024 THE EFFECTS OF WETTABILITY AND INTERFACIAL FORCES ON THE DEPRESSURISATION OF WATERFLOODED RESERVOIRS

R.I. HAWES, R.A. DAWE and C.A. GRATTONI
Imperial College, Department of Earth Resources Engineering, Royal School of Mines,
Prince Consort Road, London SW7 2AZ, UK

INTRODUCTION

The critical gas saturation when gas released from solution first becomes mobile is an important parameter in determining the economic viability of depressurising a reservoir after it has been waterflooded. If the value of the critical gas saturation is high, some considerable time elapses before any gas is produced, so that its discounted value is reduced, whereas a low value of critical gas saturation produces an early return on the investment.

Our earlier study of the physical processes of nucleation, growth and mobilisation of the gas released from solution (1) showed that the behaviour is controlled by the oil/water interfacial tension if the oil has a positive spreading coefficient and the matrix is water-wet. A mathematical model was developed to describe this behaviour (2), which was also consistent with the results from high pressure core experiments performed by Kortekaas and van Poelgeest (3, 4), and by Scherpenisse et al (5). Subsequent visual experiments using a two component hydrocarbon mixture in a glass micromodel (6) suggested that both rock wettability and the oil spreading coefficient could substantially influence the value of the critical gas saturation. These experiments showed that rock wettability affects the growth pattern for the developing gas bubbles, and could also affect the gas nucleation behaviour.

In order to confirm the qualitative behaviour observed in the micromodels, a series of experiments with different spreading coefficients and matrix wettability have been performed to provide quantitative data, and the results of these experiments are reported in the following paper.

EXPERIMENTAL APPROACH

The experiments were performed using a large 13 x 30 x 0.4 cm sintered beadpack, containing more than 200,000 randomly packed beads 0.850 to 1.230 mm in diameter creating pores representing reservoir rocks. These test sections had the additional merit of being transparent, so that any movement of the fluids could be observed. The glass surfaces of the models are normally strongly water-wet but oil-wet conditions could be achieved in some of the experiments by treating the surfaces with the commercially available water repellent, dimethyl dichlorosilane in 1-1-1 trichloroethane.

As in our previous experiments, the oleic phase was a simple hydrocarbon mixture consisting of n-pentane dissolved in a non-volatile oil (heavy paraffin). In a reservoir application, the gas would be released from solution by reducing the pressure below the bubble point, Figure 1a. However, since the objectives of the current experiments were to study the physical processes involved, the simpler procedure of heating the mixture to generate the pentane gas, Figure 1b, could be adopted. The three phase mixture that was created had a positive spreading coefficient but non-spreading oil conditions could be obtained by adding a small amount of n-butyl alcohol.

Three experiments were performed; two in water-wet conditions using both a spreading ($S = +2.7$), and a non-spreading oil ($S = -1.2$) and the third in oil-wet conditions with a spreading oil ($S = +2.7$). All of the experiments were performed in the same sintered bead pack.

A diagram of the experimental set-up in which the beadpack was mounted vertically in a temperature controlled bath is shown in Figure 2. When used in water-wet conditions the beadpack was first filled with CO_2 and flooded with degassed water until it was fully saturated. It was then flooded with oil to connate water saturation and re-flooded with degassed water to produce a residual oil saturation. When used in the oil-wet condition, the procedure was to fill the test section with CO_2 then flood it with several volumes of oil, and re-flood with degassed water to the residual oil saturation.

During the experiment, the temperature of the water bath was slowly increased at a rate of about 1°C per day, starting at around 30°C . The fluids that were expelled from the beadpack were collected in test tubes in a cooled condensing section, which was kept at a temperature below 18°C by circulating water through an outer jacket. At this temperature the pentane vapour condensed and became mixed with any non-volatile heavy paraffin that was produced in the effluent. The amount of the n-pentane component was determined by evaporating it from the mixture and weighing the condensing section before and after this operation. The non-volatile oil component was then extracted with a petroleum-ether to leave only water in the tube, which was again re-weighed. Once the total amount of each of fluid produced had been measured, the individual volumes were corrected to allow for the combined thermal expansion of each fluid contained within the pack and the change in pore volume. The corrected data were then used to determine the average saturation of the individual phases remaining in the core at any time.

EXPERIMENTAL RESULTS

Water-wet media with spreading oil

The accumulated volumes of the individual components produced in the water-wet beadpack, and a spreading oil are shown in Figure 3 as a function of the beadpack gas saturation, S_g . No gas or oil was produced during the initial stages, when the gas saturation was lower than the critical value, and only water was collected in the condenser tube. This is consistent with the behaviour observed in the earlier micromodel studies. Pore scale observations have shown that the oil phase was disconnected at connate water conditions, and the positive spreading coefficient ensured that any gas released from solution formed as bubbles within the oil ganglia. These gas bubbles were also disconnected and were immobile. As the volume of gas increased, the bubbles grew displacing the oil and thinning the oil film around it. When the gas saturation reached a critical value of 9%, a sufficient number of bubbles had become connected to allow gas to flow through the matrix, and out of the beadpack. Note that although the gas started to flow out of the test section when the saturation reached 9%, the gas saturation also continued to increase as more gas was released from solution. Note also that some of the non-volatile oil was produced as soon as gas flowed out of the core, and at the end of the experiment oil accounted for about 35% of the liquid phase collected. Thus the expansion and growth of the gas bubbles had mobilised oil ganglia that were initially trapped within the matrix by interfacial forces. In this spreading oil case the oil becomes redistributed as films around the gas bubbles, and when these bubbles became connected, the oil films would also be reconnected, as a result of which the oil could be transported upwards with the gas. As the quantity of gas and oil flowing out of the test section increased, the amount of water displaced tended to decrease, and when the gas saturation reached about 25%, the flow of water out of the test section virtually ceased as shown in the Figure 3.

Water-wet media with non-spreading oil

With a water-wet matrix and non-spreading oil, the behaviour was generally the same as with the spreading oil, Figure 4. Once again no gas or oil was produced until the gas saturation reached a value of 11%, and when the gas started to flow, some of the non-volatile oil was produced with it. When the gas saturation reached a value of about 25%, water production effectively stopped. The fact that the critical gas saturation was similar in magnitude to the value for the spreading oil suggests that the controlling parameter for gas mobility is similar for the two cases; probably the oil/water or gas/water interfacial tensions, which have the same order of magnitude. The most notable difference between the two cases was that less oil was produced in the non-spreading oil case even though the waterflood residual oil saturation was higher in the non-spreading case. At the end of the experiment, oil accounted for less than 10% of the liquid phase collected. This was probably due to the configuration of the phases and the fact that oil is less tightly bound to the gas phase in the non-spreading situation.

Oil-wet media with spreading oil

The oil-wet case produced very different results to either of the water-wet cases, spreading and non-spreading oil. Figure 5 shows that oil was produced with the water almost as soon as gas was released from solution. Note that in this case, oil accounted for about half of the liquid produced. The critical gas saturation at which the gas phase became mobile ($\cong 3\%$) was also very much lower than in the water-wet case. All of these results are in keeping with the behaviour observed in our earlier micromodel experiments (1, 6). Since waterflood residual oil is already in the form of continuous films because of the oil-wet condition, formation of the gas phase effectively produces an expansion of the hydrocarbon (increase in its saturation), and the oil can immediately become mobile without changing its physical form. The lower critical gas saturation was obtained because the gas/oil interfacial tension was the parameter controlling the movements of gas in this case, and gas/oil interfacial tensions are much lower than the corresponding oil/water values. In addition, the water saturation continued to decrease even when the gas saturation reached a value of 35%.

Oil production

To compare the amount of oil production a recovery factor, **RF**, has been defined as;

$$RF = \frac{So_i - So_T}{So_i} \quad (1)$$

where So_i is the residual oil saturation after waterflooding, So_T the oil saturation at a given gas saturation after depressurisation has begun. As the oil production is associated with the gas evolution and thus the critical gas saturation, the **RF** was analysed as a function of the gas saturation and cumulative gas production, Figure 6. The critical gas saturation is different for each case, and therefore the curves start at different gas saturations. The oil-wet media with spreading oil have a higher recovery at the beginning because the critical gas saturation is lower, but the recovery becomes lower than the water-wet case at higher gas saturations. For the water-wet media the recovery factor is always higher for the spreading oil, probably due to the different oil distribution (degree of reconnection) and the larger size of gas-oil interfaces, which can enhance the mass transfer across them.

CONCLUSIONS

- These experiments confirmed that rock wettability and interfacial tensions influence the recovery when gas is released from solution, such as during the depressurisation of water-flooded reservoirs.
- Our earlier visual studies with glass micromodels had suggested that the rock wettability could affect the nucleation of gas bubbles within a porous medium, and would strongly influence the growth pattern and mobilisation of the gas bubbles. The current experiments have shown that these effects are reflected in the magnitude of the critical gas saturation, and the mobility of the oil phase. The magnitude of the critical gas saturation was about the same in both experiments with a water-wet system irrespective of whether the oil was spreading or non-spreading, but it was much higher in the water-wet case than in the oil-wet case.
- The experiments have also shown that the behaviour of the oil phase depends upon the rock wettability, and on the oil spreading characteristics. In water-wet systems, for spreading oils the physical form of the oil becomes transformed from being immobile ganglia, into films in which the oil is mobile and can be transported by the gas phase. A similar behaviour occurs with a non-spreading oil, but in this case the oil is less strongly attached to the solid, and the amount of oil produced is less than that obtained with a spreading oil. In contrast, in an oil-wet system the oil phase already exists as a continuous film on the surface of the solid, and formation of the gas phase effectively expands the oil phase, enabling it to move. As a result, oil was produced as soon as the temperature increased above the bubble point.

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Figure 1- Techniques for solution gas release

Figure 2 - Diagram of apparatus

Figure 3- Cumulative effluent production data for water-wet media and a spreading oil

Figure 4- Cumulative effluent production data for a water-wet media and non-spreading oil

Figure 5- Cumulative effluent production data for an oil-wet media and a spreading oil

Figure 6 - Oil recovery factor as a function of gas saturation