Available online at www.sciencedirect.com
ScienceDirect
Journal of Petroleum Science and Engineering 58 (2007) 293 – 308
Journal of Petroleum Science & Engineering
www.elsevier.com/locate/petrol

Effect of injection rate, initial water saturation and gravity on water injection in slightly water-wet fractured porous media

H. Karimaie *, O. Torsæter

Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Received 15 November 2005; received in revised form 22 December 2006; accepted 7 February 2007

Abstract

The objective of this work was to evaluate methods for improved water injection in fractured carbonate rocks by performing experiments on outcrop core. The experimental setup consisted of a composite of 3 limestone outcrop cores with a total length of 116 cm and average diameter of 6.5 cm. The composite core (matrix) was placed in the center of a plexiglass cylinder, with the annulus between the core and the cylinder wall serving as the fracture. Water injection tests were performed by injecting water from the bottom and producing from the top. This system experienced an advancing oil/water level in the fracture. The composite core was completely immersed for 5–7 days after finishing the experiment; creating changing boundary conditions from partially to fully water immersed. Immersion type experiments were also performed separately. The effect of water injection rate and initial water saturation on oil recovery by imbibition mechanism was investigated experimentally. Water injection tests were performed at three different rates and three different initial water saturations. Breakthrough oil recovery was found to be higher when the water injection rate was low, whilst final oil recovery was less rate dependent. Alteration of initial water saturation was observed to exert minimal effect on final oil recovery, and any observed effect could be classed as experimental error. However, the rate of oil production increased with increasing initial water saturation. The results confirm that oil recovery by water injection is low in this rock type; due to oil retention by capillary forces and wettability effects. Therefore, to overcome oil retaining forces, the effect of reduced interfacial tension (IFT) on oil recovery was investigated experimentally, by choosing a low tension, equilibrated fluid system. This will increase gravity and decrease capillarity effects on the core, which in turn will result in improved recovery. The experimental results indicate that oil recovery is increased mainly due to the decreased ratio between capillary and gravity forces. Li and Horne analytical model, which incorporates both capillary and gravitational effects, was used to scale IFT and dimension successfully. Scaling results indicated that IFT and core dimension, for all experiments, could be scaled by using height of the core as the shape factor. However, using characteristic length (L_a) as the shape factor, IFT scaling worked well but dimension could not be scaled.

Keywords: Imbibition; Cocurrent; Countercurrent; Inverse bond number; Wettability; Fractured reservoirs

1. Introduction

Oil recovery by water injection in water-wet rock is mainly controlled by spontaneous capillary imbibition. However, several large and significant fractured carbonate fields are not strongly water-wet but rather

* Corresponding author. Tel.: +47 73 59 71 40; fax: +47 73 94 44 72.
E-mail addresses: hassank@ipt.ntnu.no (H. Karimaie), oletor@ipt.ntnu.no (O. Torsæter).

0920-4105/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.petrol.2007.02.002

weakly water-wet, mixed-wet or even oil-wet. Asmari limestone is one such example; an important fractured carbonate, hydrocarbon producing formation in the southern part of Iran. The Asmari limestone is of tertiary age, hard, compact, fine to coarse-grained and slightly marly anhydritic or sandy (Aguillera, 1980). The presence of fractures is evidenced by mud losses, high productivity not relatable to matrix permeability, pressure build-up characteristics, flow meter surveys, and core analysis. Initial water saturation has been observed to be in the range of 25% or less (good rock) to between 25 and 50% (poor rock). The matrix block dimensions are large enough to imply that gravity may be an effective force in oil recovery; for example, in the Haft Kel field blocks range from 2 to 4 m in height with radii of 2–2.5 m (Saidi, 1987). Therefore, the major influence on productivity is unknown and the effects of injection rate, initial water saturation and gravity on oil recovery efficiency become important questions in these fields.

Several studies about the effect of initial water saturation on oil recovery have been published by different authors but their results are not consistent. Most of the studies have been executed on water-wet samples, and there are a limited number of publications on the effect of initial water saturation in mixed-wet and weakly water-wet samples. Viksund et al. (1998) performed spontaneous imbibition tests on strongly water-wet chalk and Berea sandstone. They found that the final oil recovery by spontaneous imbibition in Berea sandstone showed little variation with change in initial water saturation from 0 to about 30%. For the chalk samples tested by Viksund et al., the imbibition rate first increased with increase in initial water saturation and then decreased slightly as initial water saturation increased above 34%. Zhou et al. (2000) studied the relationship of wettability, initial water saturation, and oil recovery by counter-current spontaneous imbibition and waterflooding in oil–water–rock (Berea sandstone) systems. They used Prudhoe Bay crude oil, a synthetic formation water, and Berea sandstone; changing the system wettability by systematic changes in initial water saturation and length of aging time at reservoir temperature (88 °C). They found that imbibition rate and final oil recovery increased with increasing initial water saturation. Tong et al. (2001) studied the effect of initial water saturation on Berea sandstone. They prepared mixed-wet sandstone by adsorption from an asphaltic crude oil and displaced it by decalin followed by mineral oil. They believe that, "*for mixed-wet cores prepared by this technique, imbibition rates were much slower than for strongly water-wet cores and were highly sensitive to initial water saturation*" and found that imbibition rate was very sensitive to initial water saturation.

Tang and Firoozababdi (2001) studied the effect of initial water saturation on oil recovery by water injection into chalk samples in fractured porous media; the chalk samples having wettability ranging from strongly water-wet to intermediate-wet. They used Kansas outcrop chalk with a porosity of approximately 30% and permeability around 0.5 mD and changed the wettability state of the samples by using Stearic acid as a surfactant. They found that the effect of initial water saturation on oil recovery depends on wettability. For a strongly water-wet condition, oil recovery by water injection can decrease mildly with increasing initial water saturation. However, for weakly water-wet conditions, the oil recovery by water injection can increase significantly with an increase in initial water saturation. According to their results the oil production rate and final oil recovery may vary depending on the rate of water injection, initial water saturation and matrix wettability.

Thus in many cases, in the cited references, both the initial water saturation and wetting conditions were changed simultaneously, which makes the scientific interpretation of the resultant effects difficult. This present work used cores which were originally weakly water-wet by nature, so that different initial water saturations could be obtained without altering wettability; hence, allowing investigation of the effect individually.

The most important forces describing the flow of liquid during the oil production process are viscous, gravity and capillary forces. In fractured reservoirs, capillary imbibition is regarded as a main mechanism for oil recovery during waterflooding. This is partly related to the fact that many of the fractured reservoirs found today are water-wet. However, for oil-wet and mixed-wet systems, the water uptake by capillary forces is quite limited resulting in lower oil recovery. Therefore, in such cases, reduction of IFT and alteration of wettability, towards a more water-wet preference, will reduce the tendency of capillarity to retain the oil. If wettability is altered to preferentially water-wet and/or capillarity is diminished, through ultra-low IFT, gravity will still tend to force oil to flow upward and out of the matrix into the fracture system. Usually capillary forces govern spontaneous imbibition at high IFT and fluid flow is countercurrent. At low IFT, i.e. in the presence of surfactants, capillary forces decrease and gravity forces will probably be more effective. In fact, in some EOR processes, such as miscible or surfactant/polymer