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Selecting the “Right” ASP Model by History Matching Core Flood Experiments

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SUMMARY

In order to design and analyze Alkaline Surfactant Polymer (ASP) pilots and to generate reliable ASP field forecasts a robust scalable modeling workflow for the ASP process is required. A starting point of such a workflow is to carry out ASP coreflood tests and history match those using numerical models. This allows validation of the models and generates a set of chemical flood parameters that can be used for field-scale simulation forecasts.

It is well established that lowering of interfacial tension due to mixing of in-situ generated soap with injected surfactant and improved mobility control due to the polymer play a crucial role in the ASP process. Therefore, all models for the ASP process take into account these mechanisms in one way or the other. However, ASP models can differ in the detail in which (geo-)chemical reactions and the phase behavior are addressed. Inclusion of more details into the numerical model could result in better understanding and more accurate prediction, but it comes at a price, viz. it requires more measured input data and increases computational time. Thus, depending on the accuracy requirements, available experimental data and time the modeling of ASP flood can be performed using different simulation approaches.

This paper describes several modeling approaches for ASP. We start with a brief description of these methods and their input requirements. Then we compare the ASP core flood simulation results demonstrating the advantages and disadvantages of presented approaches. Finally we give recommendations and guidelines on how and when the proposed models could be used.

1. Introduction

Alkaline/surfactant/polymer (ASP) flooding is an enhanced oil recovery (EOR) technique that involves the injection of a solution of surfactant, alkaline and polymer into the oil reservoir to mobilize the remaining oil. In this process the injected surfactant and the petroleum soaps generated *in situ* reduce the oil-water interfacial tension (IFT), improving the microscopic sweep efficiency (Nelson *et al.*, 1984). Moreover, the macroscopic sweep efficiency is enhanced through improvement of the mobility ratio due to the injected polymer. Another important benefit of the alkali is the reduction of surfactant retention on the rock surface, allowing for the injection of smaller amounts of surfactant. Indeed, in some cases where the crude oil does not react with the alkali, the injection of alkali is recommended to prevent surface retention of expensive surfactant. As a further improvement, the addition of a co-solvent may enhance the combined solubility of the surfactant and the polymer in the injected ASP solution and reduce the viscosity of (micro-) emulsions formed when the ASP solution contacts the crude oil.

The ASP process is usually applied to tertiary floods in the drive mode. Because of the considerable costs of the chemicals associated with the ASP flooding, an ASP slug (a fraction of the reservoir pore volume) is generally injected, and then followed by a solution of a water-soluble polymer. Typical estimated incremental recoveries for ASP flooding after water flood are of the order of 10 to 20% STOIP (Pitts *et al.*, 2006, Qu *et al.*, 1998, Vargo *et al.*, 2000).

Full understanding of the performance of the ASP process and the relevant mechanisms of oil recovery is challenging (see Hirasaki *et al.*, 2008 and references therein). This is mainly due to the complexity of the interactions between the rock surface and the injected chemicals, and the phase behaviour of the oil-soap-surfactant-brine mixture. To evaluate the effects of these phenomena and predict the performance of ASP floods a number of analytical and numerical models have been proposed.

The simplest approach for modelling an ASP flood is based on the 1D fractional-flow theory (Pope, 1980, Lake 1989). Despite a number of simplifying approximations, this analytical approach has proven to be useful and insightful. The model modifies the fractional-flow function of the water phase according to the properties of the ASP solution, making it possible to obtain the breakthrough time and the oil cut before breakthrough of the chemicals. The model is particularly powerful on the experimental scale and can be used as a simple tool for estimating the primary parameters for more complicated models. The fractional-flow theory was modified by Larson and Hirasaki (1977) to account for the mass transfer of components between the oleic and aqueous phase. Such models can predict the oil production due to oil swelling and solubilisation, which is relevant for solutions with high surfactant concentrations. Although possible, an extension of fractional flow theory to more phases and components rapidly becomes a complex undertaking (Skjæveland and Kleppe, 1992). Furthermore, fractional flow analysis is limited to one-dimensional flow and thus is not applicable for studying volumetric sweep and unstable displacement effects.

Analytical modelling of ASP flooding can be made more realistic by taking into account the volumetric sweep. Such models can be used for quick screening of ASP flooding (Paul *et al.*, 1982). If more features, such as salinity-dependent phase behaviour and IFT are added to an ASP model, or if flow in more than one dimension is to be modelled, then the relevant flow and transport equations must be solved numerically by simulators. Arguably, the reference implementation of an ASP flooding simulator is UTCHEM, developed at the University of Texas at Austin (Delshad *et al.*, 1996). Its design, which incorporates an Implicit Pressure and Explicit Concentration numerical scheme, makes its primary domain of application small scale simulation models. Nowadays, commercial packages have been developed that allow for the simulation of an ASP flood to different levels of chemical detail in geologically complex industry-standard models (STARS, ECLIPSE).

The purpose of this paper is to present and compare two numerical approaches that can be used for quick ASP screening or to model ASP flooding in field trials. First, we provide a description of an

“effective” ASP model. We then introduce an extended model in which the water chemistry software PHREEQC (Parkhurst and Appelo, 1999) is coupled to a dynamic flow simulator to take into account cation-exchange and saponification reactions (Farajzadeh *et al.*, 2011). The extended model evolved from the ASP model introduced earlier by Stoll *et al.*, (2010). Next, we validate both the effective and PHREEQC-coupled ASP models by history matching the same ASP core-flow experiment and comparing their results. Finally we conclude by comparing the results from these two numerical models.

2. Effective model

In the effective model, alkali, surfactant, polymer and NaCl are modelled as chemical “tracers” that reside in the aqueous phase. The advection equations for the “tracers” are solved using a higher-order accuracy (in time and space) solver to suppress numerical dispersion. For reasons of accuracy and numerical stability, the chemical transport solver makes use of sub-time-stepping. Physical diffusion and dispersion is implemented using operator splitting in the advection solver. This chemical transport solver has been used successfully in previous studies to describe fluid (gas-gas) mixing effects and to simulate tracer injection tests.

In the effective model petroleum acids and soaps are not explicitly modelled. It is assumed that oil contains a fixed concentration of acids, determined by the total acid number of the oil, which can be converted to soap by alkali. The molar amount of soap in a grid block is equal to the minimum of the amounts of alkali and acid in the grid block, where the latter is calculated from the oil saturation and the fixed acid concentration. Therefore, the saponification process is very much simplified.

The modelling approach is based upon the following assumptions:

- The model consists of three phases, namely aqueous, oleic and gas phases. The injected chemicals flow with the aqueous phase.
- Based on the grid block concentrations of injected chemicals, the relative permeabilities and water phase viscosity are modified locally to mimic the effect of interfacial tension reduction due to surfactant and petroleum soap as well as water viscosification due to polymer.
- Saponification is modelled according to the above described mechanism.
- Surfactant, alkali and polymer retention is represented by a Langmuir adsorption isotherm model. Desorption of chemicals is neglected.

Further details of the functional dependence of relative permeabilities and the water phase viscosity are described below.

Polymer viscosity modelling

It is assumed that polymer viscosity at a fixed shear rate as a function of polymer concentration C_p and salinity P is given by the following empirical correlation which has been described in the UTCHEM Technical Manual (UTCHEM):

$$\mu_p(C_p, P) = \mu_w [1 + (\alpha_1 C_p + \alpha_2 C_p^2 + \alpha_3 C_p^3) P^\beta], \quad (1)$$

where μ_p and μ_w are the polymer solution and water viscosities respectively. Parameters α_1 , α_2 , α_3 and β are determined by fitting Eq.1 to the experimentally measured polymer viscosity at different polymer concentrations. To account for the non-Newtonian flow of polymer solution the dependence of the polymer viscosity on the shear rate is considered. Experimental data is used to find the shear thinning/thickening factor at different share rates for the polymer viscosity μ_p given by Eq. 1. Whereas, the shear rate γ is given by Blake-Kozeny equation:

$$\gamma = c \left[\frac{3n+1}{4n} \right]^{\frac{n}{n-1}} \frac{4u}{\sqrt{8k k_{rw} \phi S_w}}, \quad (2)$$

where n is the exponent in the power law model describing the rheology of a polymer fluid (see, for example, Sorbie, 1991), u is the Darcy velocity, k is the absolute water permeability, k_{rw} is the end point water relative permeability, ϕ is the porosity, S_w is the water saturation and c is the empirical correction factor. Throughout this paper we use $n = 0.44$ and $c = 2$.

Adsorption modelling

To account for the polymer adsorption a Langmuir isotherm approach is used:

$$C_p^{solid} = a_p C_p / (1 + b_p C_p), \quad (3)$$

where C_p^{solid} is the polymer mass concentration in solid (adsorbed polymer), a_p determines the isotherm curvature, and b_p is related to the maximum polymer adsorption (a_p/b_p represents the maximum value of adsorption). Polymer retention in porous media reduces permeability, which is expressed in terms of the reduction factor (RK)

$$RK = 1 + (RRF - 1) C_p^{solid} b_p / a_p, \quad (4)$$

where RRF is the residual resistance factor estimated from the experiments.

Interfacial tension modelling

Within the context of this model, we use the term “interfacial tension” exclusively to refer to the oil-water interfacial tension. The oil-gas and water-gas interfacial tensions are assumed to be constant and unaffected by the ASP chemicals. Furthermore, we adopt the simplified oil-water phase behaviour description proposed by Liu *et al.*, (2008) and do not explicitly model the so-called middle phase, or micro-emulsion (Nelson *et al.*, 1984). Minimum interfacial tension is established if the actual salinity equals the optimum salinity. The optimum salinity, in turn, depends on the molar ratio of petroleum soap to surfactant (Liu *et al.*, 2008). Defining

$$R = \chi_{\text{Soap}} / \chi_{\text{Surf}} \quad (5)$$

where χ_{Soap} and χ_{Surf} are the mole fraction of soap and surfactant over all liquid phases, respectively. Denoting the optimum salinity of the pure soap and pure surfactant by P_{soap} and P_{surf} respectively, the optimum salinity for a mixture of soap and surfactant P_{opt} can be expressed in the following form (Salager *et al.*, 1979):

$$P_{\text{opt}}(R) = P_{\text{soap}}^{1/\left(1+\frac{1}{R}\right)} P_{\text{Surf}}^{1/(1+R)} \quad (6)$$

The link between salinity, optimum salinity and oil-water interfacial tension is established via experimentally determined solubilisation parameters. In test tube phase behaviour experiments showing three phases (oil, micro-emulsion and water), the solubilisation parameter for oil, Z_o , is defined as the volume of oil solubilised in the emulsion phase divided by the volume of the surfactant sample (surfactant mass divided by water density). Equivalently, the volume of water gives rise to the

water solubilisation parameter Z_w . We use the following empirical functions for the oil and water solubilisation parameters as a function of salinity P and optimum salinity P_{opt} :

$$Z_O(P) = Z_{opt} \exp[\tau_O (1 - P/P_{opt})] \quad \text{for } P > P_{opt} \quad (7)$$

$$Z_W(P) = Z_{opt} \exp[-\tau_W (1 - P/P_{opt})] \quad \text{for } P < P_{opt} \quad (8)$$

Here, Z_{opt} refers to the maximum solubilisation (at optimum salinity, $P = P_{opt}$) and is assumed to be equal for water and oil. The constants τ_O and τ_W are tuning parameters used to match experimental data. Based on these solubilisation parameters, the Huh correlation (Huh, 1979) is used to calculate oil-water interfacial tension. Originally, this correlation was developed to calculate interfacial tension inside the three-phase (oil, micro-emulsion, water) region. Here, we apply it to the entire salinity range. This approach is justified based on the empirical observation that the resulting interfacial tension is ultra-low only near the actual optimum salinity ($P = P_{opt}$). Away from the optimum salinity, the interfacial tension increases sharply and it will be insufficient to liberate capillary-trapped oil. The oil-water interfacial tension thus becomes

$$\sigma_{OW} = 0.3 Z^2 \text{ mN/m} \quad \text{where } Z = \begin{cases} Z_W & : P \leq P_{opt} \\ Z_O & : P > P_{opt} \end{cases} \quad (10)$$

and its minimum value at optimum salinity is $\sigma_{OW} = 0.3 Z_{opt}^2$ mN/m. For a typical solubilisation parameters of $Z_{opt} \geq 15$ one obtains a minimum oil-water interfacial tension of 10^{-3} mN/m or less.

Finally, we note that the development of the interfacial tension calculation has so far made no reference to the absolute concentration of soap or surfactant in the solution. A grading of the interfacial tension with concentration was proposed by Liu (2007). This pragmatic model assumes that the interfacial tension according to Eq. 10 is established if the total concentration of soap and surfactant C_{ST} exceeds the critical micelle concentration (C_{CMC}). On the other hand, no interfacial tension reduction occurs if the total concentration of soap and surfactant remains below $10^{-3} \times C_{CMC}$. The corresponding oil-water interfacial tension is assumed to be unchanged; the interfacial tension in this case is as if there were no chemicals added. Lastly, in the region $10^{-3} \times C_{CMC} < C_{ST} < C_{CMC}$ the logarithm of the interfacial tension is calculated by linearly interpolating between the logarithm of the original (unmodified) oil-water interfacial tension and the value of Eq. (10). Exponentiating the interpolated result yields the graded value. Note that in all cases the maximum allowed oil-water interfacial tension can not exceed the unmodified oil-water interfacial tension.

Desaturation

Finally, the polymer viscosity and the oil-water interfacial tension are correlated with the reduction of the residual oil saturation via the capillary number. Here the UTCHEM desaturation model, supported by the experimental data obtained by Delshad *et al.*, (1986) is used. Given the capillary number N_c for the aqueous phase defined as:

$$N_c = \frac{u \mu_w}{\sigma} \quad (11)$$

scaling of the residual oil saturation S_{or} with the capillary number is given by

$$S_{or}(N_c) = S_{orc} + \frac{S_{orw} - S_{orc}}{1 + T N_c} \quad (12)$$

where S_{orw} is the original residual oil saturation in the low capillary number limit and S_{orc} is the modified residual oil saturation in the high capillary number limit. The parameter T allows for the adjustment of the numerical value of the capillary number $N_c = 1/T$ at which transition from the original to the modified remaining oil saturation takes place. Throughout this paper we use $T = 60000$.

We also assume that the rest of the Corey parameters (connate water saturations, oil and water Corey exponents and relative permeability end points) scale with the capillary number according to Eq. 12.

3. ASP modelling with coupling to PHREEQC

The success of an ASP process depends on the simultaneous propagation of soap and surfactant at the front, and therefore the availability of alkali for the saponification reactions is an important consideration. The alkali can participate in several reactions in a geological formation, and these can be categorized into three main groups: (1) cation exchange, (2) precipitation (carbonate scale if sodium carbonate is used for the alkali), and, possibly, (3) mineral dissolution. Alkali consumption by these processes may cause the saponification reaction to lag behind the surfactant and polymer fronts. For this reason, the relevant chemical reactions should be considered if an accurate model of the ASP process is to be realized (Mohammadi *et al.*, 2009).

To account for the geochemistry involved in the ASP floods, Shell's dynamic reservoir simulator MoReS (Por *et al.*, 1989, Regtien *et al.*, 1985) was coupled to the aqueous chemistry software PHREEQC. PHREEQC provides the equilibrium chemistry of the aqueous solutions interacting with minerals, gases, exchangers, and sorption surfaces (Parkhurst and Appelo, 1999).

A more detailed description of the coupling of the ASP model to PHREEQC is presented by Farajzadeh *et al.*, (2011). Coupling the ASP model to PHREEQC allows for detailed modeling of geochemical reactions and the saponification process. The acids and soaps are modeled explicitly as "tracers". Moreover, we also allow for the partitioning of the soap and surfactant into the oleic phase. The partitioning coefficient depends on the optimum salinity and is given by

$$K_i(P) = \frac{c_{io}}{c_{iw}}, \quad (11)$$

where, c_{io} and c_{iw} are the molar concentration of species i (i.e. soap or surfactant) in the oleic and aqueous phases respectively. Assuming that the partitioning coefficient K is the same for both soap and surfactant, the following expression was used (Liu *et al.*, 2008):

$$\log_{10} K(P) = \begin{cases} 2 \left(\frac{P}{P_{opt}} - 1 \right) & \text{for } P > P_{opt} \\ 2 \left(1 - \frac{P}{P_{opt}} \right) & \text{for } P < P_{opt} \end{cases} \quad (12)$$

Coupling MoReS with PHREEQC provides a more detailed model for the study of the effects of the composition of the initial and injected fluids and of the rock mineralogy on the performance of the ASP process. Note that the other features of the coupled ASP model are similar to those of the effective model outlined in the previous section.

In the following sections we compare the results of these two models to experimental data and highlight their differences.

4. ASP core-flood simulations

To validate the effective ASP model, history matching of a linear ASP core flood experiment is performed. In the experiment a vertically oriented Bentheimer core was used. The core was 30 cm long and 5 cm in diameter. Before the chemical flooding the core was waterflooded to a remaining oil saturation of 50%. The chemical flood consisted of 0.3 pore volume (PV) of ASP slug injection followed by 2.5 PV of polymer solution. The injection rate for both chemical and water floods was

fixed at 0.09 ml/minute, and corresponded to a Darcy velocity of 1 ft/day. Major input parameters for the history matching are given in Tab. 1.

| | |
|---|-------|
| Porosity | 0.22 |
| Permeability (mD) | 1800 |
| Initial oil saturation | 0.5 |
| Water viscosity (cP) | 0.6 |
| Oil viscosity (cP) | 105 |
| Water density (kg/m ³) | 1015 |
| Oil density (kg/m ³) | 900 |
| Crude acid number (mg KOH/g) | 0.77 |
| NaCl in formation brine (ppm) | 3115 |
| NaCl in injected brine (ppm) | 3115 |
| Alkali Na ₂ CO ₃ concentration (ppm) | 10000 |
| Surfactant concentration (ppm) | 3000 |
| Polymer concentration in the ASP slug (ppm) | 3300 |
| Viscosity of the ASP slug @ 6 s ⁻¹ shear rate (cP) | 130 |
| Polymer concentration in the mobility buffer (ppm) | 2700 |
| Viscosity of the mobility buffer slug @ 6 s ⁻¹ shear rate (cP) | 150 |
| Optimum salinity pure soap (ppm) | 5000 |
| Optimum salinity pure surfactant (ppm) | 16500 |
| Critical micelle concentration (ppm) | 5000 |

Table 1 Input parameters for history matching of the ASP core flood experiment

Fluid and rock compressibility were assumed to be insignificant. In the experiment dead oil was used. To prevent alkali precipitation Ca²⁺ and Mg²⁺ divalent ions were removed from brine and injected water; the concentration of Na⁺ ions in the brine defines the salinity.

Production data from the ASP flooding stage are shown in Figs. 1 and 2. Production of oil and chemicals were measured from the effluent samples. In this experiment around 80 effluent samples were taken. Polymer recovery was estimated by measuring aqueous phase viscosity from the effluent samples. Viscosity values were normalized by the polymer viscosity at room temperature. The aqueous phase was also titrated for carbonate and bi-carbonate ions as well as for surfactant to estimate the alkali and surfactant recoveries.

5. History matching with the effective ASP model.

History matching results are presented in Figs. 1 and 2. In Fig.1 oil recovery data are shown. There is a reasonable agreement between experimental data and simulated results. Oil production before the chemical breakthrough (shown in Fig. 2) is well matched. However, the simulated oil production after the chemical breakthrough is different from that observed experimentally.

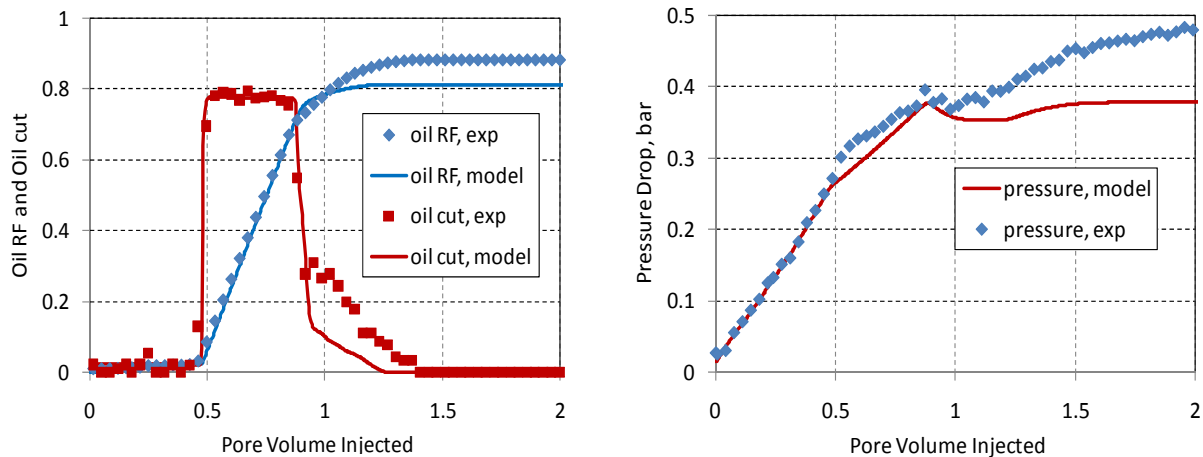


Figure 1: Comparison of the predictions of the effective ASP model with experimental data: oil recovery (left) and pressure data (right).

Comparison of the experimental and simulated pressure drop over the core shows a similar trend. Fig. 1 shows a reasonably good match until the breakthrough of chemicals. After the breakthrough the discrepancy between the simulated and measured values becomes more pronounced, and increases with the number of injected pore volumes. However, a stabilization of the pressure drop is to be expected after the oil production stops (after ~1.5 PV injected) due to the steady-state flow conditions. An increased oil recovery should only result in a higher value pressure drop plateau and not in a continuous increase in pressure drop. This was observed experimentally in some but not in all core-flood experiments carried out during the course of this study and may be caused by continuing polymer hydrolysis or polymer adsorption over time. Neither of these processes is included the ASP models used in this study.

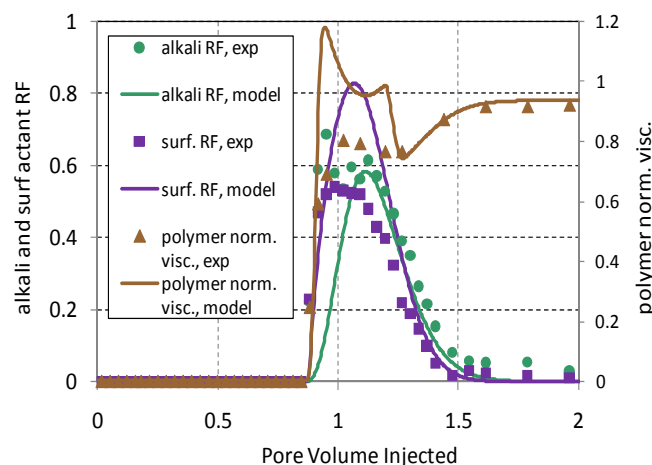


Figure 2: Comparison of the effective ASP model with experimental data: alkali and surfactant recovery and normalized polymer viscosity.

The effective ASP model approach allows chemical production to be modelled. However, one needs to keep in mind the shortcomings of the alkali and surfactant transport modelling. For the former, consumption and retardation is captured only via an ‘effective’ adsorption model. For the latter, it is assumed that the surfactant resides only in the aqueous phase. These shortcomings are resolved by coupling the ASP model with PHREEQC.

In Fig. 2 the history matching results of the production of chemicals are shown. The chemical breakthrough time and production profiles of chemicals are matched reasonably well despite the

aforementioned shortcomings. In order to match the experimentally observed data, dispersion and adsorption of the different chemicals were tuned. In these simulations we have used longitudinal dispersion with dispersivities ranging from millimetres to centimetres. These values are of the same order of magnitude as those reported earlier for the core-flow experiments (Delshad *et al.*, 1985, Mahadevan *et al.*, 2003).

In general we conclude that the effective model provides a reasonably good prediction of the ASP core flow experiments.

6. History matching with the ASP model coupled to PHREEQC.

Here we discuss the history matching results of the same set of experimental data using the ASP model coupled to PHREEQC. In this case one can use an extended experimental ASP data set for the history matching as the model includes more detailed physical and chemical descriptions of the ASP flooding.

Fig. 3 illustrates the experimental oil production and pressure drop data and compares them to the simulation results. The figure shows a good agreement between measured and simulated data. As for the effective model, a difference between experimental data and modelling results is observed after the breakthrough of the chemicals. Compared to results shown in Fig. 1 the history matching of the cumulative oil production and oil production after the chemical breakthrough have improved. This improvement can be attributed to more accurate modelling of the effects of soap and surfactant. When comparing the results shown in Figs. 1 and 3 one has to keep in mind that these simulations were performed with different matching parameters. In case of effective ASP model, the Corey exponents for the chemical flood were higher than for the ASP model coupled to PHREEQC.

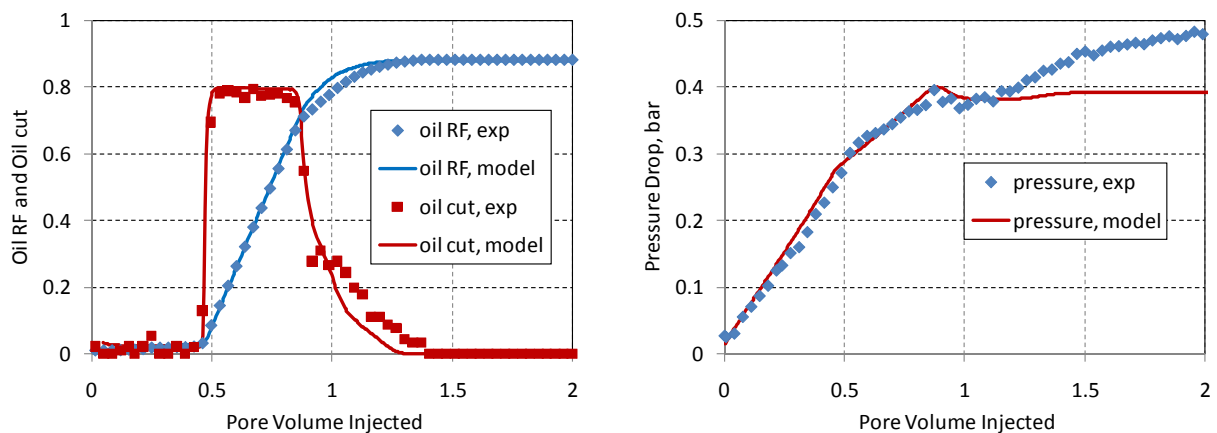


Figure 3: Comparison of the predictions of the ASP model coupled to PHREEQC with experimental data: oil recovery (left) and pressure data (right).

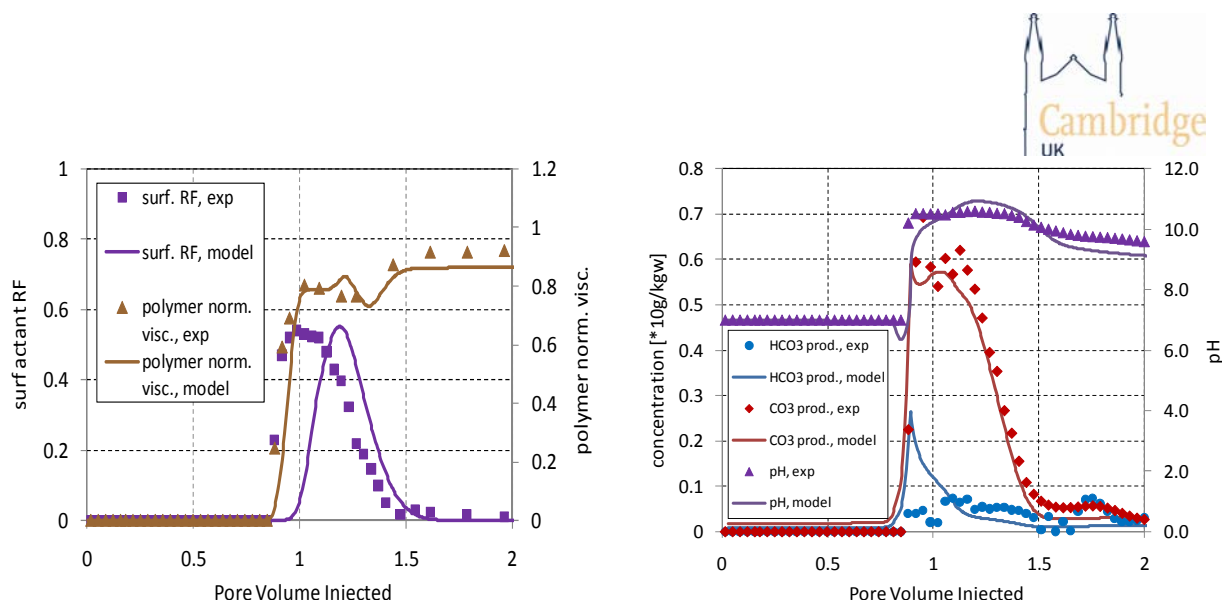


Figure 4: Comparison of the predictions of the ASP model coupled to PHREEQC with experimental data: surfactant recovery and polymer normalized viscosity (left) and pH, carbonate and bicarbonate concentrations (right).

The mismatch between the predicted and measured pressure drop values (see Fig. 3) is qualitatively similar to that shown in Fig. 1. The main difference in the two simulated pressure drops can be attributed to the higher oil recovery for the ASP model coupled to PHREEQC.

To improve the match of oil production after the breakthrough of chemicals in the coupled model, the adsorption of surfactant was increased as compared to that used in effective model. Higher adsorption resulted in delay of surfactant breakthrough as shown in Fig. 4. Additionally, more accurate modelling of salinity resulted in better match on the normalized polymer viscosity during production of the ASP slug. An advantage of the coupled ASP model over the effective model is that it can be used to study chemical parameters that drive the saponification process, and that are not available in the effective ASP model. For example, in Fig. 4 a comparison between the measured and simulated pH, carbonate and bicarbonate profiles are presented. In general, the ASP model coupled to PHREEQC is capable of matching the concentration of the produced chemicals with a satisfactory accuracy.

7. Discussion and conclusions

In this paper we have presented a detailed description of an effective ASP model and a summary of an ASP model coupled to the (geo-)chemistry package PHREEQC.

We have demonstrated that both models provide reasonable matching of the oil production and pressure drop in an ASP core flood experiment. Moreover, both models could match surfactant and polymer concentrations in the effluent satisfactorily. For the ASP model coupled to PHREEQC more detailed ASP core flood measurements such as the pH and the (bi-)carbonate concentration of the effluent could be modelled.

The main advantage of the effective model is that it is relatively simple and requires limited input data. Its limitation is that simplifying assumptions are made and because of this some matching parameters are ‘effective’ parameters. For example, alkali “adsorption” is used to model the complex process of alkali consumption and retardation and surfactant “adsorption” is used to model both adsorption to the rock and retention in the oil.

The ASP model coupled to PHREEQC is more detailed. In particular, it can handle geochemistry and models the saponification process. The advantage of this approach is that the ASP process can be studied in more depth and results of core flood tests can be interpreted in more detail. Moreover, matched parameters can be linked to real physical/chemical processes rather than being “effective” parameters. This can be of importance when up-scaling the ASP process from core to pilot scale to

field scale. The disadvantage of this model is that it is more complex and requires more experimental input data. Moreover, it is computationally more intensive.

The effective ASP model has the potential to be valuable at the screening stage of an ASP project or when one has limited experimental data. The ASP model coupled to PHREEQC allows for more detailed interpretation of core floods or pilot tests, particularly when the underlying physical or chemical processes are critical to the success of the ASP project under study.

Research is still ongoing, involving both simulation and experimental work, to better understand the applicability range of ASP models. This will also include ASP models which explicitly model the micro-emulsion phase, which are now being implemented into the Shell in-house simulator.

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