

Foamy oil PVT and Rheology Measurements

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Introduction

“Foamy oil” phenomenon is associated with primary cold production, a non-thermal recovery process, from heavy-oil reservoirs producing under solution-gas drive mechanism. The “foamy oil” hypothesis used to explain the unusually high production is still much debated. A number of heavy oil solution gas drive reservoirs show anomalously good primary performance, high oil production, and primary recovery factor (Maini et al. 1993; Sheug. 1997). The oil is produced as oil-continuous foam that contains dispersed gas bubbles at the wellhead. These reservoirs are characterized by having unconsolidated sand with an average porosity of 34% (Tremble et al., 1998), and an average permeability of 3.5 darcies (Tremblay et al., 1996). These reservoirs also experience sand production. However, some heavy oil reservoirs in North and South America exhibit foamy oil behavior and essentially have no sand production (Claridge and Prats, 1995). Production rates from cold production wells can be up to 50 (Tremblay et al. 1996; Young and Adamson, 1992) to 300 times (Yeung, 1996) higher than the rate predicted by Darcy equation without sand production and the foamy oil behavior. Several possible causes for the anomalous production behavior have been suggested and being pursued. These include the formation of wormholes and cavities around the wellbore, (Elkins, 1972; Tremblay. et al.1996. 1998) sand dilation (Loughead, 1992), in-situ formation of oil-continuous foam (Maini et al., 1993; Sheng, 1997) and enhancement of oil mobility by nucleation of large number of microbubbles (Smith. 1988; Islam and Chakma. 1990).

Few investigations have been done exclusively to correlate the apparent viscosity of foamy oil to its foam quality. Einstein (Hatschek. 1928) performed the first theoretical work on the subject of viscosity of dispersion. Various investigators differ about the range of applicability of this equation. Shen and Batycky (1996) put the applicability of Einstein’s equation for the range of foam quality of zero to 5%. Islam and Chakma (1990) measured viscosities of pregenerated foamy oils in a capillary tube of diameter of 3.2 mm. The results of their experiments showed that the bulk foamy oil viscosity, μ_b can be correlated to the gas volume fraction,

$$\mu_b = \mu_o^{1-\Phi} \mu_g^{\Phi} \quad (1)$$

Where μ_o and μ_g are the viscosity of the oil and gas, respectively.

Bora (1998) measured a pre-generated foamy oil viscosity using a plate and a cone rotational viscometer, and he concluded that the foamy oil viscosity was slightly higher than that of the live oil at the same pressure and temperature. In view of the limited knowledge of foamy oil flow behavior, this study will attempt to improve the understanding of the foamy oil flow behavior through the evaluation of the existing theories/models describing foamy oil flow behavior and through experimental work. In this study, a series of PVT and viscosity measurements runs were carried out under different conditions to investigate the foamy oil behavior.

Experimental Set-up and Procedure

The oil used in all the experiments was from the Lloydminster area, Alberta, Canada. The dead oil viscosity at atmospheric pressure and room temperature was 14000 mPa.s. Live oil was prepared by recombining the crude oil with 14% (by volume) CO₂ at a pressure of 6900 kPa (1000 psi) and room temperature.

PVT Measurements Pressure-Volume Temperature (PVT) experiments consisted of Constant Composition Expansion (CCE) runs. A fully visual JEFRI PVT cell was used to carryout the CCE runs. The PVT cell was connected to the live oil sample cylinder. Then a live oil sample was transferred under constant pressure to the PVT cell using a displacement pump. A computer controlled pump was then connected to the top of the PVT cell. The pump was then set at the desired pressure depletion rate and switched on. The volume injected into the PVT cell was measured by the injection pump and by a calibrated cathetometer. After commencement of the experiment, the cathetometer was used to measure the fluid levels, the gas height, and the gas-oil interface.

Foamy Oil Rheology Measurements Viscosity was measured using three different viscometers, Cambridge Electromagnetic (CEV), a JEFRI capillary and Haake Rotovisco RV2 viscometer. However, because of limited sample volume and phase separation, the Haake RV2 results were unreliable. In all the three viscometers, viscosity was measured at two different pressure depletion rates of 800 kPa/hr (116 psi/hr) and 41 kPa/hr (6 psi/hr) and room temperature, 22 °C.

The CEV Model SPL440 was rated to 69 MPa (10,000 psi). The viscometer consisted of a cylindrical steel vessel with a magnetic stainless steel piston immersed in the vessel cavity. The piston was moved inside the vessel by applying a force on the piston using two electromagnetic coils inside the sensor body. After the piston traveled the length of the test vessel, the magnetic field of the electromagnet was reversed as to allow the piston to return to its starting position. Viscosity was determined by measuring piston transit time for a complete cycle of piston

movement and comparing it to times of a known-viscosity calibration fluid. Figure 1 shows the CEV viscometer. A sample of about 3 cc was isobarically pushed into the Cambridge viscometer. Then additional oil sample was purged through the viscometer to insure that there was no free gas flashed during the transfer process. Due to the wide range of viscosity being measured, two pistons were used, a 2000-cp and 10000-cp. The pistons could be used for the viscosity measurement as high as 1.5 the numerical value of the piston; i.e., a 10000-cp piston operated in a viscosity range of 1 to 15000 mPa.s (cp). The accuracy was $\pm 1\%$ full-scale reading.

A schematic of the capillary viscometer set-up is shown in Figure 2. The capillary viscometer set-up consisted of high-pressure capillary tube having 1.83 m (6 ft) in length and .076 cm (0.03 inches) in diameter, two-32 cc cylinders, a positive displacement pump, and a PVT cell. Pressure drop across the capillary tube was measured using a Validyne pressure transducer. Pressure was depleted at a specified rate in the PVT cell.

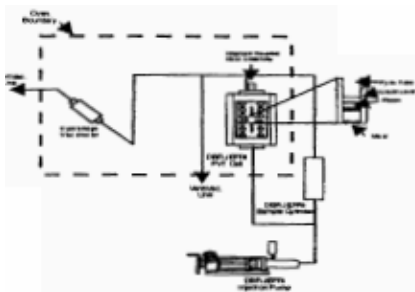


Figure 1 Schematic of the Capillary Viscometer Setup

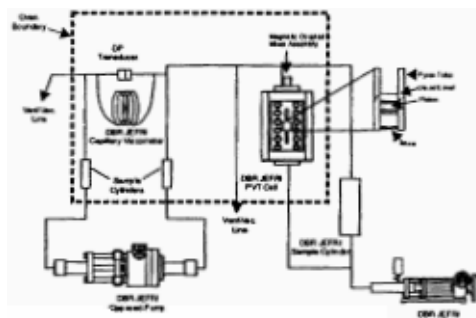


Figure 2 Schematic of the Capillary Viscometer Setup

Then a sample was transferred isobarically to the capillary tube and the 32-cc cylinders. The capillary viscometer constant was determined using a standard calibration fluid of known viscosity. The tube constant is derived from Poiseuille's equation describing laminar flow in tubes.

Discussion of PVT Results

This set of experiments was performed to investigate the effect of pressure depletion rate (PDR) on the foamy oil process. Investigating foamy oil process in heavy oil was a challenging problem due in part to the high viscosity and the dark color of the oil made it even harder to visualize what was happening during the constant composition expansion, CCE, runs. Therefore, the process of foamy oil was investigated by comparing the unaltered process, where gas, CO_2 was allowed to come out solution as closely as possible resembling the process in the reservoir, and by introducing external variables. Runs were performed with and without mixing/agitation, addition of defoamer, and presence of glass beads. The foamy oil volume as percentage of the total volume, (FOVPTV), was compared for the different cases. The foamy oil volume included liquid oil, dispersed gas, and dissolved gas below the free gas-oil interface. Two PDRs were investigated, 800 and 41 kPa/hr (116 and 6 psi/hr). All the CCE runs were carried out at room temperature, 22 °C. Table 1 below summarizes the CCE runs.

Run No.	Pressure Depletion Rate (kPa/hr)	Description of CCE Run		
		Mixing Stirring	Addition of 0.5% (By Vol.) Defoamer	Glass Beads
1	800	No	No	No
2	800	Yes	No	No
3	800	No	Yes	No
4	800	Yes	Yes	No
5	800	No	No	Yes
6 (repeat of 1)	800	No	No	No
7	41	No	No	No
8	41	Yes	No	No
(repeat of 8)	41	Yes	No	No
10	800	Yes	Yes	No

Table I. Foamy oil CCE runs done under different conditions of pressure depletion rate and room temperature.

CCE Runs at Pressure Depletion Rate of 41 and 800 kPa/hr and Room Temperature. The first CCE run was performed with no mixing and no addition of defoamer. This run resembles closely the foamy oil process as it happens in the reservoir. The bubble point pressure was found to be 5723-kPa \pm 103 kPa (830 \pm 15 psi). The bubble point was

also confirmed by PVT Pro Simulator* that gave 5716 kPa (829 psi). The Peng-Robinson equation of state was used in the simulator. This indicates little effect of supersaturation. The FOVPTV is shown in Figure 3 for all the runs conducted. As can be seen in Figure 3, the FOVPTV is 100% well below the bubble point pressure. This is very apparent for all the unmixed cases. It takes some time for the entrained gas phase to start to separate from the oil to free gas phase.

Figure 3 also shows the CCE data for the case when stirring was introduced by means of a magnetic mixer. This run started by setting the PDR of the pump at 800 kPa/hr (116 psi/hr). In addition, a magnetic mixer located at the bottom of the PVT cell was turned on. The purpose of this run was to alter the foamy oil process by changing or speeding up the coalescence of the gas bubbles as they come out of solution. As a result, the disengagement of the gas bubbles from entrapped to free gas phase is hastened. Although, the bubble point pressure was the same as the previous run, no mixing case, the amount of gas liberated into free gas was higher at any given time. Again, it appears that below saturation pressure the supersaturation was not a large contributing factor in a well-mixed system. Some of the gas bubbles remain entrapped in the oil phase in the no mixing case. However, this effect is not as large for a well-mixed system. In other words, the foamy oil process is a time dependent problem, where during the evolution of gas bubbles and the properties of the gas-oil system are changing.

Run 3 was performed at 800 kPa/hr (116 psi/hr) and with no mixing. A 0.5% (by volume) defoamer was added. The purpose of this run was to change the interfacial tension between the gas bubbles and the oil phase. Consequently, the effect of the defoamer would manifest in an increase of free gas phase and a decrease in the entrained gas. Again, the bubble point pressure was found to be the same as in the previous two runs. This was confirmed visually, where minute amount of gas was seen in the PVT cell. The FOVPTV was intermediate between the no mixing and mixing case runs. This indicates that the defoamer helped to speed up the disengagement of the gas bubble into free gas phase.

Next, the combined effects of mixing and addition of 0.5% (by vol.) defoamer were introduced in Run 4. This run was conducted at a PDR of 800 kPa/hr (116 psi/hr). Addition of the defoamer increased the rate at which gas was liberated from the dispersed to the free gas phase. Run 4 was repeated and sample was left to stabilize at each pressure point for 7 days. This run gave a lower limit as can be seen in Figure 3.

To investigate the effect of porous medium on the CCE process, Run 5 was performed in the presence of glass beads. The PVT cell was about one-third filled with 5 mm glass beads. Two screens held the glass beads together. There was only a small amount of oil above the top screen to maintain the initial pressure without having to crush the glass beads. This was important, as the live oil above the top screen would not affect the CCE run and mask the effect of the glass beads. The glass beads increased the surface area available for gas nucleation. The run was done at pressure depletion of 800 kPa/hr (116 psi/hr) with no addition of defoamer and no mixing. The curve of FOVPTV as a function of pressure for this run was similar to the case of 0.5% (by vol.) defoamer and no mixing, Run 3. It seemed that the glass beads served as nucleation sites and as a result helped in bubble coalescence. The different CCE runs performed at PDR of 800 kPa/hr are plotted previously in Figure: 3. As it can be seen from the graph, the no mixing case, Run 1, gave an upper limit and Run 10, the mixing case with the addition of defoamer, left for 7 days, gave a lower limit of the FOVPTV.

Three runs were performed at PDR of 41 kPa/hr (6 psi/hr). The same live oil sample used for the CCE runs at PDR 800 kPa/hr was used in the three runs. Run 7 was carried out at a PDR of 41 kPa/hr at quiescent condition. Run 8 was performed with the sample being stirred by the magnetic mixer as the depletion was in progress. The purpose of this run was to investigate the effect of PDR on the solution gas mechanism of foamy oil. The bubble point determined experimentally was the same for both runs within experimental error.

Comparison of Run 7, quiescent case, and Run 8, mixing case, shows that the no mixing case gave higher FOVPTV as can be seen in Figure 3. This indicates that gas bubbles, which were nucleated, entrapped in the oil phase in the unstirred case for longer time than that of the mixed case.

Comparison of runs done at faster, 800 kPa/hr, and slower, 41 kPa/hr, PDRs reveals that the fast depletion rate runs gave higher FOVFFV in the no mixing case. For well-mixed systems, both the fast and the slow PDR experiments gave similar curve of the FOVPTV vs. pressure. This indicates that stirring the sample during the depletion speeded up the release of gas. Defoamer was effective in lowering the entrained gas phase; hence, lowering the FOVPTV.

Reproducibility of CCE Results To check the experimental results obtained in the CCE runs, two experiments were repeated. Run 6 was a repeat of the quiescent run at 800 kPa/hr; And Run 9 was conducted at a PDR of 41 kPa/hr (6 psi/hr) with mixing. Figure 4 shows the reproducibility of the two runs to be very good. In the next parts of this study, we seek to quantify the effect of the entrapped gas bubbles in the displacement and their role in the anomalous foamy oil production.

Viscosity of Foamy Oil Measurement

The objective of this set of experiments was to investigate the apparent viscosity of foamy oil at different PDRS and to identify the role of viscosity, if any, on the anomalous foamy oil production, and to establish whether Claridge and Prats (Claridge and Prats, 1995) hypothesis has any experimental evidence. Claridge and Prats hypothesis assumed DB Robinson Research PVT simulator

without experimental evidence that microbubbles decrease the viscosity foamy oil. The viscosity was measured by three different viscometers, namely, Cambridge, capillary, and Haake RV-2 viscometers. The Cambridge and capillary viscometers were connected to a visual PVT cell as described previously in the Experimental Set-up and Procedures section. The pressure depletion was done in the PVT cell. The viscosity measurements were measured at pressures ranging from 7584 to 2068 kPa (1100 to 300 psi)

For the 800 kPa/hr PDR, two depletion runs were carried out with one having **0.5%** (by volume) defoamer added to the live oil sample and the other was with live oil sample, nothing added. This was done as a way to alter the solution gas mechanism of foamy oil and be able to measure the effect of the gas bubbles on the viscosity of foamy oil. In addition, the defoamer would help gas bubbles to coalesce and evolve to free gas phase faster.

Viscosity of Foamy Oil as Measured by Cambridge Viscometer The same live oil as that used in the CCE experiments was used for the viscosity measurements. Figure 5 summarizes the viscosity measurement performed with Cambridge viscometer at PDRs of 800 and 41 kPa/hr. The measured viscosity for the faster depletion rate, 800 kPa/hr, was lower than the slower PDR, 41 kPa/hr, and the case when 0.5% defoamer was added. The measured viscosity curve for the slower PDR was intermediate between the 800 kPa/hr with and without the addition of 0.5% defoamer cases. If entrained gas reduces the foamy oil viscosity, systems with defoamer have higher viscosities. Indeed the viscosity of the defoamed oil as measured by Cambridge viscometer was higher than the viscosity of the “normal” foamy oil at the same pressure below the bubble point pressure. This is most likely due to fewer bubbles being entrapped in the liquid phase. The CCE experiments with 0.5% (by vol.) defoamer case gave less swelling of the liquid phase. In other words, there were fewer bubbles entrapped in the oil phase.

To investigate the time effect on foamy oil solution gas process, viscosity was measured after leaving the sample to stabilize for one and seven days (and 8 days for 5516 kPa, 800 psi). Viscosity was measured at two pressures, 2068 and **5516** kPa (300 and 800 psi). Table 2 shows viscosity data at 2068 (300 psi) and 5516 kPa (800 psi). The viscosity as measured by the Cambridge viscometer after one and seven days were found to be substantially higher than the previously measured viscosity at PDRs of 41 and 800 kPa/hr during the depletion process at the same pressures.

It is evident from Table 2 that the viscosity increased as the foamy oil sample stabilization time increased. This is possibly due to the entrapped gas bubbles. As time passes, more bubbles disengage into free gas phase leaving the liquid oil with less entrapped gas bubbles. Furthermore, Equation 1, which used by Islam and Chakma, was used to correlate the viscosity with respect to time using the measured CCE data and published viscosity data for CO₂. The viscosity at 2068 and 5516 kPa (300 and 800 psi) as a function of time is shown in Figure 6. The equation gave a good agreement with the experimentally determined viscosities. The predicted value was within 16% of the measured viscosity value at 5516 kPa.

Conditions of Viscosity measurements	Viscosity at 2068 kPa (mPa.s)	Viscosity at 5516 kPa (mPa.s)
after 1 day	6200	
after 7 days	8350	2230
after 8 days		2200
00 kPa/hr	4200	740
00 kPa/hr, .5% (vol.) defoamer	4800	1000
1 kPa/hr	4680	850

Table 2— viscosity as measured by Cambridge viscometer

Looking back at Figure 5, the **0.5%** defoamer case, at 800 kPa/hr, gave higher viscosity than the 41 kPa/hr depletion rate. This is consistent with the CCE runs where the 41 kPa/hr gave higher FOVPTV. Based on these viscosity measurements, the concluding remark is that the longer the foamy oil sample left for stabilization the higher the viscosity. As for the PDR, viscosity was lower for the faster-PDR than for the slower one.

Viscosity of Foamy Oil as Measured by Capillary Viscometer Viscosity as measured by capillary tube for 800 and 41 kPa/hr PDRs is shown in Figure 7. The viscosity did not show the same separation between the different runs as was seen with the Cambridge measured viscosity. Moreover, the measured viscosities at different depletion rates were within **5%** from each other. This renders the capillary measured viscosity for all cases to be the same or within an experimental error of 5%. The viscosity data fit acceptably well with a Newtonian model.

Comparison of Viscosity of Foamy Oil as Measured by Cambridge and capillary Viscometers Figure 8 shows the viscosity at 41 kPa/hr (6 psi/hr) as measured by the Cambridge and capillary viscometers. As can be seen in Figure 8, both viscometers measured the same single-phase viscosity. Below the bubble point pressure, the Cambridge viscometer measurements were higher than the capillary viscometer.

Foamy oil is a two-phase system. Therefore, measured values of viscosity are only apparent single-phase viscosities of the two-phase system. These apparent viscosities may be a function of the nature of the dispersion (size and number of bubbles), the geometry of the measuring device and P, T, and shear conditions of the measurements. In the case of these experiments, the nature of the dispersion was also changing with time.

We were not able to observe the system in either the Cambridge or the capillary viscometers. We can not be certain that the nature of the dispersion was the same as observed in the PVT cell (i.e. bubble size and number,

presence of free gas phase). If the presence of a dispersed gas phase in foamy heavy oil results in lower viscosity, the Cambridge viscosity results correlate better to the observed behavior in the PVT cell. The observation that the capillary viscometer was insensitive to entrained gas volume fraction could be explained by two ways. First, the geometry of the capillary may result in apparent viscosity of these systems showing less sensitivity to amount of dispersed phase. This may be true if the capillary diameter is much larger than the bubble diameter. Another possibility is that the dispersion changes in the capillary. There was some evidence of phase separation in these runs.

Conclusions

The experimental Techniques employed here to study the PVT and rheology of foamy oil showed that the dispersed gas phase was a time dependent property of foamy oil and it influenced the viscosity of foamy oil.

1. CCE runs showed that the faster the pressure depletion rates the higher the dispersed gas phase.
2. For the same pressure depletion rate, the mixed case gave lower foamy oil volume as a percentage of total volume, less dispersed gas phase.
3. The addition of 0.5% (by vol.) defoamer helped to liberate gas bubbles otherwise would be entrained in the liquid phase, and as a result, decreased the dispersed gas phase. So, the time dependent properties of foamy oil were controlled by dispersed gas phase.
4. Inclusion of glass beads into the PVT cell changed the trend of the foamy oil volume percentage of total volume curve. It served as a nucleation sites and aided in coalescence and gas separation to free gas phase.
5. Viscosity of foamy oil as measured by Cambridge viscometer was lower for the faster depletion rate; and that the longer the sample left to stabilize the higher the viscosity. Whereas, capillary viscosity results showed less variation, within 5% from each other.
6. Cambridge viscosity results appear to correlate better with the observed behavior in the PVT cell than the capillary viscosity results.

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