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Possible Applications of MEOR to the Arab Oil Fields

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Abstract. Large quantities of residual oil will remain in the Arab oil reservoirs after the primary recovery and water-flooding stages. Because of the large sizes of the Saudi oil fields (in particular), the amount of the residual oil will be enormous. According to the latest published data, the original oil in-place in Saudi Arabia is about 700 billion barrels. Only around 250 billion barrels, 35% of total oil in-place, can be produced by conventional production methods. More than 90 billion barrels, as much as twice the proven reserve of the U.S. and Canada combined, can be added to the country's proven reserve if only 20% out of the 450 billion barrels left in-place are produced through enhanced oil recovery methods. Any method that can recover a significant part of this residual oil would be of great importance and should be investigated. Microbial Enhanced Oil Recovery (MEOR) has been recognized as a potentially cost-effective recovery method.

This paper is an investigation of the applicability of MEOR for recovering more oil under the Arab oil fields conditions. Based on the analysis of data obtained from more than 300 formations in seven Arab countries (Saudi Arabia, Egypt, Kuwait, Qatar, UAE, Iraq and Syria), the possibility of the application of MEOR to the Arabian area was studied. The basic parameters studied include formation permeability, reservoir pressure and temperature, crude oil viscosity and API gravity, formation connate water saturation and its salinity. It was found that Saudi, Iraqi and Egyptian oil fields can be very good candidates for MEOR processes. Also Qatar, Kuwait and Syria have some potential for MEOR. United Arab Emirates, however, has no potential for MEOR under its reservoir conditions.

It is expected that MEOR should recover up to 30% of the residual oil under the Arab reservoir conditions. The actual recovery, however, can only be determined through laboratory and pilot tests under field conditions. A new technology should be developed in order to be able to apply MEOR succesfully.

Introduction

Bacteria are the only microorganisms that have been proposed for enhanced oil recovery processes. They are small in size, grow exponentially and produce metabolic compounds such as gases, acids, surfactants and polymers. Bacteria also tolerate harsh environments such as high formation water salinity, high pressure and high temperature. In 1983, Bubela [1], found that the optimum metabolic temperature and rate of growth of rod-shaped bacteria increased with an increase in pressure. Moses and Springham [2, p. 178] observed that bacteria have been found to be catalytically active at high pressure. Grula *et al* [3], readily grew Clostridium in up to 75,000 ppm salt concentrations.

The earliest realization that bacteria are beneficial to the production of oil was suggested by Backman [4]. ZoBell [5] presented a process for the secondary oil recovery using anaerobic, sulfate reducing bacteria in situ. ZoBell [6] used other types of bacteria to enhanced oil recovery in laboratory tests.

In 1963, Kuznetsov *et al* [7, p 252] found that bacteria discovered in some oil reservoirs in the Soviet Union produced 2 gm of CO_2 per day per ton of rock. Later, Synyukov *et al* [8] employed micro-organisms to aid the recovery of oil.

The laboratory study of specific micro-organisms is done either for the surface production of various compounds or for the injection of cells into a reservoir for in situ production of metabolic production. Both will enhance oil recovery. Grula *et al* [9, pp 144-150] carried out laboratory tests to isolate salt-tolerant strains of some types of bacteria and then conducted field tests using them. Donaldson and Grula [10] found that some species of bacteria produce emulsifiers in salt concentrations up to 75,000 ppm. Laboratory results by Torbati *et al* [11] showed that the larger pores of Berea sandstone are plugged by the bacteria which caused a reduction of permeability leading to increasing oil recovery due to improvement in mobility ratio. Another laboratory research conducted by Bryant and Douglas [12] presented crude oil displacement mechanisms by micro-organisms.

A review of many field applications of MEOR was presented by Bryant *et al* [13]. Bryant [14] found that MEOR screening critria fit 27% of United States oil reservoirs. Recently, MEOR field applications were presented by Donaldson [15]. Hitzman [16] published a review on MEOR field testing.

Mechanisms

Many species of micro-organisms produce carbon dioxide and other gases, such as nitrogen (N_2) hydrogen (H_2) and methane (CH_4), that can improve oil recovery by increasing pressure and by reducing the crude oil viscosity leading to an improvement in mobility ratio.

Because many types of micro-organisms produce polymers, these micro-organisms have been used to plug high-permeability zones in petroleum saturated sandstones to improve sweep efficiecy and displace bypassed oil. However, these micro-organisms have been shown to reduce rock permeability [13,14,17,18; pp. 213-223]. The work in the Netherlands (Hitzman, D.O. [20]), was a selective plugging experiments using Betacoccus dextranicus and a significant increase in oil production has been reported.

Recently, the research in China reported novel micro-organisms that produce polymer, (Wang [21]). REsearchers at the University of Calgary reported a methodology for using ultra micro-bacteria to plug the formation [22].

Evaporation of volatile hydrocarbons and destruction of paraffinic compounds by micro-organisms led to high in polynuclear aromatic compounds [23] that degrade asphaltic material.

Microbes also produce low-molecular acids, primarily of low-molecular weight fatty acids, that can improve permeability in limestone and sandstone rocks with carbonaceous cementation, and thus improve oil recovery.

A potentially useful group of micro-organisms produces alcohols and ketones. These compounds are typical co-surfactants that are used in micro-emulsion solutions for stabilization and lowering of the interfacial tension promoting emulsification.

Micro-organisms produce bio-surfactant that can decrease in surface and oil-water interfacial tensions to as low as 5×10^{-3} dyne/cm [24], leading to emulsification. Several types of micro-organisms that produce bio-surfactants have been separated [25,26,27,28].

Microbes have been shown to cause wettability alteration in glass micro-models in Berea sandstone [12]. In 1986, Kianipay *et al* [29] found that the in-situ microbial growth mobilized residual oil by wettability reversal. A summary of the different microbial enhanced recovery treatment mechanisms is shown in Table 1.

Screening Criteria

The data of Middle East oil fields provide the characteristics of oil reservoirs that can be used for MEOR field projects. Extensive research is going on today in order to develop a new technology in the area of bio-technological processes that can be used under reservoir conditions of temperature, pressure, rock permeability and water salinity.

The reservoirs of the Arabian Gulf area are characterized by relatively high salinity of the formation waters. This puts a serious limitation on the use of MEOR. Most reservoir screening criteria used a TDS upper limit of 100,000 ppm. Rock per-

Table 1. Microbial enhanced oil recovery treatment mechanisms

Process	Type of micro-organism used and displacement mechanism
Enhanced waterflooding	Micro-organisms that produce low molecular weight acids (improve formation low permeability)
Improved oil recovery by gases	Micro-organisms that produce gases such as CO_2, N_2, H_2 and CH_4 (improve mobility and miscibility)
Microbial permeability modification	Micro-organisms that produce polymer and/or copious amounts of biomass (improve sweep efficiency)
Microbial polymer flooding	Micro-organisms that produce polymer (improve mobility)
Microbial surfactant flooding	Micro-organisms that produce surfactant and alcohols (improve miscibility and reduce capillary forces)

meability ranges of 1–1000 md have been reported for MEOR field project [14]. The screening criteria are presented in Table 2. No MEOR field projects have been reported where pressures and temperatures were too high for microbial growth. The usual biological limitation for temperature is about 160°F and the pressure limitation is about 20,000 psi. Saudi reservoirs temperature and pressure range from 140 to 240°F and from 2000 to 5500 psia, respectively, which means that MEOR processes can be applied with the temperature and pressure constraints. The formation rock permeability in Saudi oil reservoirs ranges from 100 to 3000 md which is a wide range for MEOR application. Sayyouh and Al-Blehed [30,31] presented a study on the screening criteria for enhanced recovery of Saudi crude oils. Enhanced recovery methods investigated in that study included thermal and non-thermal processes. MEOR was not considered in the presented non-thermal methods.

Table 2. Screening criteria [14]

	Parameter	Range suggested
1–	Reservoir rock permeability	> 75 md, unless highly fractured
2–	Reservoir depth	< 8000 ft
3–	Crude oil type	> 15° AP; as yet not enough information available for heavier crude oils
4–	Reservoir temperature	< 170°F
5–	Salinity of reservoir formation	< 10% sodium chloride; total TDS may be higher

An Example of MEOR Field Application

A good example of the MEOR field applications is the Romanian field test which was performed between 1975 and 1983. Mine wells were inoculated in seven oil reservoirs with the characteristics shown in Table 3. A significant amount of increased oil production was observed. Increased oil production was considered to be dependent on maintaining the nutrient addition. The reservoirs that had an oil viscosity below 10 cp responded best to the microbial treatment.

Table 3. Romanian field characteristics and properties [16]

Type of formation	Sand and sands with a high content of marls and clays
Depth (m)	: 336 - 1559
Temperature (°C)	: 27 - 55
Permeability (md)	: 100 - 1500
NaCl (g/l)	: 5 - 180
Oil viscosity	: 6 - 53
Oil density (Kgf/dm^3)	: 0.85 - 0.908
Oil saturation (%)	: 71 - 81

Arabian Field Data and Possible Applications

A survey of the oil field conditions that exist in more than 300 petroleum formations in the Arab world was made. A summary of the field data for each country is presented in Table 4. Figure 1 shows the variations in rock permeability for six Arab countries. It is clear that the average rock permeability ranges from less than 10 to 3000 md, which includes the permeabilities suitable for MEOR applications in Saudi Arabia, Qatar, Iraq and in some Egyptian oil reservoirs.

The average depth for all reservoirs in the Arabian area ranges from 1000 to 12,000 ft as shown in Fig. 2. UAE is not suitable for MEOR due to the high average depth range (i.e. from about 8000 to 12000 ft) as shown in Fig. 2. Syria, however, has a range of formation depth between 2000 to 6000 ft which is suitable for many types and species of bacteria. Apparently this range is beneficial because it promotes the optimum growth of micro-organisms. Figure 2 also shows that Saudi, Egyptian, Kuwaiti and Iraqi oil fields show some formation depths within the range of MEOR application.

Figure 3 shows API gravity ranges of the different crude oils. It is clear from this figure that the API gravities of the Middle East crudes are within the range of MEOR applications. However, some Iraqi crude oils are not within the range as seen in Fig. 3.

Although the oil production in Saudi Arabia, Kuwait, Qatar and UAE is essentially still in the primary and secondary phases, the production of oil in Egypt, Syria

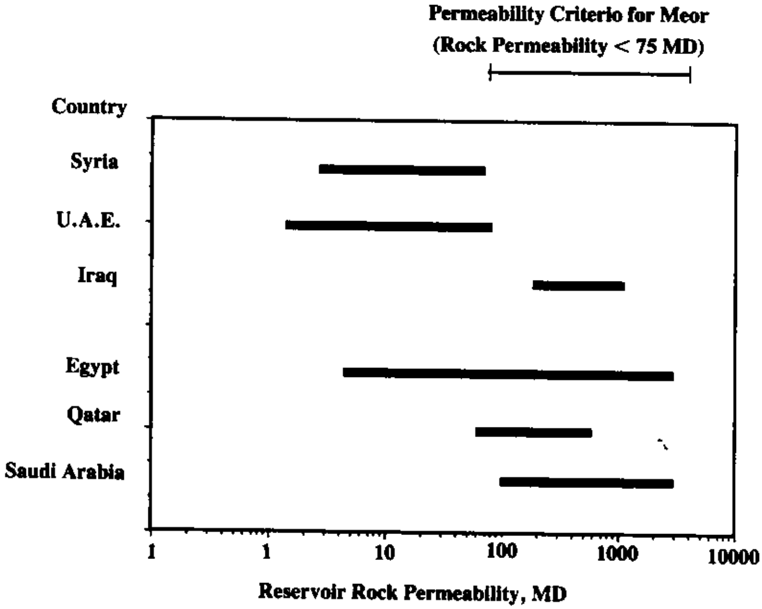

Fig. 1. Rock permeability for different Arab oil reservoirs

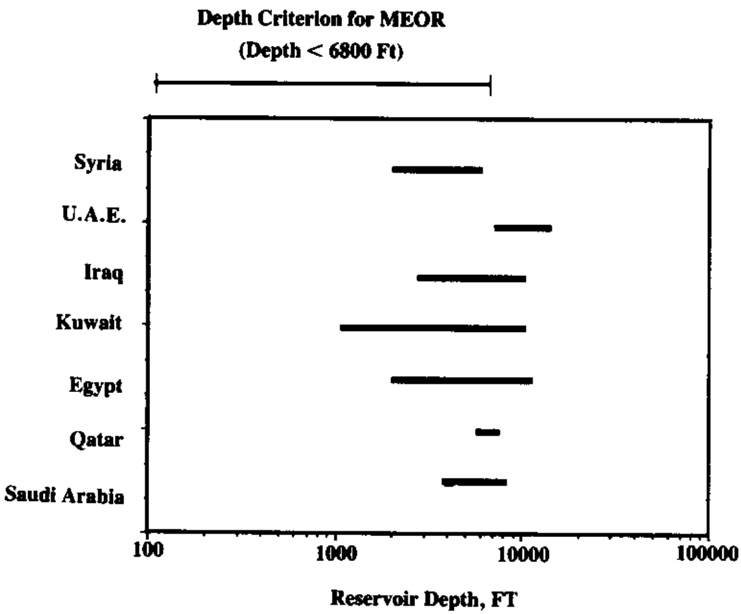

Fig. 2. Depth for different Arab oil reservoirs

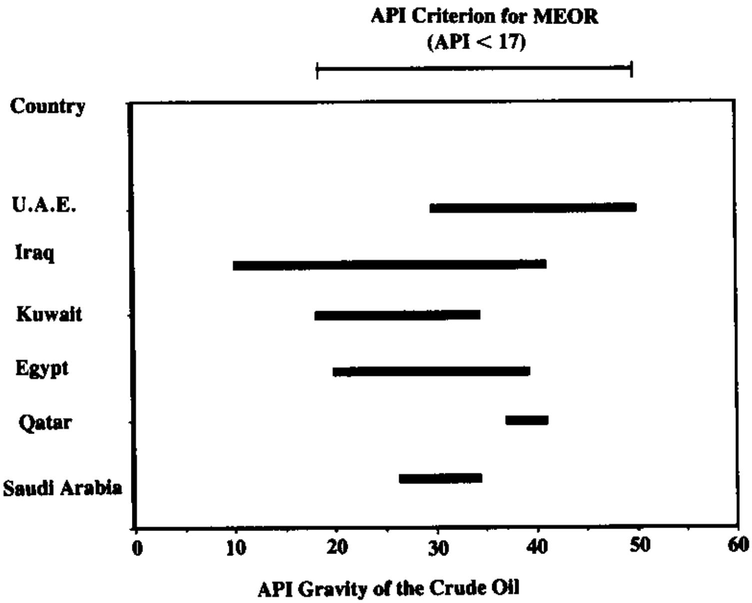

Fig. 3. API gravity for different Arab crude oils

and Iraq is mostly a secondary phase because of the age of the oil fields. The waterflooding of the existing older oilfields is becoming less efficient. The technology of microorganisms has improved to determine nutrient requirements, products of metabolism, such as gases (methane, hydrogen, nitrogen and carbon dioxide), polymer (polysaccharides and proteins), solvents and surfactants, and the limits of environmental conditions. There may be many undiscovered microbial systems that are either already existing in deep reservoirs or are capable of existence there.

The data presented in Table 1 provides the characteristics of the Arab oil reservoirs used for possible MEOR field projects. MEOR methods for improving oil recovery in depleted Egyptian and Syrian oil fields are very well suited to be applied in today's economic climate. The increased interest in MEOR recently is attributed to the low cost compared to other EOR methods. Thus, with the present low oil prices and high cost of other available EOR methods, consideration of MEOR is justified.

Limitations of MEOR

The environmental control of MEOR is of great importance. It is necessary to prevent any adverse effects on the environment when applying this recovery method.

Table 4. Oil reservoir data for different Arab countries [32]

Reservoir property	Saudi Arabia		Qatar		Kuwait		
	North area	Southern area	Onshore	Offshore	Northern area	Southern area	Neutral zone
Depth (ft)	4100 to 6800	5200 - 8000	5600 - 6600	7000	8300 to 8600	4800 - 10000	1100 - 1700
Lithology	Sandstone (Wasia)	Carbonate (Arab D)	Limestone	Limestone	Sandstone and carbonate	Carbonate except Burgan	Sandstone and carbonate
Thickness (ft)	20 - 200	100 - 300	200 - 400	80 - 400	200 - 1400		100 - 250
Porosity (%)	20 to 29	14 to 22	18		18 to 24		20 to 35
Permeability (MD)	1000 to 3000	100 to 500	65 - 150	100 - 500			
Oil gravity (° API)	27 to 34	34 to 37	37 to 42	38	28 to 33	26 to 34	18 - 23
Water salinity* (ppm)	-	-	-	-	-	-	-

* Relative high salinity in the Arabian Gulf area.

Table 4. Oil reservoir data for different Arab countries – (Continued)

Reservoir property	Iraq		UAE			Syria	Egypt
	North area	Southern area	Onshore	Offshore	Dubai		
Depth (ft)	2800 to 6500	10000 - 11000	7500 - 7900	8500 - 9150	7500 to 12900	2000 - 6000	2105 - 11900
Lithology	Carbonate	Sandstone	U. Thamana limestone	U. Thamana limestone	Limestone		Sandstone and carbonate
Thickness (ft)	-	200 - 300	81 - 170	100	-	-	-
Porosity (%)	20	20 - 25	25 - 30	19 - 29	-	-	-
Permeability (MD)	200	400 to 1000	15 - 80	1.5 - 30	3 - 70	5.3 3000	
Oil gravity (° API)	14 to 42	Sallow heavy oil 10 deeper light oil 34 - 42	41 to 44	37 to 39	30 to 50	-	20 - 38
Water salinity* (ppm)	-	-	-	-	-	-	1500 - 250000

One of the possible effects is the stimulation of indigenous sulfate-reducing bacteria which causes bio-corrosion in oil fields. The possible contaminations of surface, ground water and agriculture land during bacterial transport are of major environmental concern associated with MEOR field application.

Sometimes the mineral content of the initial water in the oil formation may inhibit the growth of the selected bacteria. Injected and connate water salinities equal or less than 100,000 ppm is required for the application of the MEOR process. Some types of microorganisms, however, can live in higher salinity environment, although great efforts will be needed to identify such organisms that resist high salinity conditions.

The enviromental parameters of the reservoir will limit the types of microorganisms which can be used for the situ processes. These parameters include permeability, temperature, pressure, salinity, salt composition, pH, the nature of the residual oil and nutrient limitation. A new technology is being considered in the search for ways to apply bacteria to oil recovery. Great effort is being expanded by microbiologists to understand the complex subsurface environment of a petroleum reservoir in relation to bacterial metabolism. This may indicate the lack of experience in this new area of enhanced oil recovery.

Conclusions

Based on the analysis given in the present study, the following conclusions are reached:

1. Extensive laboratory and field research should be carried out in order to develop a new technology in the area of microbial enhanced oil recovery under reservoir conditions of temperature, pressure, permeability and formation water salinity.

2. Saudi, Iraqi and Egyptian oil fields can be good candidates for MEOR. Qatar, Kuwait and Syria have some potential for MEOR. UAE, however, has no potential for this process considering the reservoir conditions.

3. Depleted oil fields in Egypt, Syria and Iraq can be activated by injection of micro-organisms which can be beneficial in producing more oil.

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إمكانية تطبيق الاستخلاص الميكروبي للزيت لحقول الزيت العربية

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ملخص البحث. تتبقى كميّات كبيرة من الزيت المتخلف في مكامن الزيت العربية بعد مراحل الاستخلاص الأولى والغمر بالماء. وبسبب الأحجام الكبيرة لحقول الزيت السعودية خاصة فإن الكميّات المتخلفة من الزيت ستكون كبيرة جدًّا. وطبقًا لآخر الإحصائيات المنشورة فإن كمية الزيت الأصلي في المملكة العربية السعودية تقدّر بحوالي ٧٠٠ بليون برميل. ويمكن إنتاج حوالي ٢٥٠ بليون برميل فقط (أي حوالي ٣٥ بالمائة من كمية الزيت الأصلي) بطرق الإنتاج المعروفة. وعند إمكانية استخلاص كمية تقدّر بحوالي ٢٠ بالمائة من الكمية المتبقية وهي ٤٥٠ بليون برميل بالطرق المحسّنة سوف يتم إضافة أكثر من ٩٠ مليون برميل (ضعف احتياطي الولايات المتحدة وكندا) إلى احتياطي المملكة المؤكد. ولذلك فإن أي طريقة من طرق الإنتاج المحسّن للزيت ستكون على قدر كبير من الأهمية ويجب دراستها جيدًا. ومن هذه الطرق التي أثبتت أنها قليلة التكاليف وعالية الفعالية هي طريقة الاستخلاص المحسّن بواسطة الميكروبات (البكتريا).

وتهدف هذه الدراسة إلى بحث إمكانية تطبيق الاستخلاص المُحسّن بواسطة البكتريا لحقول الزيت العربية. وبناءً على تحليل المعلومات من أكثر من ثلاثمائة طبقة في سبعة أقطار عربية (المملكة العربية السعودية ومصر والكويت وقطر والإمارات العربية والعراق وسوريا) تمت دراسة إمكانية تطبيق هذه الطريقة للمنطقة العربية، والعوامل الأساسية التي تم دراستها هي نفاذية الطبقة وضغط ودرجة حرارة المكمن ولزوجة الزيت الخام وكثافته ودرجة تشبع الماء الأصلي في الطبقة وملوحته. ووجد أن حقول الزيت في مصر والسعودية والعراق مناسبة جدًّا لعمليات الاستخلاص الميكروبي، وقد يمكن تطبيق هذه الطريقة في كل من قطر والكويت وسوريا. وبناءً على ظروف مكامن الإمارات المتحدة فإن هذه الطريقة لا يصلح تطبيقها.

ومن المتوقع استخلاص ٣٠ بالمائة من الزيت المتبقي في ظروف مشابهة لظروف المكامن العربية باستخدام هذه الطريقة. ويمكن إيجاد الاستخلاص الحقيقي من خلال الاختبارات المعملية والتجريبية باستخدام الظروف المكمنية. ويجب الاستمرار في الأبحاث لإيجاد تقنية جديدة لتطبيق ناجح لطريقة الاستخلاص الميكروبي للزيت.