ANALYZING RETENTION VIA PARTICLE MOBILITY COREFLOODING

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ABSTRACT

This paper presents a way to screen for particle retention through a core plug. Various injection rates were tested on two core plugs of different lengths to achieve base values for final saturation, differential pressure profiles, and breakthrough times. Berea sandstone cores and synthetic North Sea water were used for these tests. Final saturations were around 60% for all cores. Differential pressure profiles slightly increased throughout the duration of the core flooding tests for all scenarios except the lowest injection rate.

INTRODUCTION

As reservoir engineers develop new particles for enhanced oil recovery (EOR), certain screening criteria must be developed to determine the feasibility and potential of injecting these particles into petroleum reservoirs. If the particles have not been previously injected into reservoirs, a study should assess whether or not injection would lead to particle build-up on the rock grains, thereby causing permeability impairment and ultimately reservoir damage. The mass of the particles retained in the core can be divided into two groups: particles adhered to the solid surfaces and particles suspended in the liquid in pores spaces [1]. The objective of the method proposed in this paper is to determine the mass of the particles adhered to the solids surfaces.

The vertically-oriented particle mobility coreflooding (PMC) procedure has been developed as part of a screening program to evaluate new particles. The procedure is designed for those who have added EOR particles to an aqueous injection fluid and need to determine the particle mobility through the reservoir. Particle concentration analysis conducted on the effluent can reveal the retention of the particles in the porous media via mass balance. Retention will be primarily a result of adsorption onto rock grains if the particle diameter is smaller than the pore throat. Therefore, this procedure should be conducted after stability tests have confirmed that the particles do not aggregate during the course of the PMC tests.

The PMC tests are conducted with initially unsaturated cores. This is to mitigate the effects of diffusion on the effluent concentration. When the core is initially saturated with the base aqueous fluid prior to injection of the particle-enriched fluid, diffusion can occur into zones of flow stagnation (figure 1a). These zones occur when a pore has an opening but not an exit. The concentration gradient at the interface between the flowing phase and the zone of stagnation causes the particle diffusion [2]. Mechanical dispersion as a result of velocity differences at the interface will result in additional particle loss to the dead-end pore [2]. However, mechanical dispersion is weaker perpendicular to the flow path, so transverse dispersion is dominated by particle diffusion until very high velocity values are reached [3].

The diffusion process would dilute the number of particles in the effluent concentration, making it difficult to determine what percentage of the lost concentration is due to diffusion into dead ends and what is due to adsorption onto solid surfaces. The core could initially be saturated with the same concentration of the EOR particle fluid which will be flooded, but then adsorption would begin prior to the flooding, making it difficult to get an accurate picture of how the adsorption capacity is changing over time due to fluid injection. This is why the core is initially unsaturated (figure 1b).

The coreholder is mounted vertically to maximize the saturation potential. When a dry core is flooded horizontally, there is a large area that remains unsaturated, especially at the outlet region (figure 2a). The vertically orientation utilizes the natural gravity segregation of the air and aqueous fluid to better saturate from the bottom and upwards (figure 2b). Pore geometry (and thereby effective porosity and permeability) plays a large role in the final saturation. The impact of the core orientation will be more pronounced with longer cores than with shorter cores and with lower flow rates than with higher flow rates. Higher flow rates will also result in a smaller value of particle retention as demonstrated with polystyrene colloids in unsaturated porous media [4] and with silica nanoparticles in saturated porous media [1]. The primary reason is because higher flow rates decrease the residence time of the particles in the porous media, giving them less time to react with the system [1].

PROCEDURE

In the PMC procedure, a dry core plug was mounted vertically in a core holder. A sleeve pressure of 20 bars was applied. The EOR fluid was injected from the bottom of the core, and effluent samples were collected from the outlet at the top (figure 3). Particle mobility and retention could be calculated by evaluating inlet and effluent particle concentration. The fluid breakthrough time, differential pressure, final saturation, and pre- and post-flooding porosity and permeability of the core were evaluated. Cores can first be tested with the aqueous dispersion fluid, rinsed and dried, and then retested with the EOR particle additive for comparison. It is important to fasten the core holder, pressure gage, reservoir, and all flow lines so that results from different tests can be confidently compared.

During the test, pressure readings were taken and samples were collected every pore volume (for the 4.5 cm core) and every half pore volume (10 cm core) for further analysis. When using a new particle-enriched EOR fluid, these effluent samples are what can be analysed for changes in pH, particle concentration, particle size distribution, etc. It is then recommended that effluent samples are taken at higher resolutions, for example every ¼ PV, to better characterize particle mobility.

Each core was flooded such that five pore volumes of samples could be collected, resulting in six pore volumes being injected into the core. Immediately after the fifth pore volume had been collected, the core was taken out of the apparatus and weighed to determine the final saturation. The core was then placed in a soxhlet filled with methanol and rinsed for at least seven hours. It was then dried in an oven at 60 C for at least three days. Helium porosimeter and air permeameter measurements were taken after each flood. The core flooding procedure was performed using injection rates of 0.3 ml/min, 1.0 ml/min, 2.0 ml/min, and 3.0 ml/min for the 4.5 cm long core and using 1.0 ml/min and 2.0 ml/min for the 10 cm core.

MATERIALS

Two Berea sandstone cores drilled from the same block were used in this study. Both had a diameter of 3.81 cm (1.5 in.). Core 1 had a length of 4.5 cm (1.77 in.), and core 2 had a length of 10 cm (3.94 in.). Core 1 had an initial porosity of 16% and permeability of 275 mD. Core 2 had an initial porosity of 16% and permeability of 400 mD. Porosity was measured with a helium porosimeter, and permeability was measured with air and corrected by use of the Klinkenberg effect.

Synthetic North Sea water was mixed and used for the injection fluid. It was a mixture of deionized water, sodium chloride, sodium hydrogen carbonate, sodium sulfate, calcium chloride, magnesium chloride, strontium chloride, and potassium chloride. This resulted in a salinity of 3.53 wt% and a viscosity of 1.025 cP.

RESULTS

The differential pressure profiles and breakthrough times for each core flood are presented in figure 4. As expected, breakthrough times were quite consistent across all core floods. Differential pressure steeply increased at the beginning of the core flood, but then flattened out after breakthrough. For all injection scenarios except the 0.3 ml/min rate, the differential pressure continued to increase in a pattern such that there would be a plateau followed by a quick jump in pressure before plateauing again. This suggests that the core saturation is still increasing throughout water injection. The plateau regions could be where saturation has reached a pseudo-equilibrium state, and then the quick rises could be where the injected water has suddenly penetrated a previously empty zone.

The final saturation of the 4.5 cm core varied from 56 to 59%. There was no visible trend with end saturation vs. flow rate, and all the results are within the standard error. The final saturation of the 10cm core floods were 62% and 64% for the 1 ml/min and 2 ml/min floods respectively. Porosity and permeability values did not vary much between floods.

CONCLUSIONS

- This method can be useful for calculating the retention capacity of a core plug when flooded with a new particle-enriched EOR fluid.
- This method results in about a 60% final saturation. This will vary slightly with core length and injection rate. Particle retention would also alter this value when EOR fluids are injected.
- For all injection rates except 0.3 ml/min, the differential pressure profile continued to increase slightly. This suggests that the core saturation is still slightly increasing throughout the duration of the core flooding tests for all of the other scenarios.

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FIGURES

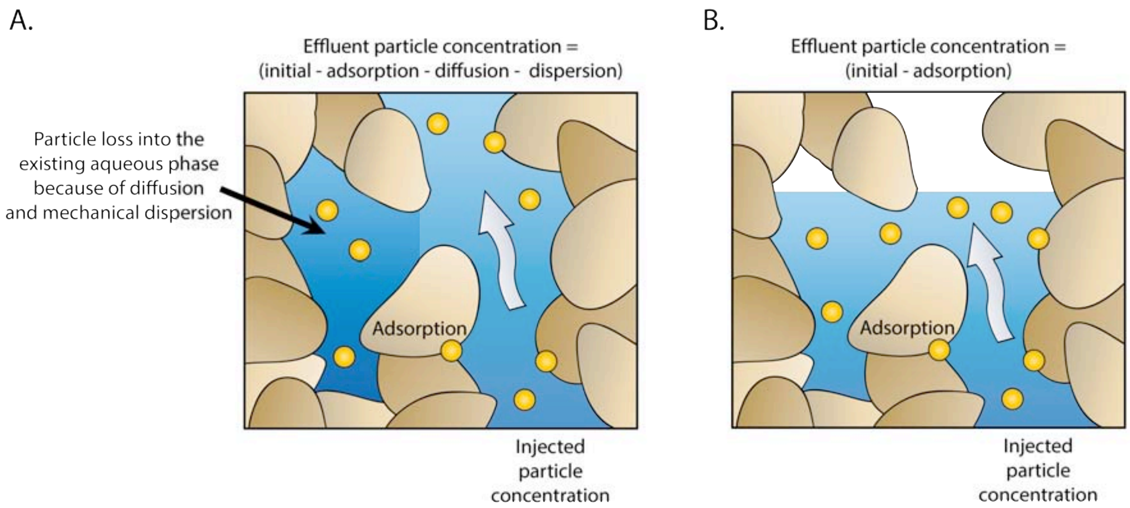
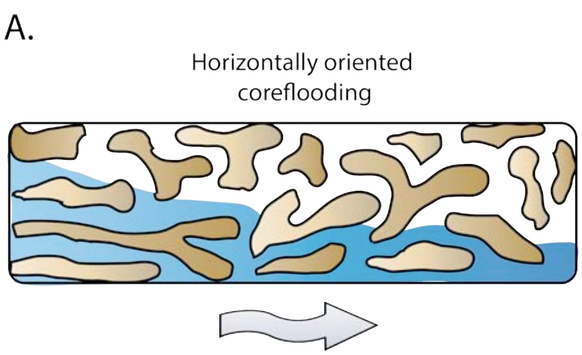


Figure 1. Conceptual drawing of how a core initially saturated with an aqueous fluid will affect the effluent concentration vs. a core initially unsaturated. **A)** When a core is initially saturated with an aqueous fluid prior to EOR fluid injection, particle diffusion and mechanical dispersion will occur, diluting the overall concentration. When the effluent sample is taken, it is impossible to determine how much of the missing concentration is from particle adsorption to the rock grains and how much is from particle loss into the aqueous fluid. **B)** When the EOR fluid is injected into a dry core, the difference in the effluent concentration from the injected concentration is solely adsorption. This figure assumes no mechanical entrapment is occurring.



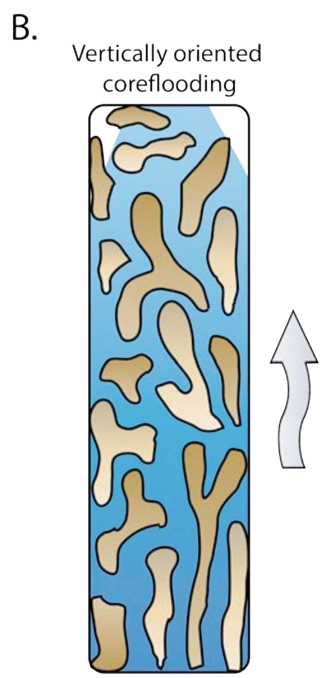


Figure 2. Conceptual drawing of how core orientation affects saturation. **A)** When a horizontally orientated core is flooded, there will be a high saturation at the inlet face, but a large portion of the outlet will remain unsaturated due to gravity segregation. **B)** In a vertically orientated core where the fluid is injected from the bottom, the saturation will be more evenly distributed because of the gravity segregation.

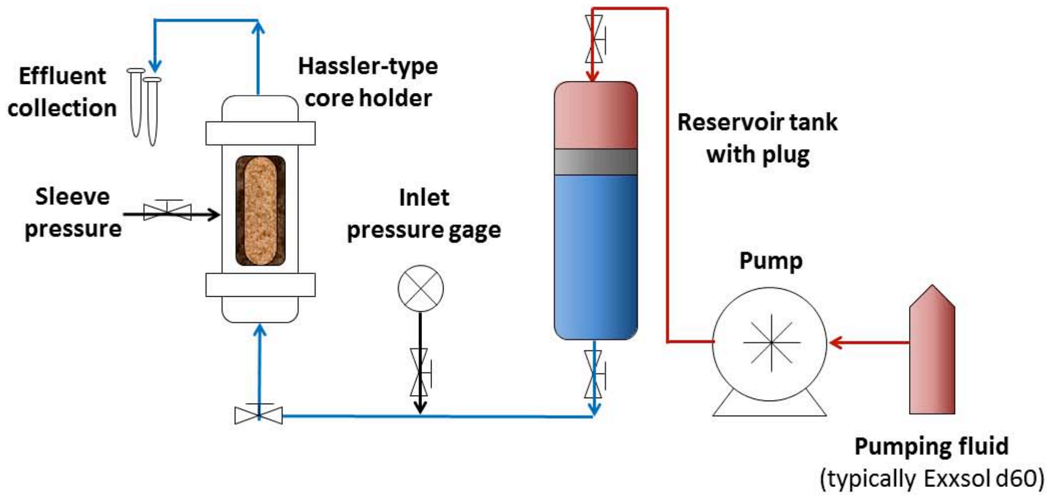


Figure 3. Schematic of the particle mobility coreflooding apparatus. The core holder, pressure gage and reservoir tank are fixed to a stand such that they have the same position for every test. The reservoir plug is not necessary if the pumping fluid and injection fluid are immiscible and it has been proved that the particles do not adhere to the liquid-liquid interface. Half of the experiments were run with the plug and half were run without. It did not affect the results because NSW and the pumping fluid are immiscible.

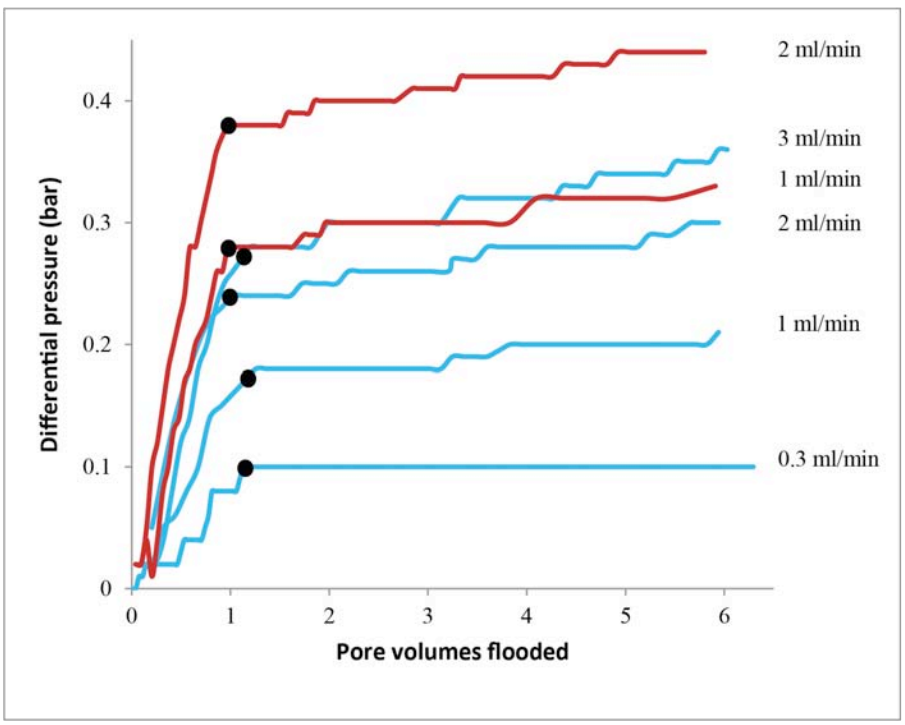


Figure 4. Differential pressure vs. pore volumes flooded for the 4.5 cm core **(blue lines)** and the 10 cm core **(red lines)** for various flow rates. Water breakthrough at the outlet is shown by black dots on the graph.