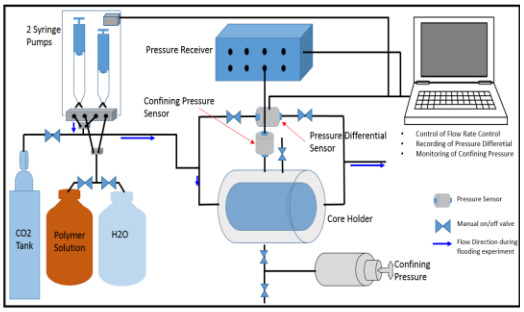

Figure 1 Experimental Set Up of Core Flooding [1]

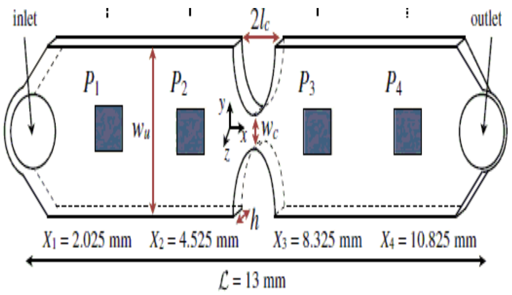

Figure 2 eVROC^{TM} Chip [3][9]

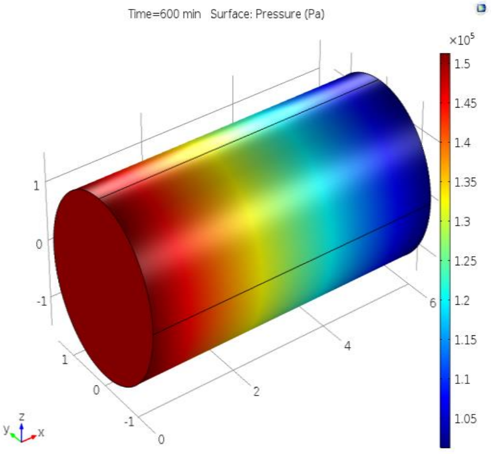

Figure 3 COMSOL Core Model

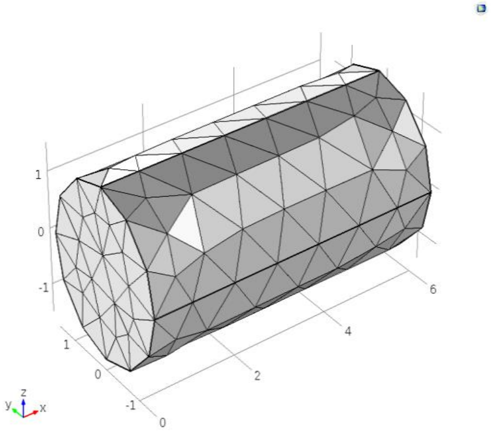

Figure 4 COMSOL Core Model Discretization

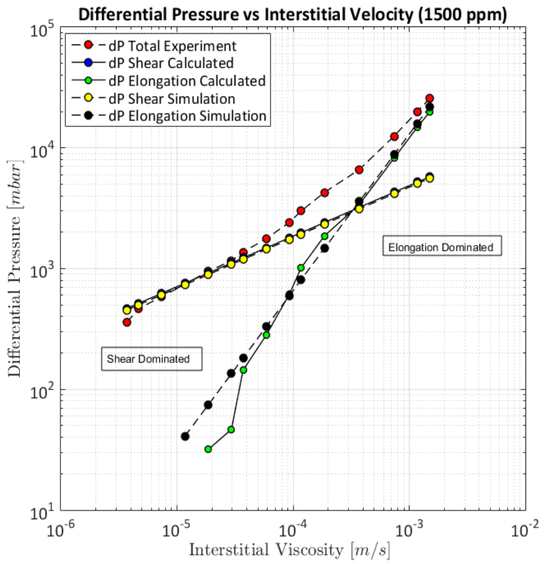

Figure 5 Core Flooding Simulation Results

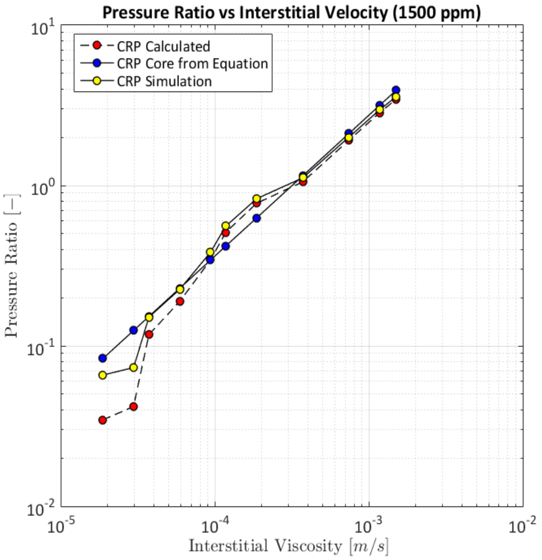

Figure 6 CR_P Ratio Simulation Results