EFFICIENCY OF GAS INJECTION SCENARIOS FOR INTERMEDIATE WETTABILITY: PORE-NETWORK MODELLING

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ABSTRACT

Enhanced oil recovery schemes often include immiscible gas injection in varying levels of water saturations under a range of wettability conditions, for example during WAG or injection into the transition zone. In this work the efficiency of gas injection is investigated at the pore-scale for intermediate-wet systems, consisting of both weakly water-wet and weakly oil-wet pores, following different drainage and water flooding scenarios. A pore-network model is employed, which has been validated against WAG experiments in intermediate-wet micromodels with near neutral-wet pores, i.e. with oil-water contact angles distributed around 90 degrees (SPE 113864). Further simulations are devoted to gas injection at different water saturations after drainage (transition zone), as well as after water flooding. The models are water-wet during drainage and have subsequently been aged to intermediate-wet, with different ranges of contact angles and fractions of oil-wet pores. For gas injection in these systems with near neutral-wet pores only oil wetting films in gas-filled pores may be present, which enhances oil phase continuity, drainage of remaining oil and oil relative permeability. The degree to which these wetting films are present leads to a large variation in residual oil saturations. Interestingly, direct gas injection after drainage often results in significantly lower residuals than gas injection proceeded by water flooding, at comparable water saturations. The other main finding is that more oil-wet of the system, better oil recovery for gas displacement.

1 INTRODUCTION

Fluid flow in porous media is determined by fluid properties and porous media structure, such as interfacial tension, contact angle, pore size distribution, coordination number, etc. Considering oil industry, both aspects can influence relative permeability, capillary pressure and oil recovery. Among all the parameters, wettability is one of the most important. Anderson and Treiber et al. [1, 2] divided wettability into three types according to contact angle values: water-wet ($0-75^\circ$), intermediate-wet ($75-105^\circ$) and oil-wet ($105-180^\circ$). In this paper, we use their wettability classification method and pay more attention to the intermediate-wet ($75-105^\circ$). Kovscek et al. [3] firstly studied pore-scale modelling of wettability in the star-shaped porous media based on observations of

Salathiel [4]. Since then, more researchers did simulation of wettability influence on oil recovery [5-11].

The previous paper (SPE 113864) compared experimental and simulated results in mixed-wet system for immiscible WAG flooding, and got qualitative and quantitative agreements, which validated precision of the 3D network model[12]. We use the same model established by van Dijke and Sorbie [13] to study interesting phenomena during gas injection in intermediate-wet system.

2 FILM MODEL THEORY

When the section of pore and throat in network model has corner (Figure 1), the general geometry condition of film existence is

$$\theta_{ij} \le \frac{\pi}{2} - \gamma \tag{1}$$

In this paper, we proposed a threshold value of contact angle, $\cos\theta^*$, for film or spreading layer existence in our 3D network model with cylindrical pores. The standard criterions for different films existence are as following:

$$\begin{cases} \cos\theta_{\mathrm{ow}} < \cos\theta_{\mathrm{ow}}{}^* & \text{Oil film around water} \\ \cos\theta_{\mathrm{go}} > \cos\theta_{\mathrm{go}}{}^* & \text{Oil film or layer around gas} \\ \cos\theta_{\mathrm{ow}} > \cos\theta_{\mathrm{ow}}{}^* & \text{Water film around oil} \\ \cos\theta_{\mathrm{gw}} > \cos\theta_{\mathrm{gw}}{}^* & \text{Water film around gas} \end{cases} \tag{2}$$

3 RESULTS AND DISCUSSION

3.1 Two Displacement Processes

We compared two gas injection scenarios: direct gas injection after oil drainage and gas injection proceeded by water flooding. The network model is fully filled with water first ($S_{\mathrm{w}} = 1$), then inject oil into the model; the next step is injecting water; lastly, gas is injected. Case 1, 3 and 5 follows the above processes description. For Case 2, 4 and 6, there is no water flooding process, after oil drainage to the same oil saturation value as the above process to compare with each other, gas is directly injected into the network model. We made the following assumptions for the 6 cases: during the oil drainage, the oil-water contact angle distributes between 75° and 105°. After the rock see the oil, the contact angle was supposed to be $75-105^\circ$ for aging. For the following procedures, water flooding and gas injection, the contact angle has the same value distribution.

From figure 2 & figure3, we can clearly see that direct gas injection always gets lower oil saturation compared with water flooding followed by gas displacement. When threshold value for oil film around gas $\cos\theta_{\mathrm{go}}{}^*$ is 0.95, oil saturation of direct gas injection is higher than that of the other process during the starting stage of gas displacement process; however, lower oil saturation of direct gas injection can be obtained at the endpoint of gas displacement. Different from $\cos\theta_{go}{}^{*}$ as 0.95, during the whole process, lower oil saturation for direct gas injection can be obtained when $\cos\theta_{go}{}^{*}$ is 0.96 or 0.97.

3.2 Gas-Oil-Water Distribution

To investigate difference between the above two displacement processes, we take Case 3 & 4, with $\cos\theta_{go}{}^{*}$ 0.96, as example to study the microscopic distribution of gas, oil and water during different gas injection stage (Figure 4). Although the value of oil saturation is equal at gas injection starting point, oil and water distribution in network is slightly different (Figure 4 a & b). During gas injection process (Figure 4 c & d), direct gas displacement prefers to flood oil located in big pores. So, direct gas injection can displace more oil finally (Figure 4 e & f).

3.3 Wettability And Aging

We also studied aging influence on gas flooding efficiency in different weakly wetting systems. After contacted with oil, the wettability of pore surface will change to be more oil-wet. In our network model, we studied two aging scenarios to compare with base case, Case 1. The first aging scenario (Case 7): the network model is initially uniform water-wet ($0.94 \le \cos\theta_{ow} \le 1$), and after oil drainage, the oil-water contact angles in oil filled pores switch to be $75^\circ - 90^\circ$, and the water filled pores do not change contact angle. The second aging scenario (Case 8): initial condition is the same as Case 7; after aging, the contact angles of oil filled pores were changed to be $75^\circ - 105^\circ$ to compare with Case 1, and the water filled pores don't change contact angles either. The left modelling parameters are the same among the three cases (Case 1, 7, and 8). Saturation paths comparison is shown in Figure 5.

At the starting point of gas displacement, oil saturation of the three cases is different. This is because oil saturation after water flooding depends not only on coordination number of the network model, but also on oil films around water or water films around oil. The initial state of cases 7 & 8: $0.94 \le \cos\theta_{ow} \le 1$, however, for case 1 $-0.259 \le \cos\theta_{ow} \le 0.259$. So, the initial state of case 1 is more oil-wet than cases 7&8. i.e. oil-wet order of the three network systems: Case 1> Case 8> Case 7. From the saturations in Figure 5, we can draw the conclusion that the more oil-wet of the system, better oil recovery for gas displacement.

Based on Case 8, we run two more cases to study the influence of water-wet fraction (equals to 1 minus oil-wet fraction) in oil filled pores after aging. The fraction of water-wet pores in oil filled pores is 0.5 for Case 8. We decrease fraction of water-wet pores in oil filled pores to 0.2 (Case 9) and increase that value to 0.8 (Case 10) to do sensitivity study. The simulation results are shown in Figure 6. The similar conclusion can be obtained that more oil-wet pores in the network model, better oil recovery for gas displacement.

4 CONCLUSIONS

Based on the pore-scale network model, we can get the following conclusions. They are true in places where three-phase flow develops. However, we should treat with caution to apply these conclusions for the field practices.

(1) The wettability condition studied in this paper is intermediate-wet ($-0.259 \le \cos\theta_{ow} \le 0.259$).Threshold vale for films $\cos\theta^*$ is set as 0.95, 0.96 and 0.97. When $\cos\theta_{go} \ge \cos\theta_{go}^*$, oil wetting films around gas were suppressed, and this has great influence on residual oil saturation.

(2) Direct gas injection is much more beneficial than gas injection proceeded by water flooding process.

(3) More oil-wet of the system and more oil-wet pores in the network, better oil recovery for gas displacement.

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Nomenclature

i : non-wetting phase;
j :wetting phase;
θ_{ij} : contact angle between phase i and j ;
γ : half-angle of corner;
$C_{S,o}$: oil spreading coefficient, 10^{-3}N/m
$\cos\theta_{go}{}^*$: threshold value for oil film or spreading layer around gas;
σ_{go} : oil/gas IFT, 10^{-3}N/m;
σ_{ow} : oil/water IFT, 10^{-3}N/m;
σ_{gw} : water/gas IFT, 10^{-3}N/m.

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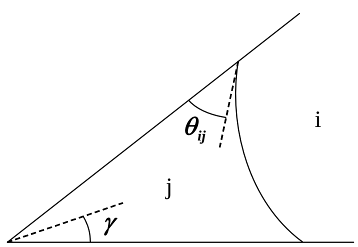

Figure 1. Two-phase occupancy at the corner of a pore

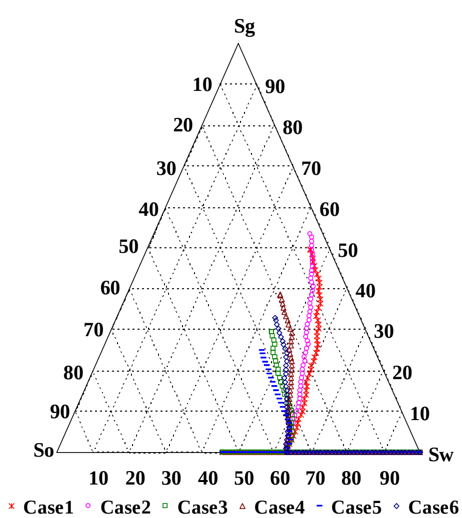

Figure 2. Saturation paths of two gas injection scenarios under different film threshold value $\cos\theta_{go}^*$ in intermediate-wet system with coordination number z=3; threshold value $\cos\theta_{go}^*$ for oil film around gas is 0.95(Case1 & 2), 0.96(Case3 & 4), and 0.97(Case5 & 6), respectively; for displacement process, case1, 3, 5 is gas injection proceeded by water flooding and case2, 4, 6 is direct gas injection after oil drainage.

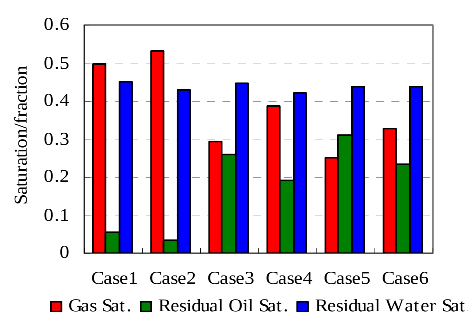

Figure 3. Three-phase saturation at the displacement endpoint

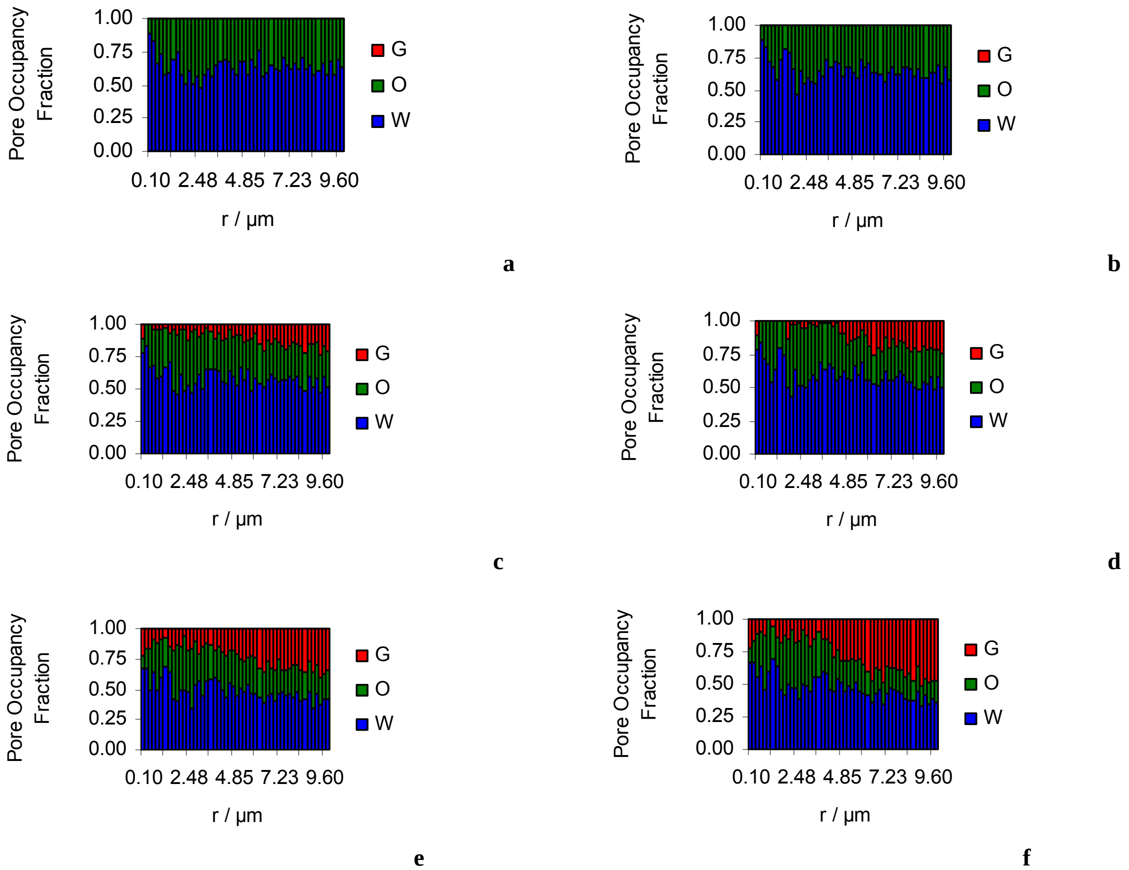

Figure 4. Pore occupancy statistics of Case3 (a, c and e) & Case4 (b, d and f) at different time, (a & b) at gas injection starting point, (c & d) when gas injection loop 1,000 time, (e & f) at gas injection endpoint.

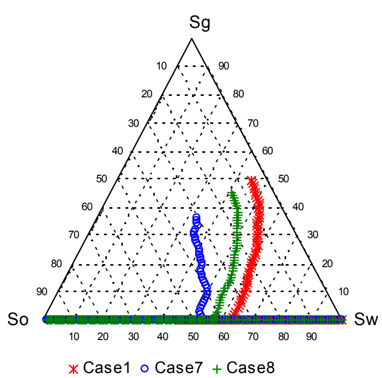

Figure 5. Saturation paths comparison, Case 7 is weakly water-wet ($75^\circ - 90^\circ$) after aging, and Case 8 is weakly water-wet ($75^\circ - 90^\circ$) and weakly oil-wet ($90^\circ - 105^\circ$) after aging.

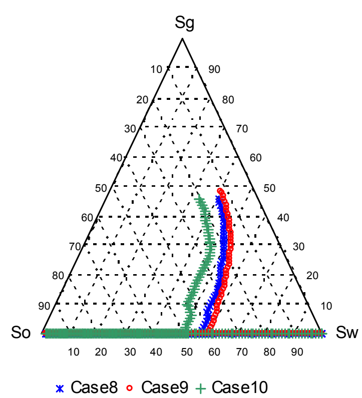

Figure 6. Saturation paths of aging scenarios with different water-wet fractions in oil filled pores, fraction of water-wet pores for Case 8, Case 9 and Case 10 is 0.5, 0.2 and 0.8, respectively.