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Microbial Enhanced Oil Recovery (MEOR) in Petroleum Reservoir

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Abstract:
Microbial enhanced oil recovery (MEOR), characterized with the virtues of low cost and environmental protection, reflects the prevalent belief in environmental protection, and is attracting the attention of more researchers. Nonetheless, with the prolonged slump in global oil prices, how to further reduce the cost of MEOR has become a key factor in its development. This paper described the recent development of MEOR technology in terms of mechanisms, mathematical models, and field application, meanwhile the novel technologies of MEOR such as genetically engineered microbial enhanced oil recovery (GEMEOR) and enzyme enhanced oil recovery (EEOR) were introduced. The paper proposed three possible methods to decrease the cost of MEOR: using inexpensive nutrients as substrates, applying a mixture of chemical and biological agents, and utilizing crude microbial products. Additionally, in order to reduce the uncertainty in the

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practical application of MEOR technology, it is essential to refine the reservoir screening criteria and establish a sound mathematical model of MEOR. Eventually, the paper proposes to combine genetic engineering technology and microbial hybrid culture technology to build a microbial consortium with excellent oil displacement efficiency and better environmental adaptability. This may be a vital part of the future research on MEOR technology, which will play a major role in improving its economic efficiency and practicality.
Microbial Enhanced Oil Recovery (MEOR) is a biological-based technology involving the manipulation of functions or structures within microbial environments present in oil reservoirs. The primary objective of MEOR is to improve the extraction of oil confined within porous media, while boosting economic benefits. As a tertiary oil extraction technology, MEOR enables the partial recovery of the commonly residual 2/3 of oil, effectively prolonging the operational lifespan of mature oil reservoirs.

Keywords: Microbial enhanced oil recovery, MEOR mechanisms, theory, Biopolymers, Field trials.

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الاستخلاص المعزز للنفط بالميكروبات في مكامن النفط

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الملخص:

إن تقنية الاستخلاص المعزز للنفط بالميكروبات، والتي تتميز بمزايا التكلفة المنخفضة وحماية البيئة، تعكس الاعتقاد السائد بحماية البيئة، وتجذب انتباه المزيد من الباحثين. ومع ذلك، ومع الركود المطول في أسعار النفط العالمية، أصبحت كيفية خفض تكلفة تقنية الاستخلاص المعزز للنفط بالميكروبات عاملاً رئيسياً في تطويرها. وقد وصفت هذه الورقة التطورات الأخيرة لتقنية الاستخلاص المعزز للنفط بالميكروبات من حيث الآليات والنماذج الرياضية والتطبيق الميداني، وفي الوقت نفسه تم تقديم التقنيات الجديدة لتقنية الاستخلاص المعزز للنفط بالميكروبات مثل الاستخلاص المعزز للنفط بالميكروبات المعدلة وراثيًا والاستخلاص المعزز للنفط بالإنزيم. واقترحت الورقة ثلاث طرق محتملة لتقليل تكلفة تقنية الاستخلاص المعزز للنفط بالميكروبات: استخدام المغذيات غير المكلفة كركائز، وتطبيق مزيج من العوامل الكيميائية والبيولوجية، والاستفادة من المنتجات الميكروبية الخام. بالإضافة إلى ذلك، من أجل تقليل عدم اليقين في التطبيق العملي لتقنية الاستخلاص المعزز للنفط بالميكروبات، من الضروري تحسين معايير فحص الخزانات

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وإنشاء نموذج سليم لتقنية الاستخلاص المعزز للنفط بالميكروبات. في النهاية، يقترح البحث الجمع بين تكنولوجيا الهندسة الوراثية وتكنولوجيا الثقافة الهجينة الميكروبية لبناء اتحاد ميكروبي يتمتع بكفاءة إزاحة ممتازة للنفط وقدرة أفضل على التكيف البيئي. قد يكون هذا جزءًا حيويًا من الأبحاث المستقبلية حول تكنولوجيا الاستخلاص المعزز للنفط بالميكروبات (MEOR)، والتي ستلعب دورًا رئيسيًا في تحسين كفاءتها الاقتصادية وعمليتها.

يعد الاستخراج المعزز للنفط بالميكروبات (MEOR) تقنية تعتمد على البيولوجيا وتتضمن التلاعب بالوظائف أو الهياكل داخل البيئات الميكروبية الموجودة في خزانات النفط. الهدف الأساسي من الاستخراج المعزز للنفط بالميكروبات (MEOR) هو تحسين استخراج النفط المحصور داخل الوسائط المسامية، مع تعزيز الفوائد الاقتصادية. كتكنولوجيا استخراج نفط ثالثية، تمكن MEOR من الاسترداد الجزئي لثلثي النفط المتبقي بشكل شائع، مما يطيل العمر التشغيلي لخزانات النفط الناضجة بشكل فعال.

الكلمات الرئيسية: تعزيز استخلاص النفط بالميكروبات، الآليات، النظرية، التجارب الميدانية.

1-INTRODUCTION:

Microbial Enhanced Oil Recovery (MEOR) technology is the process of introducing or stimulating viable microorganisms in an oil reservoir for the purpose of enhancing oil recovery. 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, surfactant, acids & polymers. Bacteria also tolerate harsh environments, such as high formation water salinity, high pressure and high temperature.

The basic requirements of microbial EOR are similar to those used in a biological evaluation as:

(i) Reduction of interfacial tension of rock, oil and water system.
(ii) Improvement in mobility ratio.

(iii) Increase in permeability of rock.

1.1 Effects of Microbial EOR:

The following are the effects of injection of bacteria:

a) There is a production of organic and inorganic acids as it can dissolve CO_3 and increase K.

b) There is production of gases like H_2, CH_4 and CO_2. These gases mix with oil and increase recovery.

c) Surfactants and biopolymers release hydrocarbon and reduce plugging of water zone, i.e., reduction of water fingering.

1-2-Primary Operations:

Primary oil recovery involves using natural pressure to push oil towards production wells. In these operations, oil flows from the reservoir to the production wells naturally due to the pressure present in the reservoir. Primary operations include the use of water or gas drive to increase pressure and push oil towards the wells.

1-3- Secondary Operations:

Secondary operations are used after primary operations to enhance oil recovery efficiency. These operations aim to improve oil flow. Secondary operations include water or gas injection into the reservoir without altering the properties of crude oil.

1-4-Tertiary Operations:

Tertiary operations are more complex and advanced, and they are employed to increase oil recovery after primary and secondary operations have failed. Tertiary operations involve the application of advanced techniques such as steam injection, liquefied gas injection, and advanced chemical injection. Steam injection is used to heat the oil and reduce its viscosity, making it easier to extract. Liquefied gas injection is used to increase pressure and push the oil towards the wells. Advanced chemical substances are utilized to alter the properties of the oil, such as reducing its viscosity, with the goal of improving recovery as shown in the Figure(1), [1].

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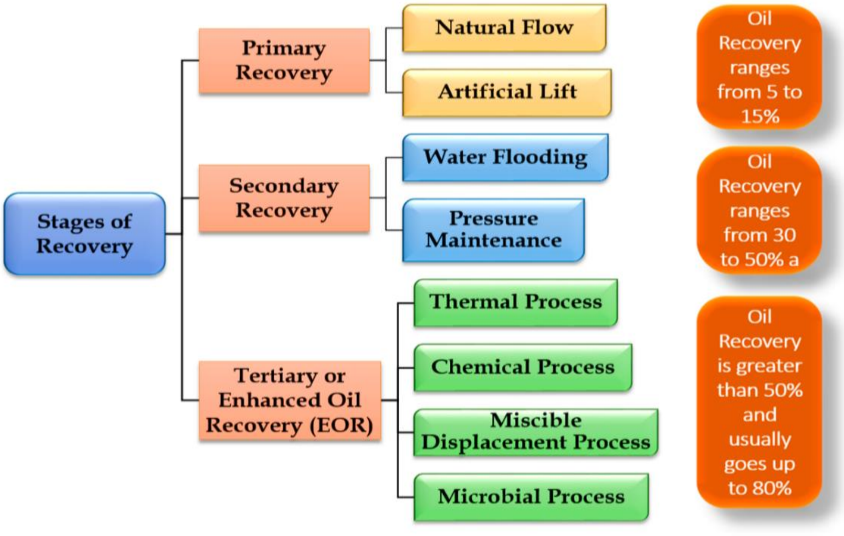

Figure (1): Schematics on the classification of the oil recovery phases.

Despite the importance and effectiveness of previous enhanced methods for extracting crude oil, significant amounts of crude oil remain trapped in wells that are difficult to extract. This has prompted researchers to search for new methods to enhance productivity and extract heavy and highly viscous oil.
One modern enhanced method for extracting crude oil that has gained considerable attention is the use of certain bacterial strains. The activity of these microorganisms is exploited to release the heavy oil trapped in rocks and reduce its viscosity, thereby allowing the resumption of oil pumping from wells that have ceased production.

2- Microbial Enhanced Oil Recovery:

2-1- Definition of processes:

Microbial Enhanced Oil Recovery (MEOR) is a process that relies on the use of naturally occurring bacteria in oil fields or intentionally adding specific bacteria. These bacteria feed on organic materials present in the oil fields and convert them into useful chemical compounds, such as acids and gases.

When the bacteria grow and interact with the organic components in the oil field, they produce compounds that help improve oil recovery.

The MEOR process is implemented by injecting bacteria into oil wells. The bacteria move through the rocks and interact with the organic materials to generate beneficial chemical compounds. The activity of the bacteria and their impact on oil recovery are monitored and assessed through the analysis of oil samples and measurements of changes in viscosity and chemical properties.

The advantages of using the MEOR process include increased oil recovery efficiency and improved oil flow, leading to increased productivity and reduced costs. Additionally, it is considered an environmentally friendly and sustainable technique as it utilizes naturally occurring bacteria in the environment without the need for harmful chemical additives [2].

3. THEORY:

Figure (2) illustrates microbes inside an oil drop. To get microbes to grow and multiply fast enough, scientists are test in ways to inject food into a reservoir for the microbes to eat. Some microbes feed on nutrients in a reservoir and release gas as part of their digestive process, creating a gas reservoir or gas cap over oil.

Microbes can also be used to block off flow channels within a reservoir. After many years of waterflooding, most of the water eventually finds the easiest path through the oil reservoir, bypassing other parts of the reservoir. To send the water to other parts of the reservoir, microbes and their food are mixed together and injected into the waterflood. By multiplying their numbers, they block off the short-circuiting water pathways, improving water-flood efficiency in other parts of the reservoir.

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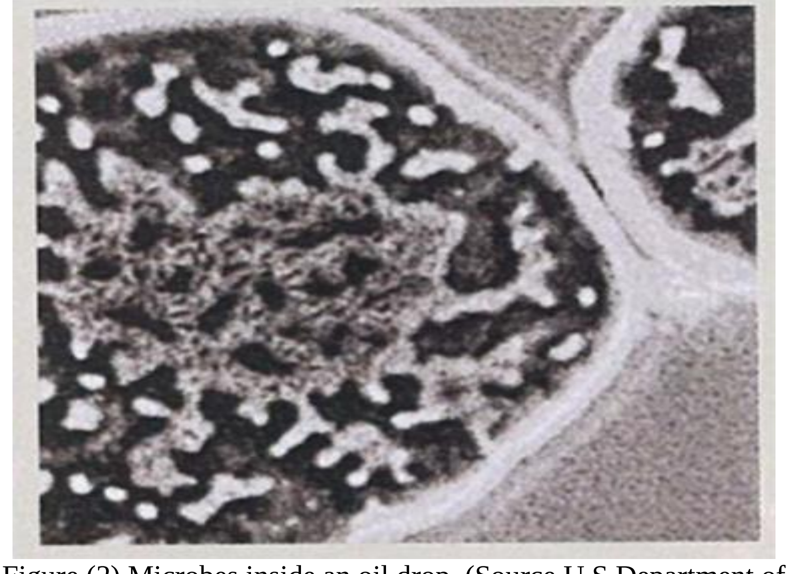

Figure (2) Microbes inside an oil drop. (Source U.S Department of Energy, 2006)

Most bacteria have a natural ten ency to attach to rock surfaces rather than free float in liquid. In a petroleum reservoir, bacteria may attach to rock, start to grow, and then produce exo-ploymers that help them attach to each other, as well as rock surfaces. Such growth is termed a biofilm and offers the advantages of protection from biocides, while encouraging the bacteria to best use nutrients and other resources, Figure (3). Bacteria that are introduced to reservoirs through water flooding will flow over preexisting biofilms; some bacteria will attach themselves to these biofilms and grow. Occasionally, some bacteria detach from the biofilm and move with the liquid, or by their own motility and colonize other areas deeper in the reservoir. Fundamentally, the mechanisms that govern oil release due to beneficial microbial growth are very much the same as the proven and demonstrable chemical and physical effects derived from well-known conventional EOR methods and products that are introduced at the surface. However, even though microbial and conventional systems are similar in terms of oil releasing mechanisms, they differ significantly in other ways. The unique attributes of microbial systems are not shared by conventional, non-biological systems that rely on massive additions of product at the injection wellhead. Instead, microbial systems function in- situ throughout the aqueous phase of the reservoir, including the water-rock, water-oil interfaces, and can be deliberately manipulated and directed to continually produce at the molecular and pore level, gases, solvents, surfactants and other bio chemicals. These bio-products are well-known oil-releasing mechanisms that have a chemical and physical effect on the oil.

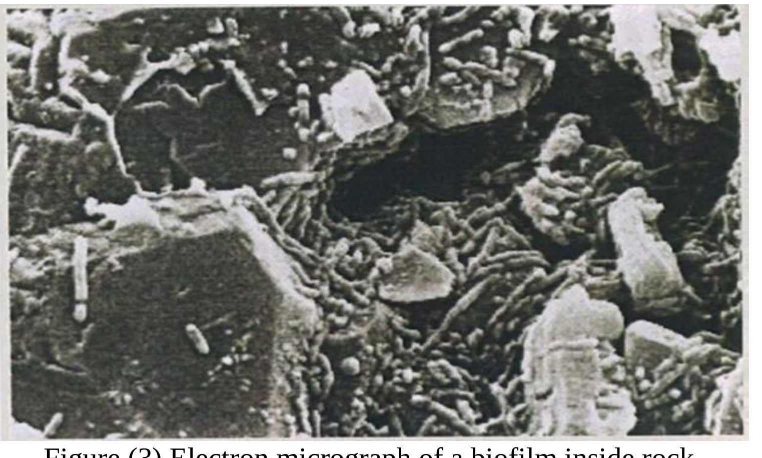
Figure (3) Electron micrograph of a biofilm inside rock.

Why we needed MEOR?

- A large properties of crude oil, a valuable and non-renewable energy resources, is left behind in the ground
- A dire need to produce more crude oil to meet the worldwide rising energy demand.
- Previously un-extractable reserves are more costly to produced.
- MEOR Þ Extra 20 -30% oil recovery.

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4- MEOR Mechanisms:

Understanding MEOR mechanism is still far from being clear. Although a variety of explanations has been given in isolated experiments,[3][4] it is unclear if they were carried out trying to mimic oil reservoirs conditions.

The mechanism can be explained from the client-operator viewpoint which considers a series of concomitant positive or negative effects that will result in a global benefit:

- *Beneficial effects*. Biodegradation of big molecules reduces viscosity; production of surfactants reduces interfacial tension; production of gas provides additional pressure driving force; microbial metabolites or the microbes themselves may reduce permeability by activation of secondary flow paths. The growing nitrate reducing bacteria will compete food with the sulphate reducing bacteria, and generate nitrite to kill the sulphate reducing bacteria, therefore conquer the activities of sulphate reducing bacteria, reduce H_2S concentration, mitigate downhole corrosion caused by sulphate reducing bacteria, acid producing bacteria, [5][6][7] etc.
- Sweep the unswept oil. Permeability reduction can be beneficial due to bioclogging if the MEOR is designed and implemented properly. If it is not designed and deployed properly, microbial metabolites or the microbes themselves may reduce permeability by activation of secondary flow paths by depositing: biomass (biological clogging)[8][9], minerals (chemical clogging) or other suspended particles (physical clogging). Positively, attachment of bacteria and development of slime [10][11],i.e. extracellular polymeric substances (EPS), favour the plugging of highly permeable zones (thieves zones) leading to increased sweep efficiency as shown in the Figure(4).

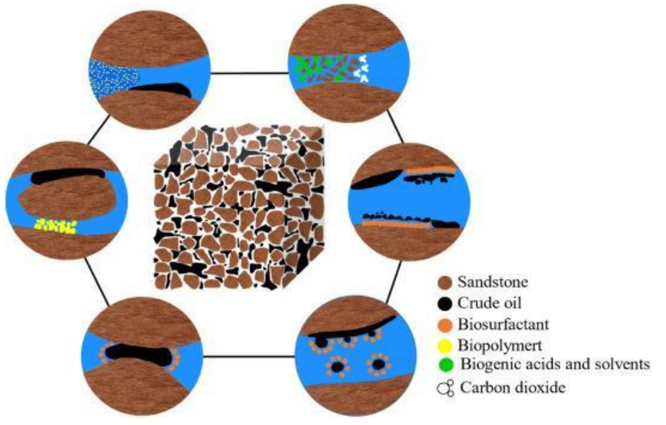

Figure (4): The role of microbial products in the process of MEOR.

5- Effects of Microbial EOR:

The following are the effects of injection of bacteria:

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b) There is production of gases like H_2, CH_4 and CO_2. These gases mix with oil and increase recovery.

c) Surfactants and biopolymers release hydrocarbon and reduce plugging of water zone, i.e., reduction of water fingering.

The basic requirements of microbial EOR are similar to those used in a biological evaluation as,

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(ii) Improvement in mobility ratio.

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6. Strategies:

Changing oil reservoir ecophysiology to favour MEOR can be achieved by complementing different strategies. In situ microbial stimulation can be chemically promoted by injecting electron acceptors such as nitrate; easy fermentable molasses, vitamins or surfactants [12]. Alternatively, MEOR is promoted by injecting exogenous microbes, which may be adapted to oil reservoir conditions and be capable of producing desired MEOR agents Table (1).

Table 1. Possible applications of products and MEOR agents produced by microorganism.[5]

MEOR agents	Microbes	Product	Possible MEOR application
Biomass, i.e. flocks or biofilms	*Bacillus* sp. *Leuconostoc* *Xanthomonas*	Cells and EPS (mainly exopolysaccharides)	Selective plugging of oil depleted zones and wettability angle alteration
Surfactants	*Acinetobacter* *Bacillus* sp. *Pseudomonas* *Rhodococcus* sp .*Arthrobacter*	Emulsan and alasan Surfactin, rhamnolipid, lichenysin Rhamnolipid, glycolipids Viscosin and trehaloselipids	Emulsification and de-emulsification through reduction of interfacial tension
Biopolymers	*Xanthomonas* sp .	Xanthan gum	Injectivity profile and viscosity modification, selective plugging
	Aureobasidium sp.	Pullulan	
	Bacillus sp.	Levan	
Acids	*Clostridium* *Enterobacter* Mixed acidogens	Propionic and butyric acids	Permeability increase, emulsification
Solvents	*Clostridium*, *Zymomonas* and *Klebsiella*	*Acetone, butanol, propan-2-diol*	Rock dissolution for increasing permeability, oil viscosity reduction
Gases	*Clostridium*	Methane and hydrogen	*Increased pressure, oil swelling, reduction of interfacial section and viscosity; increase permeability*
	Enterobacter		
	Methanobacterium		

This knowledge has been obtained from experiments with pure cultures and some times with complex microbial communities but the experimental conditions are far from mimicking those ones

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prevailing in oil reservoirs. It is unknown if metabolic products is cell growth dependent, and claims in this respect should be taken cautiously, since the production of a metabolite is not always dependent of cellular growth.[13]

There are two main types of microbial processes used in oil and gas engineering:

1- Acid Production: In this process, acid-producing bacteria are used to produce organic acids, such as acetic acid and lactic acid, from the organic materials present in the oil fields. These acids work to corrode and dissolve the oil-trapping rocks, increasing oil flow and facilitating its extraction.

2- Oil Viscosity Reduction: This process utilizes selected bacteria that produce enzymes that help break down and degrade the large molecules in the oil, resulting in viscosity reduction. With reduced viscosity, the oil flows more easily, contributing to increased oil extraction from the field.

7- Considration of processes:

7-1- Selection of suitable bacteria:

It is necessary to select bacteria that can adapt to the conditions of the oil field and have the ability to convert organic materials into useful compounds for improving oil extraction. Choosing the appropriate bacteria, cultivating them, and ensuring their proliferation in the required quantities can be a challenge in itself.

7-2-Process control:

Achieving precise control over the microbial process is essential to ensure its effectiveness and timely execution. This requires continuous monitoring and supervision of the bacteria process and control of environmental factors that may affect it, such as temperature, humidity, oxygen levels, and nutrient concentrations.

7-3-Environmental impact:

Necessary precautions must be taken to control any potential negative impact resulting from the use of bacteria in oil fields. Some bacteria may alter the characteristics of rocks and could cause leaks or contamination in groundwater. Therefore, studying and evaluating the environmental impact of bacteria usage and implementing appropriate preventive measures is crucial.

7-4 Economic cost:

Microbial processes may be relatively costly compared to traditional methods of oil extraction. The cultivation, proliferation, and process control of bacteria require additional financial resources and operating costs. Accurate economic studies should be conducted to determine the feasibility of microbial processes from an economic standpoint.

7-5- The Microbial used in EOR processes:

There are several bacteria used in the microbial process in oil and gas engineering. The bacteria used vary according to the specific application and environmental conditions [14][15], Diagram of MEOR Figure(5) and bacteria used in EOR operations as shown in the Figure(6) and Figure(7):

1- Cyanobacteria: Used to enhance oil extraction from oil sands.

2- Bituminophyceae: Used to break down heavy and viscous hydrocarbons in oil.

3- Bacillus: Used to improve oil extraction and purification.

4- Pseudomonas: Used in the treatment of oil waste and reducing the concentration of organic pollutants.

5- Thiobacillus: Used to convert sulfur into harmless compounds in oil fields.

6- Clostridium: Used to convert hydrocarbons into methane gas and improve oil extraction.

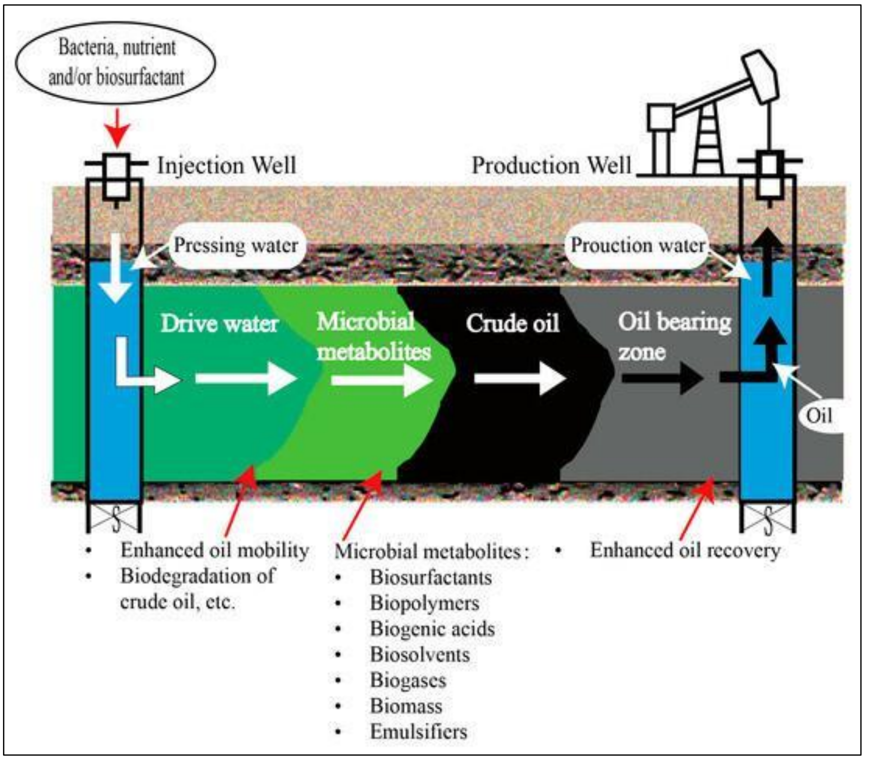
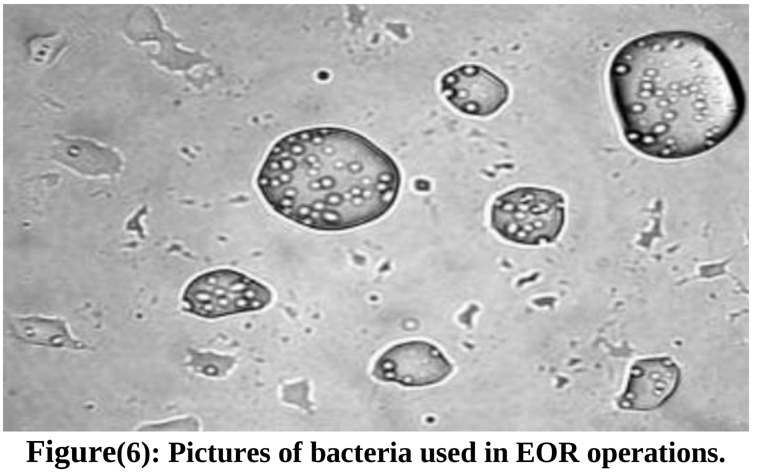


Figure (5): Diagram of MEOR.



Figure(6): Pictures of bacteria used in EOR operations.

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Figure(7): Pictures of bacteria used in EOR operations.

7.6 Locations that used of microbial EOR processes:

1- United States: Bacteria have been used in oil and gas fields in the United States to increase oil recovery and improve well productivity. One prominent company in this field is Biosource, which offers microbial techniques to enhance oil extraction location map in Figure(8) .

2- Canada: Canada also utilizes bacteria techniques in the oil and gas industry, particularly in the purification and improvement of oil sands and reducing their environmental impact. Biote is well-known for providing sustainable technological solutions for treating contaminated water in the oil sands industry.

3- United Kingdom: Bacteria have been used in the UK to improve oil and gas extraction from wells and increase production. BiomeTech is an emerging company in this field, utilizing bacteria to enhance oil and gas extraction in the North Sea fields.

4- Norway: employs bacteria techniques in oil and gas fields to improve oil extraction and reduce environmental pollution. BioSørvek operates in this field and offers innovative solutions to improve production efficiency and minimize environmental impact.

5- Russia: Russia uses bacteria techniques in the oil and gas industry to enhance oil extraction and treat oil waste. Biotech and Siberian Petrochemical are working on developing bacterial technologies to enhance production and improve the quality of petroleum products.

6- Kuwait: also utilizes bacteria techniques in the oil and gas industry, particularly in oil waste treatment and purification of contaminated water. PetroTech is well-known for providing innovative solutions for waste treatment and improving water quality in the oil and gas industry.

7- Australia: Thermophiles Used to improve oil extraction from acidic and volcanic rock. Methanogens Used to convert saturated hydrocarbons into methane gas.

8- United Arab Emirates :Sulfate-reducing bacteria Used to reduce sulfur deposits and improve the quality of water used in the oil industry.

9- Brazil :Bacillus bacteria Used to enhance oil extraction and reduce calcium and iron deposits.

10- Iraq: Thermophiles Used to improve oil extraction from acidic rocks.

11- China: Clostridium Used to convert hydrocarbons into methane gas and improve oil extraction Figure(9).

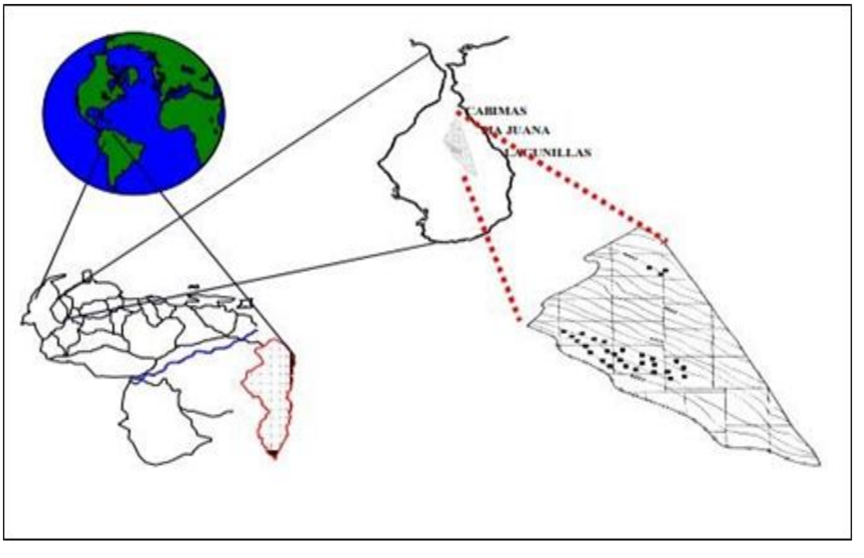

Figure (8): LOCATION MAP AMERICA.

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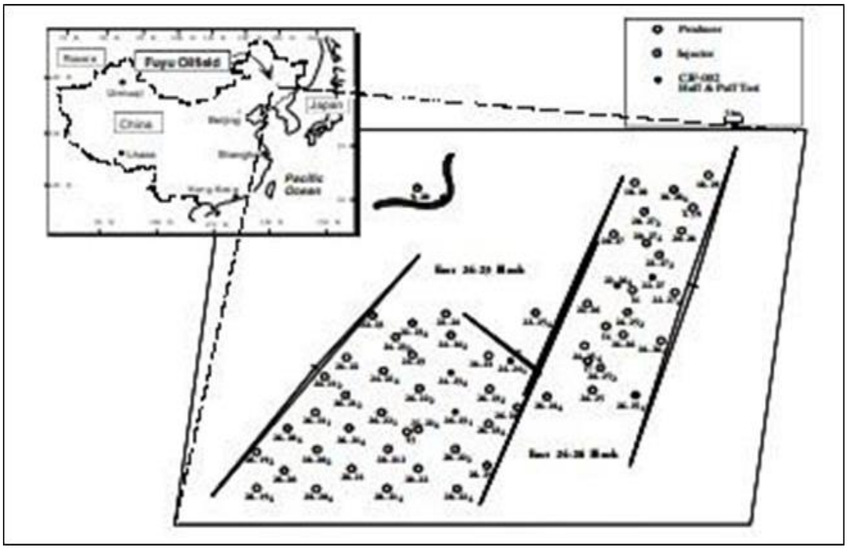

.Figure(9): LOCATION MAP CHINE

8- Environmental conservation through enhanced microbial oil extraction processes (EOR):

Environmental conservation in the context of microbial usage involves taking measures to reduce negative environmental impacts and preserve environmental health. Here are some ways in which the environment can be conserved in microbial processes:

8-1-Waste management:

Proper handling of waste generated from microbial processes, such as appropriate disposal of chemicals used or dealing with end products in environmentally friendly ways.

8-2-Environmental monitoring:

Preserving the environment requires careful and continuous monitoring to assess the environmental impacts of microbial processes and ensure compliance with relevant environmental standards and regulations.

8-3-Awareness and training:

Promoting awareness of the importance of environmental conservation among those involved in microbial processes and providing necessary training on environmentally friendly practices and conservation techniques.

8-4-Use of natural microbes:

Preferably utilizing natural microbes already present in the surrounding environment, rather than genetically modified microbes, to minimize potential negative effects.

8-5- The economic cost of using microbial enhanced oil recovery (EOR) processes:

The economic cost of the microbial process in oil extraction can vary depending on several factors. These costs are influenced by the scale of the operation, the type of bacteria used, and the applied treatment technology:

8-5-1- Cost of acquiring the bacteria:

There may be expenses associated with the development and production of the bacteria used in the oil extraction process.

8-5-2- Research and development costs:

Developing and improving microbial techniques for oil extraction may require research and development efforts, which can incur associated costs.

8-5-3- Application and operational costs:

These include the expenses of implementing and operating the microbial process, such as purchasing and installing the necessary equipment, training personnel, and maintaining the system.

8-5-4-Process monitoring costs:

Monitoring and overseeing the process may require additional expenses to ensure the effectiveness of the bacteria and the safety of the surrounding environment.

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8-5-5- Problems:

i) Biomass Build-up: The growth of the bacteria is so high and it accumulates at one place to choke the formation channels.

ii) Eating of Crude Oil: Bacteria selected should be such not to reach the crude oil.

9. Advantages

There is a plethora of reviewed claims regarding the advantages of MEOR. There are lots of publications in the website www.onepetro.com maintained by the Society of Petroleum Engineering and other websites or databases. Some field applications are also shared by petroleum microbiology companies. Advantages can be summarized as follows:

- Injected microbes and nutrients are cheap; (the injection of microbes is out of date. The new microbial EOR technology does not need to inject microbes to the reservoir, but only inject nutrients to stimulate the indigenous microbes[6])
- easy to handle in the field and independent of oil prices.
- Economically attractive for mature oil fields before abandonment.
- Increases oil production.
- Existing facilities require slight modifications.
- Easy application.
- Less expensive set up.
- Low energy input requirement for microbes to produce MEOR agents.
- More efficient than other EOR methods when applied to carbonate oil reservoirs.
- Microbial activity increases with microbial growth. This is opposite to the case of other EOR additives in time and distance.
- Microbial nutrients are biodegradable and therefore can be considered environmentally friendly.

10. Disadvantages

- Microbial growth is favoured when: layer permeability is greater than 20 md; reservoir temperature is inferior to 85 ^{0}C,

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- salinity is below 100,000 ppm and reservoir depth is less than 3,500 m.
- The recent cases proved that there is no corrosion during MEOR based on continuous field monitoring results. In addition, the stimulated indigenous microbes do not affect crude oil qualities, and there is no sign of increasing microbes in the produced liquid.

11. Conclusions and outlooks:

As global oil prices have prolonged slump in recent years, it is urgent to decrease the cost of MEOR further in order to seek better returns. Compared with other three recovery techniques, the microbial oil recovery technology takes advantage of relatively inexpensive, environment-friendly, and pollution-free. This paper reviewed abundant field trials, which confirmed the superiority and feasibility of MEOR technology. But meanwhile, some factors are still strict the widespread application of MEOR technology, including the intricacy of the MEOR process, the unstable success rate, the low product yield and the low oil recovery. Therefore, future research work should focus on solving these urgent problems. The first issue is the cost of microbial products. Through the study of relevant literature, this paper summarizes the following possible methods to reduce the cost: (1) Using abundant and cheap agro residue or industrial waste as a substrate for bacterial growth whenever possible; (2) Using biological products in combination with chemical products; (3) Using crude microbial products whenever possible, eliminating the cost of expensive purification. The next issue is that the complex reservoir environment has a great impact on microbial growth and the success rate of microbial displacement technology. Therefore, before microbial flooding, it is necessary to structure a more systematic reservoir screening criteria, analyze the reservoir characteristics and microbial diversity of each well systematically, and establish the corresponding mathematical model of MEOR. At the same time, it is also feasible to construct strains with outstanding tolerance to harsh reservoir environment by genetic engineering technology. Moreover, the application of genetic engineering technology and microbial consortium

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construction technology may be a breakthrough for microbial oil recovery in the future. The former enables the creation of functional oil recovery bacteria with excellent performance, while the latter creates perfect microbial consortia. The combination of both may enhance the practicality of MEOR technology.

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