Gas- and Liquid-Phase Relative Permeabilities for Cold Production From Heavy-Oil Reservoirs

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Summary
Solution-gas drive with two heavy oils, a mineral oil with a viscosity of some 32,000 cp (at 24°C), and a heavy crude with viscosities of 85,000 cp and 9,200 cp (at 24 and 35°C, respectively) is carefully studied. Both oils show recovery in excess of 10% at test termination; the recovery for the heavy crude exceeds 15%. Had we continued the test, the recovery could have been higher.

From the measured pressure and fluid-flow rates, gas and oil relative permeabilities are estimated by a simple mathematical expression. The results establish that high recoveries are mainly caused by the low gas relative permeability. The results on mineral oil and heavy crude also demonstrate that the widely held belief that efficient solution-gas drive in heavy crude is caused by the foamy nature cannot be justified. An increase in temperature would reduce the oil viscosity, which in turn increases the gas mobility, thereby reducing the efficiency of solution-gas drive for cold production.

Introduction
Gradual progress in the understanding of the high efficiency of solution-gas drive in heavy-oil reservoirs has been made in recent years.1-6 Basic mechanisms and reservoir engineering parameters, however, remain unknown. Most authors attribute the high efficiency of solution-gas drive in heavy-oil reservoirs to foam; the term "foamy crude" is used to describe the process.7,8,9 We have not shared this viewpoint and have purposely avoided the use of the term "foamy oil".6,9

This work centers on two important issues related to cold production from heavy-oil reservoirs. The first issue relates to the relevance of the foamy nature of a heavy crude to recovery efficiency. For this purpose, in one set of experiments we use a viscous mineral oil, which supposedly cannot be foamy, to examine its efficiency under solution-gas drive.

The second issue relates to gas- and liquid-phase mobility and the influence of temperature and gravity force. Gas and oil relative permeabilities are the prime parameters for the study of solution-gas drive in heavy-oil reservoirs. In a previous work,7 we concluded that the gas phase may not be continuous during two-phase flow; gas flow is intermittent. Grattlon et al.10 have also reported a similar observation from solution-gas drive in a waterflooding residual oil process for a heavy mineral oil. The presumption that in immiscible two-phase flow, the effective permeability-to-liquid phase becomes zero when that phase is disconnected has also been rejected by Avraam and Payatakers.11 These authors carried out a systematic study of immiscible two-phase flow in a visual micro-model and observed that disconnected oil contributes substantially to the flow. In the second set of experiments, we use a heavy crude to study in detail recovery performance at two temperatures: 24 and 35°C. For both the viscous mineral oil and the heavy crude, gas- and liquid-phase relative permeabilities for the solution-gas drive process are estimated based on measured production rates and pressure drop across the core.

In this paper, we first present the experimental apparatus, the fluid and rock system, and the procedure for performing the experiments. Then, the measured and observed data are presented. A simple mathematical model is used to estimate gas- and liquid-phase relative permeabilities. At the end, several conclusions are drawn from the work.

Experimental

Fluids and Porous Media. A silicone oil (commercial product of Accusilic Inc., Boss-100, Canada) with API gravity of 14.4 and a crude oil (oil-E) with API gravity of 9 are used as the oil phase. Methane is used as the gas phase in all the experiments. Oil and gas are mixed in a high-pressure cylinder at a solution gas/oil ratio (GOR) of 6.5 vol/vol to prepare the live oil. The properties of the live oils are presented in Table 1. The oil viscosity is measured with a capillary viscometer at the test temperatures and at three different flow rates [10, 30, and 50 cm^3/hr in a tube with an inside diameter (ID) of 1.5 mm]. The viscosity does not change with the flow rate. Distilled water is used to calibrate the capillary viscometer before the viscosity measurement. The silicone oil is clear, and we can observe gas-bubble nucleation, growth, and coalescence and flow behavior from the transparent coreholder. The sand in the coreholder is made up of clean Ottawa sand with a grain size of 212-355 μm. The sand is placed in a clear acrylic tube with an ID of 6.35 cm. At the top of the sandpack, a 1.5-cm layer of coarse sand (grain size of 600-800 μm) is used to prevent gas holdup under a stainless steel screen with an opening of 425 μm. The measured absolute permeability, porosity, and pore volume are 13.7 darcies, 35.6%, and 608 cm^3, respectively (Table 2). The permeability is measured by using normal decane (in a liquid state).

Apparatus. Fig. 1 shows a sketch of the experimental apparatus, which is similar to the one described in Ref. 9. The main component is the visual coreholder, which can be rotated up to 180° along its middle and center. For silicone-oil tests, the window allows observing and video recording the flow pattern of gas bubbles. An ISCO pump is used for measuring oil and gas production during the test by reversing the movement of the piston (the depletion process). Two Validyne pressure transducers are mounted at both ends of the sandpack to measure pressure; the reading accuracy is ±0.5 psi. Two differential pressure transducers are mounted at the middle of the coreholder for measuring the differential pressure across the sandpack; the reading accuracy is ±0.01 psi. The coreholder, pressure transducers, capillary viscometer, and ISCO pump are placed in an air bath, and the temperature is controlled with an accuracy of ±0.1°C. A high-pressure cylinder containing the live crude oil, a gas/oil separator for measuring gas- and oil-production rates, and a heater are placed outside the air bath. A computer installed with LabView software (an automation software by Natl. Instrument Corp., Texas) is used to control the air-bath temperature and to record pressure data.

Procedure

The sandpack is evacuated for more than 4 hours before it is saturated with normal decane to measure permeability and porosity. More than 2 PV live-silicone oil is then injected at a pressure 30 to 50% higher than bubblepoint pressure to displace normal decane. After termination of the tests with the silicone oil, a similar procedure is applied for the live heavy-crude tests. The ISCO
pump at a refilling mode is used to control the outlet pressure. At late stages of saturation establishment, produced solution GOR is measured every 50 cm³ to examine the uniformity of the oil in the porous media. Once a uniform fluid is established in the sandpack, injection is stopped for 48 hours to allow pressure and temperature to become stable. Thereafter, the valve at the outlet end of the core is opened to the ISCO pump, and the depletion process is initiated. The initial expansion rate is 2.0 cm³/d for all tests. After gas breakthrough, the expansion rate is raised one time for silicone oil tests (from 2.0 to 3.0 cm³/d) and three times for oil-E tests (from 2.0 to 3.0 cm³/d, 3.0 to 4.0 cm³/d, and 4.0 to 6.0 cm³/d).

For the tests with the vertical coreholder, the gas and oil are produced from the top; for the test with the horizontal coreholder, the gas and oil are produced from the end with window. The first 6.5-cm³ gas production is measured in the graduated window placed at the outlet end of the coreholder (see Fig. 1). When the gas begins to flow out from the window outlet, the gas and oil production are directly measured with the ISCO pump and the gas/oil separator. This procedure includes isolating the outlet of the coreholder from the pump, displacing all fluids in the pump into the gas/oil separator, and resuming depletion. This process lasts less than 10 minutes. The produced-oil volume at the core outlet is readily known because the oil formation volume factor is very close to 1. The produced gas volume equals the difference between the expansion volume (readings from the pump) and the produced-oil volume. Gas and oil productions are usually measured every 0.01 PV. The pressure and differential pressure data are automatically recorded by the computer. Using the video camera, the gas-flow pattern from the porous media into the window (for silicone-oil tests) is studied.

At the completion of one test, the coreholder is placed vertically with the window at the bottom. The system is pressurized to a pressure higher than the bubblepoint pressure of the test oil to dissolve the gas. Approximately 2.0 PV test oil (fresh oil) is injected from the bottom to displace the previous oil. After the sandpack is saturated with the test oil (fresh live oil), the coreholder is reoriented for the next test.

**Results**

Six depletion tests are conducted with the two viscous oils. For silicone oil, the two tests are performed under the same test conditions for duplication with the coreholder placed vertically at the temperature of 24°C. For oil-E, four depletion tests are conducted at temperatures of 24 and 35°C. In one test, the coreholder is maintained in the horizontal position; in the others, the coreholder is vertical. Table 3 presents the experimental data. In the following, we will discuss the results.
TABLE 3—SUMMARY OF VARIOUS TESTS

<table>
<thead>
<tr>
<th>Oil</th>
<th>Test 1 Silicone Oil</th>
<th>Test 2 Silicone Oil</th>
<th>Test 3 Oil-E</th>
<th>Test 4 Oil-E</th>
<th>Test 5 Oil-E</th>
<th>Test 6 Oil-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>T, °C</td>
<td>24</td>
<td>24</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>p, psia</td>
<td>354</td>
<td>339</td>
<td>506</td>
<td>713</td>
<td>517</td>
<td>523</td>
</tr>
<tr>
<td>p, psia</td>
<td>100</td>
<td>100</td>
<td>177</td>
<td>149</td>
<td>129</td>
<td>137</td>
</tr>
<tr>
<td>ΔV, cm³</td>
<td>134</td>
<td>149</td>
<td>142</td>
<td>170</td>
<td>193</td>
<td>180</td>
</tr>
<tr>
<td>q, cm³/d</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>q, cm³/d</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>q, cm³/d</td>
<td>—</td>
<td>—</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Sₚₜ, %</td>
<td>1.2</td>
<td>1.1</td>
<td>—</td>
<td>5.5</td>
<td>5.4</td>
<td>5.3</td>
</tr>
<tr>
<td>R, % OOIP</td>
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<td>12.3</td>
<td>15.0</td>
<td>16.0</td>
<td>16.1</td>
</tr>
</tbody>
</table>

*Coreholder is positioned horizontally.

Silicone-Oil Tests (Tests 1 and 2). The results of the duplicate runs for the silicone oil are similar. We only present the results for Test 2 in detail.

**Pressure.** The pressure decline with expansion volume ($\Delta V$) is plotted in Fig. 2. There is a regime of single-phase flow before the pressure drops to the critical supersaturation pressure of 153.1 psia. The pressure-drop rate in the single-phase flow regime is approximately 59.4 psia/d. Thereafter, the pressure increases approximately 5.0 psia in 6 hours before the pressure begins to decrease at a nearly constant rate of 0.91 psia/d. This rate remains constant until the expansion rate is increased from 2.0 to 3.0 cm³/d at $\Delta V = 104.0$ cm³. The pressure drop for Tests 1 and 2 are identical. When the test is stopped at $p = 100$ psia, the pressure remains constant, and the differential pressure is zero, indicating that there is no supersaturation.

**Gas-Bubble Behavior.** When the pressure drops to the critical supersaturation pressure (corresponding to $\Delta V = 5.97$ cm³), the first gas bubble is observed on the surface of the coreholder. (The nucleation site may not be the surface of the coreholder.) Then, quick nucleation of gas bubbles is observed. In approximately 10 minutes, 14 gas bubbles are found on the surface of the coreholder, randomly from the bottom to the top. All the gas bubbles are tiny (<0.1 mm in diameter). When the expansion volume increases from 6.11 to 6.26 cm³, the number of gas bubbles on the surfaces of the coreholder increases to about 120. After that, the increase in the number of gas bubbles is slow, and the growth of the gas bubbles begins. The number of gas bubbles increases to 150 at $\Delta V = 7.43$ cm³. Their size is approximately 5.0 mm in diameter, and they are isolated (see Fig. 3a). With a further increase in expansion volume, the gas bubbles coalesce to form gas strips, which are composed of several gas bubbles. At $\Delta V = 11.47$ cm³, approximately 20 to 30% of the gas bubbles become connected and form gas strips in a width of 5 to 6 mm and a length from 20 to 100 mm (Fig. 3b); some gas strips on the surface begin to migrate upward and coalesce with other gas bubbles on their way up. At $\Delta V = 19.3$ cm³, approximately 70% of gas bubbles are connected, and the length of the gas strips further increases from 200 to 250 mm (Fig. 3c). The estimated upward velocity of the gas strips on the surface is around 0.64 to 0.91 cm/d.

The measured differential-pressure data for Test 2 are presented in Figs. 4 through 6. Note that all differential-pressure data in this paper are the pressure drop across the core caused by viscous forces and exclude the gravity contribution. The measured differential-pressure data match the phenomena of nucleation, growth, and upward movement of gas bubbles. After the first gas bubble is observed (at $\Delta V = 5.97$ cm³), the differential pressure begins to fluctuate between 0.24 and 0.274 psi. Two hours later, the differential pressure quickly increases from 0.274 to 0.378 psi in 0.12 PV incremental expansion (see Fig. 4). The differential pressure decreases to 0.34 psi and begins to fluctuate between 0.307 and 0.342 psi (see Fig. 5). When the gas begins to flow out of the core at $\Delta V = 12.0$ cm³, the intensity and amplitude of fluctuation in differential pressure increase with expansion volume (see Fig. 6). The average differential pressure first decreases from 0.32 to 0.27 psi and then gradually increases to 0.37 psi with expansion volume. The critical gas saturation for the silicone oil is estimated to be around 1.1%. Note that the critical gas saturation is measured based on the flow of the gas from the core to the visual window. The conventional material balance may not provide reliable results because of supersaturation.

**Gas-Flow Pattern.** We observed gas flow from porous media into the window in the form of a stream of gas bubbles and intermittence (note that here, we are referring to the gas bubbles in the window). Table 4 presents the measured data for the gas-flow pattern. The gas flow occurs about 1 to 2 times per day during the early period ($\Delta V<20$ cm³), and it increases to 6 to 7 times per day during the late period ($\Delta V>120$ cm³). The number of gas bubbles for each flow period also increases from approximately 10 to approximately 38 with the expansion volume. The bubble size (diameter) only increases from 0.15 to 0.30 cm at expansion volumes of 20 to 120 cm³, respectively. We can estimate the gas-flow rate based on the size and the number of gas bubbles and the frequency of intermittent gas flow in a given time period. The results are consistent with the measured gas-production rate at the outlet end of the core to be presented later. Assuming that each stream of gas bubbles is connected in the core, we can estimate the minimum gas-slug size that can flow upward in porous media. The data from Table 4 show that (1) the minimum volume of the mobile-gas slug in the silicone oil/sandpack system is approximately 0.073 cm³ (2) the volume of the mobile-gas slug increases with expansion volume. The velocity of gas in the open space in the lower part of the window filled with silicone oil is estimated to be about 1.5 to 2.5 cm/min, depending on the size of the gas bubbles. This value is much less than that in normal decane (about 300 cm/min).
Oil and Gas Production. Oil recovery vs. the expansion volume is presented in Fig. 7. Gas begins to break through from the core at \(\Delta V = 12.0 \text{ cm}^3\), but the amount of gas in the produced stream remains low initially and increase gradually. The final oil recovery at the termination of the test is 10.3% [original oil in place (OOIP)]. As Fig. 7 shows, had we continued the test, oil recovery would have been higher. This figure also reveals that there is an increase in the slope of the recovery curve around the time when the expansion rate is increased from 2 to 3 cm\(^2\)/d. This increase is small and, as we see later, does not affect the gas-phase relative permeability.

The oil- and gas-production rates at the outlet of the sandpack, \(q_o\) and \(q_g\), are presented in Fig. 8. After the gas breaks through from the core, the oil-production rate decreases quickly (from 2 to about 1 cm\(^3\)/d), and the gas-production rate increases quickly (from 0 to about 1 cm\(^3\)/d). Later, change in oil- and gas-production rates with the expansion volume is gradual. Before the expansion rate increases from 2 to 3 cm\(^2\)/d, the oil-production rate is approximately 0.5 cm\(^3\)/d. An increase in the depletion rate causes an increase in both gas- and oil-production rates, but the ratio of produced gas to oil does not change significantly. The total gas production from this test is 1380 cm\(^3\) (at standard conditions), which is approximately 34.9% of the initial solution gas; the low gas-production rate implies that gas mobility in the silicone oil is low. This is an important finding; it establishes that there is a radical difference between gas flow in open space and in porous media (see Ref. 9).

Oil-E Tests (Tests 3 through 6). Test 4. Tests 3 and 4 are performed for duplication. The coreholder is vertically positioned, and the temperature is 35°C. The results for these two tests are similar. Here, we only present the results for Test 4.

Pressure. Pressure and differential pressure vs. expansion volume are presented in Fig. 9. The depletion starts at \(p = 713\) psia with an initial expansion rate of 2.0 cm\(^2\)/d. The pressure-drop rate in the single-phase flow regime is about 60 psia/d, which is the same as that for the silicone oil. At the critical-supersaturation pressure of 346 psia, the expansion volume is 11.85 cm\(^3\). Subsequently, the pressure increases to 358 psia in 10 hours and remains constant for approximately 5 hours. After that, the pressure begins to drop at a very low rate. The rate of pressure decline is 4.0 psia/d for \(q_1 = 2.0\) cm\(^3\)/d, 6.0 psia/d for \(q_2 = 3.0\) cm\(^3\)/d, 6.0 psia/d for \(q_3 = 4.0\) cm\(^3\)/d, and 6.0 psia/d for \(q_4 = 6.0\) cm\(^3\)/d (\(q_1\), \(q_2\), \(q_3\), and \(q_4\) are the expansion rates; see Fig. 9). In this test, the expansion rate is raised three times (at \(\Delta V = 50\), \(\Delta V = 75\), and \(\Delta V = 152\) cm\(^3\)), respectively; the pressure vs. the expansion volume has no sharp discontinuity, implying low or negligible supersaturation. It should be pointed out that the rate of expansion (or pressure decline) before gas-phase formation is expected to affect the critical-gas...
Fig. 6—Differential pressure vs. expansion volume in Test 2: silicone oil.

saturation and recovery. The effect of rate after gas-phase formation may not have a significant effect provided that the balance between viscous, gravity, and capillary forces is not already too much.

The differential pressure in the single-phase flow regime is approximately 0.073 psi. It increases to 0.10 psi as soon as the first gas is observed on the surface of the coreholder at $\Delta V = 11.85$ cm$^3$. Then, the differential pressure slowly increases to 0.12 psi. Similar to the silicone-oil test, the differential pressure begins to fluctuate because of the growth and coalescence of the gas bubbles. The amplitude of fluctuation in differential pressure increases further when the gas begins to flow out of the core. The average differential pressure, however, remains at 0.12 psi.

At the termination of this test, the measured supersaturation is zero (the pressure remains constant), and the differential pressure becomes zero within 2 hours after the test is stopped.

Gas-Bubble Behavior. Because the oil is black, we cannot observe the gas-flow pattern from the window. Only the nucleation, growth, and coalescence of gas bubbles can be seen on the surface of the coreholder.

The first gas bubble, with a very tiny size, is observed on the middle of the coreholder at $\Delta V = 11.85$ cm$^3$. Note that this bubble may have been evolved from an active site within the bulk-oil phase (such as asphaltene micelles). About 5 minutes later, 10 gas bubbles are observed on the whole surface. The gas-bubble nucleation rate is very fast between $\Delta V = 13.32$ cm$^3$ and $\Delta V = 17.71$ cm$^3$. The number of gas bubbles is approximately 100 at $\Delta V = 13.32$ cm$^3$, but it quickly increases to about 1,000 at $\Delta V = 17.71$ cm$^3$. The size of the gas bubbles increases from 0.2 mm to 1.0 mm in this period of expansion; all gas bubbles are isolated. Then, the increase in the number of gas bubbles is slow, but they continue to grow. We found that the growth of gas bubbles is not the same at the bottom as it is at the top of the surface. At $\Delta V = 23.32$ cm$^3$, gas bubbles on the upper surfaces increase to 2.5 to 3.0 mm in diameter, but those in the middle and in the bottom surface are only 1.0 to 2.0 mm in diameter. Therefore, the gas bubbles on the upper surface begin to coalesce. At the same time, the size of gas bubbles on the middle and low surfaces increases to 2.5 mm. At $\Delta V = 33.68$ cm$^3$, the gas bubbles on the upper surface are approximately 5 to 10 mm in length and 3 to 4 mm in width; some of the gas bubbles become partially connected. At $\Delta V = 43.25$ cm$^3$, approximately 70% of the gas bubbles are connected, and the saturation on the entire core surface is uniform. This observation is later used to assume that the gas saturation is uniform in the core. Soon after, gas bubbles begin to flow from the core into the window, accompanied with a wild fluctuation in differential pressure. The critical-gas saturation for oil-E is approximately 5.5%. At $\Delta V = 70$ cm$^3$, most gas bubbles are connected, and about 15 to 20% of the surface of the coreholder is covered by gas bubbles. Fig. 10 shows the gas bubbles observed in Test 4. Similar to Fig. 3, the distribution of gas bubbles is nearly uniform throughout the core surface, but the gas-bubble density is much higher for oil-E (2 bubbles/cm$^3$).

Oil and Gas Production. The oil recovery is presented in Fig. 11. At gas breakthrough, the recovery from the core is 7.5% (OIP), which is much higher than that obtained for the silicone oil. The final oil recovery is 15.0% (OIP), which includes 2% produced by liquid expansion. Had we continued the test, oil recovery would have been higher.

The oil- and gas-production rates vs. expansion volume are presented in Fig. 12. Similar to silicone oil, the oil-production rate decreases by 50% after the gas begins to flow out of the core. Correspondingly, the gas-production rate quickly increases from 0 to approximately 1.0 cm$^3$/d. Both gas- and oil-production rates increase when the expansion rate is increased from 2 to 3 cm$^3$/d and from 3 to 4 cm$^3$/d, respectively. When the expansion rate is further increased from 4 to 6 cm$^3$/d, the oil-production rate does not increase; only gas production increases. Figs. 11 and 12 reveal that an increase in expansion rate does not change the pattern of oil recovery.

The total gas production is 1920 cm$^3$ (at standard conditions) at the termination of the test, which is approximately 48% of the initial solution gas.

Test 5. This test is conducted with a vertical coreholder at a temperature of 24°C to study the effect of temperature.

Pressure. Pressure data vs. expansion volume in Test 4 ($T = 35^\circ$C) and Test 5 ($T = 24^\circ$C) are presented in Fig. 13. The pressure-drop rate in the regime of single-phase flow ($\Delta V \leq 7.0$ cm$^3$), $dP/dt$, is approximately 61.6 psi/d for Test 5. The bubble-

### TABLE 4—GAS-BUBBLE FLOW PATTERN IN TEST 2

<table>
<thead>
<tr>
<th>$\Delta V$ (cm$^3$)</th>
<th>Frequency of Gas Flow (day$^{-1}$)</th>
<th>No. of Gas Bubbles Per Flow</th>
<th>Gas-Bubble Diameter (cm)</th>
<th>Gas Volume Per Flow (cm$^3$)</th>
<th>Gas-Flow Rate (cm$^3$/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1–2</td>
<td>8–12</td>
<td>0.15–0.20</td>
<td>0.07–0.11</td>
<td>0.15–0.22</td>
</tr>
<tr>
<td>40</td>
<td>3–4</td>
<td>18–22</td>
<td>0.20–0.25</td>
<td>0.17–0.22</td>
<td>0.77–0.90</td>
</tr>
<tr>
<td>60</td>
<td>4–5</td>
<td>20–25</td>
<td>0.25–0.30</td>
<td>0.19–0.24</td>
<td>0.96–1.20</td>
</tr>
<tr>
<td>100</td>
<td>5–6</td>
<td>30–35</td>
<td>0.30–0.35</td>
<td>0.24–0.28</td>
<td>1.20–1.68</td>
</tr>
<tr>
<td>120</td>
<td>6–7</td>
<td>35–40</td>
<td>0.30–0.35</td>
<td>0.30–0.33</td>
<td>1.80–2.31</td>
</tr>
</tbody>
</table>

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point pressure and critical-supersaturation pressure are different for Tests 4 and 5. In Test 4, the first gas bubble is evolved at \( p = 347 \) psia; for Test 5, the first gas bubble is evolved at \( p = 317 \) psia. The pressure-drop rate after gas evolution is slow and is similar for Tests 4 and 5. Although the expansion rate is raised three times (at \( \Delta V = 50, 75, \) and \( 155 \text{ cm}^3 \)), respectively, the linear relationship between pressure and expansion volume is not influenced. The pressure difference between Tests 4 and 5 decreases with expansion volume. At the termination of the test, the pressure difference decreases to 7 psia. Because of the increase in gas volume in the core, a decrease in pressure difference is expected.

**Differential Pressure**. Differential pressure for Tests 4 and 5 is different (see Fig. 14). In the single-phase flow regime, the differential pressure for Test 4 is 0.075 psi, but for Test 5 it is 0.26 psi. As soon as the gas phase is evolved in the core, the differential pressure increases from 0.075 to 0.12 psi for Test 4 and from 0.26 to 0.38 psi for Test 5. The increase in differential pressure with the decrease in temperature is related to the effect of oil viscosity. Similar to those observed for previous tests, the differential pressure begins to fluctuate after the gas breakthrough. The amplitude of fluctuations in differential pressure for Test 5 is greater than that for Test 4. This behavior is also related to the viscosity effect.

**Gas-Bubble Behavior**. The nucleation, growth, coalescence, size, and density of gas bubbles are similar for Tests 4 and 5. For Test 5, the first gas bubble with a diameter of 0.2 mm is observed on the middle of the coreholder as soon as the pressure reaches the critical-supersaturation pressure (\( p = 317 \) psia). The number of gas bubbles quickly increases to 50 in about 60 minutes (at \( \Delta V = 7.2 \text{ cm}^3 \)). The estimated number of gas bubbles is about 300 at \( \Delta V = 8.1 \text{ cm}^3 \), 1,000 at \( \Delta V = 10.9 \text{ cm}^3 \), and 2,000 at \( \Delta V = 14.1 \text{ cm}^3 \). Therefore, the increase in the number of gas bubbles is slow. The size of the gas bubbles increases from 0.3 to 1.0 mm as the expansion volume increases from 12.1 to 14.0 cm\(^3\); all the gas bubbles are isolated. At \( \Delta V = 35 \text{ cm}^3 \), more than 70% of the gas bubbles on the surface are connected, and the estimated gas-bubble density is approximately 3 to 5 bubbles/cm\(^2\). The gas-bubble distribution is uniform across the core. Gas breakthrough occurs at \( \Delta V = 39 \text{ cm}^3 \). Therefore, critical-gas saturation is about 5.3%. There seems to be a higher gas-bubble density in Test 5 than in Test 4 (see Fig. 15).

**Oil and Gas Production**. Oil recovery vs. expansion volume for Tests 4 and 5 is shown in Fig. 16. For the expansion volume from zero to 68 cm\(^3\), the recovery curves for Tests 4 and 5 are identical. Then, the recovery curves begin to diverge. The oil-production rate for Test 5 remains higher than that for Test 4. The oil recovery at the termination of the test is 16% (OOIP) for Test 5 and 14% (OOIP) for Test 4 (note that the initial pressure is approximately 580 psia). Fig. 16 indicates that temperature could affect the oil recovery after the gas becomes mobile. At a lower temperature, the oil viscosity increases, and the dispersed gas-bubble mobility decreases. Lower gas mobility is accompanied by higher oil recovery. A simple experiment is performed by measuring the gas-release rate dispersed in oil in an open space (a graduated cylinder) with live oil-E at \( T = 24 \) and 35°C, respectively. The pressure of the live oil is reduced from 1,000 psia to atmospheric pressure, and the oil is injected into the graduated cylinder. Numerous micro gas bubbles are evolved in the oil phase. Thereafter, as the gas bubbles leave, the apparent oil volume decreases. The results presented in Fig. 17 show that the gas-release rate increases with an increase in temperature.

**Test 6**. This test is performed with the horizontal coreholder at \( T = 24\)°C. The main objective is to study the effect of gravity. Recently, Urgell \( et \ al. \) \( 11 \) also performed some tests with a horizontal core, but they did not report the recovery performance after gas breakthrough. The critical-gas saturation is the same for horizontal and vertical cores in the work of Urgell \( et \ al. \) as it is in our work. In Test 6, the horizontal core is rotated 180° around its center at \( \Delta V = 68 \text{ cm}^3 \) for the reason that will be discussed later. Before rotation, the exit of the window is positioned at the upper part of the cylindrical window (which is horizontal for this test). After rotation, the exit of the window is positioned at the lower part of the window.

**Pressure**. Fig. 18 shows pressure vs. expansion volume for Test 5 (vertical) and Test 6 (horizontal). For Test 6, the first gas bubble is observed at \( p = 314 \) psia, and the supersaturation in pressure is 20 psi, which is close to that of Test 5 (22 psi). The overall pressure behaviors for Tests 5 and 6 are similar.

**Differential Pressure**. Differential pressure data for Tests 5 and 6 are presented in Fig. 19. Before gas breakthrough, the differential pressure for Test 6 is similar to that for Test 5. After gas breakthrough, the differential pressure for Test 6 decreases quickly from 0.3 to -0.02 psi and remains less than 0.2 psi for approximately 3 days. Then, the differential pressure increases continuously to 0.6 psi, followed by a continuous decrease to 0.04 psi. The differential pressure for Tests 5 and 6 is similar after the horizontal core is rotated by 180° (upside down). After the rotation, the differential pressure for Test 6 begins to fluctuate between 0.05 and 0.55 psi, as it does for Test 5. The amplitude of differential pressure for Test 6 is smaller than that for Test 5 after the expansion rate increases from 4 to 6 cm\(^3\)/d at \( \Delta V = 154 \text{ cm}^3 \). The average differential pressure for test 6 in single-phase flow regime is 0.23 psi; it is approximately 0.36 to 0.41 psi in a two-phase flow regime.

**Gas-Bubble Behavior**. Gas-bubble nucleation, growth, and coalescence in Tests 5 and 6 are similar up to an expansion volume of 32 cm\(^3\). After that, there is a small gas patch of about 0.2 cm in width and 0.5 cm in length (continuous gas phase) at the top surface of the coreholder near the core outlet for Test 6. The size of the gas patch grows slowly. At \( \Delta V = 68 \text{ cm}^3 \), it increases to approximately 0.5 cm in width and 3.0 cm in length. From this observation, we believe that gas bubbles move upward slowly by gravity force only toward the outlet end of the core. After the core is rotated, the gas patch disappears. We carefully observe the gas-bubble distribution at the top surface and the bottom surface, but we do not observe significant differences in gas-bubble distribution. Even at the end of the test, we do not find a continuous gas
phase (or gas patch) at the top surface again. It seems that no gas segregation occurs after rotation of the coreholder.

Oil and Gas Production. Oil-recovery curves for Tests 5 and 6 are shown in Fig. 20. Before gas breakthrough, the oil-recovery performance for Tests 5 and 6 is similar. However, after gas breakthrough, the oil-production rate quickly decreases from 1.9 to 0.4 cm^3/d in 5 days; correspondingly, the gas production rate increases from 0.1 to 2.6 cm^3/d. We attribute this result to the effect of gas segregation as mentioned earlier. After the core is rotated and the expansion rate is raised from 3 to 4 cm^3/d, the oil rate increases significantly (see Fig. 20). The oil recovery for Test 6 after rotation of the coreholder is systematically higher than that of Test 5 by a small amount. Total oil recovery is approximately 16.1% (OORP), and total gas production is approximately 1798 cm^3 for this test. The gas- and oil-production rate for Test 6 is similar to that of Test 5, except in the early period after gas breakthrough (results are not shown).

Apparently, the gravity effect on oil production for the horizontal core test is dependent on the expansion rate. For Test 6, 2 days after the core is rotated by 180°, the expansion rate is raised from 3 to 4 cm^3/d (at ΔV=75 cm^3). An increase in the expansion rate could increase the viscous force, which drives gas bubbles horizontally toward the core outlet. In all the vertical tests, the flow is 1D, based on visual observation. In the horizontal test (Test 6), the flow apparently is influenced by gravity at the low expansion rate. The increase in gas saturation at the top of the core outlet before rotation affects the two-phase flow.

Gas and Oil Relative Permeabilities. Mathematical Model. The oil- and gas-phase production rate, as well as the differential pressure data, are available for all the tests. Based on the observed
features of the tests, we assume that (1) gas and oil flow are at a pseudosteady state because the average differential pressure across the core is nearly constant for a given expansion rate; (2) gas and oil saturations across the core are uniform, as evidenced by the observation of gas bubbles from the coreholder surface and very low differential pressure across the core (less than 0.4 psi for our system); and (3) flow is 1D. In our belief, nucleation active sites are mainly within the oil phase, and the pore pressure from the inlet to the outlet of the core is nearly the same for our system. From these assumptions (we will get back to item 2 in the next section), we derive a mathematical model for phase relative permeabilities (see the Appendix):

$$k_r = \frac{\mu_q L}{2kA(\Delta p + \rho g L \sin \theta)}$$  \hspace{1cm} (1)$$

where $k_r$ = relative permeability, $\mu$ = viscosity (cp), $q$ = phase volumetric rate (cm$^3$/sec), $L$ = length of the core (cm), $k$ = absolute permeability (darcies), $A$ = cross-sectional area (cm$^2$), $\rho$ = density (g/cm$^3$), $\Delta p$ = differential pressure (atm), $g$ = gravitational constant, and $\theta$ = the angle from the horizontal plane (degree). Subscript $i$ is the phase index (gas or liquid phase). Note that in Eq. 1, $\Delta p$ is the pressure difference from the inlet and the outlet; therefore, it includes the effect of gravity.

**Estimation of $k_{ro}$ and $k_{re}$** Eq. 1 is used to estimate gas and liquid relative permeabilities with average differential-pressure data.

The absolute permeability inferred from the data of single-phase flow for silicone oil and oil-E is not the same. The inferred absolute permeability measured for silicone oil is approximately 10 darcies; for oil-E, it is approximately 3.5 darcies. These values are less than that measured with n-decane (13.7 darcies). This discrepancy is believed to be related to the viscous-elastic behavior of a viscous fluid at a very low rate (2 cm$^3$/d); the oil viscosity may change with the flow rate. The change in the inferred absolute permeability may be caused by a change in oil viscosity. We have used the inferred absolute permeability from the single-phase flow regime of each test and the measured oil viscosity at a high rate to calculate the relative permeabilities.

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**Fig. 16**—Oil recovery in Test 4 (T=35°C) and Test 5 (T=24°C): Oil-E.

**Fig. 17**—Effect of temperature on gas release in open space: Oil-E.
The calculated gas and oil relative permeabilities for Test 2 (silicone oil) are shown in Fig. 21. The oil relative permeability decreases from 1 to approximately 0.2 when the gas saturation increases from 0 to 9.5%. After the gas becomes mobile at $S_g = 1.1\%$ (see Table 3), its relative permeability increases quickly from 0 to $1.0 \times 10^{-2}$. The early part of the gas relative permeability is presented with a dashed line to indicate the possible effect of high supersaturation. After gas flow, we expect a decrease in non-equilibrium (decrease in supersaturation). From $S_g = 2.5\%$, the increase in gas relative permeability is slow. At the termination of the test ($S_g = 9.3\%$), the gas relative permeability is approximately $1.0 \times 10^{-6}$, which is five orders of magnitude less than oil relative permeability at the same gas saturation.

The gas and oil relative permeabilities for Test 4 are plotted in Fig. 22. The relative permeability of oil-E is similar to that of silicone oil. Once the gas begins to flow out of the core at $S_g = 5.5\%$, the gas relative permeability increases quickly from 0 to $6 \times 10^{-6}$. After that, the gas relative permeability increases slowly. The oil relative permeability decreases from 1 to 0.35 when the gas saturation increases from 5.5 to 12.7%. At the termination of the test, the gas relative permeability is approximately $2 \times 10^{-5}$, which is very small in comparison to oil relative permeability at the same gas saturation. The gas and oil relative permeabilities for the silicone oil system have the same trend as oil-E.

Fig. 23 shows gas and oil relative permeabilities at $T=24^\circ C$ and $T=35^\circ C$ for oil-E. Oil relative permeability does not change appreciably with temperature. However, when the temperature increases from 24 to 35°C, the gas relative permeability increases by two orders of the magnitude (from $10^{-2}$ to $10^{-1}$). Fig. 24 shows the oil and gas relative permeabilities from horizontal and vertical cores. Both oil and gas relative permeabilities are of the same order for Tests 5 and 6.

**Fig. 21—Gas and oil relative permeabilities in Test 2: silicone oil.**
Fig. 22—Gas and oil relative permeabilities for Test 4: Oil-E.

Fig. 23—Gas and oil relative permeabilities in Test 4 (T=35°C) and Test 5 (T=24°C): Oil-E.

conclude that viscosity is the major parameter in solution-gas drive of heavy oils. Results from Tests 2 and 5 demonstrate that the widely held belief that the foamy nature of crude oil contribut...  

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References


Fig. 24—Gas and oil relative permeabilities in Test 5 (vertical) and Test 6 (horizontal): Oil-E.

Acknowledgments

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From \( \frac{\partial P_p}{\partial x} = -\frac{\mu_p}{\phi k_h} v_c \), \( v_c = \frac{\partial P_p}{\partial x} \) (A-11) with respect to \( x \),

\[
\Delta p_p = -\frac{\mu_p}{\phi k_h} \int_0^L v_c \, dx - \rho_g L \sin \theta \quad \text{(A-12)}
\]

We can derive the expression for \( v_c(x) \) similarly to that of \( v_c(x) \):

\[
v_c(x) = -\frac{\partial P_p}{\partial x} \quad \text{(A-13)}
\]

where \( \frac{\partial P_p}{\partial x} \) can be expressed by

\[
\frac{\partial P_p}{\partial x} = \frac{\partial P_p}{\partial x} - \frac{\partial P_0}{\partial x} + \frac{\partial P_l}{\partial x} \quad \text{(A-14)}
\]

Substituting Eqs. A-13 and A-14 into Eq. A-12 and integrating with respect to \( x \),

\[
\Delta p_p = \frac{\mu_c L}{2k_h} \left( \frac{\partial P_p}{\partial x} - \frac{\partial P_0}{\partial x} + \frac{\partial P_l}{\partial x} \right) - \rho_g L \sin \theta \quad \text{(A-15)}
\]

Rearranging Eq. A-15, we finally derive the equation for calculating gas relative permeability:

\[
k_r = 2k (\Delta p_p + \rho_g L \sin \theta) \quad \text{(A-16)}
\]

Eqs. A-9 and A-16 can be used for estimating gas and oil relative permeabilities for a depletion process. These two equations can be cast into the following equations by eliminating the compressibility:

\[
k_r = \frac{\mu_c \alpha}{2k (\Delta p_p + \rho_g L \sin \theta)} \quad \text{(A-17)}
\]

\[
k_r = \frac{\mu_c \alpha L}{2k (\Delta p_p + \rho_g L \sin \theta)} \quad \text{(A-18)}
\]

**SI Metric Conversion Factors**

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*Conversion factor is exact.

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