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INFLUENCE OF RESERVOIR PARAMETERS ON BACTERIAL ENHANCED OIL RECOVERY

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ABSTRACT

The aim of this paper is to show the scope of the applicability of bacteria for enhanced oil recovery (EOR) in the oil reservoirs. The Application of conventional EOR-techniques is economically problematic because of the high production costs and oil prices fluctuation. For this reasons other tertiary methods have to be developed to minimize the economic risk of oil recovery. One solution to this problem is the Microbially Improved Oil Recovery (MIOR). With this method, oil mobilization is due to the injection of bacteria into an oil-bearing reservoir.

In this paper, the methods to find suitable bacteria, the assessment of their oil mobilizing abilities and the determination of the responsible mechanisms for oil mobilization will be also discussed.

Static Autoclave experiments (without reservoir rock) and dynamic flooding tests have been carried out.

With the help of the static experiments under reservoir conditions (pressure, temperature and salinity), two oil mobilizing bacterial strains have been found.

Flooding experiments were carried out under reservoir conditions, in order to verify the ability of applied bacteria to mobilize residual oil in place and to detect the oil mobilizing mechanisms.

It was found, that the most important factors influencing the oil mobilization are:

the permeability reduction factor of the reservoir pores and the change in wettability due to the growth of bacteria.

1. INTRODUCTION

In oil reservoirs about 70% of the original oil in place (OOIP) remains as residual oil in place (ROIP) after primary and secondary oil recovery because of geological and physical conditions.

By means of Enhanced Oil Recovery (EOR), additional oil is recoverd. The application of the conventional EOR-treatments is not always economical. For this reason, efforts are made to develop alternative tertiary methods with a lower economical application risk. One of these alternatives is the application of mobilizing microorganisms in reservoirs.

The intention of this work is the investigation on several microorganisms that mobilize residual oil under reservoir conditions. The following aims are pursued:

- Identification of oil mobilizing due to pure and mixed bacterial cultures,
- Investigation of oil mobilization mechanisms caused by microorganisms, and
- Quantification of the increase in sweep efficiency.

The bacteria strains were isolated from oil reservoirs as pure and mixed cultures.

The investigation was carried out by means of dynamic flooding tests on core samples of unconsolidated sand (with and without carbonate) and consolidated sandstone. In order to isolate suitable bacterial strains, static autoclave screening tests were performed. These tests are not so time-consuming as the flooding experiments and they also allow varying the environmental parameters that have an influence on the microbial growth and metabolism. The flooding experiments however were performed under reservoir conditions to detect the mobilization of residual oil in place.

2. MATERIALS AND METHODS

In the experimental work, two different crude oils (Crude oil K and E) from oil reservoirs were used. The oil samples were collected from wellheads under nitrogen atmosphere, to avoid the oxidation of crude oil samples. The chemical and physical properties of the crude oils were determined and are summarized in Table 1.

Table 1. Chemical and physical properties of used crud oils

Oil Sample	Pour Point, [°C]	Density at 40 °C, [g/cm^3]	Viscosity at 40 °C, [cp]	Aliphatic Hydrocarbon, [w.%]	Aromatic Hydrocarbon, [w.%]	Hetro-Hydrocarbon, [w.%]
K	-8.0	0.861	11.0	21.3	55.3	23.4
E	12.0	0.890	199.5	22.5	34.2	42.6

The basic medium for cultivation of the strains was Cooper's minimal medium [1].

The applied bacterial strains were already adapted to oil reservoir conditions. All tested strains are facultative anaerobic and have a length of 1.9 to 2.9 μm and a width of 0.6 to 0.8 μm. The selected bacteria must be able to migrate into the pores of the reservoir rock and, additionally, have to be resistant against the existing reservoir conditions. The salt content of different nutrient solutions was adjusted to the reservoir brine concentration and to the optimum salinity that is harmful for the selected microorganisms.

Static Autoclave Experiments

Static experiments were carried out in high-pressure autoclaves filled in by degassed and demineralized water as a hydraulic liquid. Three sample flasks of 35-ml volume could be placed in each autoclave. Every sample flask contained 15 ml of the medium to be cultivated and 16 ml of sterile crude oil. After inoculation of filled flasks with 1 ml of exponentially grown culture ($5x10^8$ cells/ml), the growth, the fermentation metabolites, such as acids, alcohols and polymer produced by tested microorganisms were detected. Different times of incubation at pressures of up to $197x10^5$ pa and at temperatures up to 50 °C were selected. The concentration of metabolites; pH-value of the water phase; dynamic viscosity of both phases, interfacial tension between water phase and oil phase and water content in the oil phase were determined after the appropriate incubation time. The strains that did not cause a significant change in the mentioned physical properties were disqualified and no further investigations were carried out on these.

Dynamic Experiments

The control and optimization of the oil mobilizing ability of the selected bacterial strains is performed by means of dynamic flooding tests, which simulate reservoir conditions.

The aims of the flooding experiments are the investigation of the effectiveness of the produced microbial metabolites in reservoir rock and the determination of the petrophysical parameters of oil and its mobilization mechanisms. The flooding apparatus is similar to that used by other researchers [2-5]. The clay- and lime-free sandstone core samples with a distribution of pore sizes between 15 and 25 μm and an absolute permeability between 2.2 and 4.7 μm^2 were used through this study.

Two salt solutions were used namely: a model brine with a salinity of 10 w.-% NaCl and an original reservoir brine obtained from an oil field.

Experimental Procedures

After determining their petrophysical parameters and the core properties were determined. All cores were placed in Teflon tubes, assembled with core holders and sterilized at 165 °C for 3 hrs. An overburden pressure of 197×10^5 pa was maintained.

Each sandstone core was evacuated and afterwards flushed with CO_2 for 15 min. The cores were evacuated again, saturated with brine (10 % NaCl) and flooded with crude oil. The original oil in place (OOIP) was determined as the volume of brine displaced by oil flooding. The cores were flooded with model brine until residual oil saturation (ROS) was reached. Figure 1 shows the significant course of oil saturation corresponding to the injected water volume until residual oil saturation was reached. The obtained data are also given in table 2.

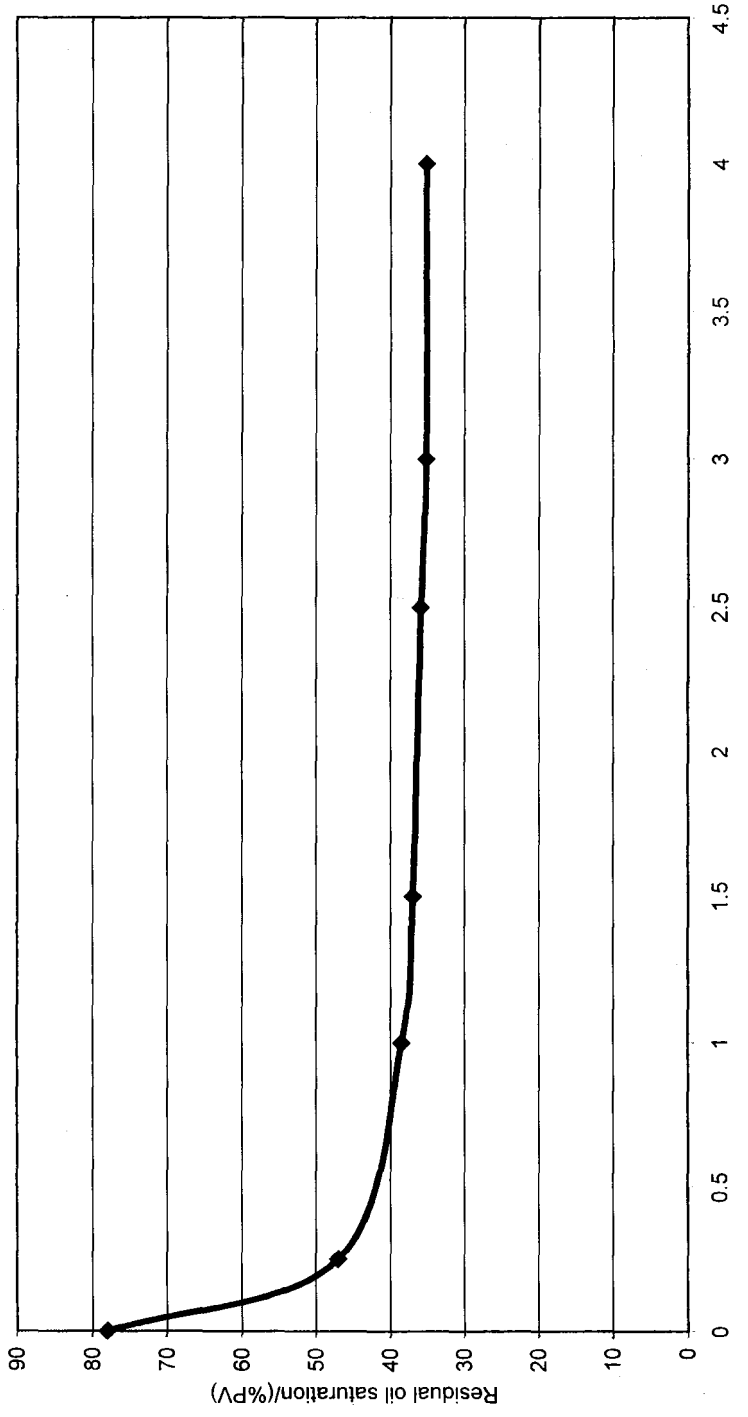

Fig. 1. Residual oil saturation versus injected water volume before bacterial treatment

Table 2. Residual oil saturation versus injected water volume before bacterial treatment

Injected water volume, [PV]	0	0.25	1	1.5	2.5	3	4
Residual oil saturation, [%PV]	78	47	38.5	37	35.9	35.2	35.2

After adjusting the reservoir conditions, such as overburden pressure, residual oil saturation, salinity, and temperature, the bacterial treatment was started. The cores have been treated with 0.5-0.6 pore volume (PV) of pure or mixed culture of bacteria in nutrient solution (1:4 v/v) in the absence of oxygen. The injection was immediately stopped after bacterial concentration in the displaced fluid reached the starting concentration. Together with every newly applied bacterial strain, a control core was saturated with nutrient solution only to verify the effect of the nutrients alone on the core properties. The inoculated cores were kept at 30 °C and 50 °C, respectively. At the end of the incubation time, the cores were flooded with the same brine which has been used to saturate the cores. A Darcy flooding velocity of 0.3 m/d (1 ft/D) has been chosen for all experiments. The physical as well as the chemical properties of the displaced fluids (oil and brine) were measured, moreover the core parameters after bacterial treatment were determined. The inoculation of some cores was repeated several times to stimulate remaining bacteria in the core to an additional growth for oil mobilization.

Recovery Efficiency

The main goal of an application of microorganisms into a reservoir is an increase in the sweep efficiency. The additionally mobilized a mount of oil (ΔS_o) is determined as a difference between residual oil saturation after water flooding (S_{orw}) and residual oil saturation after bacterial treatment (S_{orb}) and the recovery efficiency E_r can be calculated as:

$$E_r = (\Delta S_0 / S_{orw}) \cdot 100\%$$

Permeability Reduction Factor

The determination of the effective permeability of the core samples after the bacterial treatment is necessary to calculate the permeability reduction

factor (PRF). The PRF describes the ratio between effective permeability after bacterial treatment (K_{wb}) to that before bacterial treatment (K_{wsor}) and can be given as:

$$PRF=[1-(K_{wb}/K_{wsor})]\cdot 100\%$$

The PRF provides information about the in situ growth of microorganisms and about the production of metabolites, such as biomass and biopolymers. A permeability reduction is due to a preferred growth of bacteria in higher permeable rock zones. This means a heterogeneity reduction of the reservoir rock, which increases the volumetric sweep efficiency of the reservoir.

Wettability Change in the Rock Surface

The wettability of a reservoir rock is one of the important factors that influences the sweep efficiency of a reservoir. The wettability varies between water-wet and oil-wet.

An investigation of the wettability has been carried out through the measurement of the contact angle. The contact angle was measured in presence of oil and reservoir water mixed with metabolites of different pH-values on a pure silica surface. Values in the range of 90 ° were determined, which means that no capillary forces have to be overcome at the oil mobilization and transport through the rock pores. This phenomenon will also lead to the increase of the sweep efficiency. Figure 2 shows the relationship between measured contact angle and pH of metabolites in presence of oil and the obtained data are also given in table 3.

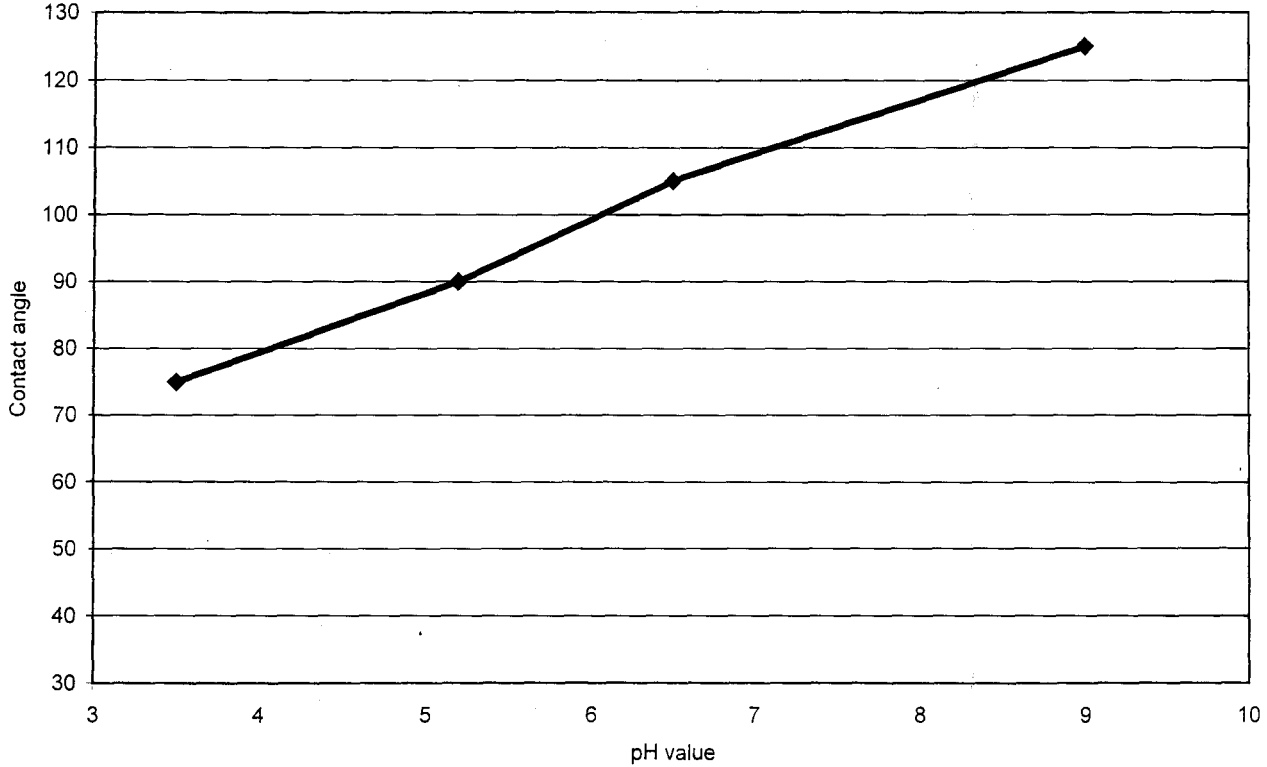

Fig. 2. Relationship between measured contact angle and pH

Table 3. Relationship between contact angle and pH

PH	3.5	5.2	6.5	9
Contact angle, [°]	75	90	105	125

3. RESULTS

Static Experiments

With the help of the static experiments, the parameters, which influence the growth of different microorganisms, were determined. The effects of the temperature, pressure, salinity and oil type on bacterial metabolic activity were studied.

Different bacterial strains could grow in the presence of oil samples; however, the growth of the microorganisms is dependent on the oil composition. The presence of oil reduced the growth rate as well as the production of metabolites. Figures 3 as well as table 4 show the effect of the crude oil on polymer production by one of the used strains.

Table 4. Effect of crude oil on the polymer production of the bacteria in function of incubation time

Incubation time [day]	0	2	3	5	8	11
Viscosity of water phase [cp]; **K-oil**	1.2	7.2	6.8	6	7	8
Viscosity of water phase [cp]; **E-oil**	1.2	4	4.1	4	3.8	3.7

In presence of crude oil K, the dynamic viscosity increased to a value of 8 cp after an incubation time of 11 days while the viscosity of the water phase in the presence of crude oil E did not exceed a value of 4 cp under the same conditions.

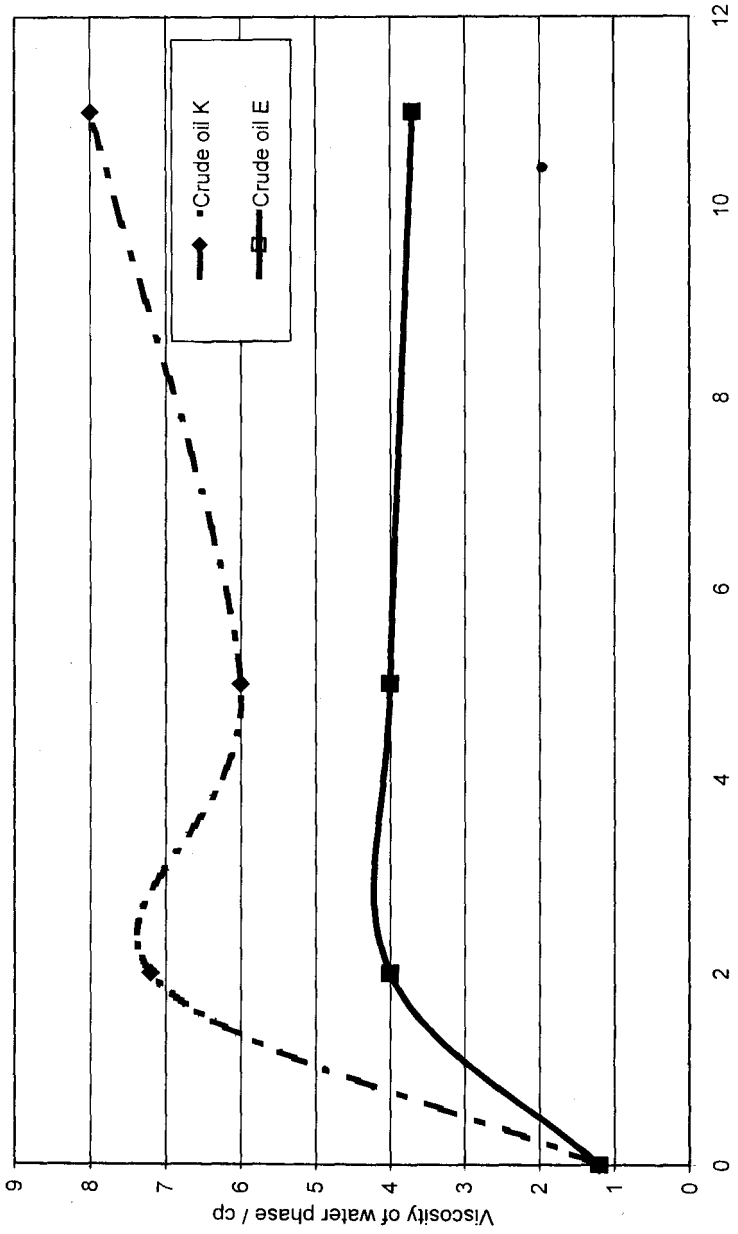

Fig. 3. Effect of crude oil on polymer production

The incubation temperature of the strains is also an important factor for the growth rate and for the production of metabolites. Figure 4 and table 5 show the influence of the incubation temperature on the production of polymer at 30 °C and 50 °C in the presence of crude oil K.

Table 5. Effect of temperature on the polymer production of the bacteria in function of incubation time in presence of oil sample K

Incubation time [day]	0	2	3	5	8	11
Incubation temp. at 50 °C	1.2	1.7	1.65	1.6	1.3	1.3
Incubation temp. at 30 °C	1.2	7.5	7	6.2	7	8

The tested strains are able to grow up to 50 °C, even though the growth of the bacteria suffered rapidly at temperatures above 30 °C. In contrast, the increase of pressure shows no significant influence on the growth of the bacteria.

The influence of salinity on the bacterial strains was also studied. At a concentration of 5 % NaCl, a production of biomass was observed, while the viscosity increased slightly. At a higher salinity (10 % NaCl), no production of biomass was observed and the viscosity remained at the same value as at salt concentration of 5 % NaCl. Moreover, the microorganisms need an adaptation time to start growing and producing metabolites. The needed time period depends on the reservoir parameters and was determined by the remaining nutrients (sugar) in the water phase.

Dynamic Core Flooding Experiments

The isolated bacterial strains, which showed an ability to grow in the static experiments under reservoir conditions, were further examined in core flooding experiments to ensure their ability in enhancement of oil recovery.

Several flooding experiments have been conducted and showed that the isolated strains could mobilize residual oil. The inoculated cores were stored at different temperatures and incubation times as previously mentioned and were flooded with water. Table 6 presents the core and oil recovery data. No oil was produced from the control cores.

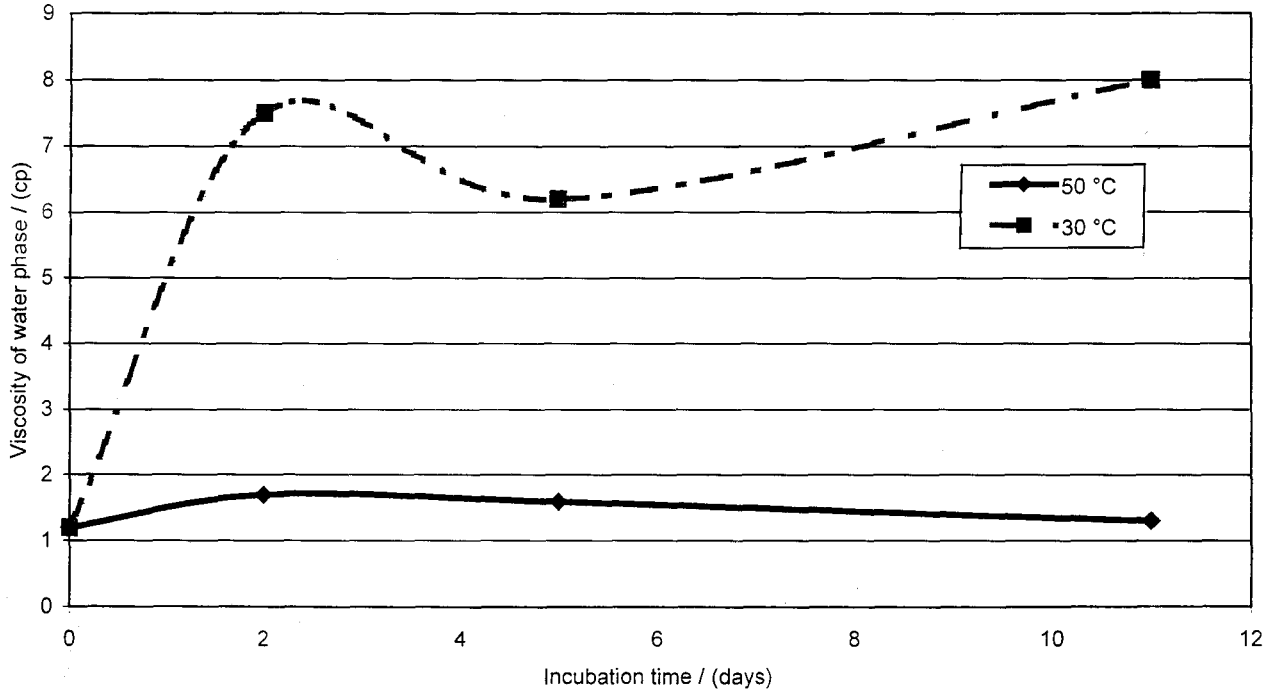

Fig. 4. Influence of the incubation temperature on the production of polymer

Table 6. Core and oil recovery data

Core No.	Temp. (°C)	K_{abs} (μm^2)	K_{wsor} (μm^2)	K_{wb} (μm^2)	PRF (%)	OOIP (%PV)	S_{orw} (%PV)	S_{orb} (%PV)	E_r (%ROIP)	MIOR recovery (%OOIP)
1	47	2.5	0.494	0.473	5	76.7	32.5	30.7	5.5	2.3
2	47	3.3	0.513	0.350	32	77.7	35.2	27.5	21.9	9.9
3	30	2.7	0.188	0.108	43	72.7	34.4	31.2	9.3	4.4
4	30	4.5	0.405	0.193	52	74.0	31.7	24.7	22.1	9.5
5	47	4.7	0.691	0.632	8	63.0	36.3	25.0	31.0	17.9
6	47	2.9	1.23	1.165	6	70.5	35.9	28.6	20.3	10.4

Figure 5 and table 7 show the course of oil saturation before and after bacterial treatment.

Table 7. Residual oil saturation versus injected water volume before bacterial treatment

	Before bacterial treatment							After bacterial treatment				
Injected water volume, [PV]	0	0.25	1	1.5	2.5	3	4	4.5	5	5.5	6.5	7
Residual oil saturation, [%PV]	78	47	38.5	37	35.9	35.2	35.2	32	30	29	7.5	27.5

The achieved sweep efficiency varied from 3 % to 31 % of the residual oil in place (ROIP). The application of mixed culture showed a small increase in sweep efficiency (3 %). This means that the application of pure cultures is more efficient than the mixed culture.

The microbial activity influences the physical parameters of the fluid content in the core samples. However, this study could show that other mechanisms were responsible for the mobilization and transport of residual oil through the rock pores, such as permeability reduction and change in wettability (reduction of capillary forces). The permeability reduction is due to the growth of microorganisms and the adherence of biomass as well as biopolymer to the rock surface.

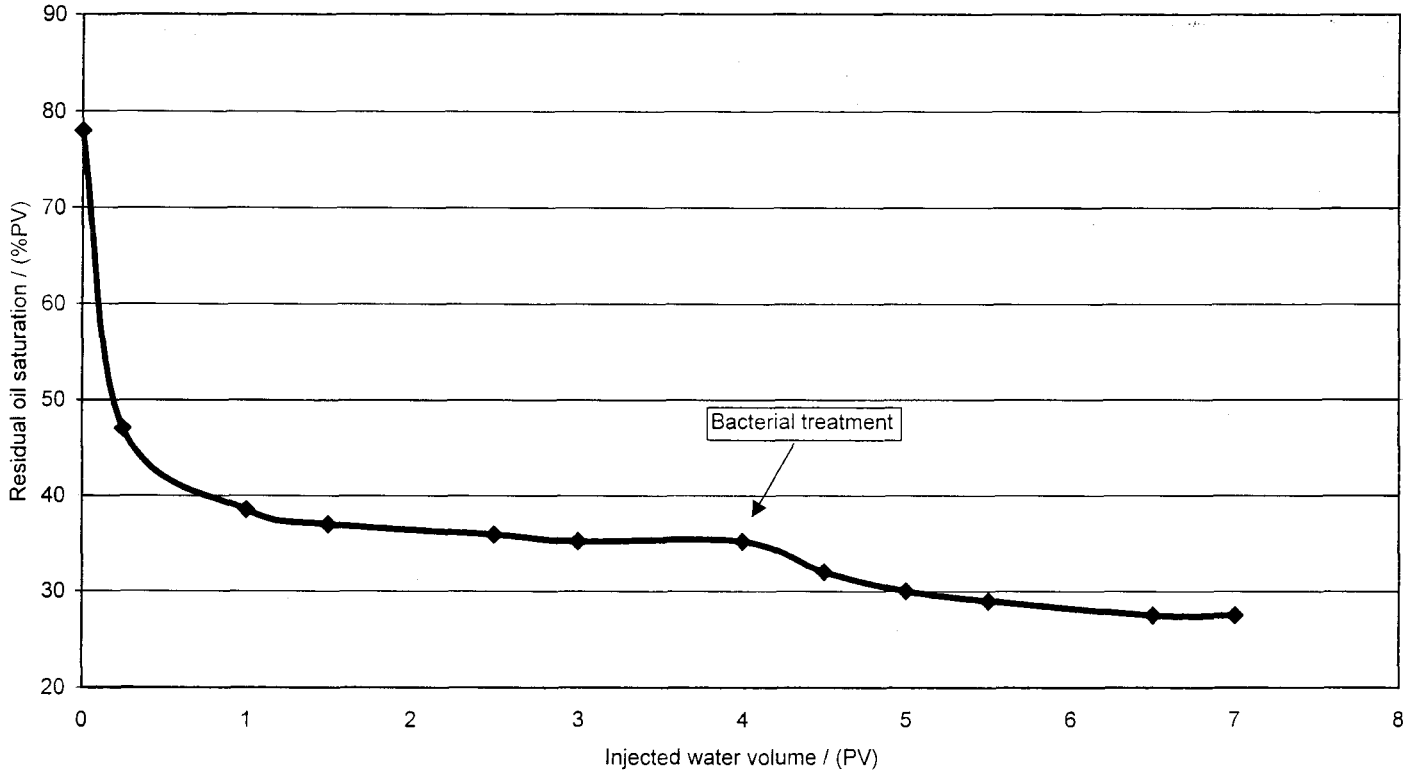

Fig. 5. Course of residual oil saturation before and after bacterial treatment

The permeability reduction, caused by plugging of high permeable pores, leads to the diversion of water into lower permeable zones. This fact causes a better volumetric sweep of the reservoir. Scanning electron microscopy (SEM) confirmed an in situ growth of bacteria.

Figure 6 shows SEM of the rock surface before bacterial treatment.

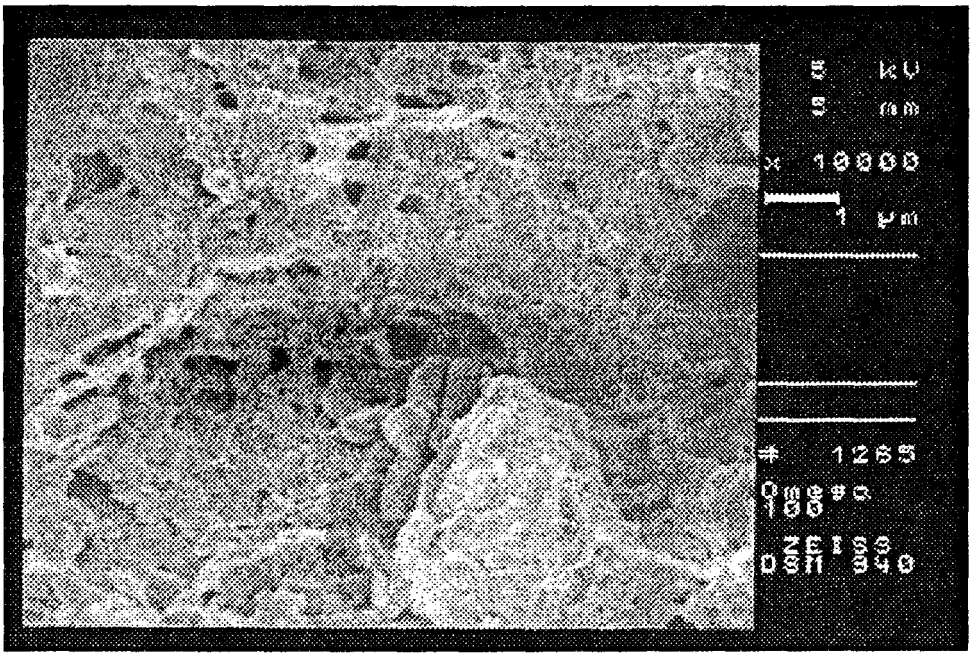

Figure 6- Rock surface before bacterial treatment

Figure 7A and B show the attachment of the microorganisms and their metabolites on the rock surface.

The experiments carried out on material containing carbonate showed a better sweep efficiency than those on silica core samples. This effect is due to the chemical composition of the rock materials. However, even with the in situ growth of the microorganisms, a reduction of permeability in carbonate containing core samples was not observed. This phenomenon can be explained by the effect of two competing processes namely, a reduction of permeability caused by the growth of bacteria and an improvement of permeability caused by the production of organic acids, and subsequently, the solution of carbonates.

Figure 7A- SEM shows rock surface attached by microorganisms

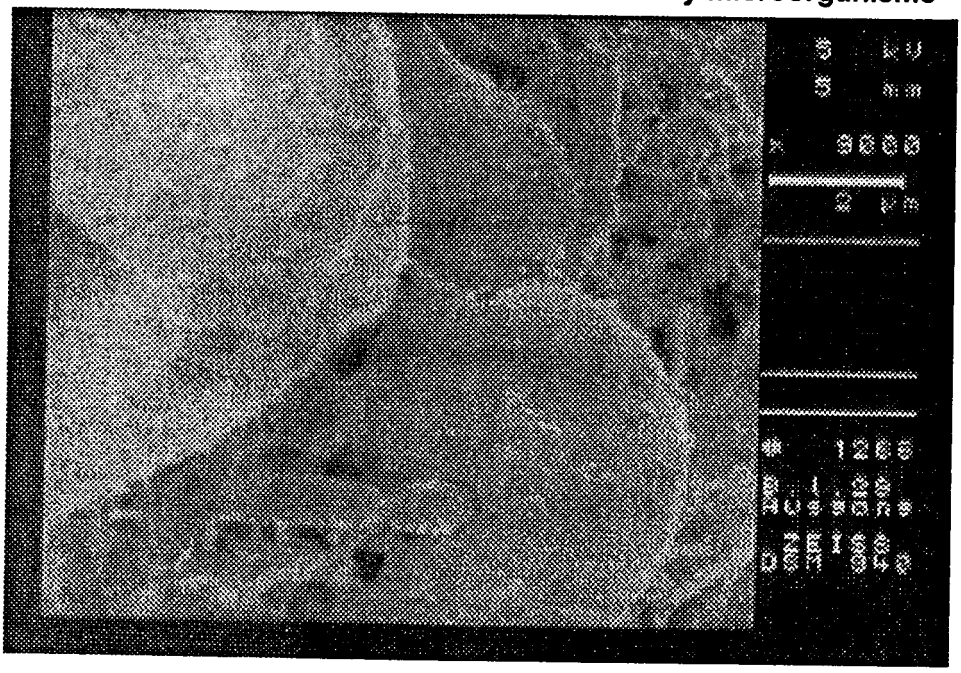

Fig. 7B. SEM shows rock surface attached by microorganisms and biomass.

The residual oil mobilization can also be affected by the production of gases. Under anaerobic conditions, the isolated strains produced CO_2 and N_2, which are supporting the sweep efficiency. All mechanisms discussed lead to a reduction of residual oil saturation, and the microbially induced sweep efficiency can be expressed by the following formula:

$$(\Delta S_o)_{MIOR}=(\Delta S_0)_{biomass}+(\Delta S_0)_{biopolymer}+(\Delta S_0)_{wettabilit}+(\Delta S_0)_{ga}$$

4. CONCLUSIONS

MIOR is a potentially attractive way to recover additional oil from reservoirs when conventional operations become uneconomical. Several bacterial strains have been isolated which have favorable characteristics for in situ MIOR. The scope of this work was to investigate the applicability of isolated bacteria under reservoir conditions. The mechanisms leading to mobilization of residual oil in place due to in situ effectiveness of microorganisms were identified and described. Two independent methods, static autoclave tests and flooding tests, have been used to investigate the MIOR-ability of bacteria. By means of the static autoclave experiments, a significant influence of the reservoir parameters on the growth of bacteria had been demonstrated. The effect of such parameters as oil composition, reservoir temperature and salinity were determined. The presence of oil samples, especially at high temperature, significantly changes the metabolic activity of the bacteria.

The dynamic flooding experiments on reservoir rocks were necessary for a final assessment of the microbial strains. The results of the dynamic flooding tests showed clearly that injectivity and migration of the isolated strains are ensured. The tested strains are also able to mobilize oil under reservoir conditions. The factors responsible for the mobilization of residual oil due to bacteria are:

- The reduction in permeability due to the adhesion of biomass and microorganisms on the grain surfaces of the reservoir rock.

- The metabolites of the bacteria (such as Acids, biopolymer and gases) contributed also to the increase of the oil mobilization

- In flooding tests performed in the presence of carbonate rock samples, higher oil mobilization were obtained as compared to flooding tests in

sandstone cores. This fact is due to the wettability behavior of carbonate rocks.

Flooding tests with mixed cultures have shown less oil mobilization than tests carried out with pure cultures. This means that different bacterial strains may have negative impact on each other.

The activity of the microorganisms can be controlled by the amount of injected nutrients. Flooding experiments using only nutrients did not lead to any oil mobilization.

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