Increased oil recovery from Halfdan chalk by flooding with CO_2-enriched water: a laboratory experiment

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Injection of CO_2 is a method that may increase the recovery of oil from Danish chalk reservoirs in the North Sea. The method is used elsewhere, particularly in North America, but has so far not been used in the North Sea and has nowhere been used for chalk reservoirs, and the performance of the method when used for North Sea chalk is therefore uncertain. A laboratory flooding experiment was conducted at the Geological Survey of Denmark and Greenland on a sample from the Nana-1X well of the Halfdan oil field in the Danish North Sea in order to test the efficiency of CO_2-enriched water to produce additional oil from chalk. The sample is a low-permeability chalk from the Ekofisk Formation and represents rocks that are marginal to the Halfdan reservoir in an economical sense.

Outline of the experiment

For the flooding experiment, four 1.5 inch core plug samples were assembled to form a composite sample with a total length of 28 cm and a pore volume of 92 ml. The flooding experiment was conducted at a fluid pressure of 282 bars, a hydrostatic confining pressure of 429 bars, and a temperature of 85°C. These are conditions similar to those of the Halfdan reservoir. First the oil content, S_o, of the sample was adjusted to 77.7% of the pore volume (PV), the remaining pore fluid being simulated formation water. The sample was then brought to reservoir conditions, aged for three weeks to restore the wettability to reservoir conditions and then flooded with simulated formation water until oil production from the sample had ceased. After changing the flooding fluid to CO_2-enriched water, flooding was resumed and sustained until oil production had declined to a negligible level. Flooding was then stopped, the rig was cooled and depressurised, and the sample was dismounted. Both flooding operations were conducted with the sample in a vertical position from the bottom towards the top. A thorough description of the experiment is given in Olsen (2007).

Fig. 1. Oven with high-pressure equipment used for the experiment described in this paper. The oven is 160 cm high. The arrow shows the core holder that was used for the experiment.

Experimental set-up

The experiment was conducted in a rig that simulates reservoir conditions. The rig consists of a Hassler-type core holder, a number of pressure cylinders for the experimental fluids, an acoustic separator for quantifying the fluid production, a differential pressure transducer for permeability measurement, and a high-pressure pump system for generating confining pressure, flow and pore fluid pressure. The core holder, pressure cylinders, separator, and differential pressure transducer are all situated inside a thermostatically controlled oven (Fig. 1).

Temperature and fluid pressure conditions were based on data from the adjacent Dan field reservoir, and corrected for the 250 m depth difference between the two reservoirs, Halfdan being the deeper. The temperature was corrected using a temperature gradient of 0.04°C/m. Assuming pressure correspondence between the two reservoirs, the Halfdan fluid pressure was estimated by extrapolation from the Dan field using a pressure gradient of 0.075 bar/m. Temperature, pressure and gradient values are from Jørgensen (1992). The oil used in the experiment was degassed crude oil from the Dan field. The water composition was similar to that of formation water from the Halfdan field. Fluid densities were measured at GEUS, while the water viscosity at reservoir conditions was estimated from data on the viscosity of similar brines. During the experiment differential pressure across the sample, pore fluid pressure, hydrostatic confining pressure, flow

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Table 1. Flooding experiment to enhance oil recovery: sample characterisation

	Initial characterisation	Final characterisation	Change	Percent change
Dry weight (g)	613.37	609.05	–4.32	–0.70
Diameter (cm)	3.77	3.77	0.00	0.07
Length (cm)	28.32	28.24	–0.07	–0.26
Bulk volume (ml)	318.56	316.92	–1.64	–0.52
Porosity (% bulk volume)	28.77	29.09	0.32	1.10
Pore volume (ml)	91.64	92.18	0.53	0.58
Gas permeability (mD)	0.62	0.76	0.14	23

rate, cumulative injected fluid volume, produced oil volume and temperature were continuously logged. Before and after the flooding experiment the sample was characterised by measuring a number of parameters (Table 1).

Water flooding

The water flooding took place with a constant flooding rate of 0.62 ml/h and lasted 33 days with a total water injection of 490 ml or 5.35 times the pore volume. Results of the water flooding are presented in Fig. 2. Water breakthrough occurred after 77 hours when the water throughput was 0.458 times the pore volume. Before breakthrough, oil was produced from the sample at the same rate as the water was being injected. After breakthrough, the rate of oil production dropped sharply and continuously. A low oil production rate was sustained for a considerable time, but stopped completely before the flooding was terminated. A total oil volume of 0.053 times the pore volume was produced after breakthrough. Total oil production during the water flooding was 0.496 times the pore volume or 63.8% of the oil originally present in the sample.

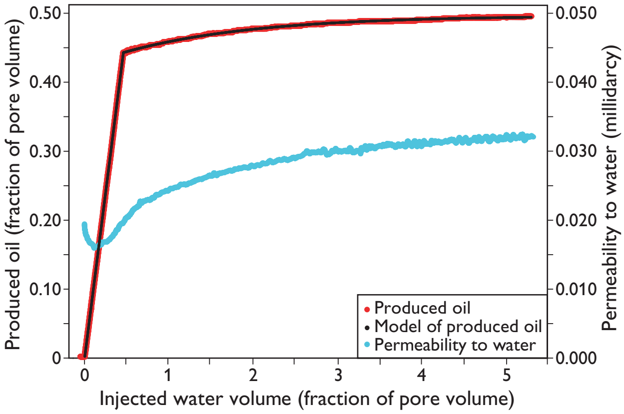

Fig. 2. Produced oil volume (N_p) versus injected water volume (V_{inj}) during flooding with water. Model before breakthrough: $N_p = 0.98 \times V_{inj}$. Model after breakthrough: $N_p = 0.50 - 0.08 \times \exp(-V_{inj}/1.57)$. Fluid saturation (fraction of pore volume): initial water saturation = 0.223, water breakthrough at water saturation = 0.666, final water saturation = 0.719, produced oil = 0.496.

A model was developed that fits the oil production (Fig. 2). Before breakthrough, the oil production shows a linear relationship with the injected water volume. After breakthrough, the oil production shows an exponentially decreasing relationship. Both relationships show a nearly perfect fit to the actual oil production.

Measurements of differential pressure across the sample were used to calculate the water permeability during the water flooding (Fig. 2). At the end of the water flooding the differential pressure had stabilised, indicating that fluid movement within the sample had stopped. Both the oil production and permeability curves show typical water-flooding development.

Flooding with CO_2-enriched water

The flooding with CO_2-enriched water was carried out at the same rate as the water flooding, i.e. at 0.62 ml/h. It lasted 64 days, and the total throughput of CO_2-enriched water was 949 ml or 10.4 times the pore volume. The CO_2-enriched water had a CO_2-content of 26.6 standard m^3 CO_2/standard m^3 water corresponding to a CO_2-saturation of 100% at 85°C and 282 bars fluid pressure (Chang *et al.* 1998).

Diffusion of CO_2 between oil, CO_2-enriched water and water without CO_2 may cause the oil within the separator to either swell or shrink as CO_2 diffuses between the fluid phases. Such volume changes are troublesome as they cannot be distinguished from oil being produced from the sample. In an attempt to establish equilibrium between separator oil and CO_2-enriched water, an amount of CO_2 was added to the separator before starting the CO_2-enriched flooding and allowed to equilibrate with the separator fluids for nine days. Using the data of Chang *et al.* (1998) the amount of CO_2 was adjusted so as to create the same CO_2-saturation in the water of the separator as in the brine used for flooding.

Figure 3 presents a plot of oil produced during the CO_2-enriched flooding versus time. The oil production curve has

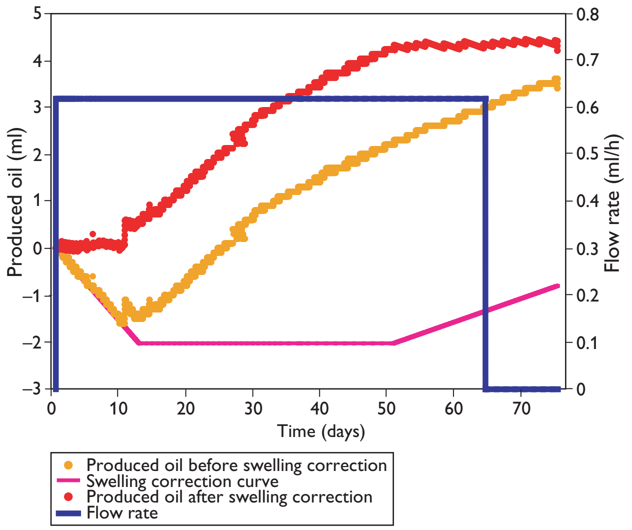

Fig. 3. Swelling correction curve for flooding with CO_2-enriched water with production curves before and after correction.

a peculiar shape with an initial negative slope, indicating that the volume of oil in the separator was reduced. As oil cannot flow from the separator, the negative slope indicates that the oil in the separator shrank in volume during the first part of the CO_2-enriched flooding. After the section with negative slope, the slope of the oil production curve changes to positive and obtains the appearance of an ordinary oil production curve with oil apparently being produced at a low rate right until the end of flooding. After cessation of the flooding the rig was left undisturbed for 10.8 days, with the conditions of the rig being the same as during the CO_2-enriched flooding, except that the fluid delivery pump was stopped. During this time the separator continued to register an increase in oil volume, at a rate that was indistinguishable from the rate during the final part of the CO_2-enriched flooding (Fig. 3). As the construction of the rig prevents oil from flowing to the separator when the delivery pump is stopped, the apparent oil production after flow-stop is considered to represent swelling of the oil within the separator. The situation appears similar to that at the beginning of the CO_2-enriched flooding, only that swelling takes place instead of shrinkage.

During flooding with CO_2-enriched water it is expected that no oil is produced from the sample before oil affected by the CO_2 has moved to the outlet end of the sample. It is therefore reasonable to assume that the initial section of the oil production curve with negative slope represents the time before breakthrough of the CO_2-enriched water and the first produced oil. The section with negative slope then represents a period without oil production and should be horizontal. The section of the oil production curve after flow-stop should also be horizontal as no oil can be produced without flow. Using these arguments a swelling correction curve has been constructed (Fig. 3). As oil shrinkage in the separator changed to oil swelling during the experiment, a section with neither shrinkage nor swelling is present in the middle part of the correction curve. This part of the curve indicates equilibrium in the separator. The correction curve of Fig. 3 therefore consists of three linear segments indicating shrinkage, equilibrium and swelling. A true correction curve probably would have a gradually changing slope, but in the absence of more information, linear line segments have been used.

The data are interpreted as follows: At the start of flooding with CO_2-enriched water, the pore space of the sample contained 66 ml of CO_2-free water while the fluids of the separator were CO_2-saturated. During the first week of the flooding, the CO_2-free water of the sample flowed to the separator and caused the oil of the separator to shrink as CO_2 diffused from oil to water. After breakthrough of CO_2-enriched water, the CO_2 content of the water in the separator gradually increased. After some time the direction of CO_2 diffusion changed, causing the oil of the separator to swell, a condition that continued after the end of the flooding.

Figure 4 presents oil production curves for flooding with CO_2-enriched water with and without correction for swelling. Compared to the water flooding, the amount of oil produced during flooding with CO_2-enriched water was small. Total oil production was 0.047 times the pore volume equivalent to 6.1% of the oil originally present in the sample, if swelling correction is applied, and 0.032 times the pore volume or 4.2% of the oil originally present in the sample, if swelling correction is omitted. The swelling correction is considered valid, and hence the corrected values are preferred.

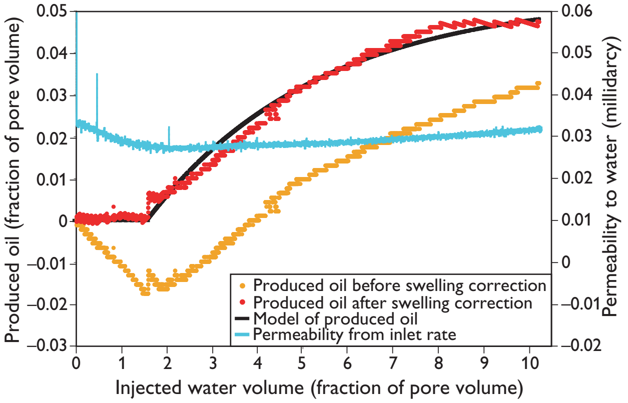

Fig. 4. Produced oil volume (N_p) versus injected fluid volume (V_{inj}) during flooding with CO_2-enriched water compared to production curves with and without correction for swelling. Model before breakthrough: $N_p = 0$. Model after breakthrough: $N_p = 0.05 - 0.08 \times \exp(-V_{inj}/3.8)$. Fluid saturation (fraction of pore volume): water saturation before CO_2 flood = 0.719. **With** swelling correction: water saturation after CO_2 flood = 0.767, oil production during CO_2 flood = 0.047. **Without** swelling correction: water saturation after CO_2 flood = 0.752, oil production during CO_2 flood = 0.032.

Fig. 5. The inlet end of the composite sample showed a dissolution structure after flooding with CO_2-enriched water. The star-like shape is governed by the arrangement of the distributor channels in the end pieces of the core holder.

A model has been developed that approximates the oil production profile (Fig. 4). The fit is reasonable, although inferior to the fit obtained for the water flooding (Fig. 2). The inferior fit is at least partly caused by the smaller volume changes compared to the water flooding, causing a greater relative experimental uncertainty.

Dissolution effects

The bulk volume of the sample was reduced by 1.64 ml during the experiment (Table 1), equivalent to a grain volume loss of 1.17 ml. This is attributed to a distinct dissolution structure that was found at the inlet end face after the experiment (Fig. 5). The structure was due to dissolution of the chalk by the CO_2-enriched water. Dissolution structures were not visible on the other surfaces of the sample. Porosity of the sample increased by 0.32% of the bulk volume during the experiment (Table 1), which indicates that 1.01 ml of grain material were dissolved from the interior of the sample during the experiment. Combining the bulk volume loss and the porosity increase indicates a total dissolution of 2.18 ml of grain material, which is equivalent to the loss of 5.91 g of calcite. The measured weight loss was 4.32 g, which is considered to agree within the experimental uncertainty (Table 1).

The gas permeability increased by 23% during the experiment (Table 1), which is remarkable compared to the modest increase in porosity. The increase in both porosity and permeability was evenly distributed among the four subsamples, indicating a certain amount of dissolution throughout the sample (Olsen 2007). The evidence shows that dissolution took place both close to where the CO_2-enriched water entered the sample and within the sample. A small length reduction (Table 1) occurred due to the formation of the dissolution structure.

Conclusions

Water flooding of a low-permeable Ekofisk chalk sample from the Nana-1X well in the Danish North Sea resulted in an oil saturation of 28.0% of the pore volume with an oil recovery of 63.8% of the oil originally present in the sample. Flooding with CO_2-enriched water corresponding to 10.4 times the pore volume increased the oil recovery by 6.1% of the oil originally present in the sample, resulting in a final oil saturation of 23.3% of the pore volume. Compared to the water flooding, the flooding with CO_2-enriched water increased the final oil recovery by 9.6%. A correction procedure was applied to correct for diffusion processes within the separator of the rig. At the inlet end of the sample a dissolution structure was created by the CO_2-enriched water. The rest of the sample was visually unaffected by the flooding, but the injection resulted in a 1.1% increase in porosity and a 23% increase in gas permeability, which shows that some dissolution took place within the pore space of the sample.

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