Measurements of Supersaturation and Critical Gas Saturation

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Summary. Supersaturation and critical gas saturation were measured for two core samples with different pore structures. In these measurements, a pump with a constant rate of expansion was used to avoid steep pressure changes. Binary mixtures of C10-C10 at two saturation pressures were used as the fluid system. The surface tension of the binary mixtures varied from 2 to 13 dyne/cm. The data show that pore structure could significantly affect the degree of supersaturation. The supersaturation in a porous medium with small pores may be less than in a porous medium with large pores. The critical gas saturation data of this work are lower than literature values. Measurements on a chalk sample reveal critical gas saturations of about 0.5%.

Introduction

Critical gas saturation (e.g., in a two-phase gas/oil system) is defined as the minimum gas saturation at which gas-phase flow can occur. Its value often is established from the extrapolation of the gas relative permeability for an external gasdrive process. Another approach used less frequently is the measurement of gas saturation at the point when the gas phase becomes mobile under an internal gas-expansion condition. These two methods are fundamentally different, and critical gas saturation is of a different nature for external and internal gasdrive processes. The appearance of the gas phase in an internal expansion process is a heterogeneous bubble nucleation phenomenon, where the formation of a new phase requires work supplied by the environment surrounding the site where the nucleus will appear. (The work of nucleus formation is $W_d$, where $W_d$ is the surface tension and $d$ is the surface area of the nucleus.) Also, thermodynamic considerations require supersaturation for the initiation of the nucleation. The growth of the initial nucleus (critical nucleus), caused by expansion and agglomeration of various nuclei, and mobilization of the connected bubbles in an internal gas-expansion process, is entirely different from the gas-phase mobilization in external gasdrive systems. The subject of this study is critical gas saturation for an internal gas-expansion process.

Knowledge of critical gas saturation is important for estimating recovery in a solution-gas-drive reservoir and methane production from geopressed aquifers. Measured values of the critical gas saturation in the literature range from 2% to 27% PV. For solution-gas-drive reservoirs, and particularly for fractured petroleum reservoirs, high values of critical gas saturation mean high oil recoveries. A 15% gas saturation could imply >15% oil recovery. Oil on the other hand, for geopressed aquifers, only low values of critical gas saturation (i.e., <0.5%) could give substantial recovery. In a study of the methane productivity from geopressed aquifers, Doscher et al. concluded that, for methane-saturated brine reservoirs, critical gas saturation is the most important parameter.

Our literature review shows a large difference in the value of critical gas saturation. In addition to rock and fluid systems, this difference may be a reflection of the experimental techniques, neglect of supersaturation effects on the estimation of critical gas saturation, and some core-length effects. In this paper we first review the literature. Because supersaturation could influence the value of critical gas saturation, our literature review includes supersaturation data in porous media along with critical gas saturation measurements.

Literature Review

An early paper by Kennedy and Olson reported that, in a C1/kerosene mixture with both silica and calcite systems, saturations were up to 770 psi. At this high value, bubbles formed quickly and violently. For a supersaturation of 30 psi and less, no bubbles were observed. Visual inspection of the experiments showed that bubbles formed on the crystal/hydrocarbon surface in preference to the glass/hydrocarbon interface or to the body of the liquid. The bubble-formation frequency was a function of supersaturation, and (3) silica and calcite crystals had identical effects and a small amount of water and crude oil had no effect on the results. The quartz and calcite minerals that Kennedy and Olson used were cut from large natural crystals and had rectangular faces, with a total area for each crystal averaging 0.70 in.2. Stewart et al. showed the existence of supersaturation during laboratory solution-gas-drive experiments (Fig. 2 of Ref. 9). They concluded from laboratory measurements that some limestones may show a significant difference in gas/oil relative permeability relationships between internal and external gasdrive processes. However, it appeared that supersaturation had no effect on the relative permeability characteristics of intergranular-pore-space rocks.

In 1953, Wood repeated Kennedy and Olson’s work on a 4-md core using reservoir oil. At a supersaturation of 27 psi, no gas bubbles formed, even after 15 hours. This value is close to the 30 psi supersaturation that Kennedy and Olson reported.

In a continuation of the work in Ref. 9, Stewart et al. performed a systematic study of the role of supersaturation in oil recovery by solution-gas-drive in limestones. Their findings are similar to those in their previous study. In a 6-ft-long core, with a mixture of C1/C10-C12 and a bubblepoint pressure of 200 psig, a supersaturation of more than 20 psi was estimated at a pressure decline rate of 10 psi/D. Tests on this core showed a difference in recovery depending on the rate of pressure decline. Later, Wilcand and Kennedy concluded from a number of experiments that a definite degree of supersaturation, varying from 14 to 15 psi for different rocks and fluid systems, can be imposed without bubble formation. In his laboratory study of oil recovery by solution-gas-drive for a 5-ft core (k = 10 md), Hard DY observed a supersaturation of 300 psi during early stages of a test with a production rate of 0.013 in.3/D. The core PV was 26.85 in.3.

Chateneven et al., in a microscopic study of solution-gas-drive behavior, observed that a state of supersaturation was reached before a gas bubble was formed. For their particular fluid system, it often was necessary to reduce pressure by as much as 50% of total initial pressure before any free gas could form. In terms of absolute quantity, however, the supersaturation was only about 7 psi. Chateneven et al. made two important observations: (1) after a gas bubble formed, it became continuous with other gas structures, forming a long and narrow continuous phase, and (2) capillarity significantly affected structure growth.

In visual model studies, Wall and Khurram observed that nucleation occurred with a degree of supersaturation (higher rates of pressure decline were associated with greater degrees of supersaturation) and that visible gas bubbles formed, grew, and then coalesced. Typically, in the final growth stages, few (perhaps only one) filaments of linked gas bubbles were propagated to the top of a vertical column packed with sand grains. Eight through 16 directly or indirectly addressed supersaturation, formation of bubbles, and in some cases, coalescence of gas bubbles. Experimental data and visual observations were the bases of the work. Refs. 17 through 20 focused on the measurement of...
critical gas saturation and discuss its relationship to capillarity and supersaturation.

Dumore conducted solution-gas drive experiments in a transparent model filled with glass beads (k = 350 and 15 darcies). The fluid system was a mixture of C1/ethane-novasol with a bubblepoint pressure of 52.7 psia at about 72°F. For pressure decline rates of 12.3 and 1.23 psi/D, the fluid under expansion was super-saturated throughout the experiment (3 days for the 12.3-psi/D rate and 30 days for the 1.23-psi/D rate). Dumore reported only mean free-gas saturation but not the saturation at which the gas began to flow. Like Handy's data, Dumore's data showed that maximum supersaturation occurs after the first gas bubbles develop. Visual inspection of gas saturation development in Dumore's experiments shows a disconnected agglomeration of gas bubbles. Dumore's main conclusion, based on simple arguments and his data, was that the amount of free-gas saturation depends on capillarity: higher free-gas saturation occurs at lower capillary pressure and lower free-gas saturation occurs at higher capillary pressure.

Madaouli reported an extensive data set of critical gas saturations for several rock and fluid samples. Critical gas saturations were measured mainly for a vertical core with lengths of 14 to 16 in. Madaouli argued that, at the onset of gas flow, gravity forces (buoyancy) should exceed capillarity and therefore a minimum core length would be required to eliminate end effects (viscous effects are assumed to be small because of low flow rates). Pressure decline rates in Madaouli's experiments were mostly in the range of 15 to 200 psi/D. In one of the experiments, critical gas saturation was almost independent of the pressure decline rate (0.78 to 170 psi/D), so all the data of Ref. 18 were based on the assumption of zero supersaturation. Madaouli's critical-gas-saturation data varied from 4.4% to 26.4% PV. These values are on a residual, water-free basis.

Argrall and Iffy measured critical gas saturation for both vugular and intergranular rocks using reservoir crudes and a simple fluid. Like the Madaouli study, their experiments were conducted on vertical core and assumed zero supersaturation. However, they developed a simple model of supersaturation that indicates a threshold supersaturation for the initiation of nucleation that is independent of the pressure decline rate. Argrall and Iffy's critical-gas-saturation data varied from 1.7% to 6.3% PV for the intergranular-porosity cores and from 17.4% to 26.4% for the vugular cores. All their data were measured with a pre-established constant water saturation.

Recently, Moulou and Longeron reported the measurement of critical gas saturation of a 2-in.-long core with a C1/C2/C10 mixture of 412.5-psia bubblepoint pressure at 100°F. The only variable in their experiment was the pressure decline rate, which influenced both the supersaturation and the value of the critical gas saturation. Critical gas saturations at pressure decline rates of 0.435 and 72.5 psi/D are 6% and 12% PV, respectively.

In view of the above background, an experimental and theoretical research program was initiated to measure and model supersaturation and critical gas saturation. In this paper, we report the results of experimental work on supersaturation and critical gas saturation data for two rock samples of different pore sizes. Rock and fluid samples were selected so that the influence of surface tension, pore structure, rate, and possible length effects on critical gas saturation could be examined.

**Experimental Details**

**Apparatus, Fig. 1** is a schematic of the experimental setup used to measure the supersaturation and critical gas saturation. The core holder containing the cylindrical core sample was placed vertically and connected at the top to an optical cell for gas-production detection. The dead volume of the space and tubing between the top of the core and the optical cell was 0.039 in.3. The vertical tubing connecting the core holder to the optical cell was 0.083 in. in ID and 4.01 in. long. The upstream end of the optical cell had an ID of 0.09 in. and a length of 1.6 in. Therefore, the volume of the piping from the top of the core to the detection site of the optical cell was 0.03 in.3. The dead volume of the space between the bottom face of the core and the bottom valve was 0.046 in.3.

The core holder, optical cell, and tubing and valves were placed in an oven controlled to a set temperature within ±0.3°F. The dual-piston displacement pump, tubing from the oven to the pump (tubing diameter was 3/4 in.), pressure transducer tubing, and connections were outside the oven. Room temperature was kept nearly constant with a temperature variation of ±1.8°F during the experiment. (Room temperature was around 70°F.) The pump with the piston at the top position had a dead volume of 0.55 in.3. The internal volume of the tubing valves and fittings outside the oven was 0.27 in.3. Our preference was to put the pump inside the oven, but the pump design precluded its use in the oven.

The pump has a single-stroke volume of 2.44 in.3 with a volumetric rate between 0.088 and 3.515 in.3/minute. It was used in the withdrawal mode to conduct supersaturation and critical gas saturation runs. This mode of operation allows a smooth pressure decline in the single-phase region.
Core Preparation and Properties. Berea sandstone and outcrop chalk samples were used in the experiments. Table 1 lists sample dimensions and properties. To mount the sample in the core holder, it was first wrapped in a single layer of heat-shrunk Teflon TM, then in aluminum foil. A new layer of heat-shrunk Teflon wrapping included the two metal end pieces. The whole assembly was put into a Viton TM rubber sleeve and installed in the core holder. The multilayer sleeve minimizes diffusion from the core.

Before the experiments, the core sample in the wrapping was flushed clean with a 50:50 mixture of methanol and toluene. Its porosity and liquid permeability then were measured. In each experiment, the core was saturated with a C1/n-C10 fluid mixture. Usually, 2 PV of the hydrocarbon mixture was flooded through the core. Before the start of the experiment, the pore pressure of the fluid was raised to at least 600 psi above the bubblepoint pressure.

Figs. 2 and 3 show the pore-entry radius of the Berea and chalk samples. These figures were prepared from mercury capillary pressure measurements. Figs. 2 and 3 indicate that both the Berea and chalk samples have uniform pore-entry radii in comparison with those observed in some North Sea sandstone reservoirs.

**Procedure.** The pressure of the undersaturated fluid was reduced continuously by withdrawing fluid from one of the pump pistons (Fig. 1) at a constant volumetric rate. This procedure for instigating pressure decline, unlike the use of a pressure regulator device, avoids any steep pressure change. Volume expansion rates for these experiments were set at 0.088, 0.176, 0.439, and 0.791 in.3/D. During the first part of some experiments, the confining pressure was reduced manually to maintain a constant net confining pressure of about 290 psi. The purpose of adjusting the confining pressure was to reduce rock compressibility effects. However, to have smooth pore pressure decline, at a pressure of 100 to 150 psi above the bubblepoint, confining pressure regulation was discontinued. During this phase of the experiment, the effect of confining pressure change on the rock PV was measured. For each experiment, the pore pressure, pump withdrawal volume, optical cell response, oven temperature, and room temperature were recorded as functions of time.

**Fluid System**

A C1/n-C10 mixture was used as the fluid system, primarily because of the availability of phase-behavior and volumetric,22 surface tension,23-25 viscosity,26,27 and diffusion coefficient27 data for this binary system. These data are required to model supersatura-

tion and critical gas saturation and for the measurements of this study.

Reamer et al.22 gave the phase behavior and volumetric data of C1/n-C10 mixtures. Fig. 3 of Ref. 22 shows some scattering in the dewpoint data. Reamer et al. mentioned that the uncertainty of the measurements at 100°F was somewhat greater than the precision of the measurements. They also pointed out that, because of the probable loss of a small quantity of n-C10, a much higher uncertainty could have resulted at 100°F than at higher temperatures. Because we were ready to conduct all our experiments at about 100°F, we decided to measure the bubblepoint pressure at this temperature. Accurate knowledge of the bubblepoint pressure is critical in the estimation of supersaturation. Table 2 shows our measured data and the values from Reamer et al. (A linear interpolation of the data of Table IV of Ref. 22 was made.) The C1 and n-C10 used in preparing mixture 1 were less pure than in other samples. In the interpolation of the data from Ref. 22, an amount of C1 was added to C1, and n-C11 to n-C10. A similar approximation was made when the equation of state (EOS) was used to compute the volume expansion (described next).

The Peng-Robinson EOS28 (PREOS) was used to compute increase in volume as a function of pressure decrease (Figs. 4 through 11). The PREOS first was adjusted to match the measured and computed bubblepoints by changing binary interaction coefficients. Then it was used to compute volumetric behavior for both the undersaturated liquid and the two-phase region. The PREOS without volume translation30 accurately predicted the gas-phase density in the two-phase region. The accuracy was verified by comparing the computed and measured values of gas density from Reamer et al. Generally, liquid density predictions are not reliable with cubic EOS. Some form of volume translation30 is required to enhance the accuracy of liquid density prediction. However, the simple use of the PREOS proved to be accurate enough for the computation of volume expansion of the mixtures in Table 2. This accuracy also was verified by comparing computed values and measured liquid expansion data from Reamer et al.

The volume expansion plots of Figs. 4 through 11 (solid line) are computed from the PREOS at the appropriate temperatures. Be-

<table>
<thead>
<tr>
<th>Sample</th>
<th>L (in.)</th>
<th>d (in.)</th>
<th>φ (%)</th>
<th>( V_r ) (in.3)</th>
<th>k (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berea</td>
<td>19.45</td>
<td>1.54</td>
<td>22.3</td>
<td>8.07</td>
<td>605</td>
</tr>
<tr>
<td>Chalk</td>
<td>19.88</td>
<td>1.48</td>
<td>40.4</td>
<td>13.74</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**Fig. 2—Normalized distribution function vs. pore-entry radius for the Berea sample.**

**Fig. 3—Normalized distribution function vs. pore-entry radius for the chalk sample.**
TABLE 2—COMPOSITION AND BUBBLEPOINT PRESSURE DATA AT 100°F

<table>
<thead>
<tr>
<th>Number</th>
<th>Mixture</th>
<th>Composition</th>
<th>Bubblepoint Pressure (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>This Study</td>
</tr>
<tr>
<td>1</td>
<td>C₁₂</td>
<td>28.52%/C₇₂</td>
<td>1,056</td>
</tr>
<tr>
<td>2</td>
<td>C₁₂, 65.14%/C₇₂</td>
<td>0.22%/n-C₁₀, 94.36%</td>
<td>3,029</td>
</tr>
<tr>
<td></td>
<td>n-C₁₁₂</td>
<td>0.34%</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>C₁₂, 29.84%/C₂₀</td>
<td>0.02%/n-C₁₀, 70.00%</td>
<td>1,121</td>
</tr>
<tr>
<td>4</td>
<td>C₁₂, 65.66%/C₂₀</td>
<td>0.05%/n-C₁₀, 34.36%</td>
<td>3,038</td>
</tr>
</tbody>
</table>

cause in the two-phase region the vapor and liquid pressures are assumed to be equal, the supersaturation is zero. The effect of rock expansion also is included in the computed volume expansion plots. As stated earlier, the bulk of the fluid system was inside a temperature-controlled cabinet, while the pump and some connections were in a temperature-controlled room. During the test periods for all tests, the fluid in the pump and connections in the room was at a pressure above its bubblepoint. The computed expansion data of Figs. 4 through 11 reflect the state of fluids both inside the cabinet and in the room.

In relation to Table 2 data, it should be emphasized that bubblepoint pressure is sensitive to the composition. A small variation in the amount of C₁₂ from 30.50 to 30.02 mol% gives a bubblepoint pressure of 1,108 psia instead of 1,122 psia (at 100°F). Because accurate knowledge of the bubblepoint is necessary to estimate supersaturation, special attention was given to measuring the bubblepoint pressure. A dead-weight tester was used in all measurements. The bubblepoint pressure data are accurate within ±2 psi of the values listed in Table 2. The composition data are based on the GOR of separation test and therefore may not have the same degree of accuracy as the bubblepoint. However, with an accurate bubblepoint pressure, we feel confident in using the composition data in Table 2 to compute both the bubblepoint pressure at temperatures close to 100°F and the volumetric expansion.

**Results**

Using rock samples from Table 1 and mixtures from Table 2, we conducted a number of experiments. The rate of expansion was controlled by setting the pump at a constant withdrawal rate. The experiment results for the Berea sample are given first; the chalk sample experiment results follow.

**Berea Experiments.** The Berea and chalk samples were used for two different fluid mixtures. At bubblepoint pressure and 100°F, Mixtures 1 and 3 have a ϕ of about 13 dyne/cm, and Mixtures 2 and 4 have a ϕ of 2.1 dyne/cm. The ϕ difference allows examination of the influence of this parameter on the critical gas saturation and supersaturation. The runs with Mixtures 1 and 3 are designated high-ϕ experiments; Mixtures 2 and 4, low-ϕ experiments.

**High-ϕ Experiments.** Duplicate runs with Mixture 1 at a pump withdrawal rate of 0.088 in.³/D were conducted. Fig. 4 shows the results. The fluid pressure was initially about 2,000 psia for both runs. It was reduced to about 1,200 psia for the start of the tests. At this pressure, the confining pressure was set at about 1,490 psia. Table 3 gives the oven temperatures for these two and other runs. The solid line in Fig. 4 is the computed expansion behavior with zero supersaturation. The change in the slope of the line at 1,200 psia is caused by the accounting of rock pore volume change resulting from a net overburden pressure increase. Below a bubblepoint pressure of 1,071 psia, the same type of adjustment in volume was made (an alternative below the bubblepoint pressure would have been to adjust the pressure rather than the volume).

Comparison of expansion behavior without supersaturation and data of Runs 6 and 7 reveals that, in the undersaturated region, the measured data follow the computed expansion (as expected). Below a bubblepoint pressure of 1,071 psia, the measured data show the same behavior as in the undersaturated region. This behavior implies that the fluid in the porous medium has the same compressibility as the liquid. Only at the minimum pressure of 1,013 psia does the pressure begin to rise because of gas bubble formation. But unlike supersaturation in open space where a sharp rise in pres-

![Fig. 4—Pressure-expansion behavior of Mixture 1 for Runs 6 and 7—Berea sample.](image)
sure occurs, there may be a gradual pressure increase in the porous medium. Fig. 4 shows that the period of pressure rise is followed by a much longer period of slow pressure decline because of expansion. During expansion, gas-phase saturation increases but does not flow. Finally, as the gas-phase saturation in the rock builds up, it begins to flow. The saturation at which gas flow occurs is the critical gas saturation. The last data points in Fig. 4 (designated by open circles) correspond to the gas saturation at which the optical cell signal shows gas production. Before this, only liquid had passed through the cell. After gas breakthrough, gas and liquid flow. The amount of gas production gradually increases. All the runs with Berea showed an increase in gas production with time. Fig. 4 shows that the critical gas saturations for duplicate runs are very close. This figure also shows that, during the last test period, a constant supersaturation of about 20 psi prevails.

The volume of the gas phase before mobilization for Runs 6 and 7 are 0.085 and 0.079 in.³. These values give critical saturations of 1.4% and 1.3%, respectively. Once the gas begins to flow from the core, it moves freely to the visual cell under the influence of gravity. The reason is that gravity force exceeds the capillary force in a 0.08-in. tubing for the condition of all the experiments (for $\sigma=13$ dyne/cm, the gravity force of a gas stream 0.12-in. long exceeds the capillary force).

Fig. 5 shows the pressure-expansion data for a high withdrawal rate of 0.439 in.³/D. As in Runs 6 and 7, the initial pressure was reduced from 2,000 to 1,400 psia. From 1,400 to 1,200 psia, the net overburden pressure was manually kept constant at about 290 psi. At 1,200 psia pore pressure, the manual adjustment was stopped. As a result, below this pressure, the net overburden pressure increased slowly. The data of Fig. 5 show that a pronounced supersaturation below the bubblepoint pressure of 1,071 psia prevails. The initial supersaturation follows liquid compressibility behavior. At about 938 psia, bubble nucleation begins and the pressure rises. A gradual decrease in supersaturation continues for a while. In the last stage of the experiment, the supersaturation seems to decrease slowly. The last data point of Fig. 5 shows the saturation at which gas passes through the optical cell. The volume of gas in the core at the time of mobilization is around 0.16 in.³. The critical gas saturation for Run 8 is therefore around 2%. Fig. 5 shows that if the assumption of zero supersaturation is made, the
material-balance approach of Modaoui and Abgrall and Iffy significantly overestimates the critical gas saturation.

**Low-o Experiments.** Mixture 2 (Table 2) was used to conduct experiments with volume expansion rates of 0.088 and 0.439 in.³/D. The main purpose was to examine the influence of surface tension on supersaturation and critical gas saturation. Figs. 6 and 7 show the results for pump withdrawal rates of 0.088 and 0.439 in.³/D. Before the experiments, fluid pressure was kept at about 4,100 psi.

Fig. 6 shows the computed expansion with zero supersaturation and the measurements for a withdrawal rate of 0.088 in.³/D. The data show that the fluid remains supersaturated with no noticeable nucleation to a pressure of about 3,600 psi. At this pressure (i.e., critical supersaturation pressure) nucleation starts, but the pressure does not increase afterward. Fig. 6 also indicates that supersaturation decreases to a stage where it becomes negligible. At the onset of gas production (detected by the optical cell), the volume of gas in the core is 0.09 in.³. This gives a critical gas saturation of about 1.1 % PV. A comparison of pressure-expansion behavior of Runs 6 and 7 with Run 10 implies that higher surface tension gives a higher critical supersaturation.

Fig. 7 shows the results of duplicate Runs 12 and 14 for a pump withdrawal rate of 0.439 in.³/D. The undersaturated fluid data follow almost the same trend as the computed expansion. The difference between the data and computed values could be a reflection of a small temperature variation of the fluid with time. Bubble nucleation for both Runs 12 and 14 initiates at about 3,550 psi. This pressure is about 100 psi below the bubblepoint pressure. Because of nucleation and diffusion, the pressure begins to rise slowly. Consequently, supersaturation decreases. At later stages, there is practically no fluid supersaturation inside the rock. Critical gas saturation for both runs is around 1.5% PV.

**Experiments on Chalk.** Mixtures 3 and 4, which are similar to Mixtures 1 and 2, were used to perform high- and low-o experiments on the chalk sample. Comparison of the chalk and Berea sample test results would be of interest in examining the influence of pore structure on supersaturation and critical gas saturation.

**High-o Experiments.** Figs. 8 and 9 show the results of expansion experiments with Mixture 3. In these experiments, the fluid pressure was reduced from 1,800 to 1,500 psi to begin the tests. The pressure, dropped as a result of expansion. The pressure drop below the bubblepoint is along the extension of the liquid-phase compressibility for both Runs 17 and 18. The minimum pressure (i.e., maximum supersaturation) for Run 17 is slightly higher than for Run 18. The slight difference may be related to the expansion rate in these two runs. After the maximum supersaturation, the fluid pressure begins to increase quickly. As a result, supersaturation becomes negligible. For Run 18, where the rate of PV expansion is close to that of Run 8, the maximum initial supersaturation is higher than for Run 8. Comparison of the pressure-expansion behavior of these two runs (Figs. 5 and 9) shows that supersaturation is more pronounced for the Berea sample.

Regarding critical gas saturation, two exploratory runs, as well as Runs 17 and 18, gave different gas saturations at the point of gas mobilization. The critical gas saturations for these four runs
varied from a minimum of 0.6% to a maximum of 1.2% PV. Capillary-pressure data of the chalk sample give a capillary threshold height higher than the sample length. Therefore, one may speculate that boundary effects may interfere with development of critical gas saturation. This point is under investigation and will be dealt with in a forthcoming publication.

Low-pressure experiments. Mixture 4 was used to conduct the experiments at low σ on the chalk. Fig. 10 shows the expansion data at a pump withdrawal rate of 0.791 in.³/D. (As in all the previous runs, the pressure of the fluid in the core initially was dropped. The drop in pressure for this run is 300 psi.) The pressure-expansion behavior for Run 19 follows the computed liquid behavior to the bubblepoint of 3.667 psi. Below the bubblepoint, the supersaturated fluid does not behave as a liquid, which indicates that bubble nucleation may begin as the pressure drops below the saturation pressure. The degree of supersaturation also is significantly less than that of the comparable experiment on the Berea. Fig. 10 also gives the gas volume at which gas phase begins to flow. The critical gas saturation from this figure is about 0.8%. Fig. 11 shows the pressure-expansion data of duplicate Runs 20 and 22 at a pump withdrawal rate of 0.439 in.³/D. In the undersaturated region, the data closely follow the computed values. Below the bubblepoint pressure of 3.667 psi, the fluid behavior is similar to that of Run 19. The minimum pressure for the initial supersaturation for Runs 20 and 22 is about 10 psi higher than that of Run 19. This difference could be related mainly to the rate of volume expansion. The saturation at which gas begins to flow is about 0.7% and 0.6% PV for Runs 20 and 22, respectively.

A run with a pump withdrawal rate of 0.176 in.³/D also was conducted with Mixture 4. The critical gas saturation for this run was 0.6% PV. The initial supersaturation was about 10 psi.

Discussion and Conclusions

A simple experimental procedure was used to measure both the supersaturation and the critical gas saturation. A pump with a fixed expansion rate was used in all measurements. The use of a pump in the expansion mode avoids the steep pressure changes that often are associated with a pressure regulator. Other investigators used pressure regulators to control the rate of pressure decline. If steep change in pressure results from use of a regulator, one may expect higher critical gas saturation and higher supersaturation.

We did not put the pump inside the oven, and pump temperature control was a problem in some runs. In most of our experiments, there was little variation in room temperature, less than 0.5°F. In some tests, however, room temperature varied as much as 3.5°F. We had to repeat some experiments because of the temperature variation. Overall, a better temperature control both in the oven and outside (within ±0.1°F) would be desirable. This type of temperature control was a shortcoming of the experiments discussed here. Practical design considerations also necessitate a certain amount of dead space in the pump when the piston is at the top position. If the pump is in the oven, the formation of the gas phase may complicate the interpretation of the data. This type of complexity was avoided in our experiments.

An in-depth analysis of supersaturation will be presented in a forthcoming publication. However, we can draw the following conclusions from the experiments reported in this paper.

1. Supersaturation in a porous medium of the type used here is a stable process. Duplicate runs give similar supersaturation behavior, and a sudden rise in pressure does not occur at the initial maximum supersaturation.

2. Some of our experiments indicate that, even at high expansion rates in the laboratory, supersaturation in porous media could become negligible. This contradicts early works,8,10,14 which imply that supersaturation may not be only a laboratory phenomenon but could exist even in petroleum reservoirs.

3. Pore structure could significantly affect the degree of supersaturation. The supersaturation in a porous medium with small grains may be less than in a porous medium with large grains. Initiation of bubble nucleation (critical supersaturation) also might be different in different porous media.

4. The critical gas saturation could be related to both supersaturation and pore structure. As supersaturation decreases, critical gas saturation also decreases. A similar conclusion could be drawn from the Moule and Longeron20 experiment.

5. Critical gas saturations of this work are lower than data reported in the literature. For some experiments on the chalk sample, critical gas saturation is around 0.5%. Saidi21 also discusses field evidence of low critical gas saturation.

Nomenclature

\[ A = \text{surface area of a bubble, } L^2, \text{ in}^2 \]
\[ d = \text{diameter, } L, \text{ in.} \]
\[ k = \text{permeability, } L^2 \]
\[ L = \text{length, } L, \text{ in.} \]
\[ V_p = \text{poro volume, } L^3 \]
\[ \phi = \text{porosity, } \% \]
\[ \sigma = \text{surface tension, mN/m} \]

Acknowledgments

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References


**SI Metric Conversion Factors**

\[
\text{dyne/cm} \times 1.0^+_{\text{T}} = \text{mN/m} \\
\text{in.} \times 2.54 = \text{cm} \\
\text{in}^2 \times 6.4516 = \text{cm}^2 \\
\text{in}^3 \times 1.638706 = \text{cm}^3 \\
\text{md} \times 9.869233 = \text{μm}^2 \\
\text{psi} \times 6.894757 = \text{kPa}
\]

*Conversion factor is exact.*

SPEFEE