Reply to Discussion of Measurements of Supersaturation and Critical Gas Saturation

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We fail to see the validity of this discussion. However, we hope our response will clarify some misconceptions of Saidi and in the literature on the subject of critical gas saturation in porous media. We divide Saidi’s discussion into two main propositions.

1. Initial gas flow in a core during depressurization is caused by the flow of gas bubbles from the top of the core. This may be different from the bulk-gas flow, therefore, the critical gas saturations reported in Ref. 1 may be too low.

2. Material balance (based on the equilibrium criterion) should be used to calculate gas saturation and critical gas saturation. Supersaturation has a negligible effect on gas saturation.

Propositions 1 and 2 are false, and we reject them unequivocally. In the text, we briefly state the physical principles of gas evolution in porous media and discuss the invalidity of these propositions.

When the pressure of an undersaturated (i.e., compressed) liquid decreases below bubblepoint pressure at constant temperature, the driving force for new phase formation is the chemical potential difference of components between the gas and bulk-liquid phases. Therefore, the liquid should be supersaturated to create a new gas phase. Supersaturation is defined as \( S_{\text{eq}} = p - p_b \), where \( p_b \) is equilibrium pressure and \( p \) is liquid-phase pressure. We define critical supersaturation pressure as the pressure where a detectable volume of new gas phase would form. Among other factors, the critical supersaturation pressure, \( p_{\text{cs}} \), would depend on the pressure-decline rate (Ref. 2 has a detailed discussion). In laboratory pressure-depletion experiments of an initially undersaturated oil in a core, \( 1 - p_b/p_0 \) (\( p_0 \) = bubblepoint pressure) would be greater than zero. Its value depends on the pressure-decline rate, oil type (i.e., surface tension), and reservoir medium type. For practical low laboratory rates (for \( p_b = 500 \) psi), \( p_b - p_{\text{cs}} \) could vary from 20 to 100 psi only because of rate. After the gas-phase evolution, supersaturation generally decreases, but the liquid phase could be supersaturated even after the gas flow.

In a recent theoretical study, we demonstrated that the gas-phase evolution in porous media for laboratory conditions, and maybe even at field scale, is an instantaneous nucleation process. At critical supersaturation pressure, a limited number of gas bubbles would form in the core. Because the supersaturation at the time of gas-bubble formation is at least one or two orders of magnitude more than the hydrostatic pressure variation in a 6- to 24-in. core, the hydrostatic pressure is not expected to affect gas-bubble distribution. The low-pressure drop across the core caused by flow from supersaturated liquid expansion also has a negligible effect. Therefore, gas bubbles will be distributed across the core length and will grow mainly by diffusion (in light oils). Gas is not produced during the initial stage of bubble growth. As a result of bubble growth, a gas saturation is reached, at which gas flow occurs. Gas will not flow continuously from the core as Saidi suggests. It is a discontinuous process.

We reject Saidi’s concept that initial gas flow in a core during depressurization is caused by the flow of gas bubbles from the top of the core. This proposition is in line with neither the theoretical model described in Ref. 2 for gas-phase evolution and growth nor with our recent laboratory measurements. In our experiments on supersaturation and critical gas saturation, \( S_b \), we observed a few gas bubbles early in the experiments, but these bubbles were easily distinguishable from massive gas flow from the core. The initial few bubbles were from the dead space above the core, not from the top of the core.

We currently are investigating the solution-gas-drive process in light- and heavy-oil reservoirs using a high-pressure visual core holder to observe the evolution, growth, and pattern of gas production. New measurements in the visual core holder reconfirm our previous work that critical gas saturation for light oils is in the range of 0.5% to 2%. The current visual experiments also reveal that isolated gas bubbles do not leave the top of the core. A filament of gas stream composed of hundreds of bubbles flows out of the core at discrete intervals. We will publish the results soon.

Regarding Proposition 2 of the discussion, we refer to Fig. R-1, prepared from data in Ref. 1. The solid line represents the equilibrium condition between gas and liquid phases. The intersection between the solid line and the dashed line represents \( p_b \). The PVT of the Berea sandstone in which the two tests were performed was \( \approx 123 \) cm\(^3\). The last data points for the low-expansion- and high-suspension-rate tests represent the point of gas flow detected by the optical cell signal. There is significant supersaturation for both tests, particularly the high-rate test. If one uses material balance as Saidi advocates, the gas-phase volume would be about 5.0 cm\(^3\) for the high-rate test. This gas volume is designated by \( V_{\text{gas}} \) in Fig. R-1. The true value of the gas is, however, \( \approx 2.6 \) cm\(^3\) (i.e., \( V_{\text{gas}} = 2.6 \) cm\(^3\)). Therefore, the critical gas saturation from material balance would be about twice the true value when supersaturation is accounted for; critical gas saturation, \( S_{\text{eq}} \), from material balance is \( \approx 3.8 \% \), whereas the true value is close to 2%.

We suggest that some of the reported critical gas saturation data in the literature are overestimated because supersaturation was neglected. To avoid the error resulting from material balance (i.e., equilibrium assumption), one must have a knowledge of supersaturation. Note that, in Fig. R-1, we assumed that the volume of the liquid phase was equal to the initial liquid volume at bubblepoint pressure. This assumption introduces a negligible error in \( S_b \) because of the large difference between methane density as a gas and apparent methane density in the liquid phase. Gas volume data of Ref. 1 are, therefore, very accurate—within \( \pm 0.03 \) cm\(^3\).

In addition to the two main propositions, Saidi makes a number of other comments. Some of his suggestions and points follow.

1. Measurement of GOR by a separator and a pressure-decline rate of 1 psi/day are appropriate for critical gas saturation measurements. We stated in Ref. 1 that the use of a pump in the expansion mode avoids steep pressure changes often associated with a regulator. In older experimental setups, such pressure changes may have been difficult to notice. Even good logging systems may not detect such pressure fluctuations. Only rapid analog pen plotters may be able to register pressure fluctuations. To avoid pressure fluctuations that affect critical gas saturation, we purposely used a pump in place of a regulator.

2. Field pressure-decline rates are not practical in laboratory studies. A pressure-decline rate of 1 psi/day may not be practical, particularly if one begins with an undersaturated fluid with a pressure \( \approx 50 \) to 100 psi above bubblepoint. We need a theoretical understanding of gas-phase formation and the solution-gas-drive process to interpret laboratory results. Refs. 2 and 3 present our theoretical work in this area. This work makes an important contribution to the theory of the initial stages of gas evolution in porous media: however, a general model for bubble growth in porous media for light and heavy oils, critical gas saturation, and gas mobility has not been developed.

3. Bulk gas flow usually occurs when pressure decreases to \( \approx 20\% \) to 25\% below \( p_b \). If Saidi is suggesting that bulk-gas flow should correspond to gas saturation when pressure declines to 20% to 25% below \( p_b \), then he is in error. As we have stated, we reject the notion of bulk-gas flow. For our experiments, at pressures 20% to 25% below \( p_b \), 15% to 20% gas saturation will be realized. Saidi appears to suggest that critical gas saturation for the rock and fluid systems used in our work should be 15% to 20%. These very high values for the rock/fluid systems used in Ref. 1 have already been rejected (typical values for the conditions of our tests are 0.5% to 2%).

SPE Formation Evaluation, June 1994
3. The effect of oil-pressure variation on gas saturation (correction for mean hydrostatic pressure), volume correction of apparatus during pressure decline, and PVT inaccuracy should be taken into account. The effect of hydrostatic pressure on gas saturation in all the experiments of Ref. 1 is negligible. The maximum variation of hydrostatic head is ≈ 0.5 psi. This small pressure variation when compared with 1,000- and 3,500-psi pressures (the pressures at which experiments were performed) has very little effect on gas saturation (<0.03%). The volume correction for expansion has been accounted for; however, it is small. We are not sure what Saidi means by PVT inaccuracy. Bubblepoint pressures were measured accurately. The expansion below bubblepoint was calculated from the equation of state accurately. Gas volume is also very accurate.

4. What is the effect of the pressure-decline rate on $S_o$? All the tests except one (Run 17) showed an increased critical gas saturation with an increase in volume-expansion rate. Therefore, the general conclusion is that the value of the critical gas saturation increases with rate. The explanation for Run 17 is provided in Ref. 1. The data of Moulu and Longeron* show a similar rate effect on critical gas saturation. There is no contradiction on the effect of rate on critical gas saturation in Refs. 1 and 4.

Saidi's other comments, such as references to our own and others' work, are either inaccurate or speculative. Conclusion 2 from Ref. 1 states that for some rock-fluid systems, supersaturation could be negligible. We did not offer a conclusion on the influence of surface tension on critical gas saturation. We used others' conclusions in the introduction of Ref. 1 and avoided unjustified interpretations.

References


SI Metric Conversion Factors

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