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Water film rupture in blocked oil recovery by gas injection: Experimental and modeling study

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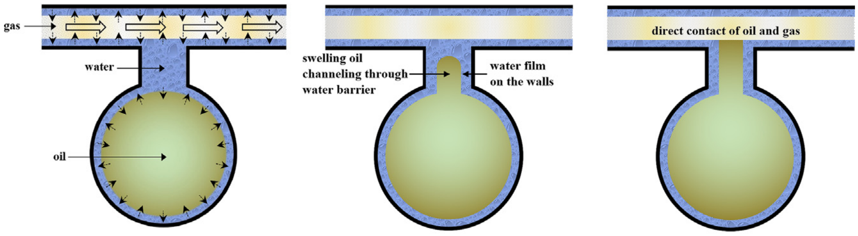
HIGHLIGHTS

- Micromodel experiments are performed on dead-end pores to study water film rupture.
- A new mathematical model is proposed to estimate water rupture time.
- The presence of water film on the pore walls of water-wet media is modeled.
- Non-ideal mixing is considered in water rupture modeling for the first time.

GRAPHICAL ABSTRACT



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ABSTRACT

Water shielding phenomenon generally occurs after waterflooding in water-wet rocks, and impedes direct contact between the oil and the injected gas in tertiary gas injection processes. In this work, a set of visualization experiments were performed on micromodel patterns including designed dead-end pores with a film of water on the surface of pore bodies, which is a more realistic representation of porous media. The experiments were conducted at different miscibility conditions, and the required time for water to be displaced from the throat by the swelling of oil was measured for first contact miscible (n-C_5/CO_2) and immiscible (n-C_{10}/CO_2) systems. In the next step, a model was proposed to simulate the results of the experiments, based on the work of Bijeljic et al. (2003). As the impact of non-ideal mixing in this process has not been previously discussed in the available literature, the new model was developed by taking into account the changes in the partial molar volumes of oil and gas components using the PR and the SRK equations of state, and also by considering the mass transfer from the surrounding water on the pore body into the shielded oil. The rupture times predicted by the model were compared with the measured experimental data, as well as those reported by Campbell and Orr (1985). It was found that inclusion of partial molar volumes of components improves the accuracy of the model. The results also revealed the significant role of the water film on the pore body surfaces in mass transfer rate between the phases in water-wet media. The close agreement between the results of the model proposed in this study and the experimental data shows that it can be helpful for developing more accurate multiphase compositional models.

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1. Introduction

Waterflooding is the most commonly used secondary oil recovery method in the oil industry; but even in homogenous reservoirs with high sweep efficiency, a major part of oil remains behind in the form of immobilized pore-scale ganglia surrounded by water. In such cases, tertiary miscible gas injection is considered as an effective method to recover the remaining oil. Therefore, it seems essential to investigate the recovery mechanisms of the trapped oil by gas and to recognize the engaged parameters in the production process of hydrocarbons to gain a comprehensive knowledge about the behavior of oil reservoirs under tertiary gas injection. As a result, in this study it has been tried to perform a fundamental study on the recovery of the trapped oil in dead-end pores by gas injection after waterflooding, both theoretically and experimentally.

In water-wet media, a thin continuous water film is present on the surface of the reservoir rock in pores and throats. After waterflooding, due to the increase of water saturation, this film coalesces into a water layer in some narrower throats, isolating the oil behind from the main oil bank in the reservoir in form of ganglia or dendrites. When gas is injected into the system, the water barrier formed previously impedes direct contact between the blocked oil and the injected gas on the other side, making the oil inaccessible by gas, and preventing mass transfer between the phases in order to attain miscibility. This phenomenon is generally referred to as “water shielding” or “water blocking”. However, the injected gas manages to reach the stagnant oil through dissolving in water and diffusing into oil. As gas diffuses into oil, the non-flowable oil swells gradually pushing the water, until it completely displaces the water barrier present in the throat, and unblocks itself.

Water shielding has been observed in laboratory experiments on cores by various researchers. Raimondi et al. (1961) experimented miscible displacement in the presence of two phases. Their observations indicated that the displacement of oil, as non-wetting phase, becomes less efficient as the water saturation is increased above the irreducible range. However, the trapped oil is not completely isolated by water, and is recoverable by miscible displacement. Thomas et al. (1963) studied miscible displacement in both the wetting and non-wetting phase in two-phase systems. The results showed that dispersion is a function of saturation, and a part of saturation effect is as a result of trapping of the displacing and displaced fluid in dendritic structures or dead-end pores due to the presence of a second phase. Raimondi and Torcaso (1964) investigated the distribution of the oil phase resulting from increasing and decreasing the water saturation by imbibition. They concluded that oil is trapped upon imbibition of water, and it is the trapped oil which seems to make tertiary recovery operations uneconomic. Stalkup (1970) performed displacements of laboratory oils by propane in sandstone cores in the presence of high water saturations. The experiments revealed that only part of the oil is flowable in the presence of high water saturation, while the other part remains motionless in locations blocked by water. Although, this trapped oil can be recovered by molecular diffusion into the flowing propane. He also observed that oil trapping for strongly water-wet sandstones is more severe than weakly water-wet reservoir rocks. Shelton and Schneider (1975) assessed the effect of mobile water saturation on oil recovery from sandstone cores by miscible displacement. They found out that in contrast to the water-wet case, trapping of hydrocarbon does not occur in oil-wet porous media. Nevertheless, diffusion contributes to the recovery of the trapped non-wetting phase, and the required contact time is directly related to the saturation of water. Similar results confirming the unfavorable effect of water saturation as well as the importance of rock wettability on the severity of oil trapping were obtained by Lin and Huang (1990), Tiffin et al. (1991), Wylie and Mohanty (1997, 1999) and Cable et al. (2004) who also conducted laboratory core experiments to study the performance of tertiary miscible displacements.

The mechanism of shielded oil recovery during tertiary gas injection has been investigated using micromodel experiments in several studies. Campbell and Orr (1985) studied the recovery of oil from dead-end pores, with and without the presence of water barriers shielding the oil, by using a visual pore-scale micromodel. As a part of their work, they performed a visual experiment with micromodel, in which Soltrol™ 130 (a mixture of C_9 through C_{13} branched alkanes) in a dead-end pore shielded by water was recovered by CO_2. Displacement was conducted at 77 °F (25 °C) and 1200 psia (8.3 MPa), in which CO_2 is first contact miscible with the oil. Fig. 1 illustrates the process of the displacement. As CO_2 diffuses through the water, the oil swells, displacing the water barrier. Eventually, the water film is dislodged by the flowing CO_2, and then the oil in the pore is recovered, just when no water is present after 26.5 h.

Their visual observations implied that the efficiency of both first contact and multiple contact miscible displacements were much higher in the absence of water. Kantzas et al. (1988) conducted visualization experiments of displacing residual oil by gravity assisted inert gas injection in water-wet micromodels. They observed that when air is allowed to enter the model, gas-water interface passes through large pore throats and enters pore bodies. It then moves to occupy the pore body and pushes the oil blob out of the pore. The coalescence of oil blobs forms an oil bank which grows with time as it moves towards the production end. In addition, oil films are formed behind the oil bank in the pores invaded by air which maintain hydraulic continuity and allow leakage of oil towards the oil bank. Oren et al. (1992) investigated mechanisms of mobilization and recovery of waterflood residual oil during tertiary gas injection in 2-D strongly water-wet glass micromodels for systems with positive and negative spreading coefficients. Their experiments showed that oil recovery was significantly higher for the positive spreading system, due to flow through thin but continuous oil films. Laroche (1998) studied secondary and tertiary gas injection in heterogeneous wettability micromodels. He concluded that most of the time gas invades the oil-wet pathways which have the least resistance, as water bridges in water-wet regions drastically increase the resistance to flow. He also observed

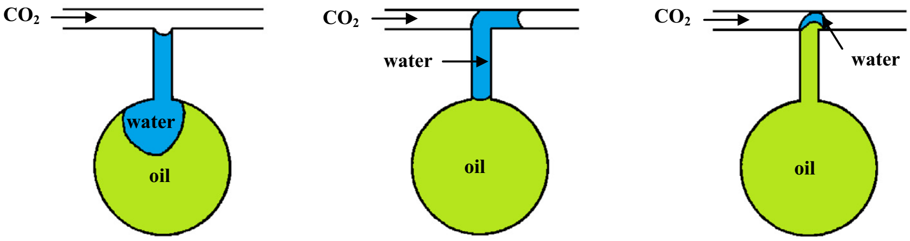

Fig. 1. Illustration of tertiary miscible displacement performed by Campbell and Orr (1985) - recovery of Soltrol shielded by water in a dead-end pore by CO_2 - from left to right: start of CO_2 injection; position of water barrier after 18 h; and position of water barrier after 26.5 h.