Experimental Investigation of Hot Water Injection into Carbonate Heavy Oil Reservoir

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Abstract

The major mechanisms on hot water injection are: thermal expansion, viscosity reduction, wettability alteration and oil / water IFT reduction. In this study, hot water injection experiments were carried out using unpreserved carbonate core samples obtained from the oil zones of a heavy oil reservoir. These experiments were conducted at reservoir condition and in various temperature ranges up to 500°F using a wide variety of oils. The final oil recovery, residual oil saturation, irreducible water saturation and pressure drop were compared in each experiment. Results show that it is possible to recover a high percent of oil using high pressure/temperature injection, even from heavy oils in carbonate reservoirs. In a heavy oil system, the oil production to hot water injection ratio is high, but the values are less than the reported values for conventional heavy oil reservoirs. Also, it was found that the residual oil saturation decreases and irreducible water saturation increases when the temperature increases.

Keywords: Hot water injection carbonates rocks, Residual oil saturation, Irreducible water saturation, Heavy oil, Core flood

1. Introduction

Many believe that the era of conventional oil will soon come to an end and heavy and non-conventional oil will be replaced by easy producing oils. There are more than 1600 billion barrels of heavy oil in carbonate rocks and most of these kinds of reservoirs require thermal enhanced oil recovery methods for production [1]. Also, low-permeability fractured carbonate reservoirs contain a large volume of the worldwide oil resources [2].

Thermal enhanced oil recovery methods that have been applied in the field include hot water drive, steam injection and in situ combustion. Because of the presence of water in all petroleum reservoirs, the flow of hot water will occur to some extent in all thermal recovery processes. Oil viscosity decreases many folds upon heavy oil heating and therefore the mobility ratio of the fluids in the heated zones is more favorable than the cold water injection. This results in better macroscopic displacement efficiency and would improve the ultimate recovery.

The improvement in recovery of viscous crude oils by hot fluid injection is primarily due to the improved oil mobility and reduction in residual oil saturation. Fig. 1 shows, schematically, the effect of oil gravity on the most significant mechanisms in hot fluid injection. As it seems, in heavy oil reservoirs, the objective of hot water is to increase production by reduction in oil viscosity.

Although there are published work on hot water injection into sandstone rocks and carbonate reservoirs, it seems there is not much published study about hot water injection into low-permeability carbonate reservoirs [4-10, 12]. Therefore, the objective of this study was to investigate hot water injection into low-permeability carbonate rocks in heavy and medium oils.

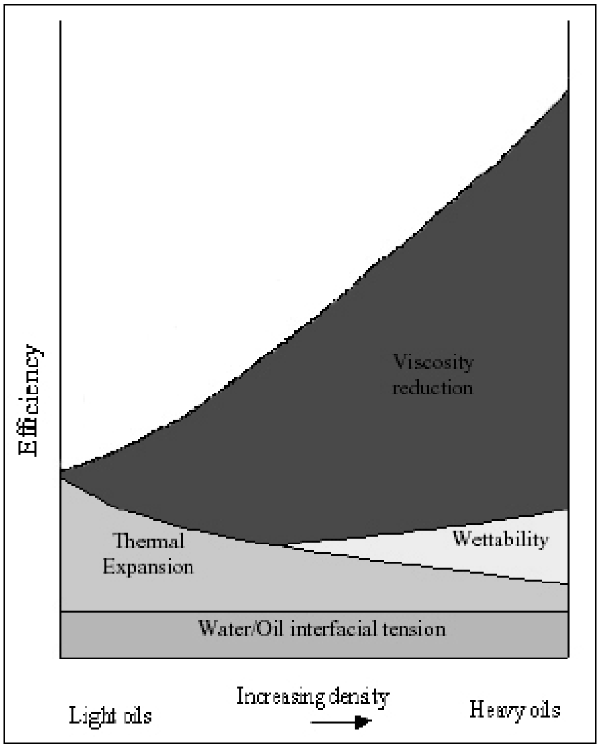

Figure 1. Relative contributions of various mechanisms on the displacement efficiency of oil by hot water injection [3]

2. Experiments

2-1. Material

2-1-1. Fluid Properties

Heavy oil from an Iranian field was used in this study. Density, dead oil viscosity at 100°F and the mole fraction of C_7^+ fraction of this sample is given in Table 1.

Table 1. properties of the used oil in the experiments

Density of oil @ standard condition ,gr/cc	0.95
Dead Oil Viscosity @100°F,cp	2094
C7+ , %	84.81

2-1-2. Rock Properties

Low-permeability carbonate rock is used in this study (Table 1). The core is dolomite. The absolute permeability of the sample was 3 md. Due to the carbonate nature of the core, special care was needed to be cut as small plugs from the whole core. After cutting, the sample was washed completely with toluene and dried in an oven at more than 300°F for at least 24 hours to remove all possible oil and fines from rocks. The core plug diameter and length were about 4 and 8 cm at all experiments, respectively.

Table 2 shows the measured porosity and absolute permeability of the sample. The absolute permeability of this core was 3 md which is an indication of no fractures and low-permeability core sample.

Table 2. porosity, permeability and lithology of the core used in experiments

Preferred Lithology	Dolomite
Porosity,%	21
Absolute Permeability, md	3.0

2-2. Equipment

Fig. 2 shows a schematic representation of the displacement apparatus used in this study. This apparatus includes three sections: Injection, coreholder and production. Water was injected using two ISCO-LC-5000 positive displacement pumps which were working in parallel. These pumps can inject with high accuracy from 0.10 to 400 cc/hr at pressures higher than 4000 psi. The injected water is heated in the steam generator at the desired temperature. A Fenwal temperature controller was used to inject the hot fluid at constant temperatures. For oil injection, a mercury Ruska pump which can inject at pressures higher than 10000 psi was used. This pump also has two parallel limbs which allow continuous injection. It was possible to inject oil at a constant rate and pressure with this pump.

The coreholder was built from stainless steel capable of loading overburden pressure over 10000 psi and operating temperatures up to 650°F. Coreholder heads were sealed with rubber O-rings and Teflon pads. Nitrogen was used as overburden fluid. Overburden pressure was always 200 psi more than the core pressure. Back pressure regulator was used to control the core pressure and maintain the system in the two-phase mode (oil-hot water) and prevent steam formation. The coreholder and measurement tools were placed in an oven to control its temperature, as shown by the dotted line in Fig. 2. A fan was blowing air inside the oven to maintain a constant temperature inside the oven.

The effluent was collected in graduated cylinders for analysis and separation of oil and water. Production fluid was cooled in a condenser before collection. Graduated cylinders were used to measure the produced fluid. Due to the formation of emulsion, the weighting method of the the produced fluid would not yield correct results.

Pressure and temperature transducers and pump calibrations were checked before each experiment. The accuracy of the measurement system of the production fluids, thermocouples and pressure transducers, were 0.05 cc, 2°F and 10 psi, respectively. The dead volumes of all of the flow lines were measured and considered in all material balance calculations.

2-3. Experimental Procedure

After washing and drying the cores, they were placed into the coreholder and vacuum was applied for about one hour to all flow lines and the core. After establishing enough vacuum, the core is saturated with water and then absolute permeability was determined at the experiment temperature. No significant difference in absolute permeability was observed. To reach ion exchange equilibrium between the rock and water components, 24 hours were allowed prior to each experiment.

The irreducible water saturation can then be established by displacing water by oil at the experiment temperature and pressure. For high temperature cases, oil was heated up to the experiment temperature during injection to attain injectivity and thermal equilibrium.

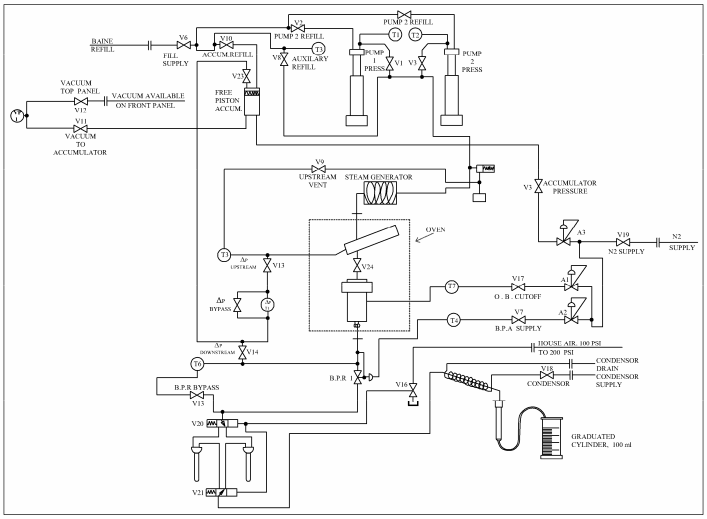

Figure 2. Schematic of experimental apparatus

Oil injection continued until the water fraction of the produced fluid decreased below 1%. After establishing the irreducible water saturation, the oven temperature was fixed at the desired level and the system was allowed to reach thermal equilibrium. In most runs, more than 5 days passed before the oil reached equilibrium with the water at high temperature and pressure. During this period, oil was produced due to thermal expansion. This ensured that no oil was produced during thermal injection due to expansion. After reaching the thermal equilibrium, as indicated by cessation of oil production, constant rate water flooding was started in a vertical direction. The waterflood was continued until oil production ceased.

3. Results and Discussion

The results of two experiment sets for two different oil samples, i.e., medium oil and heavy oil will be analyzed. Table 3 summarizes those experiments and operational conditions.

Table 3. operational condition of the experiments.

Core Name	Crude Oil	Temperature,°F	Average Pressure ,psi
MN-X	Heavy Oil	200	1800
		300	1400
		450	1000

In the following sections, the results of these tests are presented.

This set of experiments was carried out to determine the effect of injection temperature on heavy oil recovery. The experiments were conducted at three different temperatures, namely 200°F, 300°F and 450°F. As a result of the preliminary tests, in this set of experiments the system is allowed to reach thermal equilibrium and hot water flood was started at the desired temperature. After the cores under vacuum were saturated with water, the temperature of the oven was set to the experimental temperature. Oil flooding was then conducted until the irreducible water saturation was reached. Eventually, hot water flooding was performed. At the end of each experiment, the core was washed with toluene and acetone and then the same process was repeated for the next two higher temperatures. Due to relatively medium injectivity of the system (3md), it was possible to inject hot water at higher constant rates. Hot water was injected at 12, 15 and 20 cc /hr in 200, 300 and 450°F runs, respectively.

Figs. 3 and 4 show the oil recovery and pressure drop of these experiments, respectively. As is seen, in the first two temperatures, initially the pressure drop jumps up and then decreases until it finally becomes stable. This phenomenon is due to the fluid compressibility [11]. Part of the fluid displaced by the constant rate of the pump was absorbed by the fluid compressibility effects. Therefore, the actual rate which occurs in the core should be less than the amount that is flowing through the pump. So pressure in the inlet goes up and subsequently, pressure drop also goes up. Also, as seen from Fig. 4, when the temperature increases, pressure drop fluctuation damps out and at 450°F it is ceased. This could be attributed to the increase of oil mobility due to viscosity reduction at higher temperatures.

The final oil recovery at 200°F test is 47%, while when temperature increases to 300°F and 450°F the recovery increases up to 71% and 83%, respectively. Also, the stabilized cumulative oil/hot water ratio are 0.07, 0.13 and 0.12 for the 200,300 and 450°F, respectively. The viscosity reduction in heavy oils is much higher than in light oils; therefore, the heating process will be more efficient than lighter ones.

3-1. Effects of temperature on irreducible water and residual oil saturation

The effects of temperature on irreducible water saturation and residual oil saturation in sandstone systems have been studied previously. However, there is little published literature regarding a work on carbonate systems. Fig. 5 shows that the irreducible water saturation increased linearly with increasing temperature, while the residual oil saturation decreased non-linearly with increasing temperature. It should be mentioned that due to the high viscosity of the oils used in these experiments, it is a very time consuming task to reach the real end points. Therefore, the end points were found from extrapolation.

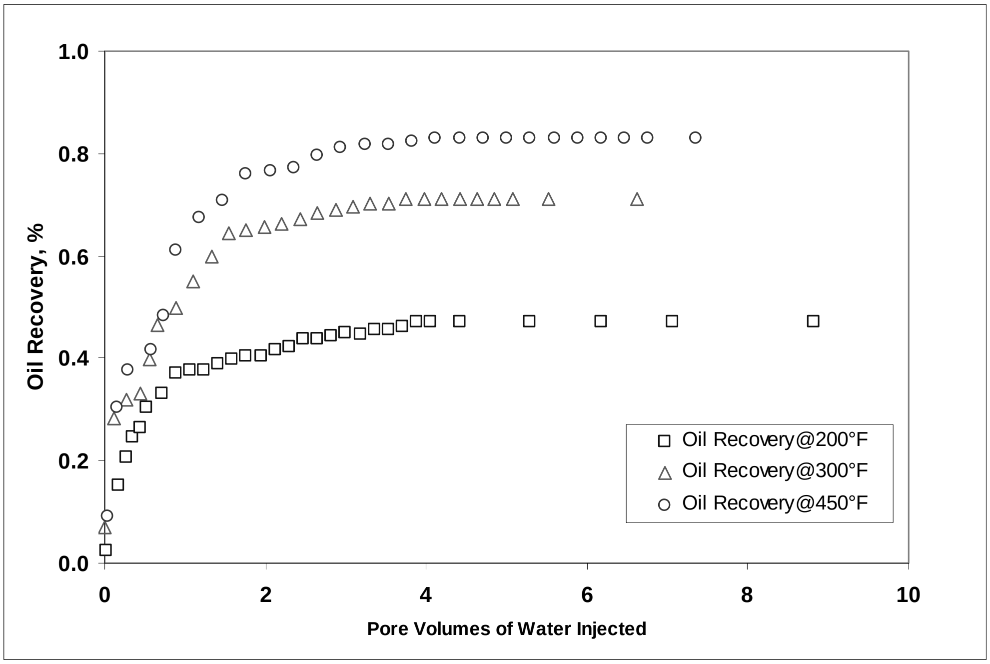

Figure 3. Comparison of the oil recovery at 200, 300 and 450°F

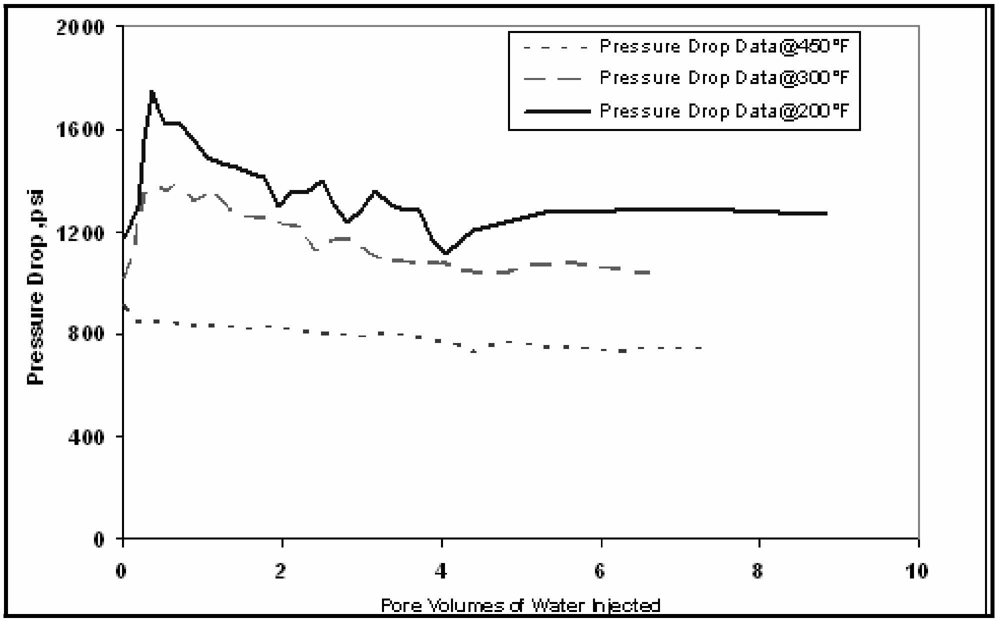

Figure 4. Comparison of the pressure drop at 200, 300 and 450°

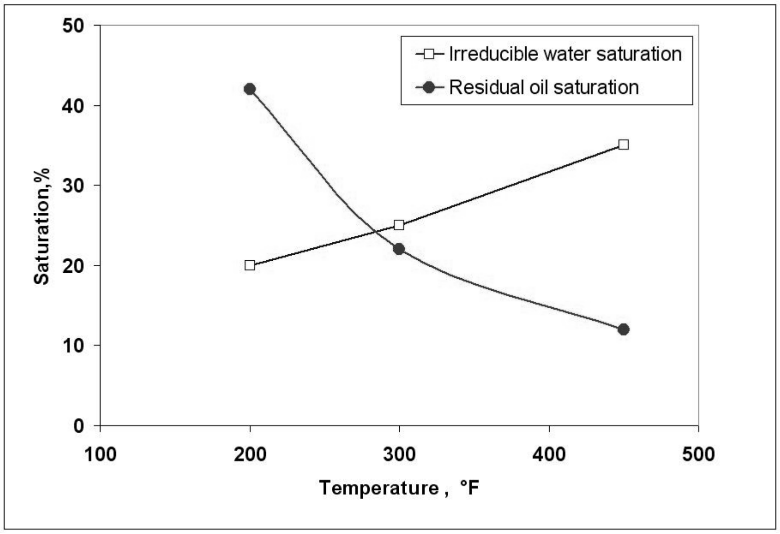

Figure 5. Irreducible water saturations and Residual oil saturation versus temperature

4. Conclusions

Based on the results of this investigation, the following conclusions could be drawn for the hot water injection into Low-Permeability carbonate heavy oil systems and the related flow functions under reservoir conditions:

1. The residual oil saturation non-linearly decreases with increasing temperature.
2. The Irreducible water saturation increases with temperature.
3. It is possible to recover a high percent of oil using high pressure/temperature injection, even from heavy oils in low-permeability carbonate reservoirs.
4. In the heavy oil system, the oil production to hot water injection ratio is high, but the values are less than the reported values for conventional heavy oil reservoirs.

Nomenclature

Symbols

k	Permeability, md
S	Saturation, fraction
EOR	Enhanced oil recovery
PV	pore volume

Greek letters

μ	Viscosity, cp

Subscripts and superscripts

o	Oil
or	Residual oil
irr	Irreducible saturation
w	Water
wi	Initial water

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