# 036 AN EXPERIMENTAL AND NUMERICAL STUDY OF POLYMER ACTION ON RELATIVE PERMEABILITY AND CAPILLARY PRESSURE

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## **1. Introduction**

Injection of polymer or gels in oil or gas production wells is commonly used, among other techniques, to reduce the water cut when excessive water production occurs. The success of this technique results from the blocking ability of hydrophilic polymers or gels to selectively reduce water relative permeability with respect to oil permeability. In spite of several experimental results on polymer or gel injection in various kind of porous media samples -sandstone, limestone, etc.- during the last decade (Schneider & Owens, 1982; Zaitoun & Kohler, 1987, 1988; Zaitoun & al., 1989; Daw & Zang, 1994; Liang & al., 1994; Barreau et al., 1996; Liang and Seright, 1997), the physical mechanisms description is still incomplete. In fact, if experimental results agree on the selective action of the polymer, several possible explanations of the phenomenon have been put forth (Liang and Seright, 1997): i) shrinking of the gel, ii) fluids partitioning, iii) wall effect, iv) wettability effect. In addition, most of the studies reported in the literature are focused on relative permeability and modification of end point saturations and very little information is available on capillary pressure (Barrufet & Ali, 1994). Even if capillary effects are most of the time of little interest near wells since viscous effects are dominant there, this quantity can however provide useful informations at the laboratory scale to help understanding the physical mechanisms during polymer injection and the resulting pore structure modification.

In this work, unsteady state oil-water flow experiments on water-wet sandstone cores were performed before and after polymer has been injected. Relative permeabilities were determined over the whole range of water saturation and capillary pressures were directly measured on the core.

The results of these experiments seem to indicate that a major effect of the polymer adsorption is the reduction of pore diameter. To check the phenomenological validity of this hypothesis, a pore-scale two-phase flow numerical model was run allowing computation of relative permeabilities and capillary pressure.

# 2. Experimental

## 2.1 Materials and procedure

**Polymer**: A high-molecular-weight nonionic polyacrylamide (PAM) dissolved at 2500 ppm in a synthetic brine -50g/l KI, 0.4g/l NaN<sub>3</sub>- was employed. After complete dissolution of the powder, the solution was filtered in order to remove any aggregates or microgel.

*Oil*: A mineral oil of 10.5 mPa.s dynamic viscosity at room temperature was used. Interfacial tensions between oil and brine and between oil and polymer solution were respectively 33 N.m<sup>-1</sup> and 28 N.m<sup>-1</sup>.

*Core sample* : A Vosges sandstone of  $0.25\mu m^2$  permeability and 23% porosity was used. A mineralogy study on this material showed a composition of quartz, feldspars and clays (7%), covering almost entirely the grains population.

**Experimental setup**: The experimental flow equipment is represented in Fig. 1. Oil, brine and polymer solution, were injected in the porous medium by the means of an alternate syringe pump. The core was positioned horizontally on a two-dimensional rig moving a  $\gamma$ -ray attenuation device used to measure the in situ water saturation. Pressure drop along the core and production at the outlet were measured continuously during the experiment. Capillary pressure was directly measured on the core during the imbibition processes using semi permeable membranes -oil-wet at the top and water wet at the bottom-

positioned on six pressure taps equally distributed along the porous medium. Semi permeable membranes were replaced after polymer injection to avoid plugging problems. Water saturations and pressure difference between wetting and non-wetting phases -i.e. capillary pressures- were always measured at the same intervals of time and same positions during the different cycles of each experiment.

Experimental procedure : Flow tests were run with the following sequences.

- 1) Brine saturation of the vacuumed core.
- 2) Initial oil flood at high flow-rate. Measurement of  $S^{1}_{wi}$  and  $K_{o}@S^{1}_{wi}$ .
- 3) First low flow-rate waterflood. Water saturation profiles, pressure drop, recovery and capillary pressure were measured during the overall displacement. At the end of this stage, S<sup>1</sup><sub>or</sub> and K<sub>w</sub>@S<sup>1</sup><sub>or</sub> were determined.
- 4) Low flow-rate polymer injection. Adsorbed polymer fraction was determined from the polymer front delay at the outlet relative to one pore volume injection time.
- 5) Brine displacement, after polymer adsorption, in order to remove the non-adsorbed polymer remaining in the core. Measurement of  $S_{or}^2$  and  $K_w @S_{or}^2$ .
- 6) High flow-rate oil displacement in the presence of adsorbed polymer. Measurement of  $S^2_{wi}$  and  $K_o @S^2_{wi}$ .
- 7) Low flow-rate water displacement in the presence of adsorbed polymer. Measurement of S<sup>3</sup><sub>or</sub> and K<sub>w</sub>@S<sup>3</sup><sub>or</sub>.

# 2.2 Experimental results

The adsorbed polymer quantity was 97  $\mu$ g/g, leading to an estimated polymer layer thickness of 0.49  $\mu$ m (Barreau et al., 1996).

End point data before and after polymer injection are summarized in Table1 and indicate that irreducible water saturations are significantly higher after polymer adsorption while residual oil saturations are almost unchanged.

In Fig. 2 and 3 are reported time evolutions of water saturation profiles -averaged over four points in a cross section- before and after polymer adsorption. We note that the displacement front is much more spread out in the absence of adsorbed polymer than in the presence of it. This can be understood as a result of the balance between viscous and capillary effects.

Capillary pressure relationships measured before and after polymer adsorption are plotted in Fig. 4. In addition to the above mentioned increase of the initial water saturation, a dramatic increase of capillary pressure after polymer adsorption over the whole saturation range can be observed. Since interfacial tensions between oil and water on the one hand and oil and polymer solution on the other hand are almost the same, the increase of capillary pressure is representative of pore throat size reduction when polymer is adsorbed. One can easily figure out the meaning of this assumption if a simple bundle of capillary tube is used to represent the porous medium. The capillary pressure, which is proportional to the interfacial tension and wetting angle and inversely proportional to the tube radius, can only be increased if the tube diameter is reduced, keeping all other parameters constant. This effect will be examined in more details in the subsequent numerical study.

The relative permeabilities, shown in Fig. 5, were determined using a minimization software -FISOLE<sup>TM</sup>-(Chardaire & al., 1989) that simultaneously estimates relative permeabilities and capillary pressure from experimental measurements. In our case, we used recovery, pressure drop, saturation profiles and capillary pressure as experimental data to determine the relative permeabilities. From these estimations, one can notice that the ratio between oil relative permeabilities (at irreducible saturations) before and after polymer adsorption is equal to 1.6 while the ratio between water relative permeabilities (at the residual saturation) is equal to 22.1. Several drainage-imbibition cycles in the absence of polymer were performed on a similar core and a very weak hysteresis effect was found (Barreau et al., 1996). This excludes an experimental artifact of this kind and confirms the selective action of the polymer.

## 3. Numerical tests

The above results on both capillary pressure and relative permeabilities suggest, in addition to other effects mentioned in the literature (Zaitoun & Kohler, 1988; Liang & Seright, 1997), that a possible mechanism to explain such a behavior is a reduction of the pore diameter due to polymer adsorption. The

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validity of such an hypothesis is now checked by performing numerical two-phase flow experiments on a model 2D pore geometry. Rather than reproducing direct experimental configurations, the goal of this part of the work is to investigate the phenomenology of the process.

# 3.1 Geometry and hypotheses

The model pore geometry used in this study consists of a water-wet infinite succession of two dimensional, periodic, of period  $le_1$ , convergent-divergent cells in which the oil-phase (o) flows trough the center (Fig. 6). We assumed gravity to have negligible contribution compared to viscous and capillary effects and we solved the two-phase Stokes flow resulting from the application of an external pressure gradient, he<sub>1</sub>, in the axial direction in the computational domain shown in Fig. 7. The solution to this problem depends on the five following parameters : the water saturation,  $S_w$ , the water to oil viscosity ratio,  $\mu_w/\mu_o$ , the ratio of capillary to external applied forces,  $\gamma/hl^2$  where  $\gamma$  is the oil/water interfacial tension, and geometrical dimensionless characteristics H1 and H2 of the cell (see Fig. 7). To simulate the presence of the polymer, we assumed, for simplicity, that the adsorbed polymer layer is immobile and fully water saturated with a constant thickness e<sub>p</sub>, as depicted in Fig. 7.

# 3.2 Method and algorithm

The two-phase flow is solved using a boundary element technique after the boundary value problem has been reformulated in its equivalent integral form (Ladyzhenskaya, 1969; Pozrikidis, 1992; Barreau & al., 1995). First, the oil-water interface satisfying mass and momentum balance equations according to the applied pressure gradient was sought iteratively (Barreau, 1996). Once this stationary solution has been reached, relative permeabilities  $k_{r_{\alpha}}$  and capillary pressure  $P_c$  were computed according to :

$$k_{r\alpha} = -\left(l^{3}\sum_{S_{in\alpha}} \mathbf{v}_{\alpha} \cdot \mathbf{e}_{1} \Delta l\right) / k_{o} A_{\alpha} \qquad \alpha = \mathbf{w}, \mathbf{o}$$
(1)  
$$P_{c} = \gamma / h l^{2} \langle \mathbf{C} \rangle |_{\Gamma_{w\alpha}}$$
(2)

where  $S_{in_{\alpha}}$  is the portion of the cell entrance within the  $\alpha$ -phase,  $\mathbf{v}_{\alpha}$  the  $\alpha$ -phase velocity,  $\Delta l$  the boundary element length,  $\mathbf{k}_{\alpha}$  the effective permeability to oil in the absence of polymer at the irreducible water saturation,  $A_{\alpha}$  the area of the computational domain occupied by the  $\alpha$ -phase and  $\langle C \rangle |_{\Gamma_{un}}$  the mean

# curvature along the stationary interface $\Gamma_{wo}$ .

Identical calculations were performed without any adsorbed polymer layer in a first step and in the presence of the polymer layer in a second step, leading to a reduction of H1 and H2, i.e. of the pore diameter, in accordance with  $e_p$ . The overall procedure was repeated for increasing water saturations, reproducing a complete steady-state imbibition process.

## 3.3 Results

Computational results presented in the following were obtained with : H1=0.417, H2=0.167,  $e_p=0.05$  and  $\mu_w/\mu_0 = 9.09 \times 10^{-2}$  which corresponds to an oil with a dynamic viscosity of 11mPa.s.

*Irreducible water saturation :* the irreducible water saturation is systematically higher after polymer is introduced in the model. Although this directly follows from our hypothesis of a fully water saturated polymer layer, this is in accordance with experimental observations.

**Relative permeabilities :** relative permeability results obtained for  $\gamma/hl^2 = 0.1$ , 1 and 10 are represented in Fig.8 as functions of the water saturation. These data clearly indicate that the simplified model used here for the adsorbed polymer layer is able to reproduce a selective action since the relative permeability reduction is roughly twice larger for the water-phase than for the oil-phase at S<sub>w</sub>=07 (see Table 2). This selective behavior increases with  $\gamma/hl^2$ .

**Capillary pressure :** capillary pressure curves obtained with  $\gamma/hl^2 = 1$  and computed from Eq. 2 are represented in Fig. 9 as functions of the water saturation. The capillary pressure modification induced by the reduction of the pore diameter is in accordance with our experimental observation. In fact, after polymer layer has been introduced, the capillary pressure is strongly increased indicating that the pore diameter reduction yields a significant increase of the mean curvature of the oil-water interface.

#### 4. Conclusions

The effect of adsorbed polymer on oil-water flow was studied from direct experiments on sandstone cores. As already mentioned in the literature, our experiments indicate that :

i) irreducible water saturation increases after polymer has been injected. This can be explained by a - small- contribution of polymer hydration water and mainly by the fact that smaller pores are closed to oil flow,

ii) relative permeability curves clearly exhibit a selective action of the polymer since the water relative permeability is much stronger reduced than the oil relative permeability.

In addition, our direct measurements showed that the presence of the adsorbed polymer yields a strong capillary pressure increase.

All these results suggest that a significant mechanism might be a net pore size reduction resulting from the adsorbed polymer layer. The phenomenological validity of this hypothesis was checked with the aid of a numerical model. Making use of a simplified polymer layer model, direct pore-scale numerical simulations of oil-water flow were performed in a model-pore geometry. They correctly reproduce phenomena observed physically.

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TABLE 1 - END POINT DATA BEFORE AND AFTER POLYMER												
S <sup>1</sup> <sub>wi</sub>	$K_o @ S_{wi}^1$ ( $\mu m^2$ )	S <sup>1</sup> <sub>or</sub>	$K_w @ S_{or}^1$ . ( $\mu m^2$ )	S <sup>2</sup> <sub>or</sub>	$K_w @ S_{or}^2$ . ( $\mu m^2$ )	$S_{wi}^2$	$\frac{K_o@~S_{wi}^2}{(\mu m^2)}$	S <sup>3</sup> <sub>or</sub>	$K_w @ S_{or}^3$ ( $\mu m^2$ )			
0.327	0.222	0.336	0.0155			0.492	0.138	0.328	0.0007			



Fig. 1 Experimental setup.











after polymer injection.



Fig. 5 Modification of water and oil relative permeabilities before and after polymer injection.



Fig. 6 Pore model geometry.

Fig. 7 Domain configuration for computation.



Fig. 8 Computed relative permeabilities before and after polymer injection.

Table 2 - Relative permeabilities before and after polymer at S <sub>w</sub> =0.7											
	$\gamma/hl^2$	<sup>2</sup> = 0.1	$\gamma/hl$	<sup>2</sup> = 1	$\gamma/hl^2 = 10$						
	k <sub>rw</sub>	kro	k <sub>rw</sub>	k <sub>ro</sub>	k <sub>rw</sub>	k <sub>ro</sub>					
Before polymer	0.0417	0.5074	0.0188	0.235	0.0273	0.3834					
After polymer	0.0215	0.3710	0.0079	0.196	0.0101	0.3594					
kr reduction	1.94	1.37	2.38	1.20	2.70	1.07					



