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Correlations of viscous fingering in heavy oil waterflooding

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HIGHLIGHTS

- Three distinct regions of viscous fingering in heavy oil waterflooding are proposed.
- Numerous small fingers in early stage degenerate into a single finger at later stages.
- Number of fingers is not flowrate-dependent and it grows with square root of time.
- Finger width is comparable with pore size and length/width increase in early stage.
- Onset of fingers sideway growth is when sharpest increase in population growth occurs.

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ABSTRACT

In order to include viscous instability in modeling heavy oil waterflooding, it is essential to predict the nature of viscous instability. It is still unclear as to whether previous findings of viscous fingering in immiscible displacements in the presence of high single-phase permeabilities and linear displacement schemes are valid in displacement schemes similar to oil-field patterns (e.g., five-spot) and what the effect of dispersion (caused by varying velocity profiles) is on viscous fingering. To overcome the limitations of previous studies of viscous fingering in immiscible displacements, we conduct experiments in low-permeability, one-quarter five-spot patterns. The correlation of experimentally measured oil recoveries, pressure drops, saturation profiles, viscous fingers length and width, dynamic population of fingers, and rate of growth of fingers population with time and front position are discussed. Study of viscous fingering patterns in heavy oil waterflooding conducted in this work provides new insights into the onset of fingering and fingers development.

1. Introduction

Heavy oil waterflooding has widely been practiced worldwide, and particularly, in western Canada for several decades. To properly tailor waterflooding to a heavy oil reservoir, it should be optimized using numerical simulation, which is challenging because of limited knowledge of viscous fingering effects in heavy oil waterflooding. Thus, to include viscous instability in modeling heavy oil waterflooding, it is essential to predict the nature of instability.

A summary of literature for viscous fingering in immiscible displacements is compiled in Ref. [1]. The compiled literature in Ref. [1] reveal that although considerable attention has been paid to viscous fingering in immiscible displacements in the presence of high single-phase permeabilities and linear displacement schemes, it is still unclear whether previous findings are valid in displacement schemes similar to oil-field patterns (e.g., five-spot) and what the effect of dispersion (caused by varying velocity profiles) is on viscous fingering. The only study that has investigated viscous fingers for different five-spot patterns, namely five-spot and inverted five-spot (in addition to line-drive pattern), is the work of Henderson et al. [2] where they used three-parameter Kozeny–Carman generalized equation to trigger and describe immiscible viscous fingers in fractal heterogeneous porous media. While this work provides detailed insight into the fingering behavior during waterflooding in heterogeneous oil reservoirs, the experimental behavior of such fingers remains unclear.

To overcome the limitations of previous experimental studies, experiments are conducted in low-permeability, one-quarter five-spot patterns. In order to examine the viscous fingering in heavy oil waterflooding, experiments are conducted in a relatively low-permeability (i.e., $(1.79 \pm 0.12) \times 10^{-12}\ m^2$), one-quarter

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five-spot pattern. The porous medium in this study is the lowest-permeability nonlinear one-quarter five-spot injection-production scheme designed for studying the viscous fingering to date. To obtain information including fingers length and width, dynamic population of fingers, rate of growth of fingers population and number frequency of the fingers, techniques are devised for capturing statistically representative fingering patterns. Moreover, oil recoveries, pressure drops, and saturation profiles are monitored and analyzed as well. Study of fingering patterns in heavy oil waterflooding provides new insights into the onset of fingering and fingers development and growth.

2. Experimental

The experimental set-up and its components are detailed in a previous publication [3]. Fig. 1 provides a schematic of the synthetic porous medium. The micromodel is 60 mm in length and width with pore body and throat diameters of 647 and 280 μm, respectively. Further details of the physical properties of the micromodel are given in Ref. [4]. Also, the crude oil viscosity is 80.6 mPa s and the water–crude oil equilibrium IFT is 8.4 mN m^{-1}. The detailed physical properties of the crude oil and measurement procedures are given in Refs. [1,4]. To conduct a heavy-oil waterflooding experiment, a syringe pump is used to inject the heavy oil into the micromodel. Micromodel is now 100% saturated with the heavy oil (brown[2] color in images given in Fig. 1). Then, a high-accuracy Quizix pump is used to inject dyed water (dyed water is blue in images in Fig. 1). The water injection flowrate is 0.0008 cm^3/min. All the measurements and the experiment were conducted at constant temperature of 25 ± 0.2 °C. Further details of experimental procedures can be found in Ref. [1].

3. Results and discussion

Table 1 and Fig. 1 summarize the quantitative and qualitative features of frontal growth and fingering during heavy oil waterflooding, respectively. Fig. 1 shows the fingering patterns at different times during the displacement until water breakthrough (time = 720 s). The macrofingers start to develop at the very early stage of the process (displacement time = 120 s). During this time, a sharp build-up in pressure is observed (Fig. 6a). Afterward, macrofingers grow peripherally along the edge of the micromodel (displacement times = 240–360 s) during which the injection pressure (and thus, the pressure difference across the medium) continues to build up. During this stage, a minor, slow diagonal frontal advance is also observed. After the simultaneous peripheral and diagonal growth of the frontal advance during the intermediate displacement time, the onset of sideway growth of the fingers is observed (displacement time = 420 s). The sideway growth of the fingers (or spreading phase of the viscous fingering pattern), which is orthogonal to the diagonal distance traveled by the front, is shortly terminated (displacement time = 480 s) long before water breakthrough. After the sideway growth of fingering pattern is terminated, peripheral frontal advance becomes the dominant mechanisms again until water breakthrough. Once peripheral frontal advance approaches the producer (displacement time = 720 s), water breakthrough occurs and the pressure drop starts to decline gradually (Fig. 6a).

The viscous fingering patterns observed in this study are associated with very unfavorable mobility ratio displacement at high-interfacial tension (IFT) flow (IFT of 8.4 mN m^{-1}), because water (viscosity of 0.9 mPa s at 25 °C) is used to displace heavy oil (viscosity of 80.6 mPa·s at 25 °C). Also, the injected water contains no surfactant, meaning that the oil–water IFT is high. For unfavorable mobility ratio displacement at high-IFT flow, Gupta and Greenkorn [5] showed that numerous incipient fingers occur at the very beginning of displacement, and that they degenerated into a single finger at a later stage. The viscous fingering patterns of heavy-oil waterflooding (Fig. 1) confirm the findings of Gupta and Greenkorn [5]: small fingers occurred during the early displacement stage degenerate into a single finger at a later stage.

In addition, the wettability of a porous medium is largely determined by the first fluid contacting the pore walls and grains. Thus, the micromodel in this study can be assumed to be preferentially oil-wet. Since water displaces heavy oil from the micromodel, a drainage-type immiscible displacement is conducted. Thus, the viscous fingering patterns of heavy oil waterflood in this study are associated with drainage-type waterfloods in quasi-3-D medium at high-IFT flow. Pavone [6] reported viscous fingering patterns of drainage-type waterfloods in 3-D consolidated media at high-IFT flow, where instabilities were shown that looked like fingers and the presence of stable displacements behind the unstable front was detected. As opposed to the results of Pavone [6], the viscous fingering patterns in Fig. 1 indicate finger-like instabilities both in front and behind of the unstable front of heavy-oil waterflooding at high-IFT flow. Similarly, fingering patterns of heavy-oil polymer flooding at low-IFT (IFT of 0.0065 mN m^{-1}) flow indicate finger-like instabilities both in front and behind of the unstable front [1].

In heavy oil waterflooding, saturation profiles in Fig. 1 do not show any stable zone before water breakthrough whereas Pavone [6] concluded that in some high-IFT waterflood experiments, a stable zone progresses along the porous medium at constant velocity. This is not in agreement with the resulting viscous fingering patterns of this study and those of heavy-oil polymer flooding at low-IFT [1], which can primarily be attributed to much more unfavorable mobility ratio during heavy-oil low-IFT polymer flooding [1] and waterflooding. Extremely unfavorable mobility ratio causes the creation of the irregular fingers in the absence of connate water saturation in both heavy oil waterflooding (Fig. 1) and low-IFT polymer flooding [1]. Paterson et al. [7] reported that at high-IFT flow condition and in the absence of connate water saturation, injection of water creates less irregular fingers.

To depict a general picture, fingering patterns in viscous-modified low-IFT liquid–liquid flow in Ref. [1] (low-IFT polymer flooding) indicate that where IFT (and hence capillary effects) is low, the main unstable displacement front is developed into a primary finger. This primary finger advances along the shortest injector-to-producer path. In addition, numerous small side branches (quasi-perpendicular to the main primary finger) form. At the same time, pressure drop decreases with time as higher viscosity crude oil is being displaced by the lower viscosity injected fluid along the main finger. In contrast, during high-IFT liquid–liquid flow (high-IFT waterflooding) with high capillary effects, the main finger does not take the shortest path to the producer. Moreover, as compared to low-IFT polymer flooding, there are significantly less side branches in high-IFT waterflooding. Pressure drop in high-IFT waterflooding increases until the finger starts to bend toward the producer, then it slightly decreases until water breakthrough.

Care has been taken during etching the porous one-quarter five-spot pattern onto the glass plate. In doing so, uniform-concentration solutions of both hydrofluoric and nitric acids were applied onto the entire glass plate during the etching process. The measured etched pore size throughout the micromodel fluctuates by only ±10 to ±15 μm (see Ref. [4] for further details). Hence, as

[2] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.