EXPERIMENTAL INVESTIGATION OF PVT PROPERTIES OF FOAMY OIL

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ABSTRACT

Investigating the properties of live heavy oil, as the pressure is dropped from the original reservoir pressure to ambient pressure, can aid in interpreting and simulating the response of heavy oil reservoirs undergoing primary production. Foamy oil has a distinctly different and more complex behavior compared to conventional oil as the reservoir pressure depletes and the gas leaves solution within the oil. Solution gas separates much more slowly from the oil, thus conventional PVT measurements are not trivial to perform. In this paper, we present novel experiments that utilize x-ray CT scanning and low field NMR techniques. These non-destructive tomographic methods are capable of providing unique in-situ measurements of how oil properties change as pressure depletes in a PVT cell. Experiments were initially performed at a slow rate, as in conventional PVT tests, allowing equilibrium to be reached at each pressure step. These results are compared to non-equilibrium tests, whereby pressure declines linearly with time, as in core flood experiments. The findings presented in this work lead to interesting insights into the unique nature of foamy oil, and valuable data for predicting foamy oil properties.

EXPERIMENTAL METHODOLOGY

A slow expansion of live oil experiment was performed by expanding a piston cylinder using an ISCO pump. Huerta *et al*. (1996) have shown that after 24 hours the pressure did not change appreciably, thus in these experiments a volume increment was withdrawn once daily. CT and NMR measurements were performed on the pressure vessels before and after the water volume was removed. There was no mixing of the live oil sample, in order to see the gas trapping by the oil.

A fast pressure depletion experiment was also performed. Instead of using a pump to withdraw fluid from the waterside of the piston, a backpressure regulator (BPR) was connected to the waterside, and set above the bubble point pressure. The pressure on the gas side of the BPR was reduced through a mass flow controller at a constant rate of pressure depletion. The rate of depletion for the CT scanner and NMR experiment were 2.37 kPa/min and 2.38 kPa/min respectively.

The CT scanner used was a third generation General Electric CT/i scanner and the technique used for the imaging was 120 kV and 80 mA. The resolution of measurement or the volume of each pixel for this case is 0.049 cm x 0.049 cm x 0.1 cm. The NMR used is a low field relaxometer supplied by the Ecotek Corporation, and operates at a frequency of around 1.2 MHz. NMR measurements were taken at an echo spacing of 0.3 ms, with 5000 echoes, a repolarization time of 10 sec, and 30 trains. The slow depletion

experiment took 12 minutes. In the fast depletion experiment, the data needed to be acquired much faster; therefore an echo spacing of 0.1 ms, with 500 echoes, a repolarization time of 1500 sec and 100 trains were used.

CT SCANNING OF LIVE OIL

A scout scan was used to determine the location of the oil within the piston. CT images were then taken at discrete cross-sectional slices along the length of the oil portion of the piston cylinder. CT numbers are related to the density of the bulk fluids by CT scanning various oils, water and solvents of known densities using the same scanning technique within the transfer vessel in which the experiment was performed. Therefore, a system-dependent linear equation was used to generate the liquid oil density from the CT numbers.

Gas volume is a strong function of pressure (from the real gas law); therefore after the gas volume was obtained from the CT images, the volume was corrected to ambient pressure. The remaining volume of solution gas at any pressure was then calculated by subtracting the free gas saturation, obtained from the scanned images, from the original volume of dissolved gas in the oil (known from gas/oil ratio measurements). This volume of solution gas was divided by the dead oil volume to obtain the solution gas/oil ratio as a function of pressure.

The single-phase oil formation volume factor (OFVF) was calculated from the live oil density and the dead oil density measured from CT. In this, method since the mass of the vessel is constant, the OFVF is calculated as a ratio of the dead oil density and the live/foamy oil density. All of these properties can be calculated as a function of pressure, in order to show the PVT response of live and foamy oil.

CT Results

The first gas bubble was visible at the bubble point pressure at the top wall of the vessel. After gas was first formed at the top of the vessel, gas continued to grow at this location. In the slow depletion experiment, the standard deviation within the oil remained low for the course of the experiment. However, in the fast expansion experiment, the standard deviation within the oil increased, indicating gas was also forming within the oil and rising to the top of the cylinder. Individual gas bubbles were not visible, given the coarse voxel size, until low pressures, at which point gas visibly forms within the bulk fluid.

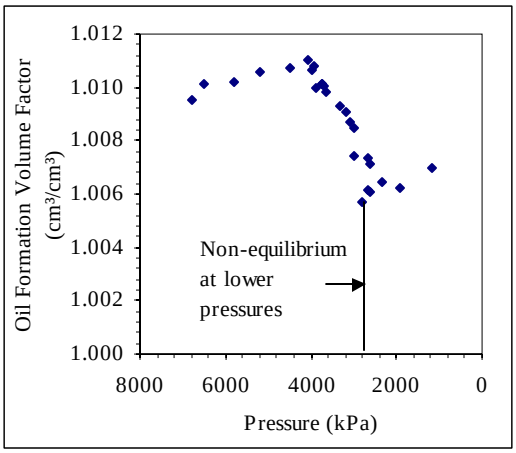

Figure 1: OFVF for slow volume expansion.

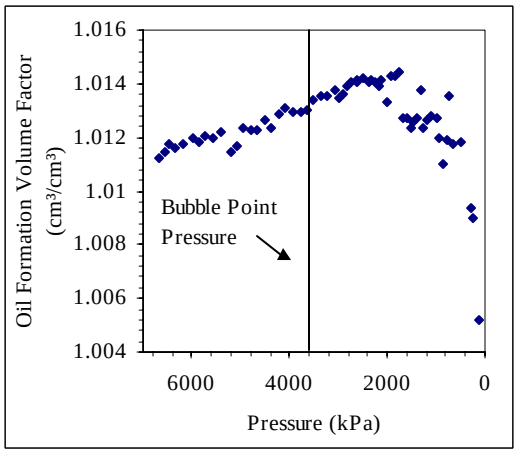

Figure 2: OFVF for fast volume expansion.

The OFVF is plotted as a function of pressure in Figure 1 and Figure 2 for the slow and fast expansion rates respectively. As pressure declines above the bubble point, the single-phase OFVF increases. This indicates that the oil volume is expanding, but the gas remains dissolved. Below the bubble point the OFVF declines; the oil is becoming less compressible as the free gas is formed. Below 2769 kPa for the slow expansion experiment the volume was expanded quickly in several large steps. The increase in the volume expansion rate results in a corresponding increase in the OFVF curve. This shows that the high depletion rate caused the oil volume to expand with the gas remaining within the oil. The behaviour at high depletion rates demonstrates the extended gas trapping within the oil. As shown in Figure 2, supersaturation delays the decline in the OFVF until the pressure is 2200 kPa when the oil is expanded rapidly. After this point the OFVF declines quickly. The OFVF in the fast depletion experiment is much more noisy once gas starts leaving solution, compared to the slow expansion experiment. This also demonstrates the gas separation from heavy oil.

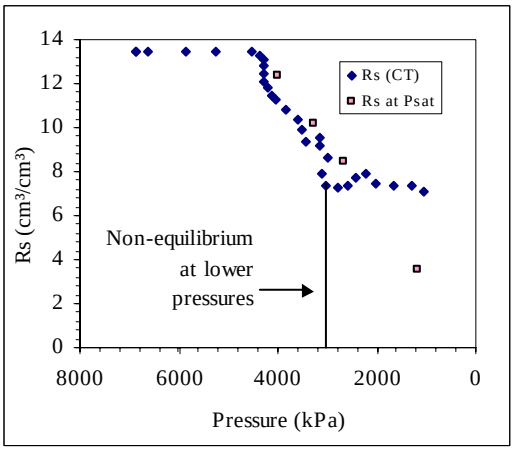

Figure 3: Solution GOR for equilibrium test.

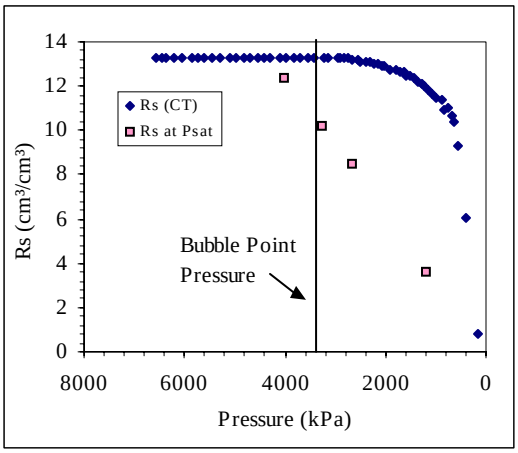

Figure 4: Solution GOR for fast depletion test.

The solution gas/oil ratio, R_s, measured from CT scanning as gas formed with declining pressure is plotted in Figure 3 and Figure 4. Also, in Figure 3 and Figure 4 the solution gas oil ratio measured as gas was dissolved in the oil at different saturation pressures is shown. For the slow depletion, the gas in solution declines somewhat linearly below the bubble point and matches the measured saturation pressures. This demonstrates that the CT scanning techniques can be used to measure the solution gas/oil ratio. Beyond 2769 kPa in Figure 3, the solution gas/oil ratio measurements were non-equilibrium; as a result of the rapid expansion the gas remains trapped within the oil. The rapid expansion test (Figure 4) shows that there is a delay until far below the bubble point before the solution gas/oil ratio starts to decline due to supersaturation. At these higher depletion rates, gas also cannot leave solution from the oil as quickly, which explains the non-linear trend observed.

What is unique about the CT results is that they have been measured in-situ and in 3D, along the entire length of the piston cylinder. This data was all gathered during the same CT experiment, and the numbers presented are averaged over the entire length of the cylinder. This should therefore be more statistically valid than measurements obtained only at the window of a PVT cell. Additionally, CT imaging has yielded information that cannot be readily obtained in conventional PVT studies. For example, for fast depletion rates below the bubble point, free gas is present within the oil, not just in the upper regions of the cylinder. The effect of performing experiments at a constant depletion rate, as compared to slow volume increment pressure decline, is seen in the shape of the oil PVT properties before and after the release of gas. While endpoint values (*ie.* above the bubble point and close to ambient pressure) are similar in both sets of experiments, the PVT properties respond differently. When the pressure is declined rapidly, changes in the OFVF and solution gas/oil ratio are delayed due to supersaturation and slow gas liberation from the oil.

NMR MEASUREMENTS OF HEAVY OIL

Above the bubble point pressure, gas is fully dissolved in the oil; therefore the oil behaves as a single-phase fluid and its viscosity can be measured using a capillary or cone and plate viscometer. Once gas leaves solution, however, oil and gas will flow as a two-phase, highly compressible mixture, meaning that the viscosity predicted using a capillary viscometer is no longer accurate. Since NMR measurements do not require the oil to be flowing, this technique is valid for both dead and live oil analysis. In this manner, NMR can be used to determine the liquid viscosity of oil as pressure declines and free gas is formed.

NMR Model

Measurements of dead oil viscosity were made using a Brookfield cone and plate viscometer for comparison at several temperatures. The oil measured in this study was the same heavy oil used for the CT scanning PVT experiments. The live oil viscosity was measured above the bubble point using a capillary viscometer at 30°C. Oil samples were heated and measured in the NMR to obtain the spectra at the same temperatures as the

measured viscosities. In performing these measurements it was realized that the NMR borehole is at a constant temperature of 30°C. Therefore experiments within this machine occur at 30°C not at 23°C. As a result, the CT scanning results measured at room temperature cannot be directly compared with the viscosity results from the NMR. However, the trends with declining pressure can still be compared.

Bryan *et al*. (2005a and 2005b) used a correlation between RHI and T_{2gm} to predict the RHI and from this the in-situ viscosity. Since the RHI is essentially predicted as a non-linear function of T_{2gm}, this work takes a more direct approach. The oil T_{2gm} results obtained at the different temperatures from the NMR spectra are directly plotted with the viscosity measured in the viscometer to develop a polynomial. The assumption made in using this oil viscosity model to predict live oil viscosity is that the effect of dissolved gas on the oil viscosity is the same as that of temperature (i.e. oil containing solution gas at elevated pressures behaves similarly to less viscous oil at ambient pressures). This assumption can be validated using Eyring's theory of liquid viscosity. When gas is dissolved into the oil, the gas effectively causes the oil molecules to separate further from one another, giving the same effect as increased temperature. In this manner, oils containing dissolved methane behave similarly on a molecular level to lower viscosity oils at ambient pressures, and the dead oil NMR viscosity model can be used to predict live oil viscosity. In this approach, therefore, the oil T_{2gm} is obtained from the spectra and the viscosity is calculated from the correlation (Goodarzi, 2006).

NMR Results

The NMR viscosity model was tuned using four points at different temperatures for dead oil. In order to improve the accuracy of the model, more points should be measured. Figure 5 demonstrates that above the bubble point the viscosity is essentially constant at the measured live oil value, while below the bubble point the viscosity increases.

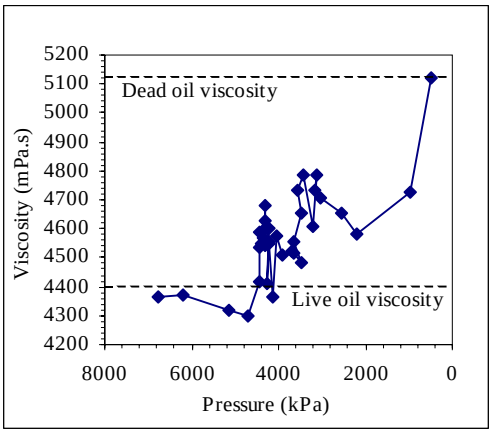

Figure 5: Viscosity for slow expansion.

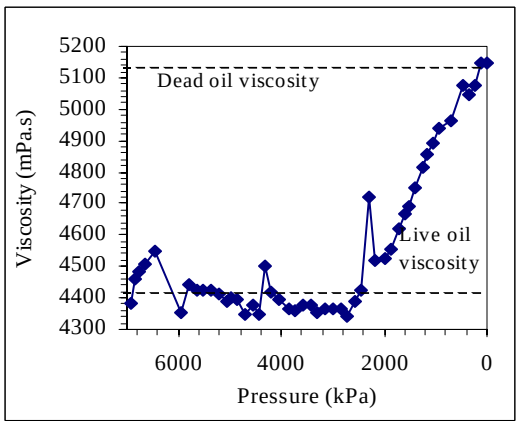

Figure 6: Viscosity for fast expansion.

Directly below the bubble point there is considerable scatter in the viscosity data for the slow depletion. This could be due to several reasons. The NMR was calibrated before measurements were run each day. This involved removing the oil sample holder and then calibrating the imposed magnetic field to the volume of the standard sample. The sample volume of the NMR vessel used in the experiment was larger than the volume of the standard, possibly affecting the results. Nevertheless, this calibration was performed every day so this effect should be the same for all of the measurements. The most likely reason for the scatter in the measurements is the noise in the machine from day to day. Sometimes it would take several attempts for the machine to calibrate to a reasonable range of amplitude while other days calibration was much smoother. This indicates that the machine was not operating at the same degree of stability over the entire experiment. NMR machines also are affected by ambient electrical or radio-frequency noise in the atmosphere and the artifacts in the data could be the result of this. In addition, these machines are most stable when they are constantly in use; in this case the machine was left idle and run only once a day. In the fast depletion experiment, the machine was run frequently, and the data from this experiment were much less noisy.

Despite the noise in the data, they seem on average to follow the conventional trend in that below the bubble point, viscosity increases somewhat linearly with decreasing pressure. At pressures approaching ambient pressure, when most of the gas has finally left solution (according to Figure 5) the oil viscosity increases much more rapidly towards the dead oil value.

Similar behavior is observed in Figure 6, for the constant pressure depletion rate experiment. Figure 6 shows that several of the data points spike above the average trend. These deviations coincided with when the machine was calibrated. During calibration, minute changes to the magnet frequency are made to optimize the signal from the volume of the standard sample. When the measurement volume is considerably different, the internal software settings shift again in order to capture this signal. Running the calibration therefore led to scatter in the data, as was seen during the equilibrium experiment. In general, however, the NMR data is considerably smoother in the fast pressure depletion experiment, when the machine was run continuously.

Figure 6 shows that the oil viscosity remains fairly constant until 2552 kPa for the rapid expansion experiment, and below this pressure the viscosity starts to increase linearly with declining pressure. The results of this experiment indicate that even at pressures well below the bubble point, the liquid oil viscosity is not significantly greater than that of the live oil. The results from the equilibrium and fast depletion experiments are similar, except that the fast depletion results are shifted to lower pressures due to the supersaturation effect. If viscosity remains low while the differential pressure in the system increases, this will result in accelerated oil rates and recovery.

DISCUSSION

At this point, the data seems to indicate that during the foamy oil period of primary production in heavy oil reservoirs, the slow gas liberation from the oil keeps the oil viscosity close to that of the live oil value. Calculating the oil viscosity from NMR data provides a measurement that only includes the molecular properties of the liquid oil, instead of externally generating a shear rate. This may provide a more accurate description of the oil viscosity behaviour. However, at this point the viscosity results can only be considered an estimate because there is no way to validate the numbers independently.

The results presented in this work demonstrate that some PVT properties can be measured using CT and NMR techniques. This is important since the PVT properties of the oil are necessary for any field simulation. In addition, measurements of the OFVF and solution gas/oil ratio obtained in slow depletion PVT experiments appear to be qualitatively different from the values measured for the fast depletion PVT results. In the fast depletion experiment, all changes in the fluid properties are shifted to lower pressures due to supersaturation. Therefore, the PVT properties measured in slow depletion should be used to describe the evolution of gas within a porous medium where the supersaturation is lower. However, perhaps multiple sets of PVT data are required to represent the evolution of gas at various distances from the wellbore.

REFERENCES

Bryan, J., Kantzas, A. and Bellehumeur, B.: "Oil Viscosity Predictions From Low Field NMR Measurements", *SPE 89070, SPEREE*, (2005a) **8**, 1.

Bryan, J., Hum, F., Kantzas, A., MacPherson, R. and Hancsicsak, T.: "In-situ Viscosity Using Low Field NMR: A Field Case Study", *International Symposium of the SCA*, Toronto, Canada, (August 21 – 25 2005b).

Huerta, M., Otero, C., Rico, A., de Mirabal, M. and Rojos, G. "Understanding Foamy Oil Mechanisms for Heavy Oil Reservoirs During Primary Production," *SPE 36749 the SPE Annual Technical Conference* Denver, Colorado, USA, (October 6-9 1996).

Goodarzi, N. *Investigating Heavy Oil Solution Gas Drive Fluid Properties and the Effect of Scale on Depletion Experiments*, MSc University of Calgary, (April 2006).