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Experimental and numerical investigation of polymer flooding in fractured heavy oil five-spot systems

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ABSTRACT

Microscopic and macroscopic displacements of polymer flooding to heavy oil at various levels of salinity and connate water saturation have been investigated. Both oil-wet and water-wet conditions in fractured five-spot micromodel systems, initially saturated with the heavy crude oil are utilized. The primary contribution is to examine the role of salinity, wettability, connate water, and fracture geometry in the recovery efficiency of the system. The microscopic results revealed that the increase in the connate water saturation decreases the oil recovery, independent of the wettability conditions. Moreover, the increase in salinity of the injected fluids lowers the recovery efficiency due to the decrease in polymer viscosity. One the other hand, the microscopic results emphasized the wettability role in the simultaneous flow of oil, the connate water, and the polymer phases. In addition, switching from the oil-wet to the water-wet medium has manifested increase in the oil recovery during polymer flooding as compared to water flooding owing to its severe mechanisms of pulling and stripping. To simulate the experimental results, the UTCHEM software has been applied, which has validated the observed data for different fractured patterns, and at various connate water and salinity of polymer solution. Furthermore, the visualized results uncovered a light stripping mechanism in the high permeable fracture. The findings of this study can be beneficial to the better understanding of the microscopic/macroscopic displacements during polymer flooding in fractured heavy oil five-spot systems. It also illustrates the successful application of the UTCHEM for predicting the roles of connate water, salinity and fracture geometry in efficiency of polymer flooding in fractured five-spot micromodels.

1. Introduction

Water flooding is widely used in the oil industry to improve the oil recovery due to its low costs and simple operations. However, its primary shortcoming is its low sweep efficiency especially in heavy oil reservoirs owing to the fingering effects. To approach this problem, it is recommended to increase the viscosity of the displacing phase, for example, by adding polymers (Chang and Wasan, 1980). The application of high polymer's molecular weight can enhance water viscosity and reduce water relative permeability with a negligible impact on oil relative permeability. As a result, the use of polymers can be more effective in comparison with the use of other chemicals (Needham and Doe, 1987). Adding polymers increases oil recovery significantly having the highest improving effect in comparison with other chemicals in individual (Sedaghat et al., 2011).

Polymer flooding mainly aims to boost the sweep efficiency defined as the ratio of oil volume contacted by the displacing agent to the initial oil in place. Sweep efficiency is affected by the mobility ratio, pore structure, reservoir rock wettability, reservoir heterogeneities including the fractures' characteristics (Craig, 1971). The use of polymer solutions improves the oil recovery by (1) its influence on the fractional flow, (2) reduction of water-oil mobility ratio, and (3) diversion of injected water toward the swept zones (Needham and Doe, 1987).

Two groups of polymers are: (1) synthetic polymers, such as hydrolyzed Polyacrylamide (HPAM) and (2) biopolymers, such as Xanthan gum. There is an extensive body of literature on the application of polymer flooding (Chang and Wasan., 1980; Needham and Doe, 1987; Sedaghat et al., 2013). The role of connate water in heavy oil chemical floods was discussed by Mohammadi et al. (2011). Additionally, the role of fracture geometry in solvent flooding has been investigated by Farzaneh et al. (2010). Nonetheless, there is a paucity of published studies addressing these roles in polymer flooding of heavy oil systems.

The UTCHEM, which stands for the University of Texas Chemical Compositional Simulator (copyright owned by The University of Texas at Austin), is a three-dimensional, multi-phase, multi-component, compositional, variable temperature, finite-difference numerical simulator. Surfactant phase behavior (Camilleri et al.,

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1987; Pope and Nelson, 1978; Prouvost et al., 1985; Satoh, 1984), three-phase relative permeability (Delshad et al., 1987), shear-thinning polymer viscosity (Wreath et al., 1990), cation exchange with clays and micelles (Bhuyan et al., 1990; Hirasaki, 1982) are included in the UTCHEM. Although some lab-scale chemical flooding simulations were examined using the UTCHEM (Mohammadi et al., 2009), there is no reported experience for the simulation of polymer flooding in fractured five-spot micromodel system.

It has been proven that microscopic visualization of the micromodel provides the opportunity to probe the existing theories and assumptions (Wilson, 1994). For example, Riazi et al. (2011) conducted a significant pore-scale observation of carbonated water injection using micromodels. Yet, they did not employ micromodels for observation of chemical flooding in five-spot systems.

In this research, 30% hydrolyzed polyacrylamide (HPAM 3330) has been used as a synthetic polymer, along with Xanthan, as a bio-polymer to monitor the role of connate water, salinity as well as wettability in fractured five-spot systems. Microscopic pictures were utilized to illustrate the displacement mechanisms in varied scenarios of polymer flooding. Moreover, physical models were designed using the UTCHEM software, by which the experiments' results were successfully predicted.

2. Experimental facilities and setup

The micromodel set-up is composed of a micromodel holder placed on a platform. It comprises a camera with a video recording system, a pressure transducer, and a precise low-rate pump. Fig. 1 demonstrates a schematic of the micromodel setup.

2.1. Micromodel setup

A highly accurate "Quizx" pump with a low flow rate was used. This pump can inject the fluid with the accuracy of 10^{-5} to 10 ml/min.

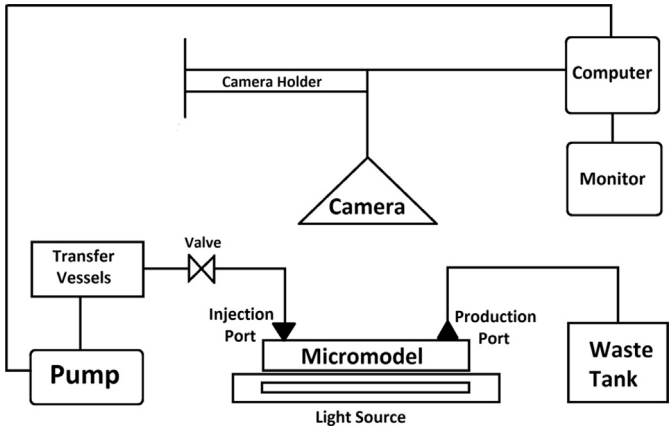

Fig. 1. Schematic of micromodel set up.

Also, a vacuum pump was utilized to wash and clean the micromodel using the distilled water and toluene. Moreover, a high-quality camera with the zooming ability up to 200 times was employed in the experiments. Pictures were taken at specified time intervals during the experiments. In addition, a microscopic camera which had been connected to a computer was used to take high-quality pore-scale pictures enabling us to investigate mechanisms of displacement.

To analyze the pictures, the saturation of fluids, given by distinct colors, must be measured. Photoshop software was used to analyze the pictures and calculate the saturation of fluids by calculating oil pixels in each image. The characteristics of each pattern were initially designed by the Corel software and engraved by laser on glass. Afterwards, the patterns of the micromodel were fused throughout the model to acquire the proper depth. The schematics of the micromodel patterns were displayed in Fig. 2. Five models with various fracture characteristics were engraved on glass and covered by another glass to create the porous media. Two input and output holes were drilled to create injection and production ports. The set had been subsequently placed in a furnace for fusing, which causes two glass plates of micromodel to adhere to each other. Physical properties of the two-dimensional models illustrated in Fig. 2 are presented in Table 1.

The following procedure was adopted to have an oil-wet micromodel: (1) thoroughly rinse the micromodel with sodium hydroxide for one hour followed by distilled water and then, dry at 200 °C for at least 15 min, (2) saturate the micromodel with the solution of 2% Tri Chloro Methyl Silane (TCMS) in dehydrate toluene which immediately creates a thin film on the internal surface of the micromodel for at least 5 min and (3) rinse the micromodel with methanol to remove excess siliconizing fluid and dry the micromodel at 100 °C for 1 h to cure the silicone coating (Romero-Zerón, 2004). As model C is water-wet, the procedure proposed by Romero-Zerón (2004) was followed as (1) rinse the micromodel with toluene to eliminate any residual oil, and then use a vacuum pump to remove any remaining liquids from the micromodel, (2) rinse the micromodel with acetone and remove

Table 1
Physical and hydraulic properties of micromodels.

Pattern	A	B	C	D	G
Length (mm)	60	60	60	60	60
Width (mm)	60	60	60	60	60
Average depth (mm)	0.1	0.095	0.095	0.1	0.095
Coordinate number	4	4	4	4	4
Pore volume (cm^3)	0.096	0.092	0.095	0.096	0.082
Porosity	52.29	52.2	52.47	52.47	50.48
Permeability (mD)	1800	1700	2000	1800	1600
Fracture length (cm)	4	2	4	4	–
Fracture opening (μm)	700	700	700	700	–
Number of fractures	1	1	1	1	–
Fracture orientation	45	45	0	90	–

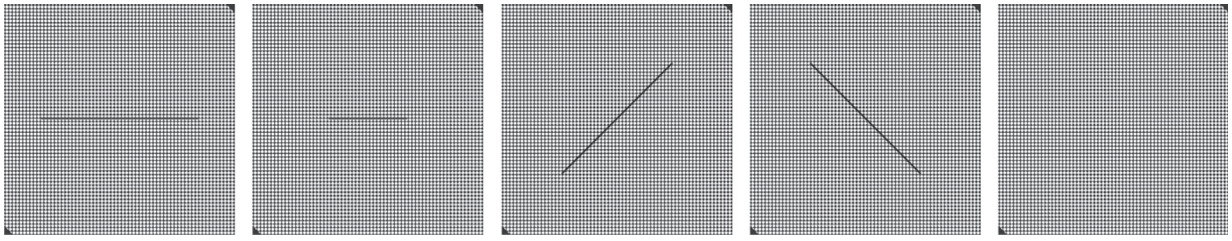

Fig. 2. Schematic of glass micromodels.

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