Investigation of the Mechanism of Enhanced Oil Recovery Methods in Fractured Carbonate Reservoirs

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***Abstract*—Fractured reservoirs are generally known as reservoirs with high production flow intensity, short life and low final recovery coefficient. Choosing the appropriate method of enhanced recovery from these reservoirs can reduce additional costs and increase production rate in less time. Water injection alone in fractured reservoirs has low efficiency, but thermal methods reduce the viscosity of the oil and improve the flow of oil to production wells by changing the rock and fluid properties. In chemical methods, chemicals improve enhanced oil recovery by changing wettability, reducing interfacial tension and reducing IFT. Microbial methods also act like chemical methods by performing chemical reactions. Miscible injection of gas in carbonate reservoirs also reduces the viscosity and swelling of the oil, and injecting it in a non-miscible form evaporates the light parts of the oil, which makes oil production easier. In this paper, after reviewing different methods of enhanced recovery from fractured carbonate reservoirs, it is tried to study the production mechanisms in each method and present the best and most appropriate enhanced recovery method, according to the existing conditions for these reservoirs.**

Keyword - Enhanced Oil Recovery, Fractured Carbonate Reservoirs, Thermal Methods, Chemical Methods, Microbial Methods

I. Introduction

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Oil production methods from oil fields are mainly divided into three categories: primary oil recovery, secondary oil recovery and tertiary oil recovery or enhanced oil recovery. Enhanced recovery methods are also divided into five general categories: water injection, thermal, chemical, miscible and microbial. According to the field and characteristics of rock and fluid and other environmental conditions, the most appropriate method can be used, [1].

A large part of the world's oil reservoirs are fractured reservoirs, so enhanced recovery of these reservoirs is very important. Fractured carbonate reservoirs with high matrix porosity and low matrix permeability can be good candidates for improving the oil recovery process. Oil recovery from these reservoirs is typically very low because about 80% of fractured carbonate reservoirs are either oil-wet or mixed-wet. The injectable water does not easily penetrate the porous oil matrix to move the oil. The wettability of carbonate reservoirs is the most important parameter controlling oil recovery, [2-6].

Water injection is commonly used to improve oil recovery, while gas injection is used to maintain pressure or promote oil gravity drainage as an improved oil recovery process or IOR. If gas injection is soluble or almost soluble, oil recovery will increase because some of the residue oil is swollen by miscibility or near-miscibility conditions. Water and gas injection to produce oil from the matrix in fractured natural reservoirs has been used mainly by gravity drainage, [7].

Fractured reservoirs have two distinct systems with different characteristics:

1. A matrix system that has high porosity and low permeability.

2. Fracture system that has low porosity and high permeability.

Accordingly, different categorizations have been made by different people. According to one of these classifications, fractured reservoirs are classified into the following two types (Fig. 1):

1. Porous fractured reservoirs

2. Non-porous fractured reservoirs

Fig. 1. Example of fractured carbonate reservoir [8]

In the first type, the porosity of the matrix system is very high and it contains a large part of the oil. Fractures act as channels that play the role of transporting oil from the matrix to the production well. In the second type, the matrix has a relatively low porosity and a large percentage of reservoir oil has been stored in the fractures themselves. In a more detailed classification, the first type is divided into three subgroups based on the frequency of the fractures:

1. High-fracture reservoirs in which the permeability of the fracture system is higher than that of the matrix (Most of Iran's fractured reservoirs are of this type).

2. Medium-fracture reservoirs in which the frequency of fractures and therefore their permeability is moderate.

3. Low-fracture reservoirs in which the number of fractures is low.

Several models have been proposed by various people to study fractured reservoirs, including [9-15].

There are different mechanisms in enhanced recovery from carbonate reservoirs, which cause enhanced recovery depending on the type of method used and the existing conditions. One of them is the reduction of viscosity, especially in heavy oils, which causes the faster and better displacement of oil towards the production well and as a result, more oil is produced. The change in the wettability of the rock from oil-wet to water-wet, which prevents the adhesion of oil to the surface of the rock matrix and water adheres instead. Reducing the interfacial tension between oil and water, which creates an oil emulsion in the water, helps to better sweep the reservoir by water, and increases oil recovery. Decreased oil density, which leads to oil lifting and higher production by production wells and also the reduction of two-phase incoherence, or in other words, the reduction of IFT, which, like the reduction of interfacial tension, help the enhanced oil recovery.

An investigation of 10 enhanced oil recovery methods in fractured carbonate reservoirs and their details is the main topic of this article.

II. WATER INJECTION METHOD

In the case of non-fractured reservoir, water injection can help enhanced oil recovery without any problems. But if the reservoir has a fracture, water injection can only be used when the fracture is partial. In this case, directional wells are used so that the direction of flow is perpendicular to the fractures, because otherwise water is wasted through the fractures, (Fig. 2). Water is not effective in carbonate reservoirs with large fractures and are also water-wet, [16].

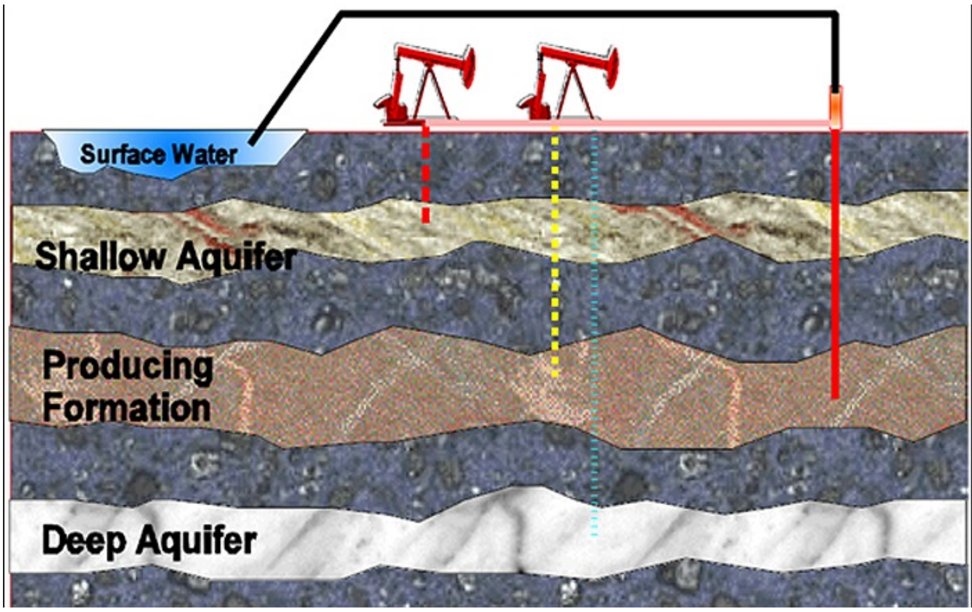

Fig. 2. Water injection method for EOR [17]

Recently, the use of smart water with surface activators (surfactants) is used to improve the performance of enhanced oil recovery, smart water is designed by adjusting and optimizing their composition in injectable water. In this method, by increasing the concentration of salts with divalent ions and decreasing the concentration of sodium chloride, the recovery of oil from carbonate reservoirs is enhanced. Reduction of interfacial tension, emulsion formation and prevention of asphaltene deposition are other mechanisms that increase oil recovery in this method, (Fig. 3).

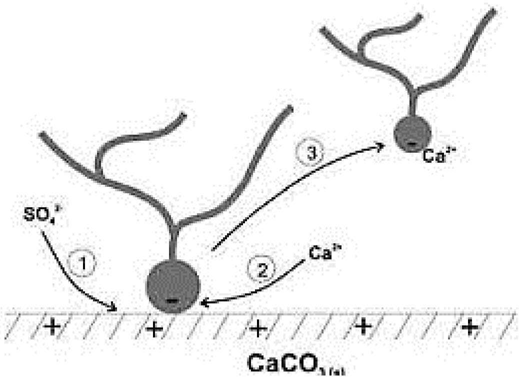

Fig. 3. smart water method for EOR [18]

Among the ions used are $Na^{+} < Ca^{2+} < Mg^{2+}$ at ambient temperature, which has been written in the order of the effect on IFT. But their effects will be inverse at high temperatures, because the increase in temperature increases the solubility of large molecules such as asphaltene in oil on the other hand, cations also reduce the asphaltene content, in such conditions, where the increase in temperature has caused the solubility of asphaltene, the presence of cations has the opposite effect and increase IFT.

III. THERMAL METHOD

In this method, using thermal energy, some properties of rock and fluid are changed and it makes it easier for oil to leave the oil reservoirs. Thermal methods include hot water injection, steam injection and in situ combustion, which causes enhanced oil recovery by reducing the viscosity of the oil, (Fig. 4).

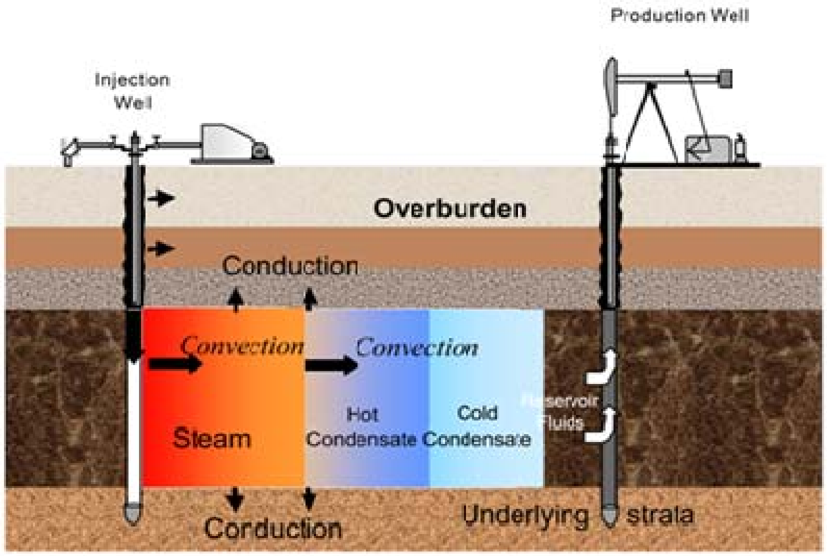

Fig. 4. Example of thermal method for EOR [19]

Other mechanisms of oil production in heat recovery from the reservoir are: change in the wettability rate of rock at high temperatures, reduction of interfacial tension between oil and water and evaporation of light oils.

IV. INJECTION OF STEAM AND HOT WATER

Steam injection is a process during which steam is injected continuously and an area (chamber) around the injection well is heated at the vapor saturation temperature, (Fig. 5).

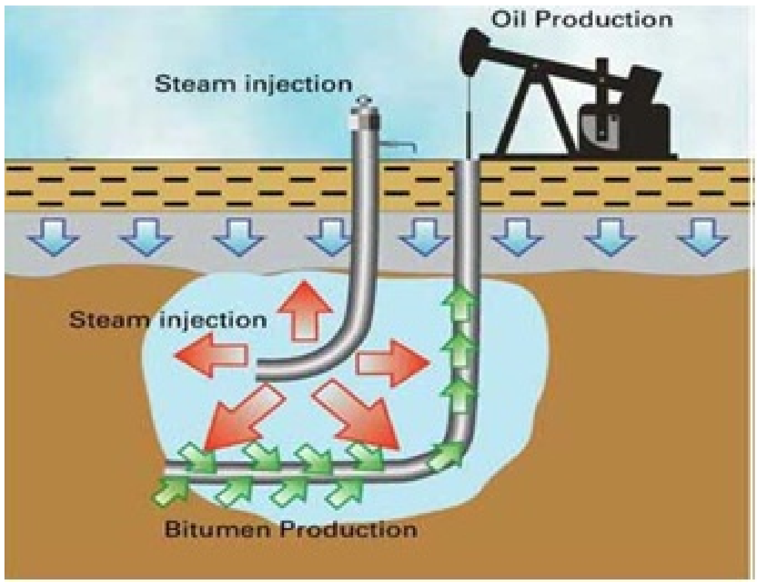

Fig. 5. Injection of steam for EOR [21]

This chamber expands toward the production well, thermally reducing the viscosity of the oil and moving the oil in a way called a volumetric sweep, [20]. This method is mostly used for high viscosity heavy oil reservoirs (e.g. Venezuela and California), (Fig. 6).

Dreher et al. (1986) conducted steam injection experiments on the cores and found that oil recovery from both homogeneous and fractured cores increased with increasing steam temperature. In these experiments, the amount of recovered oil at 200 degrees Fahrenheit was 30 percent. Also, for each injection of one mole of water at steam temperature, 1 mole of carbon dioxide was produced at the core outlet. Dreher further considers the effective parameters in oil production flow and water to oil production ratio as the size of the grid of matrix block, the steam injection flow, the initial saturations and distributions, and the amount of carbon dioxide produced, [23].

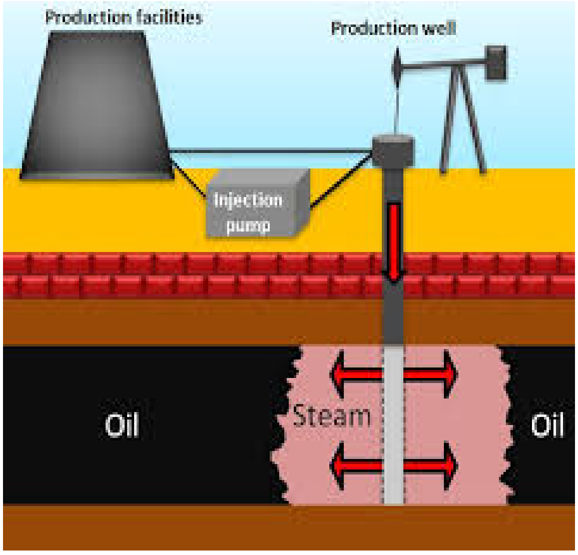

Fig. 6. mechanism of Injection of steam [22]

The factor that must be controlled in steam injection is the injection speed. The injection speed should be such that there is sufficient opportunity for heat exchange of steam and oil to create a temperature gradient inside the oil. In addition, the distance between the reservoir and the steam generation facilities must be taken into account to calculate the degree of fluid injected into the reservoir and the corrosion rate in the injected steam path.

Hot water injection is the same as steam injection method and reduces the viscosity of oil and facilitates the movement of oil to the production well.

V. IN-SITU COMBUSTION

We need a burning triangle for combustion. Since there is fuel and temperature in the reservoir, we only need oxygen and sparks for combustion. Oxygen must be guided in a controlled manner and according to parameters such as porosity, permeability and thickness of the injected reservoir and the combustion front.

Burning oil releases carbon dioxide, carbon monoxide, oxygen, nitrogen, and sometimes hydrogen sulfide and other hydrocarbon gases. Burning oil causes coke (soot oil), which reduces the permeability of the reservoir and reduces oil production. Therefore, the combustion process must be controlled in such a way that we have the lowest amount of coke produced, (Fig. 7).

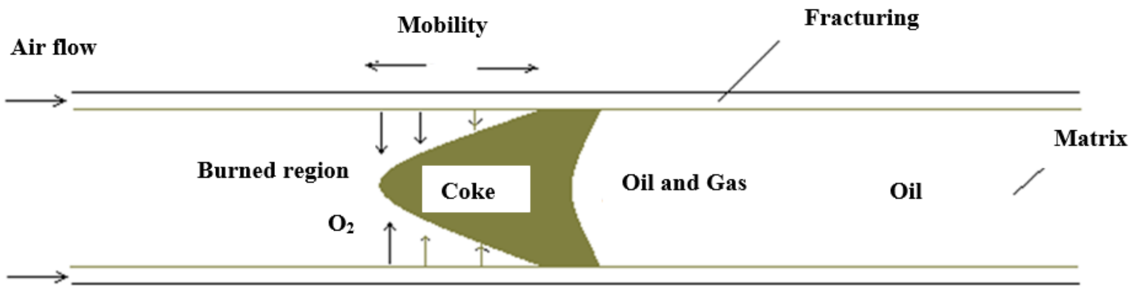

Fig. 7. Distribution of oil and coke in In-situ combustion method

In the beginning, the field application of the in-situ combustion method in fractured carbonate reservoirs failed due to the channeling of injected air through the fractures and early breakthrough, [18]. In later years, Schulte et al. experimentally tested the use of in-situ combustion in fractured reservoirs (such as Middle Eastern reservoirs: Iran and Oman) and due to the channeling of injected air through the fractures and the exclusion of the in-situ oil, the successful application of this method in fractured reservoirs was considered impossible. Schulte et al. later showed that in-situ combustion was suitable for the fractured reservoirs and resulted in high recovery rate in swept areas. In the experiments performed by these researchers, the oxygen breakthrough occurs if the flow rate of the injected air exceeds the critical flow rate of the injection. This critical discharge is controlled by the amount of fracture openings, [24].

VI. CHEMICAL METHOD

Considering the fact that most fractured reservoirs have geological heterogeneities and are often oil-wet, water injection in these reservoirs does not provide high efficiency and chemical injections can be used to change the wettability of the reservoir rock.

This is one of the most efficient enhanced recovery methods for fractured reservoirs, but a significant amount of oil remains in the reservoir, [25]. Chemical methods used include polymers, alkalis and surfactants.

VII. POLYMER INJECTION

Polymer injection methods are generally divided into two categories:

1. Injection of interfacial tension reducing materials: In this method, we inject materials into the reservoir that reduce the adhesion force between the oil and the reservoir rock and facilitate the movement of fluid inside the reservoir. The first research in this method was done in 1927, but no research was done in this field until 1952. Based on research conducted after this date, a theory was obtained that capillary force and interfacial tension are the factors that retain the residue oil in the pores of the reservoir. For this reason, to reduce interfacial tension, materials must be injected into the reservoir that reduce this force to zero.

2. Polymer injection to increase the volumetric mass of water: In this method, synthetic polymers are often used in the classification of polyacryl amide and biological polymer Xantagam. Although biological polymers are more sensitive to temperature changes, Xantagam is appropriate for this method due to its cheapness.

This method was developed in the mid-1950s, and new high molecular weight polymers were used in the 1960s, and this approach has been successful, (Fig. 8).

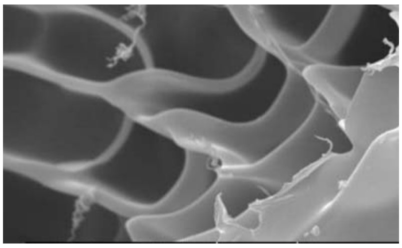

Fig. 8. Example of polymer For EOR

Chemical injection methods are usually suitable for small reservoirs due to the high cost of injected materials. When using polymers, it should be noted that these materials do not completely block the permeability of the reservoir rock. Due to the high cost of polymers, these materials are injected in a cycle of pure water and water with polymer and in the form of slugs, and water injection is used to provide pressure and this slug movement. Due to the sensitivity of polymers in terms of chemical stability, the application of the polymer is at temperatures below 100 °C, (Fig. 9).

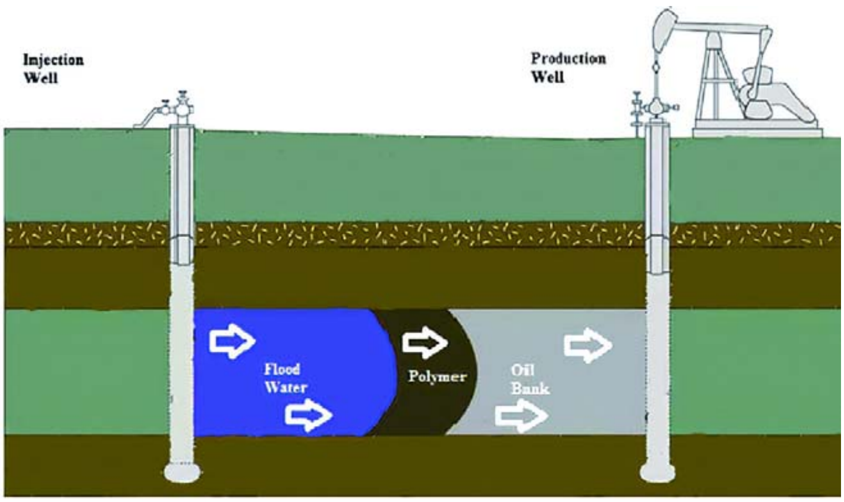

Fig. 9. Polymer injection For EOR [26]

VIII. ALKALINE INJECTION

This method requires the injection of alkaline chemicals such as caustic acid and caustic soda solution, which form surface activators by reacting with the acids in the oil, that reduce IFT and contribute in enhance oil recovery process.

IX. SURFACTANT INJECTION

Surfactants are usually organic compounds that, greatly reduce interfacial tension when spread on the surface of a liquid. Due to the high cost of surfactants, they are injected with gels, polymers and water.

In oil-wet fractured carbonate reservoirs, the injection of surfactant into the fracture and the injection of water behind it cause the oil to combine with the surfactant solution to form a microemulsion. This material has a higher viscosity than oil and ordinary solution. Fig. 10 shows the imbibition profile with two layers below the matrix. The top layer shows the microemulsion front. The bottom layer shows the surfactant solution flowing behind the microemulsion. This process is unstable because the surfactant solution has a lower viscosity than the micromodel.

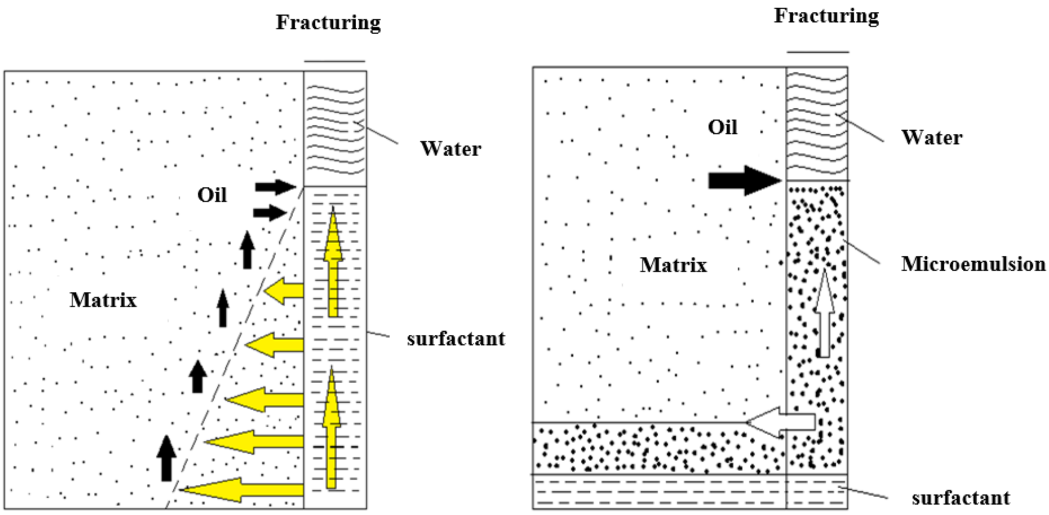

Fig. 10. Surfactant injection method for EOR

Eventually, fingering has been occurred for surfactant and this issue causes higher formation of microemulsion. Surfactant converted into microemulsion has the ability to control mobility in reservoirs with natural fracture. Displacement is also stable by gravity because the surfactant solution is denser than the microemulsion. As the microemulsion moves toward the well, it has a pressure gradient that causes the surfactant crossflow through the high permeability, the slit, to the low permeability, the matrix. It also leads to the cross of oil flow through the matrix into the fractured, which results in increased oil recovery, [27].

X. MISCIBLE AND NON-MISCIBLE INJECTION OF GAS

Examples of injectable gases in carbonate reservoirs include carbon dioxide, nitrogen, flue gas, and other hydrocarbon gases that contribute to the oil recovery process, both in miscible and non-miscible forms, (Fig. 11). One of the most important gases is carbon dioxide, which is injected both miscible and non-miscible into fractured carbonate reservoirs. In general, due to the low critical pressure of carbon dioxide, it dissolves in oil in miscible form.

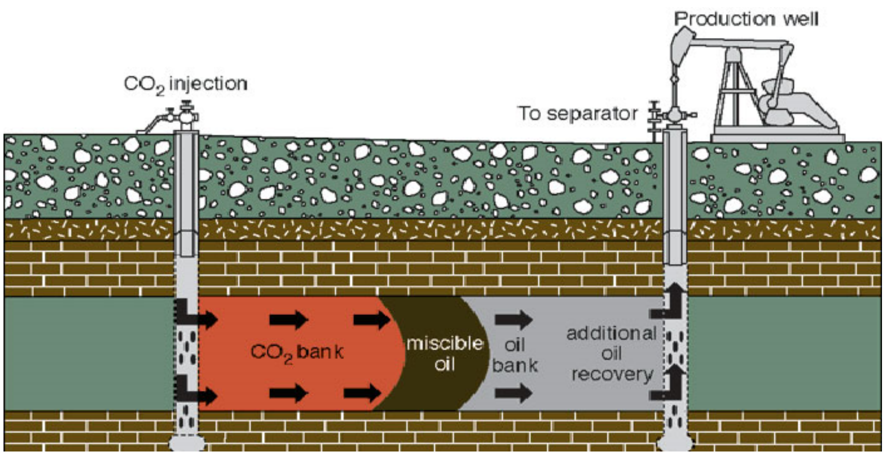

Fig. 11. Co2 injection for EOR [28]

Miscible gas injection reduces the viscosity and swelling of oil, and non-miscible injection causes the evaporation of the light parts of oil, which makes oil production easier.

An example of the application of this method is the non-miscible injection of carbon dioxide gas into Bati Raman field, the largest field in Turkey, which took place in 1986. It was the largest non-miscible carbon dioxide injection project in the world at the time, [29].

Carbon dioxide injection can be used as an efficient method of increasing oil recovery due to the high percentage of this gas in the planet Earth and environmental problems and its greenhouse effect. The largest producers of carbon dioxide in the world is inserted in Table 1.

TABLE I. The largest producers of carbon dioxide in the world [30]

Country	Annual production of carbon dioxide (million tons)	Percentage of total production
China	9839	41.22
United States of America	5270	22.08
India	2567	10.75
Russia	1693	7.09
Japan	1205	5.05
Germany	799	3.35
Iran	672	2.82
Saudi Arabia	635	2.66
South Korea	616	2.58
Canada	573	2.40

XI. MICROBIAL INJECTION

One of the applications of biotechnology is the use of anaerobic bacteria (microorganisms) in the oil industry (Fig. 12). These bacteria improve the mobility of oil by producing chemicals.

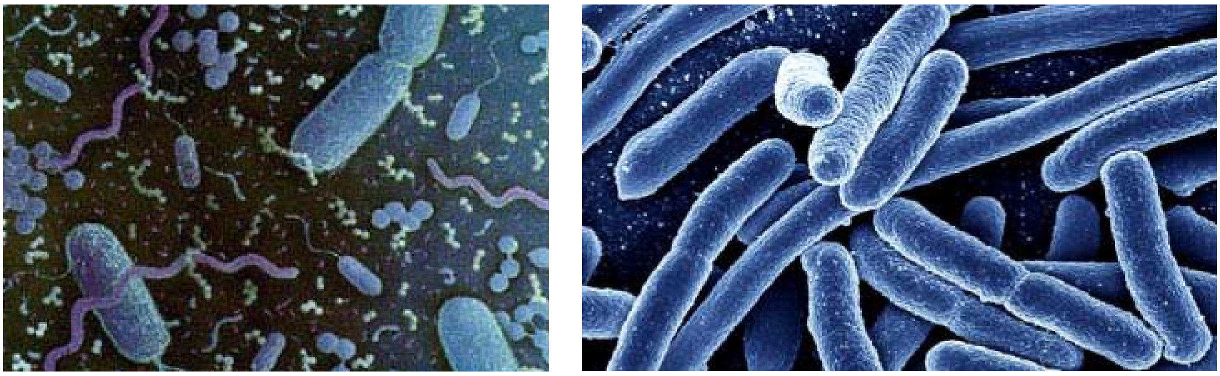

Fig. 12. Anaerobic microorganisms for EOR

The use of microbes in increasing oil production is not a new issue. The first written case was in 1913 of Davis. In 1946, Zobell recorded a process for the secondary recovery of oil using anaerobic microbes and the mechanism of dissolution of sulfate minerals.

The first enhanced oil recovery field experiment was conducted in 1954 at an Arkansas oil field with microbial method. But despite their success, these methods were abandoned due to the availability of cheap oil resources. In the 1970s, these methods were considered again due to the instability of oil prices and the trend towards biotechnology. From 1980 onwards, due to rising oil prices in various countries, these methods became more or less common, [31].

Microbes help the enhanced oil recovery process through various mechanisms:

1. Production of organic acid which leads to dissolution of carbonate rocks and development of channels.

2. Reduction of sulfur in gypsum and anhydride compounds and sulfate minerals which releases the trapped oil.

3. Production of gases such as methane, carbon dioxide, hydrogen and nitrogen that expel oil from dead spaces.

4. Production of various solvents such as ethanol, acetone and alcohol that help the mobility of the oil phase by dissolving or swelling organic sediments.

5. Production of surface activators that reduce the interfacial tension and tension of the oil-water interface and separate the oil from the rock.

6. The production of a biopolymer that selectively blocks areas of higher permeability, thereby directing the fluid flow to areas of lower permeability.

7. Decomposition of large hydrocarbon molecules and reduction of oil viscosity.

XII. Conclusion

Enhanced recovery from fractured reservoirs has its own problems due to the heterogeneous structure of this type of reservoirs. If the fracture is large, the water injection method cannot produce oil alone, because water is wasted through the fractures, but water injection can be used along with other methods. In the thermal method, some properties of rock and fluid are changed and make it easier for oil to leave the oil reservoirs. In in-situ combustion, if the oxygen is controlled according to parameters such as porosity, permeability and thickness of the injection reservoir, and the combustion front, it helps to enhance the recovery process by reducing the viscosity of the oil.

Chemical methods are also used to change the wettability of the reservoir rock and in this method a significant amount of oil remains in the reservoir. Microbial methods also act like chemical methods by performing chemical reactions. The difference is that the cost of the microbial method is high. Gases also contribute to the process of enhanced oil recovery in miscible and non-miscible manner. One of the most important gases is carbon dioxide, which is injected both in a miscible and non-miscible manner in fractured carbonate reservoirs. Carbon dioxide injection can be used as an efficient method in enhanced oil recovery due to the high percentage of this gas in the planet and environmental problems and its greenhouse effect and it is considered as the most serious option due to the properties of rock and fluid and other environmental conditions.

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