Full Length Article

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.

ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 4 July 2016
Accepted 5 July 2016

Keywords:
Waterflooding
Viscous fingering
Heavy oil
Micromodel
Alcohol
Mechanisms

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 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

http://dx.doi.org/10.1016/j.fuel.2016.07.016
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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 color2 in images given in Figs. 2–4). Then, a high-accuracy Quizix pump is used to inject alcohol-contained surfactant solution with an injection flow-rate of 0.0008 cm2/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
patterns during breakthrough and early post-breakthrough. During the second viscous fingering regime, no significant change in fingering patterns and frontal advance is observed. Change in diagonal, peripheral, and sideway propagation of fingering patterns and frontal advance is not noticeable during the second regime. The main reason behind this behavior is that the injected chemical solution tends to quickly channel to the producer following the previously established flow paths. Thus, the second viscous fingering regime (breakthrough and early post-breakthrough) corresponds to the channeling phase where the displacing phase tends to quickly channel through the least-resistant flow paths. During the second fingering regime, the number of fingers does not grow with square root of time (Fig. 7b) and it remains constant. Additionally, instantaneous growth rate of fingers population is zero during this regime (Fig. 7c) and cumulative growth rate of fingers population versus dimensionless pressure drop decreases gradually in a linear fashion (Fig. 7d).

Fig. 8 shows the dimensionless pressure drop across the porous medium versus dimensionless time after early post-breakthrough to late stage. This is the third viscous fingering regime where dimensionless pressure drop across the porous medium is not linearly correlated with dimensionless time (unlike first and second viscous fingering regimes). In the third regime, dimensionless pressure drop across the porous medium fluctuates over time. Fig. 4 shows the displacement fronts and fingering patterns at different times after early post-breakthrough to late stage. A minor peripheral advance of viscous fingering pattern takes place (displacement time = 1320–2040 s) where dimensionless pressure drop decreases sharply from 1.007 to 0.996 (Fig. 8). Then, a surge in dimensionless pressure drop from 0.996 to 1.009 is recorded during which the width and length of the two peripheral macrofingers increase and both peripheral fronts grow in size (displacement time = 2040–2820 s). Finally, dimensionless pressure drop decreases from 1.009 to 1.000 once the growing size of peripheral macrofingers is stabilized (displacement time = 2820–3780 s). More importantly, as Fig. 8b–d shows, the number of fingers decreases almost linearly with square root of time during the third fingering regime, and instantaneous growth rate of fingers population versus dimensionless pressure drop fluctuates in the negative region (Fig. 8d). As it is shown in Fig. 8c, cumulative growth rate of fingers population versus dimensionless pressure drop changes randomly. Table 2 summarizes the qualitative and quantitative features of the three proposed fingering regimes in this study.

### 3.2. Qualitative and quantitative comparisons with literature

The viscous fingering patterns during alcohol-assisted surfactant waterflooding of heavy oils in this study are associated with very unfavorable mobility ratio displacement at low-interfacial tension (IFT) flow, because alcohol-contained surfactant solution with a viscosity of 0.9 mPa s (at 25 °C) displaces heavy oil with a dynamic viscosity of 80.6 mPa s (at 25 °C). Also, the injected water contains alcohol and surfactant, meaning that the oil-water IFT is very unfavorable mobility ratio displacement at low-IFT flow. Gupta and Greenkorn [10] observed that numerous incipient fingers occur at the very beginning of displacement. However, they do not degenerate into a single finger at a later displacement stage. For unfavorable mobility ratio displacement at high-IFT flow, Gupta and Greenkorn [10] observed that numerous incipient fingers occur at the beginning of displacement, and that they degenerate into a single finger at a later stage. Hence the viscous fingering patterns of alcohol-assisted surfactant waterflooding of heavy oils are significantly different from the findings of Gupta and Greenkorn [10]. Fig. 2 reveals that numerous small fingers occur during the early displacement stage and they continue to...
grow in diagonal, peripheral, and sideway directions (but not into a single finger) at a later stage. It is clear that this difference is primarily the result of the difference in IFT and capillary forces and not due to the 2D flow in a quarter five-spot in the present work. As it will be explained, in alcohol-assisted surfactant waterflooding with low IFT, capillary forces are smaller than for waterflooding and fingers branch away and do not degenerate into a single finger as in Ref. [10]. This type of branching does not occur in 1-D waterflooding in Ref. [10] because of high IFT and hence high capillary forces [39].

It can be argued that the viscous fingering patterns of heavy-oil alcohol-assisted surfactant waterflooding in this study are associ-

Fig. 2. The first viscous fingering regime (early displacement prior to breakthrough; blue arrows: finger locations).
ated with drainage-type waterflooding in a quasi-3-D sandstone medium at low-IFT flow. One reason is because the wettability of a porous medium is largely determined by the first fluid contacting the pore walls and grains, the sandstone micromodel in this study can be assumed to be preferentially oil-wet. Also, as alcohol-contained surfactant solution displaces heavy oil from the sandstone micromodel, a drainage-type immiscible displacement is conducted. Pavone [26] reported viscous fingering patterns of drainage-type waterflooding in 3-D consolidated media at high-IFT flow. He detected finger-like instabilities and stable displacements behind the unstable front. Figs. 2–4 depict that, as opposed to the results of Pavone [26], the viscous fingering patterns in heavy-oil alcohol-assisted surfactant waterflooding render finger-like instabilities both in front and behind of the unstable front at low-IFT flow with very unfavorable mobility ratio. Similar to the results of heavy-oil alcohol-assisted surfactant waterflooding, fingering patterns of heavy-oil polymer flooding at low-IFT flow [38] and heavy-oil waterflooding [39] at high-IFT flow indicate finger-like instabilities both in front and behind of the unstable front [38,39].

In alcohol-assisted surfactant waterflooding of heavy oils, saturation profiles in Fig. 2 do not show the presence of any stable zone before breakthrough whereas Pavone [26] 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 [38] and heavy-oil waterflooding at high-IFT [39]. It is clear that this difference is the result of the difference in viscosity ratio and a significant contribution due to the 2D flow in a quarter five-spot in the present

Fig. 3. The second viscous fingering regime (breakthrough and early post-breakthrough).

Fig. 4. The third viscous fingering regime (early post-breakthrough to late displacement).
work. The absence of a stable zone is due to an extremely unfavorable mobility ratio during alcohol-assisted low-IFT surfactant waterflooding, low-IFT polymer flooding [38] and high-IFT waterflooding [39] of heavy oils, as compared to less unfavorable mobility ratio in high-IFT waterflooding of conventional oil [26]. The absence of a constant velocity is due to the non-linear 2-D displacement scheme in alcohol-assisted low-IFT surfactant waterflooding, low-IFT polymer flooding [38] and high-IFT waterflooding [39], as compared to linear displacement scheme in 1-D high-IFT waterflooding [26]. As it was mentioned in Section 1, in any non-linear scheme, such as the quarter five-spot in this study, a net effect of dispersion on viscous fingering exists, which is due to varying velocity profiles. In linear displacement experiments, there is no varying velocity profile.

As it is shown in Fig. 2, in alcohol-assisted low-IFT surfactant waterflooding of heavy oils, extremely unfavorable mobility ratio creates irregular fingers in the absence of connate water, similar to in both heavy-oil low-IFT polymer flooding [38] and heavy-oil high-IFT waterflooding [39]. As opposed, Paterson et al. [40] reported that at high-IFT flow condition, injection of water creates less irregular fingers in the absence of connate water. On the other hand, Fig. 2 suggests that fingers are created in a dispersive fashion under the low-IFT flow condition created by adding surfactant to water, which is in agreement with observations of Paterson et al. [13].

Figs. 2 and 6 show that the number of fingers before breakthrough increases with time, which is not in agreement with Croissant’s [41] correlation. He reports that the number of fingers decreases with time. This is due to extremely unfavorable mobility ratio during alcohol-assisted surfactant waterflooding of heavy oils. In fact, for heavy-oil low-IFT polymer flooding [38] and heavy-oil high-IFT waterflooding [39], the number of macrofingers before breakthrough grows with time [38,39]. Also, visual inspection of viscous fingering patterns in Figs. 2–4 indicates that the finger width in this drainage-type immiscible displacement is comparable with pore size, which is in agreement with the results of Stokes et al. [19] and Yadali Jamaloei et al. [39]. Also, viscous fingering patterns in Figs. 2–4 show that viscous fingers are on the order of the magnitude of the pores, which confirms the findings of de Haan [5]. Finally, Figs. 2–4 reveal that in alcohol-assisted

Fig. 5. Three viscous fingering regimes: (a) dimensionless pressure drop across the porous medium, and (b) number of fingers, and (c) fingers population growth (cumulative and instantaneous).
surfactant waterflooding of heavy oils, fingers width grows with time. Croissant [41] notes the same observation for high-IFT waterflooding.

One may argue what the effect of injection flowrate is on viscous fingering in heavy-oil surfactant waterflooding. In general, Fig. 6e shows that, as the front velocity or the ratio of dimensionless distance (i.e., front position) to the dimensionless time decreases, the number of fingers increases. Fig. 6e also indicates that there is no linear correlation between the number of fingers and the front velocity (i.e., ratio of dimensionless distance to the dimensionless time). It is reasonable to assume that the ratio of dimensionless distance to the dimensionless time is synonymous with the definition of front superficial velocity (and thus, injection flowrate). Therefore, according to Fig. 6e, decreasing the ratio of dimensionless distance to dimensionless time (i.e., decreasing the front velocity or injection flowrate) triggers a reduction in the dynamic population of fingers. This confirms the findings of Yadali Jamaloei et al. [39] for high-IFT heavy-oil waterflooding, where they show that although number of fingers is not linearly correlated with flowrate, it generally decreases as flowrate increases. This is not in agreement with the findings of Amiell [42] for high-IFT light-oil waterflooding. Amiell [42] reveals that for high-IFT light-oil waterflooding, the number of fingers is almost independent of flow rate. Amiell [42] also shows that the fingers shape is flow-rate dependent. On the other hand, for viscous-modified low-IFT polymer flooding in heavy oils, the number of fingers increases linearly by the decrease in the ratio of dimensionless distance to the dimensionless time [38]. Therefore, for low-IFT (this study) and high-IFT heavy-oil waterflooding [39] and viscous-modified low-IFT polymer flooding in heavy oils [38], number of fingers generally decreases as flowrate increases.

3.3. Mechanisms of viscous fingering: capillary effects, interfacial energy, and crossflow

The mechanisms of viscous fingering have not been understood comprehensively. An analysis of the literature and the results of this work suggest that capillary effects, interfacial energy, and
crossflow significantly impact viscous fingering mechanisms. It is possible to highlight the impacts of these phenomena on viscous fingering using fingering patterns in low-IFT waterflooding (this study), high-IFT heavy-oil waterflooding [39] and viscous-modified low-IFT polymer flooding in heavy oils [38], and light-oil high-IFT waterflooding [4].

Overall, fingering patterns in low-IFT polymer flooding in heavy oils indicate that where capillary effects are small (i.e., low IFT), the main unstable displacement front is developed into a primary finger [38] entailing numerous small side branches (quasi-perpendicular to the main primary finger) and it propagates along the shortest injector-to-producer path (diagonal fingering). In contrast, viscous fingering patterns of high-IFT heavy-oil waterflooding [39] (large capillary effects) indicates that the main finger (with significantly less side branches) does not take the shortest path to the producer. Instead, it grows along the top surface of the micromodel and away from the shortest path to the producer (peripheral advance). In low-IFT heavy-oil waterflooding, diagonal fingering and peripheral advance go hand-in-hand with side-way growth of numerous small side branches (see Figs. 2–4 and Table 2).

Based on these findings, it becomes evident that small capillary effects (or low IFT) cause the creation and growth of side branches. This conclusion is in agreement with the results of Chuoke et al. [4]. They report that capillary effects stabilize perturbations of short wavelengths. This means that negligible or low capillary effects tend to trigger unstable short wavelengths (i.e., numerous small side branches) during low-IFT heavy-oil polymer flooding [38] and low-IFT high-IFT waterflooding (Figs. 2–4). On the other hand, during high-IFT heavy-oil waterflooding [39], perturbations with short wavelengths are stable (less side branches) because capillary effects are much greater due to high IFT [39].

It is beneficial to depict a general picture of alcohol-assisted surfactant waterflooding (this work), waterflooding [39], and low tension polymer flooding [38]. In alcohol-assisted surfactant waterflooding in a non-homogenous system, a finger develops along the diagonal but is thwarted once it reaches a local low-permeability region, which favors fingers already developing along
the two sides of the micromodel. In alcohol-assisted surfactant waterflooding with low IFT, capillary forces are smaller than for waterflooding and fingers branch away from the micromodel sides. This type of branching does not occur in high-IFT waterflooding with high capillary forces in homogeneous micromodel until the finger along the side approaches an impermeable corner [39]. For the low tension polymer flooding in homogeneous micromodel, the growth of the initial diagonal finger is not hindered by a low-permeability region [38] and small fingers start to branch from the top side finger because of low capillary forces.

It also becomes evident that lower interfacial free energy in areas away from the shortest injector-to-producer path causes the creation and growth of peripheral fronts. The interfacial free energy increases by an increase in the interfacial area between

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**Fig. 8.** Third regime (early post-breakthrough to late stage): (a) dimensionless pressure drop across the porous medium, (b) number of fingers, (c) cumulative growth rate of fingers population, and (d) instantaneous growth rate of fingers population.

**Table 2**

Qualitative and quantitative features of the three proposed fingering regimes in this study.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Pressure drop decline (with ( t_D ))</th>
<th>Fingers population correlation (with ( \sqrt{t_D} ))</th>
<th>Instantaneous rate of fingers population growth (with ( P_D ))</th>
<th>Qualitative features</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Gentle linear</td>
<td>Positive linear</td>
<td>Positive rate (Fluctuates)</td>
<td>Onset &amp; propagation</td>
</tr>
<tr>
<td>Second</td>
<td>Sharp linear</td>
<td>Linear (zero slope)</td>
<td>Zero</td>
<td>Propagation</td>
</tr>
<tr>
<td>Third</td>
<td>Fluctuating</td>
<td>Negative linear</td>
<td>Negative rate (Fluctuates)</td>
<td>Ends</td>
</tr>
</tbody>
</table>

Onset & propagation

Onset & propagation

Onset & propagation
oil and aqueous phase in the transition zones along the sides of a finger. For a given finger length, the interfacial free energy along the top or bottom portion of the micromodel is less than that of a finger growing along the shortest path to the producer. By symmetry, half of the finger along the top or bottom portion of the micromodel would be in the adjacent quarter five-spot. Thus, the finger along the bottom or top portion of the micromodel has only one side with finger-oil interfacial area whereas a finger growing along the shortest injector-to-producer path has two sides.

Fig. 2d–k shows that it is the viscous crossflow that causes the finger growth beyond the onset of viscous fingering. Brock and Orr [25] suggest the same mechanism for the finger growth. Additionally, bypassing due to fingering is higher in the heavy-oil high-IFT waterflooding drainage [39] than in the heavy-oil low-IFT waterflooding drainage (Figs. 2–4). Viscous fingering patterns in Fig. 2 suggest that in drainage under low-IFT conditions, the frontal drive of the displacing phase occurs with cluster growth wherein microscopic inspection of fingering patterns reveals microfingers that sometimes fill the entire pore body. Overall, it appears that nearly most of the residual oil is the unrecovered oil bypassed by the fingering process. Moreover, inspection of Figs. 2–4 indicates that there is some residual oil trapped within the fingers, mostly in isolated pores. In comparison, Vadali Jamaloei et al. [34] conclude that in low-IFT forced imbibition, the frontal drive occurs with minor cluster growth and entailing microfingers that normally fill the entire pore. The visualization of the transverse flow phenomenon before the front breakthrough in Fig. 2 illustrate the formation of bypassed oil zones that grow in size as the distance from the inlet increases. As compared, Perkins and Johnston’s [8] study of transverse flow phenomenon under controlled conditions indicate that transition zones form that grow broader as the distance from the inlet increases.

4. Summary and conclusions

1. The first viscous fingering regime (during early displacement 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. During this regime, dimensionless pressure drop decreases gently in a linear fashion. Also, the number of fingers grow linearly with square root of time and instantaneous growth rate of fingers population versus dimensionless pressure drop fluctuates in the positive region.

2. During the second viscous fingering regime (breakthrough and early post-breakthrough), dimensionless pressure drop decreases sharply in a linear fashion and no significant change in diagonal, peripheral, and sideway propagation of fingering patterns and frontal advance takes place. The second regime corresponds to the channeling phase where the displacing phase tends to quickly channel to producer through the least-resistant previously-established flow paths. Moreover, the number of fingers remains constant and instantaneous growth rate of fingers population is zero.

3. During the third viscous fingering regime (after early post-breakthrough to late stage), dimensionless pressure drop is not linearly correlated with dimensionless time and it fluctuates over time. At some time during this regime, a surge in dimensionless pressure drop is recorded during which the width and length of the peripheral macrofingers increase. Then, pressure drop decreases once the growing size of peripheral macrofingers is stabilized. The number of fingers decreases almost linearly with square root of time and instantaneous growth rate of fingers population versus dimensionless pressure drop fluctuates in the negative region.

4. The viscous fingering patterns during alcohol-assisted surfactant waterflooding of heavy oils reveal numerous incipient fingers at the early displacement. These small fingers continue to grow in diagonal, peripheral, and sideway directions (but not into a single finger) at a later stage.

5. As opposed to waterflooding in 3-D consolidated media at high-IFT flow, viscous fingering patterns in heavy-oil alcohol-assisted surfactant waterflooding render finger-like instabilities both in front and behind of the unstable front at low-IFT flow with very unfavorable mobility ratio, which is similar to the results of heavy-oil low-IFT polymer flooding and heavy-oil high-IFT waterflooding.

6. In alcohol-assisted surfactant waterflooding of heavy oils, saturation profiles do not show the presence of any stable zone before breakthrough unlike conventional-oil waterflooding at high-IFT. The absence of a stable zone before breakthrough in alcohol-assisted surfactant waterflooding is similar to that in heavy-oil polymer flooding at low IFT and heavy-oil waterflooding at high IFT.

7. In alcohol-assisted low-IFT surfactant waterflooding of heavy oils, extremely unfavorable mobility ratio creates irregular fingers, similar to both heavy-oil low-IFT polymer flooding and heavy-oil high-IFT waterflooding, as opposed to light-oil high-IFT waterflooding.

8. During alcohol-assisted surfactant waterflooding of heavy oils, the number of fingers increases with time, which is in agreement with the results of heavy-oil low-IFT polymer flooding and heavy-oil high-IFT waterflooding.

9. For low-IFT and high-IFT heavy-oil waterflooding and viscous-modified low-IFT polymer flooding in heavy oils, number of fingers generally decreases as flowrate increases. For high-IFT light-oil waterflooding, however, the number of fingers is independent of flowrate.

10. It is the viscous crossflow that causes the finger growth beyond the onset of viscous fingering. In low-IFT drainage, the frontal drive occurs with cluster growth and entailing microfingers that sometimes fill the entire pore body.

Acknowledgement

The first author thanks Tehran Petroleum Research Center for providing the laboratory facilities.

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