Discussion of Measurements of Supersaturation and Critical Gas Saturation

SPE 27920

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In "Measurements of Supersaturation and Critical Gas Saturation" (*SPE Formation Evaluation*, Dec. 1992, Page 337) Firoozabadi *et al.* reported that several expansion solution-gas-drive experiments at pressure-decline rates much higher than usually occur in actual reservoirs terminated "at the onset of gas production." For this reason, they neither envisaged a gas/oil separator for measuring the GOR evolution, which is an important parameter for establishing critical gas saturation, S_{gc}, nor allowed sufficient pressure decline to measure the evolution of upward gas migration to confirm their low measured S_{gc}. This confirmation was needed because their results contradict those of Dumoré,[1] Madaoui,[2] and Moulu and Longeron.[3]

Firoozabadi *et al.*'s comments on previous investigations are not quite correct and are somewhat misleading. For example, they say "Dumoré reported only mean free-gas saturation but not the saturation at which the gas began to flow." Dumoré published only part of the research on this subject by the Iranian oil industry. From the shots taken between S_g=0.9% and 7.1% (1×10^{-5} kPa · sec) and S_g larger than 4.4% (1×10^{-6} kPa · sec) (in Dumoré's Fig. 4) and the straight-line parts of his Fig. 3, one can estimate the S_{gc} for the two visual experiments on a 0.35-md pack. Similar observations can be made for runs with bubblepoint pressures, p_b, of 60, 100, and 200 kPa (his Fig. 8) (**Fig. D-1** shows the first two).

Madaoui[2] plotted the measured GOR during the experiment, whereas Dumoré[1] measured the produced GOR's but did not report them. Fig. D-1 gives the results of these experiments.

The figure shows a supersaturated period up to a $(p_b-p)/p_b \approx 0.036$ with a smaller calculated S_g than that calculated when the supersaturation had almost disappeared. The supersaturation decreased to a small value as the pressure decreased to about $(p_b-p)/p_b$=0.1 because of a massive dispersed-gas breakthrough. The bulk-gas breakthrough took place at about $(p_b-p)/p_b$=0.22 at S_g=10%, 0.2 at S_g=10%, and 0.3 at S_g=14% for Bentheim sand with p_b=60 kPa, Fontainebleau sand with p_b=141 kPa, and Bentheim sand with p_b=100 kPa, respectively.

The large change in measured GOR also clearly indicates that the dispersed gas began to move when saturations reached the above-mentioned values. After bulk-gas breakthrough, the p/S_g straight line tends to bend. The Dumoré[1] and Madaoui[2] experiments indicate that gas breakthrough usually occurs when pressure decreases 20% to 25% below the initial oil bubblepoint pressure. Firoozabadi *et al.* stopped their experiments at a 5% pressure drop below their initial oil p_b, and they were not equipped with a separator to measure the actual produced GOR. Therefore, they were unable to measure the bulk-gas breakthrough.

Firoozabadi *et al.* also state, "Dumoré's main conclusion was that the amount of free-gas saturation depends on capillarity." Dumoré said, "it was shown that dispersion conditions depend not only on the capillary pressure, but also on the value of (r_2/r_1-1), which is related to the structure of the permeable medium," where r_2 and r_1 are pore radii of neighboring pores. "Structure" would also mean pore-size distribution; i.e., a lower-permeability sample with a more-uniform pore-size distribution favors a gas-dispersion condition more than a higher-permeability sample with a poor pore-size distribution. For example, a sample with only one pore size develops dispersion under any condition irrespective of its permeability because there is an equal chance for each pore to have the first nucleation. We also see this process when Firoozabadi *et al.*'s Figs. 5 and 8, which have similar interfacial tensions (IFT's) and about equal pressure-decline rates, are compared. The chalk sample (Fig. 8), with k/ϕ=6.75 md but a more-uniform pore-size distribution, developed dispersion rapidly, whereas the Berea sample (Fig. 5), with k/ϕ=2710 md and a wider pore-size distribution, showed much less dispersion with 1.38 MPa supersaturation pressure.

The Dumoré experiments also show that, at a low pressure-decline rate and a high IFT in usual reservoir rocks, the Muskat[4] solution-gas-drive theory fails to predict the correct S_g during pressure depletion. Whereas, at high dp/dt and low IFT, the Muskat solution-gas-drive theory would predict the measured gas saturations. Assuming that the calculated S_{gc} of Firoozabadi *et al.* at low IFT and high dp/dt is correct means that the Muskat solution-gas-drive theory also is not applicable at high dp/dt and low IFT.

Firoozabadi *et al.* say that "all the data of Madaoui[2] were based on the assumption of zero supersaturation." Such an interpretation could be based on the observation that Madaoui's measured S_{gc} are much higher than those calculated from their own experiments. Madaoui, however, did not measure a quantifiable supersaturation pressure at the bulk-gas breakthrough. Therefore, he did not need to include supersaturation pressure in this calculation. Firoozabadi *et al.* also say that "Madaoui's critical gas saturation data varied from 4.4% to 26.4%." This statement needs clarification. Madaoui, who primarily used samples with connate-water saturation, measured S_{gc}, which varied from 2.4% to 17% if the experiments with the C_1 through C_4 mixture are excluded. These S_{gc} saturations are well within the saturation range Dumoré[1] and Moulu and Longeron[3] measured.

In the Dumoré visual and high-pressure experiments and all the experiments of Madaoui[2] and Moulo and Longeron,[3] some premature gas bubbles were produced in a discontinuous manner. Madaoui,[2] however, noted this and gave an example of some premature gas-bubble production while the produced GOR was still declining (his Fig. 16). In discussing the issue with Longeron,* he confirmed detection of premature gas bubbles during depletion through a gas-detecting device placed above the sample before the bulk-gas breakthrough was observed. Visual examination of Dumoré's Figs. 5 and 6 clearly shows nucleations also took place at the top of the visual glass-bead packs at the early gas-development stage with S_g<1.5%. Therefore, the possibility exists that some gas bubbles were released from the top of the samples reported by Firoozabadi *et al.* during the early gas nucleations. Thus, one of the main issues that Firoozabadi *et al.* failed to establish was whether the measured S_{gc} "at the onset of gas detection" corresponded to the bulk-gas breakthrough or concerned premature gas bubbles released from the top of their core samples or from the dead volume above the samples. If gas release was from the last two sources during early pressure depletion, then the onset-of-gas-detection method could easily indicate gas breakthrough with a much smaller S_{gc} than the real values.

It appears that Firoozabadi *et al.* calculated S_{gc} simply by dividing volume expansion by the original oil in place (OOIP) and not through a material-balance calculation. For example, S_g=1.5% in Run 12 (or Run 14) closely corresponds to the produced oil divided by the OOIP (1.28/132.25=0.0150), which makes it appear that they did not use material balance to calculate S_g. Therefore, the factors they did not account for include (1) the effect of the oil-pressure variation on gas saturation (i.e., $p_o=p_g+C$, where C is the correction for the mean hydrostatic pressure in the core sample); (2) oil volume in the apparatus outside the core sample affected by pressure drop; (3) the volume correction for expansion of the apparatus during pressure decline; (4) gas release from live oil in the dead volumes as pressure decreased below the initial bubblepoint pressure; (5) outside temperature variation during different runs; and (6) volume changes of free-gas space. Dumoré used a differential measuring device composed of two identical vessels and kept the gas/oil contact just above the core, while gas pressure was decreased at a constant prescribed rate. In this manner, errors [including those caused by Points 2 through 5, the problem with PVT inaccuracy, and

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*Longeron, D.L., personal communication, Feb. 1993.

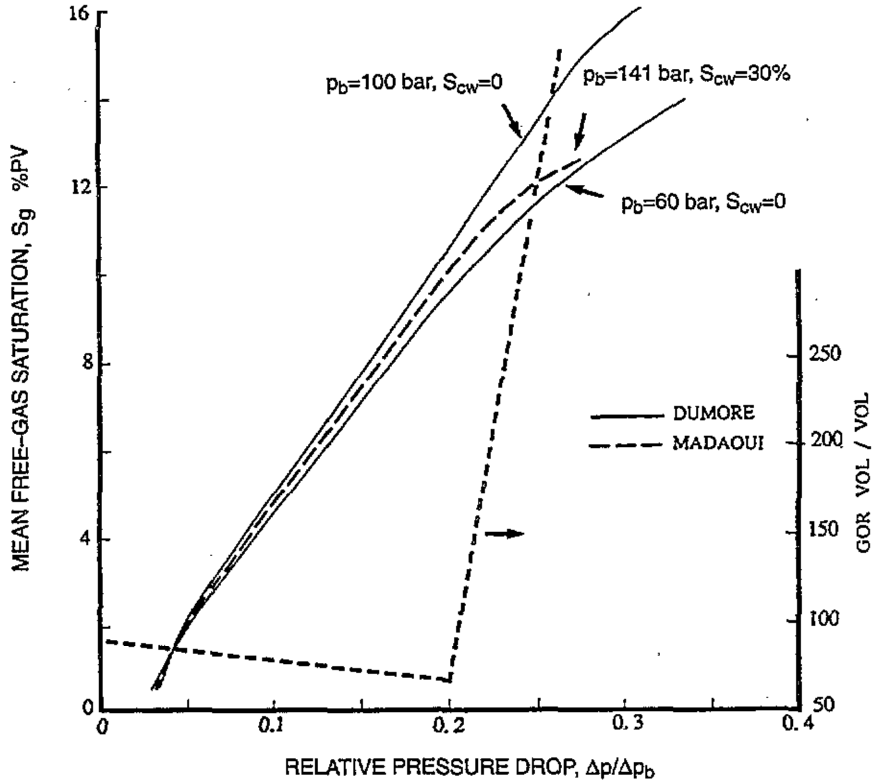

Fig D-1—Mean free-gas saturation as a function of relative pressure drop for a Benthein-sandstone core (Dumore[1]) and a Fontainbleau core (Madaoui[2]). (Pressure-decline rates are 8 × 10^{-5} bar/sec and 3.1 × 10^{-5} bar/sec, respectively.)

gas development in the dead volume (outside core)] were eliminated.

It would have been ideal to see experiments performed at a dp/dt below 6.89 kPa/d to resemble actual field performances. However, the Firoozabadi *et al.* setup was restricted by the minimum pump withdrawal rate of 1.44 cm^3/d. Therefore, their apparatus does not appear to be designed to measure the solution-gas-drive process fully under the usual field pressure-decline rates and material balance does not appear to have been used to calculate the gas saturation in the samples correctly during the experiments.

On the basis of their Runs 7 or 8 (high IFT) and Run 10 (low IFT), Firoozabadi *et al.* conclude that "a lower IFT gives a higher S_{gc}." Contrary to these runs, however, Runs 17 and 18 (high IFT) gave a higher S_{gc} than Runs 19 and 20 with a lower IFT. These two sets of experiments with similar rock and dp/dt show a similar S_{gc} difference of about 0.2% (but in opposite directions).

Firoozabadi *et al.* say that "supersaturation in porous medium of the type used here is a stable process." Their measured supersaturation lasted for a few hours in most of their runs with a total pressure drop of less than 6% of the initial bubblepoint pressure. If Runs 6 through 8 had continued for a longer time, a negligible supersaturation pressure would have been measured. Therefore, it is unclear how such a statement can be valid when the short runs show a vanishing supersaturation pressure.

They also say that "the supersaturation with small grains may be less than in a porous media with large grains" (larger pores). Dumoré's[1] experiments and theoretical development of this process[5] are contrary to such conclusions because dispersion develops more easily in larger pores than in smaller pores.

Firoozabadi *et al.* indicate that "the critical gas saturation could be related to both supersaturation and pore structure." Except for Runs 6 through 8 (with a short history), all other runs show a negligible supersaturation pressure. Therefore, it is not obvious how these parameters could be related.

They also say that "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." The two cores used in their studies had almost the same dimensions; therefore, it is unclear how length effect was studied. For example, Runs 19 and 20 have the same rock/fluid system with a 1.4-dp/dt ratio and physically gave the same gas saturation (0.8% and 0.7%, respectively). Runs 10 and 12, which showed a larger gas saturation difference (1.1% vs. 1.5%), could still be within the experimental error with the corrections that were unaccounted for when Run 12 was terminated with about 0.24 MPa lower pressure than Run 10. It is unclear how the effect of IFT or pore structure can be studied under these conditions.

Runs 17 (low dp/dt) and 18 (high dp/dt), with high IFT fluid and a chalk sample, gave gas saturations of about 1.2% and 0.6%, respectively. That is, a slower depletion rate gave a higher S_g. During all the other runs, faster withdrawal rates gave larger S_g.

Such results indicate that the Firoozabadi *et al.* concept of assuming that the detection of the first gas bubble at the top of the core sample represents the beginning of bulk-gas movement and their method of measuring and calculating S_{gc} may not be a reliable approach for estimating S_{gc}. In addition, conclusions cannot be drawn from their reported experiments about the influence of rate, IFT, pore structure, and length effects on S_{gc}.

References

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SI Metric Conversion Factors

in.^3	× 1.638 706	E+01 = cm^3
psi	× 6.894 757	E+00 = kPa

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