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SIMULATION STUDY OF POLYMER FLOODING PERFORMANCE: EFFECT OF CLAY MINERALS

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Abstract

Polymer flooding is a very important technique of improving oil recovery from sandstone reservoirs in particular, because of its applicability under a wide range of reservoir rock and fluid conditions. However, these reservoir rocks contain clay minerals with high surface activities which affect the propagation of injected polymers.

In this study, simulation study was conducted using UTCHEM, a 3-D, multiphase, multi-component chemical flooding simulator to investigate the influence of different types of clays on flooding performance and also to elucidate the mechanisms underlying polymer adsorption unto clay surfaces since clay minerals play a major role in retention of injected fluids thereby reducing the displacement efficiency. The input parameters for the different types of clays were synthetically generated. Flooding performance was evaluated in relation to oil recovery, Water-Oil Ratio(WOR), Oil rate of production, Polymer retention and Cumulative production.

In all cases, Kaolinite exhibited the most favorable performance, while montmorillonite exhibited the least. The sensitivity test carried out to elucidate the mechanisms of polymer adsorption show that there is a gradual reduction in polymer adsorption with increase in reservoir brine hardness.

Keywords: Polymer flooding; Clay minerals; Simulation; Adsorption; Polymer Retention.

1. Introduction

Polymer flooding is a subcategory under chemical flooding that enhances the recovery of oil by controlling the mobility of aqueous phase of reservoir fluid to that of oil phase. This technique increases both volumetric and displacement sweep efficiency. Polymers achieve these effects by virtue of their molecular size and structure, increasing the viscosity of the aqueous phase in that regards. In order to achieve this purpose, polymers must travel far, radially, into the reservoir so as to contact an appreciable part, if not all the areas of the reservoir. Clays embedded in the rock of reservoir formations tends to hinder the effective propagation of the molecules because of their reactivity [1]. A field-scale simulation study was carried out, using UTCHEM; a chemical flooding simulator, to investigate the effect of different types of clay minerals on polymer flood performance and to understand the conditions that support the strong adsorption of polymer during flooding. An actual field was used as a case study to perform the investigation under alternative scenarios and the polymer type is an anionic polymer (partially hydrolyzed polyacrylamide (HPAM)).

1.1 Clay minerals

Clays that exist in porous media of reservoir formations are classified into kaolinite $Al_2SiO_2O_5(OH)_4$), illite $KAl_2(Si_3AL)_{10}(OH)_2$ and montmorillonite $(Al_2.yMg^{2+}\ |_y)(Si_4.xAl_x)O_{10}(OH)_2M^+\ |_{x+y}.nH_2O$), based on similarities of set of behaviors which are surface activity, swelling tendency and effective surface area, and they have differing percentage composition from field to field. The clays exist in three morphological forms which are dispersed, structural and laminated, and they occur in segregated streaks at varying degrees of continuity that either line pore walls or fill pore throats. The high surface activity is a result of ion exchange reactions on the octahedral and tetrahedral

crystal lattices which explains their reactive nature. Their existence in the porous media causes formation damage, permeability reduction and retention of injected fluids like polymer. Several works have been able to link permeability reduction and polymer adsorption to the presence of clay particles [2-4].

1.2 Review of UTCHEM

The simulator used for the study is the UTCHEM; a 3 dimensional, multi-component, multiphase chemical flooding simulator developed at the centre for petroleum and geosystems engineering, University of Texas at Austin. It uses an IMPES solution method to simulate several species and numerous phenomena are modeled. The UTCHEM model uses a block-centered finite difference discretization that can simulate a wide range of displacement processes both at field and laboratory scale. The chemical flooding simulator has been used to carry out studies on polymer flooding and to understand the behaviors observed during flooding processes [5-6].

2. Methodology

2.1 Mathematical models of polymer flooding in UTCHEM

The continuity of mass for component κ (here, polymer) in association with Darcy's law is expressed in terms of overall volume of component per unit pore volume ($\tilde{c}_\kappa$) as

$$\frac{\delta}{\delta t}(\phi \tilde{c}_\kappa \rho_\kappa) + \vec{\nabla} \cdot \left\{ \sum_{\ell=1}^{n_p} \rho_\kappa (c_{\kappa\ell} \vec{u}_\ell - \vec{\tilde{D}}_\kappa) \right\} = R_\kappa \qquad (1)$$

Where the overall volume of component κ per unit pore volume is the sum over all phases including the adsorbed phases. n_p is the number of phases, ρ_κ is the density of pure component κ at a reference pressure. This equation takes into account the convective transport and adsorption in the permeable media. The retention of polymer molecules in permeable media is due to both adsorption onto solid surfaces and trapping within small pores. The polymer adsorption is modeled as a function of permeability, salinity and polymer concentration;

$$a_p = (a_{p1} + a_{p2} C_{SEP}) \left[\frac{k_{ref}}{k} \right]^{0.5} \qquad (2)$$

Where a_p is polymer adsorption input parameter expressed in equation (2) and C_{SEP} is the effective salinity for polymer given as

$$C_{SEP} = \frac{C_{51} + (\beta_p - 1) C_{61}}{C_{11}} \qquad (3)$$

Where C_{51}, C_{61} and C_{11} are the anion, divalent cation and water concentrations in the aqueous phase respectively. β_p is an input parameter. The viscosity of polymers also depend on its concentration and salinity, and it is represented in UTCHEM by the modified Flory-Huggins equation as

$$\mu_p^{\circ} = \mu w \left[1 + (A_{p1} C_{4\ell} + A_{p2} C^2{}_{4\ell} + A_{p3} C^3{}_{4\ell}) C_{SEP}{}^{Sp} \right] \text{ for } \ell = 1 \text{ or } 3 \qquad (4)$$

Where μ_w is water viscosity, and A_{p1}, A_{p2} and A_{p3} are empirical constants respectively for a given polymer which are determined experimentally. The permeability reduction is measured by a factor R_K modeled in UTCHEM as

$$R_K = 1 + \frac{(R_{K,\max} - 1) b_{rk} C_{4\ell}}{1 + b_{rk} C_{4\ell}} \qquad (5)$$

Where $R_{K,\max} = \max\left[\left\{\left\{1-\frac{c_{rk}(A_{p1}C_{SEP}{}^{Sp})^{\frac{1}{3}}}{\left(\frac{\sqrt{k_x k_y}}{\phi}\right)^{\frac{1}{2}}}\right\}^{-4}, 10\right]$ (6)

and c_{rk} and b_{rk} are input parameters.

2.2 Simulation study

The field case used for the simulation study is the Courtenay sand in the Chateaurenard field, southern Paris, France. A polymerflood pilot project was carried out in this reservoir and the full description of the process exists in the literature [7, 8]. Published data based on the Courtenay reservoir that was used for the simulation model is presented in Table 1. A simulation model representative of the reservoir was designed as a square reservoir with horizontal area of 1640.5 ft by 1640.5 ft. The simulation domain consists of three layers and each layer is discretized into 15 by 15 by 3 gridblocks and each gridblock has dimensions of 109.367, 109.367 and 3.608 ft for x, y and z directions respectively. The outer boundary is a no flow. The reservoir model is a heterogeneous permeability field generated statistically [9]. The polymer injection program was an injection-well-centered five spot, six step variable rate program and the polymer solution was graded into the chase water. Polymer used was a partially hydrolyzed polyacrylamide and the physical properties were synthetically generated and designed after published experimental results [7, 9]. The first part of the simulation study focused on the 3 broad classifications of clay minerals which are kaolinite, illite and montmorillonite, and the clay property parameters were also synthetically generated for the purpose (Table 2). Reservoir brine salinity was assumed constant for this study. A second part of the study was carried out to understand the conditions in the porous media that supports the adsorption of HPAMs and this was done by varying the brine (divalent cation) concentration from 0.001 to 0.008 meq/ml. The mechanism behind this technique is that HPAMs get sorbed readily onto clay surfaces due to complex formation with divalent cations by a bridge-linking reaction. For all cases, simulation was run for 1540.75 days.

Table 1 Reservoir rock and fluid data

Vertical depth	600 m
Viscosity of oil	40 cp
Reservoir temperature	30°C
Reservoir pore volume	8739400
Specific gravity of oil	27 °API
Porosity	30%
Initial water saturation	30%
Residual oil saturation	30%
TDS (Total dissolved solids)	0.4 g/l
Water viscosity	0.73 cp
OIP (Oil in place)	965700 bbl

Table 2 Input parameter for clay

Clay type	a_{p1}	a_{p2}	b_p	Q_v	β_c
Montmorillonite	20	0	100	0.135	0.9
Illite	13.5	0	100	0.0497	0.4
Kaolinite	6.5	0	100	0.0054	0.15

b_p is a parameter that controls the curvature of the adsorption isotherm of polymer which is normally determined empirically. Q_v and β_c are clay cation exchange capacity and constant respectively. a_{p1} a_{p2} are adsorption input parameters

3. Results and discussions

In the flooding performance analysis as shown in Figure 1, kaolinite exhibited the most favorable behavior with a recovery of 0.1647 incremental oil while montmorillonite exhibited the least favorable behavior at 0.1309, with illite intermediate at 0.1434. Simulation study for kaolinite saw an appreciable lowering of WOR compared to other clay types (Figure 2). Adsorption of polymer during flooding was more pronounced for montmorillonite compared to other clay types (Figure 3) and is reflected in the cumulative production of polymer at the producers (Figure 4). Analysis revealed that polymer retention for montmorillonite run is more

a function of adsorption rather than physical or mechanical trapping like the case of kaolinite. However, the retention profile for montmorillonite and illite are not reversible while they are reversible for kaolinite indicating that permeability modification due to polymer adsorption is temporary for kaolinite run unlike Montmorillonite and illite which might be permanent.

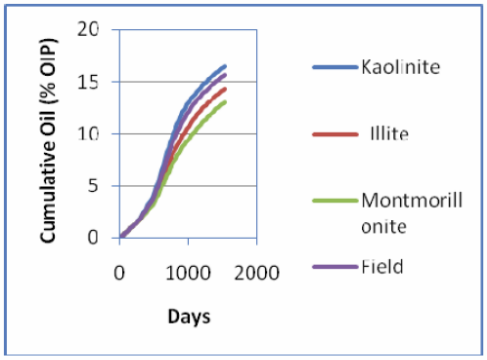

Fig.1 Cumulative Oil (%OIP) vs Days

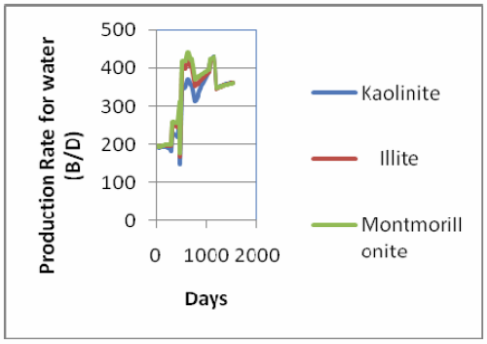

Fig.2 Aqueous phase production

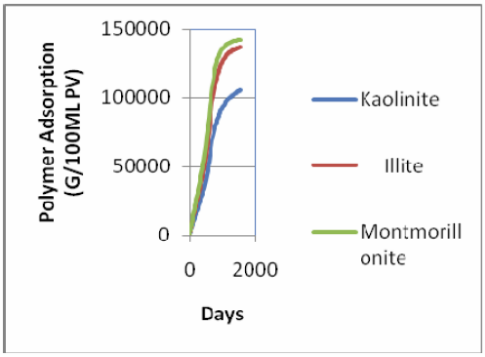

Fig. 3 Polymer adsorption vs Days

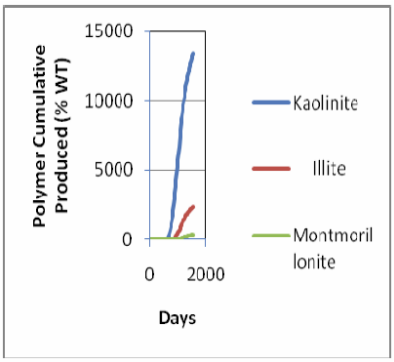

Fig. 4 Polymer production vs Days

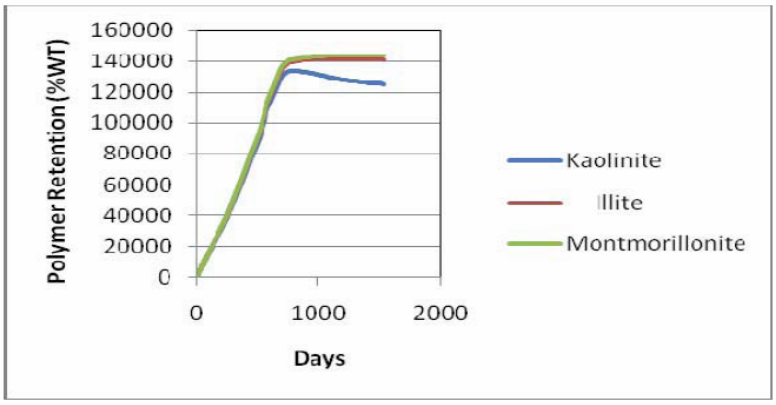

Fig. 5: Polymer Retention (% WT) VS Days

Results were compared with that of the pilot project in the Courtenay field and they bear a close resemblance to that of kaolinite analysis, attesting to the fact that kaolinite-type clay mineral is the major clay type in the Courtenay sand. On the average, all simulation runs result into a good performance, since a polymer flood must give at least a 12% incremental oil recovery to be considered a success.

There is a decrease in adsorption with increase in brine hardness. Adsorption was strictly a function of effective salinity when adsorption parameters were kept constant, thus changes in response were small. These responses can be partly explained by the depletion layer effect, and by clay site selective preference for divalent cations and complete shielding/screening of polymer molecules. Thus, hardness of reservoir brine does not favor polymer flooding (Table 3).

Table 3: Polymer analysis and oil recovery

	Cation/Polymer concentration			
Divalent	0.001 meq/ml	0.0025 meq/ml	0.005meq/ml	0.008 meq/ml
Polymer	0.01404	0.01404	0.01404	0.01404
Adsorbed	0.01185	0.01183	0.01182	0.01180
Retained	0.01313	0.01312	0.01311	0.01310
Produced	0.0009331	0.0009345	0.0009373	0.0009443
Oil Recovery	0.1567	0.1566	0.1564	0.1560

4. Conclusion

Initial permeability distribution of candidate reservoirs for polymer flooding is a very important factor for success. Even with montmorillonite as the predominant clay type, a high recovery was still recorded. In order to overcome retention due to clay effect, apart from preflushing and preconditioning, a large injection volume is recommended for a successful flooding exercise. Any condition in the pore environment that supports the coiling of HPAM molecules will reduce adsorption, however, it will also reduce its viscosifying power which will affect mobility control processes, hence, flooding designs should aim for an optimum condition whereby a mild adsorption will just boost the hydraulic conductivity of oil phase.

Nomenclature

a_p Adsorption Parameter for polymer

a_{p1} Adsorption input parameter 1 for polymer

a_{p2} Adsorption input parameter 2 for Polymer

A_{p1} Empirical constant

A_{p2} Empirical constant

A_{p3} Empirical constant

b_p Adsorption Isotherm parameter

b_{rk} Input parameter

C_{11} Water concentration

C_{51} Anion concentration

C_{61} Calcium concentration

c_{rk} Input parameter

C_{SEP} Effective salinity

$\tilde{c}$ Overall volume of component per unit pore volume

$\vec{\tilde{D}}$ Dispersive flux

k_{ref} Reference permeability

N_p Number of phases

P_α Empirical constant

Q_v Cation exchange capacity of clay minerals

R_K Source term

β_c Cation exchange constant, ionic strength

β_p Input parameter for polymer

ϕ Porosity

ρ Density

Subscripts

κ Specie or component index

l Phase index

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