Numerical Simulation of Oil Recovery by Polymer Injection using COMSOL

J. Wegner[*1], L. Ganzer[1]
[1]Clausthal University of Technology
*Corresponding author: Agricolastraße 10, 38678 Clausthal, Germany, reseng@ite.tu-clausthal.de

Abstract: In this paper we used COMSOL Multiphysics to model basic physico-chemical effects relevant in polymer enhanced oil recovery (EOR) such as non-Newtonian rheology of the displacing phase, permeability reduction, adsorption and salinity effects. COMSOL's PDE interface as well as Species Transport in Porous Media interface was used for solving the underlying mass accumulation, transport and auxiliary equations. The validity of the implementation is tested by comparing the results obtained with COMSOL with those obtained from the commercial simulator ECLIPSE Blackoil [1] which is a simulator used in the oil industry. The results show good agreement indicating successful implementation. Due to its PDE Interface and Species Transport in Porous Media Interface COMSOL Multiphysics provides a flexible framework to implement physical and chemical mechanisms relevant to polymer EOR. Although commercial software for simulation of polymer EOR processes exists, it lacks the multi-physics capabilities of COMSOL. Underlying transport and auxiliary equations can be varied or extended and other physics such as temperature or geo mechanical effects integrated. This is an important aspect in research.

Keywords: Enhanced Oil Recovery, Numerical Simulation, Polymer Flooding, Porous Media, Finite Element Method

1. Introduction

Oil extraction from porous subsurface reservoirs can be classified into three different stages, namely the primary, secondary and tertiary recovery. The latter one is also termed enhanced oil recovery (EOR).

Within the primary recovery phase the natural drive energy already available in the reservoir is utilized to produce the oil. Natural energy includes rock and fluid expansion, water influx, solution drive, gas cap drive and gravity drainage. During the primary recovery period no further energy needs to be injected into the reservoir. Later, due to oil extraction the natural drive energy declines.

To maintain production external energy sources, mainly water or gas are injected into the reservoir for the purpose of maintaining reservoir pressure and improving sweep efficiency. This phase is considered as secondary recovery.

With increasing energy demand and high oil prices sophisticated tertiary recovery technologies are implemented to extract more oil from existing hydrocarbon reservoirs. Enhanced oil recovery consists of the injection of chemicals, heat or miscible gases which are in general not normally present in the reservoir.

One of the chemical tertiary technologies which can significantly increase the oil recovery factor is termed polymer EOR. It involves the mixing of special polymers with the injection water to increase water viscosity and reduce water permeability during the flow through porous media. As a result the mobility of water is decreased, leading in a more efficient displacement process and a higher oil recovery factor. However, several physical and chemical processes accompany the flow of aqueous polymer solutions through the porous formation resulting in loss of polymer solution viscosity, hence, in lower oil recovery. Detailed understanding of these effects is crucial to successfully design polymer EOR projects.

The goal of this work is the COMSOL implementation of a numerical model capable to simulate the recovery of oil by means of polymer EOR taking into account basic physico - chemical effects. The model will be the basis for further and more detailed investigations.

2. The Polymer Flood Model

A two phase, four component polymer EOR model is implemented into COMSOL to simulate the displacement of oil by aqueous polymer solutions. The oleic phase consists of a single component oil, while the aqueous phase contains the components mobile water, polymer and salt. Although several complex physico-chemical processes influence the flow of aqueous polymer

solutions in porous media, here we make the following assumptions:

1.) The model is one-dimensional, the rock properties are homogeneous, and gravity is neglected.

2.) The process is isothermal.

3.) The oelic and aqueous phase as well as the porous media are incompressible.

4.) Polymer adsorption reduces the relative permeability of the aqueous phase only.

5.) Generalized Darcy's law is applicable to multiphase flow.

6.) Multicomponent dispersion is neglected.

7.) Salt is not adsorbed to the solid surface, but has an impact on the viscosity of the aqueous polymer solution.

8.) Salt, polymer and mobile water are fully mixed.

2.1 Flow Equations

Taking into account the above assumptions the simultaneous flow of two immiscible fluid phases in porous media can be described by the mass conservation equation for each phase. For the aqueous phase this is written as:

$$\frac{\partial(\phi S_a)}{\partial t} = \nabla \cdot \left(\frac{k_a}{\mu_a} \nabla p_a \right) + \widetilde{q}_a \qquad (1)$$

The mass conservation equation for the oelic phase is:

$$\frac{\partial(\phi S_o)}{\partial t} = \nabla \cdot \left(\frac{k_o}{\mu_o} \nabla p_o \right) + \widetilde{q}_o \ , \qquad (2)$$

where p, μ, S, k, ϕ are the pressure, viscosity, saturation, effective permeability and porosity of the porous media. The subscripts o and a represent the oelic and aqueous phases, respectively. $\widetilde{q}$ is the source/sink term.

The fact that the void space of the porous media is completely filled with the oelic and aqueous phase, leads to the following relation:

$$S_a + S_o = 1 \qquad (3)$$

2.2 Transport Equations

Polymer and salt are convected with the bulk Darcy velocity of the aqueous phase. For both, salt and polymer, a transport equation is required. The equation for polymer transport is written as:

$$\frac{\partial(\phi S_a C_p)}{\partial t} + \frac{\partial(\rho_r (1-\phi) C_{pad})}{\partial t}$$
$$= \nabla \cdot \left(C_p \frac{k_a}{\mu_a} \nabla p_a \right) + \widetilde{q}_a C_{pw} \qquad (4)$$

The equation for salt transport is written as:

$$\frac{\partial(\phi S_a C_s)}{\partial t} = \nabla \cdot \left(C_s \frac{k_a}{\mu_a} \nabla p_a \right) + \widetilde{q}_a C_{sw} \qquad (5)$$

Where C, ρ_r are the component concentration and bulk density of the rock. The subscripts p, s represent the polymer and salt components, respectively. C_{pw} and C_{sw} are the polymer and salt concentration at the injection boundary. C_{pad} is the mass of polymer adsorbed per unit mass of rock.

Due to adsorption of polymer on the rock-fluid interface, physical parameters such as the rock permeability change. In addition to adsorption, non-Newtonian rheology and salinity effects have an impact on the aqueous phase viscosity. Therefore, additional constitutive equations are required to close and couple the system of equations (1) – (5).

2.3 Cross Couplings

2.3.1 Salinity and Concentration Effects

The viscosity of the polymer solution at "zero" shear rate depends on the salt as well as polymer concentration. A mathematical relation

describing the dependence of the aqueous phase viscosity on polymer and salt concentration is the Flory-Huggins equation [2].

$$\mu_a^0 = \mu_w \left(1 + \left(a_1 C_p + a_2 C_p^2 + a_3 C_p^3\right) C_s^{Sp}\right) \quad (6)$$

Where, a_1, a_2, a_3, and S_p are fitting constants. The units of the fitting constants are selected such, that the items in the parenthesis become dimensionless.

2.3.2 Polymer Adsorption

Polymer adsorption causes a reduction of polymer concentration in the aqueous phase, hence, a reduction in aqueous phase viscosity. The degree of polymer adsorption depends on the type of polymer and rock, but in general increases with higher polymer concentrations. The relation between the concentration of polymer in the aqueous phase and the concentration of polymer in the adsorbed state is described by the Langmuir isotherm [3].

$$\frac{C_{pad}}{C_{pad}^{max}} = \frac{bC_p}{1 + bC_p} \, , \quad (7)$$

where b is a Langmuir constant, C_{pad}^{max} is the maximum polymer concentration adsorbed to the rock.

2.3.4 Permeability Reduction Factor

As a result of polymer adsorption on the rock surfaces the permeability to the aqueous phase is reduced, while the permeability of the oelic phase is unaltered. The permeability reduction factor representing the effect of polymer adsorption on the permeability of the aqueous phase is defined as $R_k = k_w / k_a$, where k_w is the water permeability. Further the permeability reduction factor can be expressed as [4]:

$$R_k = 1 + \left(R_{RF} - 1\right) \frac{C_{pad}}{C_{pad}^{max}} \, , \quad (8)$$

where R_{RF} is the residual resistance factor. It represents the decrease in rock permeability when the maximum amount of polymer is adsorbed [1].

2.3.5 Non-Newtonian Rheology

The aqueous polymer solution behaves like a non-Newtonian fluid. Often shear thinning of polymer is observed, which reduces the viscosity of the aqueous phase.

In this work we assume that the shear rate is proportional to the flow velocity. Then, the following relation can be defined [1].

$$\mu_a = \mu_a^0 \left(\frac{1 + (P-1)M}{P}\right), \quad (9)$$

where P is a viscosity multiplier, calculated from equation (6) assuming no shear effect, and M is a shear thinning multiplier. For a homogeneous and high permeable reservoir this relation may be appropriate. For low permeable and heterogeneous rocks a different approach will be required, taking into account the apparent shear rate in porous media.

2.3.7 Saturation, Capillary Pressure and Relative Permeability

In order to solve the two-phase flow problem (Equations (1) to (3)), three additional constitutive equations need to be specified. Due to curvature and surface tension of the interface between the phases, the pressure in the wetting phase is less than in the non-wetting phase. The pressure difference is defined by the capillary pressure p_c, which is expressed as [5]:

$$p_c(S_a) = p_o - p_a \quad (10)$$

In this model, we used the following capillary pressure model [5]:

$$p_c = p_t \cdot S_n^{-\frac{1}{\varphi}} \, , \quad (11)$$

where φ, p_t are the Brooks-Corey coefficient and the capillary entry pressure and S_n is the normalized water saturation defined as [5]:

$$S_n = \frac{S_a - S_{ra}}{1 - S_{ra} - S_{ro}} \, , \qquad (12)$$

S_{ra} and S_{ro} are the residual and immobile saturations of the aqueous and oelic phase. The relative permeabilities of water k_{rw} and the oelic phase k_{ro} are calculated using the Brooks-Corey correlation [5].

$$k_a = \frac{k \cdot S_n^{\frac{2+3\varphi}{\varphi}}}{R_k} = \frac{k \cdot k_{rw}}{R_k}$$

$$k_o = k \cdot (1 - S_n)^2 \left(1 - S_n^{\frac{2+\varphi}{\varphi}}\right) = k \cdot k_{ro} \qquad (13)$$

The capillary pressure derivative can be calculated analytically:

$$\frac{dp_c}{dS_w} = -\frac{p_t}{\varphi(1 - S_{ra} - S_{ro})} (S_n)^{\frac{-(1+\varphi)}{\varphi}} \qquad (14)$$

3. COMSOL Implementation

Equation (1) through (14) define the coupled flow and transport system through a number of cross couplings. In the following the implementation of the system into COMSOL is presented and initial and boundary conditions are specified.

Implementation into COMSOL requires a reformulation of the two-phase flow equations (1) through (3). Here, a fractional flow formulation is considered which transfers the two-phase flow equations into one pressure and one saturation equation. The pressure equation is given by:

$$\nabla \cdot \vec{u} = \tilde{q}_a + \tilde{q}_o \qquad (15)$$

and the saturation equation is defined as:

$$\frac{\partial \phi S_a}{\partial t} + \nabla \cdot \vec{u}_a = \tilde{q}_a , \qquad (16)$$

where $\vec{u}_a$ and $\vec{u}$ are the velocities of the aqueous phase and total velocity, respectively, which are defined as:

$$\vec{u}_a = \frac{\vec{u}}{1 + \frac{k_o \mu_a}{k_a \mu_o}} + \left(\frac{k_o k_a}{\mu_o k_a + \mu_a k_o}\right) \nabla p_c \qquad (17)$$

$$\vec{u} = -\left(\frac{k_a}{\mu_a} + \frac{k_o}{\mu_o}\right) \nabla p \qquad (18)$$

where p is the global pressure.

The fractional flow formulation has shown good results over other formulations using COMSOL [6].

Polymer and salt are convected with the velocity of the aqueous phase $\vec{u}_a$, which is used as input velocity field for the Species Transport in Porous Media Interface. The cross couplings defined in equations (6) – (14) are implemented as well. The following initial conditions need to be specified.

$$C_p\big|_{t=0} = C_{p0}, \; C_s\big|_{t=0} = C_{s0}$$

$$p\big|_{t=0} = p_0, \; S_a\big|_{t=0} = S_{ra} \qquad (19)$$

If the total rate of the aqueous phase is denoted by Q_a, the Darcy flux at the inlet boundary is given by:

$$\vec{n} \cdot \vec{u}_a = \frac{Q_a}{A} \, , \qquad (20)$$

$\vec{n}$ is the normal vector and A the cross-sectional area. Equation (20) implies that only the aqueous phase is injected into the domain. Influx boundary conditions are specified for the polymer and salt concentrations:

$$\vec{n} \cdot \left(-S_a \lambda \nabla C_p + \vec{u}_a C_p\right) = \frac{Q_a}{A} C_{pw} , \qquad (21)$$

$$\vec{n}\cdot\left(-S_a\lambda\nabla C_s + \vec{u}_a C_s\right) = \frac{Q_a}{A}C_{sw}, \qquad (22)$$

where λ denotes artificial diffusion. At the outlet boundary, the following conditions are assigned:

$$\vec{n}\cdot\vec{u}_a = \frac{Q_a}{A} \qquad (23)$$

$$p\big|_t = p_0 \qquad (24)$$

$$\vec{n}\cdot\left(-S_a\lambda\nabla C_p + \vec{u}_a C_p\right) = 0 \qquad (25)$$

$$\vec{n}\cdot\left(-S_a\lambda\nabla C_s + \vec{u}_a C_s\right) = 0 \qquad (26)$$

In COMSOL artificial diffusion λ is used to stabilize the solution of the convection equation for salt and polymer which will be discussed later. Therefore, here, diffusion is explicitly included in the equations while it is not included in the equations presented in the chapter polymer flood model.

4. Model Test and Simulation

In order to validate the implementation of the polymer flood model presented here, a generic simulation model was set-up. The results obtained with COMSOL are compared to the results obtained using the commercial finite-difference simulator ECLIPSE Blackoil by Schlumberger [1]. The input data for the simulation models are listed in Table 1. Artificial diffusion is added to COMSOL only and will be discussed later.

Table 1: Physical parameters used in simulation.

Parameter	Unit	Value
Length, l	m	300
Width, w	m	10
Height, h	m	10
Element Size COMSOL, Δx	m	1
Element Size ECLIPSE, Δx	m	0.06
Time Step, Δt	days	1

Porosity, ϕ	-	0.3
Permeability, k	m²	1e-12
Residual Oil Saturation, S_{ro}	-	0.15
Residual/ Initial aqueous phase Saturation, S_{ra}	-	0.2
Water Viscosity, μ_w	mPa·s	1
Oil Viscosity, μ_o	mPa·s	10
Capillary Entry Pressure, p_t	Pa	1e5
Brooks Corey Coefficient, φ	-	2
Constant, a_1, a_2, a_3	-	4,0,6
Constant, S_p	-	-0.24
Rock density, ρ_r	kg/m³	2650
Langmuir adsorption constant, b	m³/kg	1
Maximum adsorption, C_{pad}^{max}	kg/kg	8.4e-5
Initial Salt Concentration, C_{s0}	kg/m³	10
Residual Resistance Factor, R_{RF}	-	1.2
Artificial Diffusion, λ	m/s	5e-7

Table 2: Injection Scheme.

Time [days]	Injection Rate, Q_a [m³/day]	Salt Conc., C_{pw} [kg/m³]	Polymer Conc., C_{sw} [kg/m³]
0 - 100	10	5	0
100 - 200	10	5	1
200 - 1000	10	5	0

4.1 Injection Scheme and Results

The injection scheme is presented in Table 2. During the first 100 days only water at a salt concentration of 5 kg/m³ is injected into the reservoir (Figure 1). As the polymer slug is injected after 100 days, the salt concentration is lower than the initial concentration (Figure 3), which is favorable to maintain a higher aqueous phase viscosity. Between 100 and 200 days a

polymer concentration of 1 kg/m³ is added to the aqueous phase (Figure 2). This results in the formation of an additional oil bank which is displaced to the production side (Figure 4). After 200 days the polymer slug is displaced with water at a salt concentration of 5 kg/m³. Due to adsorption of the polymer to the rock the size of the polymer slug decreases (Figure 2) and aqueous solution viscosity is reduced. This results in a reduced efficiency of the process. Polymer breakthrough with COMSOL and ECLIPSE occurs after 1005 and 1003 days, respectivly. Taking into account the same input data given by Table 1 and 2 and shear thinning as described by equation (9) the results previously presented change. Then, the efficiency of the process is further reduced as presented in Figure 5. The size of the oil bank is reduced compared to the latter case.

4.2 Artificial Diffusion

As the capillary pressure is non-zero, the saturation equation (Equation 16) is parabolic in nature. No artificial diffusion is required in COMSOL to avoid non-monotone solutions.

Sharp fronts need to be resolved numerically in purely convective transport of chemicals such as polymer and salt. Without adding artificial diffusion (λ) the finite element method used here is unstable and oscillations occur.

Table 3: Polymer breakthrough time (BT).

Simulator	λ [m/s]	Element Size [m]	BT [days]
COMSOL	5e-7	1	1005
ECLIPSE	0	0.06	1003
	0	1	950

In case of the finite difference method used in ECLIPSE no oscillations occur, but the front is smoothed. Smoothing depends on the element size used to discretize the domain in space. Hence, both methods to find solutions to the convection equation have problems and one has to accept either oscillations or smearing of the front.

In order to show this effect in ECLIPSE another model with larger element size ($\Delta x = 1$m) but with the same input data (Table 1) is created. For COMSOL, the element size and artificial diffusion is kept constant. The ECLIPSE results using the coarse elements sizes shows increased smoothing as presented in Figure 6. The same can be shown for COMSOL by increasing λ. Table 2 lists the impact on breakthrough time for the different cases indicating differences.

5. Conclusion

Basic physico-chemical effects relevant to polymer EOR can be modeled in COMSOL. The presented results show good agreement compared to the reservoir simulator ECLIPSE by Schlumberger indicating a successful implementation. The model will be the basis for further and more detailed investigations.

6. Discussion

Due to its PDE Interface and Species Transport in Porous Media Interface COMSOL Multiphysics provides a flexible framework to implement physical and chemical mechanisms relevant to polymer EOR. Although commercial software for simulation of polymer EOR processes exists, it lacks the multi-physics capabilities of COMSOL. Underlying transport and auxiliary equations can be easily varied or extended and other physics such as temperature or geo-mechanical effects integrated. This is an important aspect in research.

7. Acknowledgements

8. References

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9. Appendix A. Figures
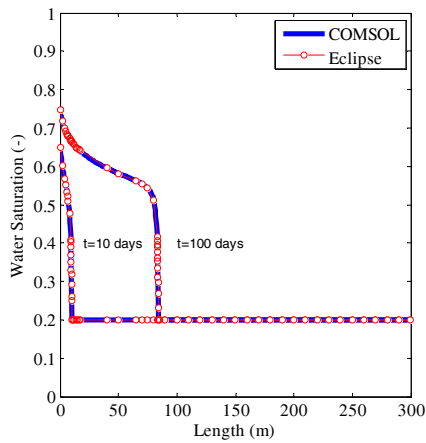
Figure 1: Water saturation after 10 and 100 days.
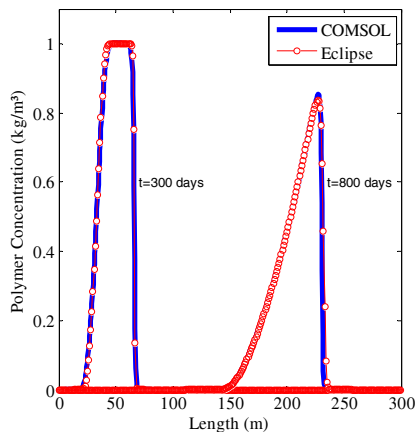
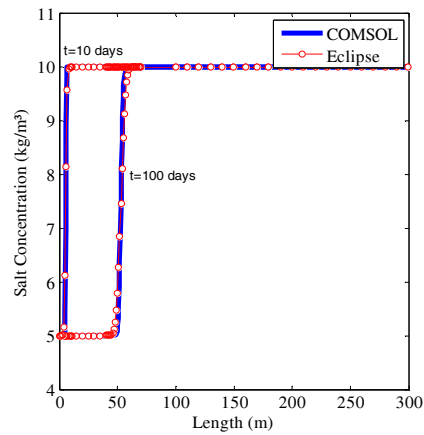**Figure 2:** Polymer concentration after 300 and 800 days.
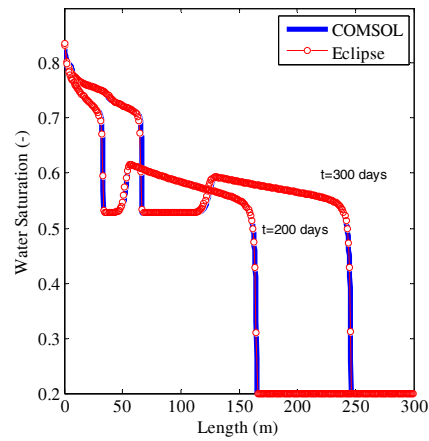

Figure 3: Salt concentration after 10 and 100 days.

Figure 4: Water saturation after 200 and 300 days.
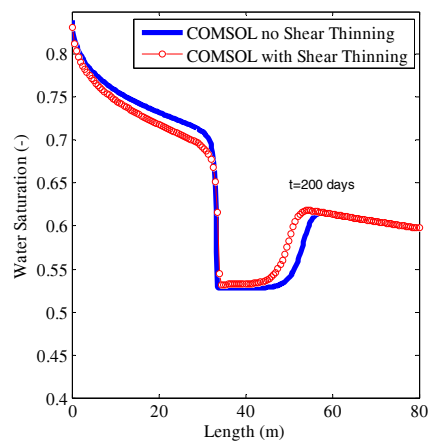

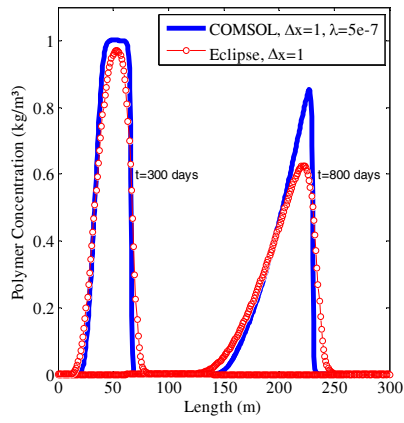**Figure 5:** Water saturation after 200 days with and without shear thinning

Figure 6: Polymer concentration after 300 and 800 days.