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Visualization and analysis of viscous fingering in alcohol-assisted surfactant waterflooding of heavy oil in a two-dimensional sandstone micromodel

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HIGHLIGHTS

- A novel 2-D low-permeability quarter five-spot sandstone micromodel is used.
- Three distinct regimes of viscous fingering are discovered.
- Features of fingers population and mechanisms of viscous fingering are analyzed.
- Comparison is made between the fingering in this study and those of literature.
- New insights into the population of fingers and mechanisms of fingering are given.

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ABSTRACT

It is essential to predict the nature of instability for incorporating viscous instability in modeling surfactant waterflooding of heavy oils. A two-dimensional low-permeability sandstone micromodel in a nonlinear quarter five-spot scheme is used for the visualization and analysis of viscous fingering in alcohol-assisted surfactant waterflooding of heavy oil. Three distinct regimes of viscous fingering are discovered and proposed. The results also suggest that it is the viscous crossflow that causes the fingers growth beyond the onset of viscous fingering. Moreover, in low-interfacial tension drainage conducted in this study, the frontal drive occurs with cluster growth and entailing microfingers that sometimes fill the entire pore body. Numerous features regarding the fingers population, onset and mechanisms of viscous fingering, and fingers development and propagation are discovered and analyzed. A comprehensive comparison is made between the viscous fingering features of this study and those of literature. This study provides new insights into the population of fingers, onset and mechanisms of viscous fingering, and fingers development and propagation in alcohol-assisted surfactant waterflooding of heavy oils.

1. Introduction

The study of flow instability began in the 1950s, when Engelberts and Klinkenberg [1] coined the term 'viscous fingering'. After Engelberts and Klinkenberg, other researchers borrowed this term to address the flow instability in porous media [2–5]. A number of studies investigated viscous fingering in the 1960s [6–8], 1970s [9,10], 1980s [11–24], and 1990s [25–29]. Some of the most recent works [30–35] focus on the impact of capillary number constituents on viscous fingering in waterflooding, surfactant waterflooding, and surfactant-polymer flooding for conventional and heavy oils. A detailed review of the viscous fingering literature can be found in Ref. [26]. Also, a more critical analysis of the literature findings is provided in Section 3 where the viscous fingering results of this study are comprehensively compared to those of the literature. Hence a detailed review of the literature is avoided here.

It is known that the size, shape and irregularity of the pores can significantly impact viscous fingering patterns [9,30]. Therefore, in this study, a small-thickness two-dimensional (quasi three-dimensional) micromodel is fabricated based on thin sections of a real sandstone sample. A sandstone micromodel has not been used for the analysis of viscous fingering patterns and mechanisms before. Additionally, previous experiments of viscous fingering in immiscible displacements are associated with high-permeability media and linear displacement schemes. Normally, displacement schemes (or injector-producer configurations) in oil-field patterns

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are identical or close to five-spot, seven-spot or other popular schemes. In any non-linear scheme, a net effect of dispersion on viscous fingering exists, which is due to varying velocity profiles. Thus, in previously conducted linear displacement experiments, the effect of dispersion (caused by varying velocity profiles) on viscous fingering has not been tested. For all these reasons, a two-dimensional low-permeability sandstone micromodel in a non-linear quarter five-spot scheme is used for the visualization and analysis of viscous fingering in alcohol-assisted surfactant waterflooding of heavy oil.

Based on frontal advance and viscous fingering patterns, dimensionless pressure drop across the porous medium, number of fingers, and fingers population growth rate (cumulative and instantaneous), three distinct regimes of viscous fingering are discovered and proposed. Numerous features regarding the fingers population, onset and mechanisms of viscous fingering and fingers development and propagation are discovered and compared to those of the literature.

2. Experimental

Gupta et al. [9] show that fingering is not independent of local macroscopic irregularity in the porous medium. Also, Yadali Jamaloei and Kharrat [30] suggest that number of fingers is strongly dependent upon the size and shape of the pores. Considering this, the size, shape and irregularity of the pores can significantly impact viscous fingering patterns. Therefore, a two-dimensional (quasi three-dimensional) micromodel is fabricated based on thin sections of a real sandstone sample. Such micromodel has not been used for the study of viscous fingering patterns before.

The experimental set-up is shown in Fig. 1. The sandstone medium is an etched glass micromodel. To replicate the actual injection-production patterns in oil fields, the sandstone micromodel is etched onto the glass surface in the form of a quarter five-spot pattern. Hydrofluoric acid and nitric acid were used in the etching process to etch the desired porous network onto the glass plate. Table 1 shows the physical and hydraulic properties of the sandstone micromodel, composition of the injected surfactant solution, and the properties of crude oil. Ethanol (purity of 99.8%) was used in the surfactant solution to minimize surfactant adsorption and precipitation [36]. Further details can be found elsewhere [34,37]. Measurements and experiment were conducted at a temperature of 25 ± 0.2 °C.

To conduct an alcohol-assisted surfactant waterflooding of heavy-oil, heavy oil is first injected into the sandstone micromodel using a syringe pump. Since prior to heavy oil injection, air is displaced from the micromodel using a vacuum pump, micromodel is now 100% saturated with the heavy oil (brown color[2] in images given in Figs. 2–4). Then, a high-accuracy Quizix pump is used to inject alcohol-contained surfactant solution with an injection flowrate of 0.0008 cm^3/min. High-quality images during the displacement (Figs. 2–4) are captured using a digital camera. The injection pressures, volumes, and flowrates are recorded via a Quizix pump interface.

3. Results and discussion

3.1. Three viscous fingering regimes

Based on frontal advance and viscous fingering patterns (Figs. 2–4), dimensionless pressure drop across the porous medium, number of fingers, and instantaneous and cumulative growth rates of fingers population (Figs. 5–8), three distinct regimes of viscous fingering are discovered and proposed: (i) early displacement prior to breakthrough, (ii) breakthrough and early post-breakthrough, and (iii) early post-breakthrough to late displacement. As it will be explained, in each of the proposed viscous fingering regimes, there exists a strong correlation between frontal advance and viscous fingering patterns (Figs. 2–4) and the dimensionless pressure drop across the porous medium, number of fingers, and fingers population growth rate (Figs. 5–8).

Fig. 5a–c reveals three distinct regimes of dimensionless pressure drop across the porous medium, number of fingers, and growth rates of fingers population, respectively. Each regime of pressure drop, number of fingers, and fingers population growth rate is further highlighted using a separate plot (Figs. 6–8). It is noted that the dimensionless displacement time in Figs. 5–8 is the time of the displacement divided by the displacement termination time (i.e., 3780 s). Also, the dimensionless pressure drop is the pressure drop across the porous medium at any time divided by the pressure drop at displacement termination time.

Fig. 6a shows the dimensionless pressure drop across the porous medium versus dimensionless time during early displacement stage prior to breakthrough. This is the first viscous fingering regime where dimensionless pressure drop across the porous medium is linearly correlated with dimensionless time. Fig. 2 shows the displacement fronts and fingering patterns at different times during early displacement stage prior to breakthrough. During this stage, the onset of diagonal fingering and peripheral frontal advance is observed (displacement time = 60–120 s). Diagonal fingering and peripheral frontal advance continues until near breakthrough of the injected chemical solution (displacement time = 840–900 s). Also, macrofingers start to develop at the very early stage (displacement time = 60 s). Macrofingers grow along the diagonal distance traveled by the front (displacement time = 120–180 s). Then, peripheral growth of macrofingers is initiated (displacement time = 300 s). During the same time period, the onset of sideway growth of the fingers is observed (displacement time = 300 s). The sideway growth of the fingers (or spreading phase of the viscous fingering pattern), which is quasi-orthogonal to the diagonal distance traveled by the front, continues until near breakthrough of the injected chemical solution (displacement time = 840–900 s). The sideway growth of the fingers continues until the fingering front approaches the production point. Clearly, the viscous fingering regime during early displacement stage prior to breakthrough is very complicated during which the onset of diagonal fingering and peripheral frontal advance, diagonal and peripheral initiation of macrofingers, and the onset of sideway growth of the fingers are observed. Diagonal fingering, peripheral frontal advance, diagonal and peripheral growth and propagation of macrofingers, and the sideway growth of the fingers go hand-in-hand during the first viscous fingering regime. During this complicated viscous fingering regime, dimensionless pressure drop decreases gently in a linear fashion (Figs. 5 and 6). During the first fingering regime, the number of fingers grows linearly with square root of time (Fig. 6b). Furthermore, instantaneous growth rate of fingers population versus dimensionless pressure drop fluctuates in the positive region (Fig. 6c). Moreover, cumulative growth rate of fingers population versus dimensionless pressure drop hits a maximum during this regime and it then declines gradually (Fig. 6d).

During the second viscous fingering regime, dimensionless pressure drop across the porous medium is also linearly correlated with dimensionless time. Fig. 7 shows the dimensionless pressure drop across the porous medium versus dimensionless time during breakthrough and early post-breakthrough. During this regime, dimensionless pressure drop decreases sharply in a linear fashion (Figs. 5 and 7). Fig. 3 shows the displacement fronts and fingering

[2] For interpretation of color in Figs. 2–4, the reader is referred to the web version of this article.