049 LABORATORY AND FIELD STUDIES ON GRAVITATIONAL EFFECT IN LOW-TENSION WATERFLOODING

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ABSTRACT

Theoretical considerations indicate the dominant role of gravitational force when emulsified oil flows in low-tension environment. Spontaneous segregation observed in vertically oriented sand columns suggests the gravity override of the mobilizing micellar solution. Experiments in horizontal sinusoidal glass capillary proved the gravitational separation of oil in extensions when it was displaced by low-tension water (LTW). Gravity override of LTW was demonstrated by visual studies on horizontal displacement at tertiary conditions in micro and linear (2D) macromodels with vertically oriented plane. They indicated the development of an instable emulsion bank behind the inclined front. The effect of segregation may result in a secondary entrapment with a subsequent decrease in oil recovery. Instability related to the emulsion bank could be minimized in gravity assisted vertical displacement.

A single-well test was performed to study the advantage of an LTW controlled segregation process in the waterflooded Szeged-Móraváros field, South Hungary, by injecting 2 wt.% active petroleum sulphonate in 1700 m³ injection water into a test well. Repeated short-time production after 120 day curing time indicated clean oil production from March 1995 to April 1997 despite the partial decomposition of surfactant at 140°C reservoir temperature. At the end of production tests oil-in-LTW-type emulsion appeared. All observations are in agreement with laboratory results.

It is concluded that gravitational effect could result in an instability and override in horizontal flow leading to an early breakthrough and a loss in the volumetric sweep efficiency in low-tension waterflooding. Gravity assisted recovery, however, when flow direction corresponds to that of the resultant of active forces, may be considered as a favourable case for low-tension processes where undesirable effects are minimized.

INTRODUCTION

The use of low interfacial tension (IFT) solutions for oil recovery enhancement was proposed first by Uren and Fahmy [1] early in our century. Much later, Taber [2] recognized the necessity of a dramatical IFT reduction to mobilize waterflood residual oil. The location and flow of the displaced oil are affected by the active viscous and gravitational forces frequently expressed by the dimensionless N_C capillary and N_B Bond numbers. Lefebvre du Pray [3] demonstrated that residual oil saturation in a synthetic porous medium can be correlated with the ratio of viscous to interfacial forces (N_C). The same was proved by Bardon and Longeron [4] in their similar studies on natural cores. While the role of the capillary number was emphasized, less attention was given to the gravitational forces as Foster [5] pointed out. Török and Gesztesi [6] presented laboratory tests which indicate spontaneous segregation and secondary entrapment of mobilized oil droplets in

low-tension waterflooding. Hornof and Morrow [7] observed fuzzy interface developed in the course of oil displacement by surfactant solutions in micromodel of horizontally oriented plane. It was related to the joint effect of viscous and gravitational forces. Török et al. [8] found that Bond-number dominates over capillary number in about 70 percent of the porous rock volume between the surrounding injection and production wells. It also indicates that gravitational effect is an important component of the mechanism often ignored in low-tension oil recovery processes.

This paper is the summary of Hungarian experiences on gravitational effect in LTW flooding based on laboratory experiments and on a gravity assisted single-well test.

LABORATORY STUDIES

Laboratory studies were performed at or near ambient conditions in the presence of dead oil or n-octane in waterflooded unconsolidated sandpacks contained by transparent models. About 0.01 mN/m IFT in the displacing water/oil system was set by sodium salts of petroleum sulphonate or dodecylbenzene-sulphonate. The mechanism was studied by videorecorded observations of static and dynamic tests.

Segregation tests. Sand in vertically oriented test tubes was saturated with oil and water and with oil and low-tension water in a proportion which corresponds to the residual oil/water ratio in waterflooded sand. No change was observed in oil/water system. In the oil/low-tension water system, however, oil segregation occurred and an oil bank developed at the top. No coalescence of rising oil droplets in low-tension environment took place. It may be explained by the dispersive effect of capillary constrictions. Minimum oil retention within the separated low-tension water phase below the oil bank was attributed to the presence of dead-end pores. Typical states of the comparative bench tests are illustrated in Figure 1. Static tests suggest that oil segregation could promote a gravity override of the low-tension displacing phase at horizontal flow conditions.

Displacement tests in periodic glass capillary. Displacement tests were performed in a horizontal glass capillary filled with oil. Typical secondary entrapment of oil droplets was observed in all domes of the sinusoidal extensions only at LTW flooding shown in Figure 2. The results indicate that when oil droplets (present in waterflooded porous media) are mobilized their segregation and a simultaneous override of the low-tension solution is a general process in horizontal displacement which is supported by the decrease in frontal velocity.

Displacement tests in micromodel. The development and progress of the displacing low-tension front was studied in porous micromodel described by Gesztesi [9]. The 76x26 mm plane of the micromodel was set vertically to promote observation of the gravitational effect at tertiary recovery conditions. In contrast to the preceeding waterflooding, a dramatical change at the front was demonstrated (Fig.3.). Primary oil bank formation at the top, a decrease in its thickness along the inclined front developed towards the bottom zone and a strong gravity override of the surfactant solution there were related to the spontaneous oil segregation within the low-tension solution.

Displacement tests in long models. Microvisual studies were repeated in a 100 cm long transparent model of 7 cm height. The thickness of the 160-200 μ m particle size sandpack was about 2 mm. Events at oil saturation, waterflooding and displacement with LTW were observed and recorded by a scanning video camera. The development of four sections could be distinguished at tertiary recovery conditions: immobile waterflood residual oil ahead of a high oil-saturation bank, a thick zone where mobilized oil exists behind the bank which is followed by the continuously injected surfactant solution in an essentially oil-free portion of the model towards the

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inlet face (Fig.4.). The basic characteristics of the oil bank were as in the micromodel, except its front which was often fuzzy. The transitional zone consists of mobile oil droplets. They temporarily survive the rise but form "clouds" of higher oil saturation and a bank when rising. The experiments in long models reflect the basic features of the foregoing tests and are in agreement with the consideration of the role of gravitational forces in low-tension processes.

Interpretation. Laboratory experiments prove the importance of gravitational force in low-tension waterflooding. It is responsible for the profile of the oil bank, the displacing front and the development of a transitional zone behind it as a consequence of the delayed mobilization of less accessible residual oil subject to secondary entrapment. The gravity override of LTW could decrease the displacement efficiency of slug-type processes in horizontal flow. Laboratory result on residual oil saturation distribution after low-tension waterflooding published by Török and Gesztesi [6], reported analyses of cores drilled after surfactant flooding for the Benton and Loudon tests by French et al. [10] and Reppert et al. [11] support these ideas. Best results may be expected in a range of paths from vertical to a direction defined by the resultant of the actual Bond and capillary numbers. This assumption is in agreement with the performance of wells at the White Castle field test described by Falls et al. [12]

SINGLE-WELL TEST

A single-well test performed in the Szeged-Móraváros field, South Hungary, aimed at the study of a gravity assisted low-tension process. The field was discovered in 1972. The reservoir rock is a fractured Lower-Triassic sandstone with dolomite breccia and a porous Miocene sandstone and conglomerate above it. The average net pay thickness is 180 m. The Miocene sandstone chosen for the test has $0.1 \mu\text{m}^2$ average permeability and 13% porosity. It contains sodium-chloride-type 8.8 kg/m^3 TDS formation water, oil of 817 kg/m^3 density at standard state and 0.19 mPa.s viscosity at 331 bars, 140°C reservoir conditions without primary gas cap. Production started in December, 1975. The field operates under waterflooding since 1981. At present it is completely watered-out.

Well TW perforated at the top of the Miocene sandstone was selected for the segregation test. (Fig.5.) It produced with 2-3 % oil cut which did not change after repeated shut in. The placement of 2 wt.% active petroleum sulphonate in 1700 m^3 injection water was realized between November 21 and December 2, 1994. Then the well was shut in. The 120 day curing period was interrupted with short time re-openings. No increase in the oil cut was observed till March 1995. Continued 3 hrs. test production with $3 \text{ m}^3/\text{hr}$ rate resulted in clean oil followed by the appearance of oil-in-LTW-type emulsion. Time and rate of test production were chosen to follow the expected segregation through clean oil production with minimum emulsion afterflow. Analyses of the effluents proved the presence of unchanged reservoir oil and the partial decomposition of sulphonate at high reservoir temperature. This character was maintained through the next two years due to the sufficient activity of the remaining surfactant, while the low oil cut did not change in the course of short time production of "blank" wells BW-1, BW-2, BW-3 around TW. The history is shown in Figure 6. It indicates efficient oil mobilization and bank formation as a consequence of segregation in the reservoir.

The results are in agreement with the laboratory observations and support the conclusions concerning the role of gravitational forces in low-tension oil recovery processes.

CONCLUSIONS

1. Gravitational force has an important role in low-tension oil recovery processes.
2. The dominance of gravitational over viscous forces are responsible for the characteristics and development of the oil bank, the transitional zone behind it and for the underdrive of the low-tension water in horizontal displacement.
3. Underdrive could unfavourably affect slug-type low-tension processes.
4. Efficient recovery may be expected in vertical flow or along a path defined by the resultant of the active gravitational and viscous forces.

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Fig.1. Intermediate state of the segregation test

Blank (A), segregated oil at the top, essentially pure LTW at the bottom and a shrinking zone of rising oil droplets between them in the presence of LTW (B)

Fig.2. Oil displacement in periodic glass capillary
Perfect displacement at waterflooding (A), segregation at 0.1 mN/m (B) and 0.01 mN/m (C) with LTW underdrive and rate influenced profile of oil in the domes shown in enlargement (D)

Fig.3. Advancing front of the 0.01 mN/m LTW in a micro-model test.

Gravity underdrive at 0.05 PV (A) and 0.10 PV (B) LTW injection is demonstrated.

Fig.4. Characteristics of the frontal zones in long model LTW flooding

Waterflood residual oil (A) ahead of the oil bank (B) driven by a zone of rising oil droplets in LTW (C) above the underdriving low-to-zero oil content LTW (D)

Fig. 5. Location and geological structure of the oil-bearing zone in the test well TW, Szeged-Móraváros field, South Hungary

Fig. 6. Net oil from test well TW during periodical 3 hrs. production with 3 m³/hr. rate