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Microbial Enhanced Oil Recovery

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1. Introduction

Nowadays the majority of the world's energy comes from crude oil. A large proportion of this valuable and non-renewable resource is left behind in the ground after the application of conventional oil extraction methods. Moreover, there is a dire need to produce more crude oil to meet the worldwide rising energy demand which illustrates the necessity of progressing Enhanced Oil Recovery (EOR) processes. These methods try to overcome the main obstacles in the way of efficient oil recovery such as the low permeability of some reservoirs, the high viscosity of the crude oil, and high oil-water interfacial tensions that may result in high capillary forces retaining the oil in the reservoir rock (Bubela, 1987).

Microbial enhanced oil recovery (MEOR) is one of the EOR techniques where bacteria and their by-products are utilized for oil mobilization in a reservoir. In principle, MEOR is a process that increases oil recovery through inoculation of microorganisms in a reservoir, aiming that bacteria and their by-products cause some beneficial effects such as the formation of stable oil-water emulsions, mobilization of residual oil as a result of reduced interfacial tension, and diverting of injection fluids through upswept areas of the reservoir by clogging high permeable zones. Microbial technologies are becoming accepted worldwide as cost- effective and environmentally friendly approaches to improve oil production (Sarker et al., 1989). This chapter provides an inclusive review on MEOR mechanisms, its advantages over conventional EOR methods, its operational problems and engineering challenges. Furthermore the mathematical modeling of MEOR process is also presented.

2. Primary production

Oil exists in the small pores and in the narrow fissures and interstices within the body of the reservoir rocks underneath the surface of the earth. The natural pressure of the reservoir causes the oil to flow up to the surface and provide the so-called primary production, which depends upon the internal energy and the characteristics of the reservoir rock and the properties of the hydrocarbon fluids. In some reservoirs, which are the part of a much larger aquifer system, a natural flow of underground waters may be the drive force (aquifer drive) to push and displace oil. The initial reservoir pressure is usually high enough to lift the oil up to surface; however as oil production progresses, the reservoir pressure is continually depleted to a point in which artificial lift or pumping is required to maintain an economical oil production rate. In other reservoirs, there may be other recovery mechanisms, such as the expansion of dissolved gas during the pressure decline. As the reservoir pressure falls below the bubble point during production, some of the more volatile components are released and come out of solution to form small gas bubbles. Initially the bubbles are trapped in the pores and then their expansion causes oil displacement (dissolved gas drive). Furthermore in some reservoirs, as the pressure fall, gas bubbles increase in size and eventually coalesce forming a continuous gas phase that flows towards the upper part of the reservoir forming a gas cap. The gas cap constantly expands as the reservoir pressure continually decreases displacing more oil (gas cap drive) to the production wells.

3. Secondary production

As the reservoir pressure declines during primary production, a critical point is reached when it is necessary to provide external energy for the reservoir to achieve additional oil recovery, which is termed secondary recovery. The extra energy can be introduced by injecting gas (gas injection) and/or water (water flooding).

Gas injection is usually only applied to reservoirs which have a gas cap where gas drive would be an efficient displacement mechanism. In Water flooding, which nowadays is one of the most common methods of oil recovery, keeps the reservoir pressure around the bubble point, thus preventing the pores to be blocked by dissolved gases. Also, according to the hydrocarbon thermodynamics, at the bubble point, the oil will have its lowest viscosity. So that, for a specific pressure gradient, the maximum amount of the oil will be displaced under this condition. After some years of operation in a field, due to the reservoir heterogeneity, the injected fluids (water or gas) flow preferentially along high permeable layers that cause these fluids to by-pass oil saturated areas in the reservoir. Therefore, an increasingly large quantity of water (or gas) rises with the oil, and by decreasing the ratio of oil to water, eventually it becomes uneconomic to continue the process and the field must be abandoned. In this situation, due to the low proportion of the oil production in both primary and secondary stages (about 30%), attention will be focused on the third stage of the oil recovery, so-called tertiary production or Enhanced Oil Recovery (EOR) for recovering more oil from the existing and abandoned oil fields (Singer & Finnerty, 1984).

4. Tertiary production or Enhanced Oil Recovery (EOR)

Generally, tertiary or enhanced oil recovery involves the extraction of residual oil after the primary and secondary phases of production. At this stage, modern and technically advanced methods are employed to either modify the properties of reservoir fluids or the reservoir rock characteristics, with the aim of gaining recovery efficiencies more than those obtained by conventional recovery methods (primary and secondary recovery stages). This can be achieved based on different mechanisms such as reducing the interfacial tension between oil and water, reducing oil viscosity (thermal methods), creating miscible displacement and increasing viscosity of the displacing fluid to be more viscous than the oil. The applied EOR method for each reservoir depends on its specifications, and requires a great deal of rocks and fluids sampling and also laboratory investigations. In general, EOR processes can be classified into four main categories as thermal methods, chemical methods, miscible or solvent injection, and microbial methods.

4.1 Thermal processes

The general principle of thermal processes which are mostly used for recovery of heavy or viscous oils is to supply the reservoir with heat energy in order to increase the oil temperature and reduce its viscosity increasing the mobility of the oil towards production wells. Thermal processes can be conducted by two different methods: steam flooding and in-situ combustion. In steam flooding, steam at about 80% quality is injected into an oil reservoir, in which by condensing the steam, its heat energy transfers to reservoir rocks and fluids. This leads to the thermal expansion of the oil and the consequently reduction in its viscosity, and the release of dissolved gases. Steam flooding is the most widely used EOR method and probably the most profitable from an economic standpoint. In the in-situ combustion method (fire flood), which is theoretically more efficient than steam flood, burning some of the reservoir oil results in heating the reservoir and displacement of the remaining oil to the producing wells. But generally, due to the complex operational problems of this method, it is not widely applied.

4.2 Chemical methods

Chemical methods (chemical flooding) are claimed to have significant potential based on successful laboratory testing, but the results in field trials have not been encouraging. Furthermore, these methods are not yet profitable. In these processes, chemicals such as surfactants, alkaline solutions, and polymers are added to the displacing water in order to change the physicochemical properties of the water and the contacted oil making the displacement process more effective. In surfactant flooding, by reducing the interfacial tension between the oil and the displacing water and also the interfacial tension between the oil and the rock interfaces, residual oil can be displaced and recovered. Moreover, in caustic flooding, the reaction of the alkaline compounds with the organic acids in the oil forms in-situ natural surfactants that lower the oil-water interfacial tension. In addition to surfactant and alkaline flooding, polymers are used to increase the viscosity of the displacing water to improve the oil swept efficiency.

4.3 Miscible displacement processes

The underlying principle behind miscible displacement processes is to reduce the interfacial tension between the displacing and displaced fluids to near zero that leads to the total miscibility of the solvent (gas) and the oil, forming a single homogeneous moving phase. The displacing fluid (injected solvent or gas) could be carbon dioxide, nitrogen, exhaust gases, hydrocarbon solvents, or even certain alcohols.

4.4 Microbial processes (MEOR)

Another tertiary method of oil recovery is microbial enhanced oil recovery, commonly known as MEOR, which nowadays is becoming an important and a rapidly developed tertiary production technology, which uses microorganisms or their metabolites to enhance the recovery of residual oil (Banat, 1995; Xu et al., 2009).

In this method, nutrients and suitable bacteria, which can grow under the anaerobic reservoir conditions, are injected into the reservoir. The microbial metabolic products that include biosurfactants, biopolymers, acids, solvents, gases, and also enzymes modify the properties of the oil and the interactions between oil, water, and the porous media, which increase the mobility of the oil and consequently the recovery of oil especially from depleted and marginal reservoirs; thus extending the producing life of the wells (Lazar et al., 2007; Belyaev et al. 2004; Van et al. 2003). In MEOR process, different kinds of nutrients are injected to the reservoirs. In some processes, a fermentable carbohydrate including molasses is utilized as nutrient (Bass & Lappin-Scott, 1997). Some other reservoirs require inorganic nutrients as substrates for cellular growth or as alternative electron acceptors instead of oxygen. In another method, water containing a source of vitamins, phosphates, and electron acceptors such as nitrate, is injected into the reservoir, so that anaerobic bacteria can grow by using oil as the main carbon source (Sen, 2008). The microorganisms used in MEOR methods are mostly anaerobic extremophiles, including halophiles, barophiles, and thermophiles for their better adaptation to the oil reservoir conditions (Brown, 1992; Khire & Khan, 1994; Bryant & Lindsey, 1996; Tango & Islam, 2002). These bacteria are usually hydrocarbon-utilizing, non-pathogenic, and are naturally occurring in petroleum reservoirs (Almeida et al. 2004). In the past, the microbes selected for use, had to have a maximum growth rate at temperatures below 80ºC, however it is known that some microorganisms can actually grow at temperatures up to 121ºC (Kashefi & Lovley, 2003). Bacillus strains grown on glucose mineral salts medium are one of the most utilized bacteria in MEOR technologies, specifically when oil viscosity reduction is not the primary aim of the operation (Sen, 2008).

5. History of MEOR

MEOR was first described by Beckman in 1926. Few studies were conducted on this topic, between 1926 and 1940 (Lazar et al., 2007). In 1944, ZoBell patented a MEOR method and continued researching on this subject. In 1947, ZoBell initiated a new era of investigation in petroleum microbiology with applications for oil recovery. ZoBell explained that the major MEOR mechanisms which are responsible for oil release from porous media, involve processes such as dissolution of inorganic carbonates by bacterial metabolites; production of bacterial gases, which reduces the oil viscosity supporting its flow; production of surface-active substances or wetting agents, and the high affinity of bacteria for solids (Lazar et al., 2007). The first MEOR field test was conducted in the Lisbon field, Union County, AR, in 1954 (Yarbrough and Coty, 1983). The improvement of MEOR in field trials was based on the injection of mixed anaerobic or facultative anaerobic bacteria such as *Clostridium, Bacillus, Pseudomonas, Arthrobacterium, Micrococcus, Peptococcus,* and *Mycobacterium* among others; selected on their ability to generate high quantities of gases, acids, solvents, polymers, surfactants, and cell-biomass. More details on bacteria's specific abilities were reviewed by Lazar (Lazar, 1991, 1996 to 1998).

The application of MEOR as a tertiary recovery technique and a natural step to decrease residual oil saturation has been reported (Behesht et al. 2008). A complete review (692 references) of the microbiology of petroleum was published by Van Hamme et al. (2003), which covered a literature review up to 2002. This publication is mainly focused on the description of the molecular-biological characteristics of the aerobic and anaerobic hydrocarbon exploitation, with some citations on the application of the microbial action on petroleum waste, microbial oil recovery, and biosensors. The aspect of petroleum microbiology that is perhaps the most important for MEOR is the ability of microbes to use hydrocarbons as the carbon and energy source. Biotechnology research has improved, which has influenced the oil industry to be more open to the evaluation of microorganisms to enhance oil production. Both indigenous and injected microorganisms are used depending on their adaptability to the specific reservoirs. In microbial enhanced oil recovery (MEOR), bacteria are regularly used because they show several practical features (Nielsen et al., 2010). Several publications state that oil recovery through microbial action takes place due to several mechanisms as follows (Jenneman et al. 1984; Bryant et al. 1989; Chisholm et al. 1990; Sarkar et al. 1994; Desouky et al. 1996; Delshad et al. 2002; Feng et al. 2002; Gray et al. 2008; Nielsen et al., 2010):

- Reduction of oil/water interfacial tension and modification of porous media wettability by surfactant production and bacterial action.
- Selective plugging of porous media by microorganisms and their metabolites.
- Oil viscosity reduction caused by gas solution in the oil due to bacterial gas production or degradation of long-chain saturated hydrocarbons.
- Production of acids that dissolve rock improving porous media permeability.

Particularly, the two first mechanisms are believed to have the greatest effect on improving oil recovery (Jenneman et al., 1984; Bryant et al., 1989; Chisholm et al., 1990; Sarkar et al., 1994; Desouky et al., 1996; Delshad et al., 2002; Feng et al., 2002; Gray et al., 2008; Nielsen et al., 2010).

6. MEOR mechanisms

Improvement of oil recovery through microbial actions can be performed through several mechanisms such as reduction of oil-water interfacial tension and alteration of wettability by surfactant production and bacterial presence, selective plugging by microorganisms and their metabolites, oil viscosity reduction by gas production or degradation of long-chain saturated hydrocarbons, and production of acids which improves absolute permeability by dissolving minerals in the rock, however, the two first mechanisms are believed to have the greatest impact on oil recovery (Nielsen et al., 2010). So that, microorganisms can produce many of the same types of compounds that are used in conventional EOR processes to mobilize oil trapped in reservoirs and the only difference between EOR and some of the MEOR methods probably is the means by which the substances are introduced into the reservoir (Bryant & Lockhart, 2000). Table 1 summarizes different microbial consortia, their related metabolites and applications in MEOR (Sen, 2008).

6.1 Biosurfactant application

Chemical surfactants are hazardous and costly compounds which are not biodegradable and can be toxic to the environment (Bordoloi et al., 2008; Suthar et al., 2008). In recent years, the increase concern regarding environment protection has caused the development of cost-effective bioprocesses for biosurfactant production (Morita et al., 2007; Fax & Bala, 2000; Abalos et al., 2001). Biosurfactants are high value products that due to their superior characteristics, such as low toxicity, ease of application, high biodegradability and tolerance even under extreme conditions of pH, temperature, and salinity, are efficient alternatives to

Microbial product	Example microbes	Application in MEOR
Biomass	*Biomass Bacillus, Leuconostoc, Xanthomonas*	Selective plugging and wettability alteration
Surfactants	*Acinetobacter, Arthrobacter, Bacillus, Pseudomonas*	Emulsification and de-emulsification through reduction of IFT
Polymers	*Bacillus, Brevibacterium, Leuconostoc, Xanthomonas*	Injectivity profile and viscosity modification, selective plugging
Solvents	*Clostridium, Zymomonas, Klebsiella*	Rock dissolution for better permeability, oil viscosity reduction
Acids	*Clostridium, Enterobacter, Mixed acidogens*	Permeability increase, emulsification
Gases	*Clostridium, Enterobacter Methanobacterium*	Increased pressure, oil swelling, IFT and viscosity reduction

Table 1. Microorganism, their metabolites and applications in MEOR.

chemically synthesized surface-active agents with potential applications in the petroleum industry (Banat et al., 2000; Cameotra & Makkar, 2004; Desai & Banat, 1997). Generally, there are three major strategies for the application of biosurfactants in oil recovery (Banat, 1995): (i) injection of biosurfactant producing microorganisms into the reservoir through the well, with subsequent multiplication of microorganisms in-situ through the reservoir rocks, (ii) injection of selected nutrients into a reservoir, thus stimulating the growth of indigenous biosurfactant producing microorganisms, (iii) production of biosurfactants ex-situ and their subsequent injection into the reservoir.

Biourfactants can contribute positively to improve oil recovery by dramatically reducing interfacial tension and also by altering the wettability of reservoir rock to displace more oil from the capillary network. When the interfacial tension at the oil–rock interface is lowered, the capillary forces that prevent oil from moving through rock pores are reduced. Therefore, the detachment of oil films from rocks can occur (Dyke, 1991; Li, 2002). Although a reduction in interfacial tension will help to mobilize the oil, a change in wettability of the pore surfaces to a more water-wet state, will release more oil from the surfaces and consequently can improve oil recovery. It has been estimated (Lake, 1989) that the interfacial tension must be lowered in the range from 0.01 to 0.001 mN/m to achieve significant oil recovery. Biosurfactants, produced anaerobically which are capable of reducing IFT to such low values, have been reported (Brown et al. 1986).

6.2 Application of gases and solvents

Some strains of anaerobic bacteria such as clostridia can produce hydrogen, carbon dioxide, methane, acetate, and butyrate by carbohydrates fermentation during the initial growth phase of the fermentation process. Additional products of this microbial process are some kinds of solvents including acetone, butanol, ethanol, isopropanol, and other solvents in lesser amounts, produced during the stationary growth phase. In an oil reservoir, these gaseous and liquid metabolites, which are produced in-situ, are dissolved in the crude oil resulting in lower oil viscosity and reduction of the capillary forces contributing to oil retention. Moreover microbes increase the pressure in the reservoir by producing gases in the pore spaces that would have been normally bypassed with conventional gas flooding operations (Bryant & Douglas, 1988). Both gases and solvents can dissolve the carbonate rock, thereby increasing its permeability and porosity (Bordoloi & Konwar 2008).

6.3 Clogging mechanism

One method of microbial improving oil recovery is by modifying the fluid flow through the reservoir by shifting fluid flow from the high permeability zones in a reservoir to the moderate or low permeability zones thus increasing the sweep efficiency by forcing the injected water to pass through previously by-passed oil zones of the reservoir (Bryant et al., 1998). The changes in flow pattern can be achieved by an increase in microbial cell mass within the reservoir. Stimulating either indigenous microbial populations or injecting microorganisms together with nutrients produce biomass and hence microbial plugging. The injected nutrient and microbes preferentially flow into the high permeability zones of the reservoir and as a result of cell growth, the biomass selectively plugs these zones to a greater extent than the moderate or low permeability zones (Crawford, 1961 & 1962). Experiments using brine-saturated sandstone cores showed that injecting nutrients and viable bacterial cells resulted in clogging of 60-80% of the pore space (Jenneman et al., 1984).

6.4 Biopolymers application

Some water insoluble biopolymers produced by certain bacteria can increase the oil recovery by the same mechanism of plugging by cell growth (Jack & Diblasio, 1985). In water-flooding operations, in which water is pumped into injection wells in the reservoir in order to force the oil up to the surface, biopolymers plug high-permeability zones to redirect the water-flood to oil-rich zones in the reservoir and the sweep efficiency increases by equalizing the permeability across the reservoir (Casellas et al., 1997; Yakinov et al., 1995; Abu- Ruwaida et al., 1991)

7. MEOR advantages

The most outstanding advantages of MEOR over other EOR technologies are listed below (Lazar, 2007):

1. The injected bacteria and nutrient are inexpensive and easy to obtain and handle in the field.
2. MEOR processes are economically attractive for marginally producing oil fields and are suitable alternatives before the abandonment of marginal wells.
3. Microbial cell factories need little input of energy to produce the MEOR agents.
4. Compared to other EOR technologies, less modification of the existing field characteristics are required to implement the recovery process by MEOR technologies, which are more cost-effective to install and more easily applied.
5. Since the injected fluids are not petrochemicals, their costs are not dependent on the global crude oil price.
6. MEOR processes are particularly suited for carbonate oil reservoirs where some EOR technologies cannot be applied efficiently.
7. The effects of bacterial activity within the reservoir are improved by their growth with time, while in EOR technologies the effects of the additives tend to decrease with time and distance from the injection well.

8. MEOR products are all biodegradable and will not be accumulated in the environment, therefore are environmentally compatible.
9. As the substances used in chemical EOR methods are petrochemicals obtained from petroleum feedstock after downstream processing, MEOR methods in comparison with conventional chemical EOR methods, in which finished commercial products are utilized for the recovery of raw materials, are more economically attractive.

8. Field trials

Microbial enhanced oil recovery methods were developed from laboratory-based studies in the early 1980s to field applications in the 1990s (Ramkrishna, 2008). In 2010, various countries allocated one-third of their oil recovery plans toward MEOR techniques. Although it has been constantly observed that the effects of MEOR projects applied to one well had positively affected oil recovery in neighboring wells, it has been recognized that several MEOR process variables must be optimized before it develops into a practical method for common field applications. These variables include a better description of the candidate reservoirs, better knowledge of the biochemical and physiological characteristics of the microbial consortia, a better handle of the controlling mechanisms, and an unambiguous estimation of the process economics. Most of the MEOR processes leading to field trials have been completed in the last two decades and now the knowledge has advanced from a laboratory-based assessment of microbial processes, to field applications globally (Ramkrishna, 2008). Portwood (1995) reported an analysis of the data based on the information gathered from 322 MEOR projects, led the evaluation of the technical efficiency and economics of MEOR, which is useful for forecasting treatments outcome in any given reservoir. A collection of significant information from field trials in the USA and Romania was considered as well in the analysis reported. Likewise, several reports discussing in-situ uses of MEOR in field trials with analysis of the results are published elsewhere (Portwood, 1995; Clark et al., 1981; Jenneman et al., 1984; Dennis, 1998; Kleppe, 2001; Youssef et al., 2007). For example, in an MEOR field trial in the Southeast Vassar Vertz Sand Unit salt-containing reservoir in Oklahoma, nutrient injection motivated the growth of the indigenous microbial populations, which reduced the effective permeability by 33% (Jenneman et al., 1996). A biosurfactant flooding process using a very low concentration of biosurfactant, which was produced by the *Bacillus mojavensis* strain JF-2, was reported to be very effective in recovering residual oil from Berea sandstone cores (Bailey et al., 2001). Also, a new model for enhanced oil production was developed for using ultra microbacteria generated from indigenous reservoir microbiota through nutrient treatment (Lazar et al., 2007). The external cell layers of such ultra microbacteria had surface-active properties. Such a microbial scheme was successfully verified in increasing oil production in the Alton oil field in Queensland, Australia (Sheehy, 1991 and 1992).

The activity of MEOR field experiments after 1990 is based on the foundation that successful MEOR applications must be conducted on water floods, where a continuous water phase facilitates the application of well stimulation procedures and the low cost of MEOR makes it a preferable option. At the same time, specific microbial applications such as microbial paraffin removal, microbial skin damage removal, microbial control souring and clogging, and those based on using ultra microbacteria are potential technologies for the additional growth of MEOR (Lazar et al., 2007). Worldwide experience in MEOR field trials during the last 40 years has been discussed by Lazar et al., (2007).

9. MEOR problems

MEOR techniques face some common problems that are outlined as follows (Lazar, 2007):

1. Injectivity lost due to microbial plugging of the wellbore—to avoid wellbore plugging, some actions must be taken such as filtration before injection, avoid biopolymers production, and minimize microbial adsorption to rock surface by using dormant cell forms, spores, or ultra-micro-bacteria.
2. Dispersion or transportation of all necessary components to the target zone.
3. Optimization of the desired in-situ metabolic activity due to the effect of variables such as pH, temperature, salinity, and pressure for any in-situ MEOR operation.
4. Isolation of microbial strains, adaptable to the extreme reservoir conditions of pH, temperatures, pressure and salinity (Sen, 2008).
5. Low in-situ concentration of bacterial metabolites; the solution to this problem might be the application of genetic engineering techniques (Xu & Lu, 2011).

10. Mathematical modeling

The current need of maximizing oil recovery from reservoirs has prompted the evaluation of various Improved Oil Recovery (IOR) methods and EOR techniques, including the use of microbial processes. MEOR is a driving force behind the efforts to come up with different and cost-efficient recovery processes (Kianipey and Donaldson, 1986). Bryant and Lockhart, (2002) examined the quantitative correlations between microbial activity, reservoir features, and operating conditions such as injection rates, well spacing, and residual oil saturation (Bryant and Lockhart, 2002). Marshall (2008) stated that a mathematical model could be used to recognize the most important parameters and their practical relationships for the application of MEOR.

Improvement of detailed mathematical models for MEOR is an exceptionally demanding task, not only as a consequence of the natural difficulty of the microbes, but also because of the diversity of physical and chemical variables that control their activities in subsurface porous media. Specific or general aims can be foreseen for modeling by researchers. In specific cases, it is desired to employ the models to maximize the yield and minimize the costs of the MEOR procedure. Main physical insights of the process can be obtained from quite simple analytical models; whereas the exact models regularly require thorough numerical computation. The important point claimed by researchers is that modeling of microbial reactions still faces strict limitations. Models are based on the relation between the residence time (τ_{res}) of the bacteria in a cylindrical reaction zone of radius r_m, depth h, and porosity φ, which is:

$$\tau_{res} = \frac{\pi r_m^2 h\phi\left(1 - S_{or}\right)}{Q} \tag{1}$$

Where Q is the volumetric flow rate and S_{or} is the residual oil saturation, and the time τ_{rsd} required for the microbial reaction to produce a desired concentration c_{req} of some metabolite.

To estimate the reaction time, Marshall (2008) posed the following assumptions: isothermal plug flow through the reactor, nutrient consumption is first order and irreversible, and that nutrients initial concentration is n_0.

The physical model on which the above argument is based is very basic, but the analysis draws interest to the important issue of reaction kinetics that has to be addressed by more complex treatments. It is possible to write a balanced chemical equation for the production of a given metabolite, but the rate of production can only be determined experimentally, and must be given by actual bacterial growth velocities (Marshall, 2008).

Several mathematical models were developed to simulate MEOR processes. The models usually included multidimensional flow of the multiphase fluid consisting of water and oil in porous media along with specific equations for adsorption and diffusion of metabolites, microorganisms, and nutrients (Islam, 1990; Behesht et al., 2008). The main multidimensional transport equations were combined with equations of different microbial features such as growth, death, and nutrient consumption.

The majority of the published mathematical models for performance of bacteria and viruses in porous media were initially stimulated by problems arising in water filtration and wastewater treatment (Corapcioglu and Haridas, 1984; Stevik et al., 2004). Such models have three major parts: Transport Properties, Conservation Law (Local Equilibrium, Breakdown of Filtration Theory, and Physical Straining), Biofilm Clogging and Related Phenomena such as the theoretical description of the biological clogging of pores. The clogging agent is coupled nonlinearly not only to the growth of the bacteria, but moreover to the flux of nutrients transported by the fluid. The origin of the earliest approaches to the development of models of this phenomenon is the idea that medium can be characterized as a bundle of independent capillary tubes (Marshall, 2008).

The first is an approximate of the transport properties of the bacteria in the fluid. In the treatment given by Corapcioglu and Haridas (1984), bacteria diffusivity was achieved by function of the Stokes-Einstein equation, which effectively treats the microbe as if it were a particle that is undergoing Brownian movement.

The second is conservation law. If chemotaxis is neglected, the concentration of bacteria in the fluid phase of a small constituent of the porous medium is defined by a partial differential equation expressing the rate of change of the concentration as the sum of terms resulting from diffusion (or dispersion), advection, and transfer between the fluid phase and the surface of the solid grains. Numerical solution of systems of equations of this general type is at the heart of computational hydrology and simulation of oil wells. The other parts of the model that must be considered are biofilm clogging and related phenomena.

For analysis of MEOR, it is interesting to present the characteristics of the water phase saturation profiles and the corresponding oil recovery curves. A mathematical model for MEOR was considered by Islam (1990), where bacterial growth resulted in plugging, decrease of oil viscosity, reduction of interfacial tension between oil and water, and gas production. In the model, interfacial tension was correlated with bacteria concentration to avoid adding another variable to account for surfactant production. In this model, it was clear that the reduction of surface tension between water and oil was the most important factor on the improvement of oil recovery (Islam, 1990).

Chang et al., (1991) improved a mathematical model depicting adsorption, growth and decomposition of microorganisms, consumption of nutrients, and other physical procedures. Due to microorganisms' organic build up, porosity and permeability were altered. Moreover, the model showed that the oil recovery increased by microbial plugging (Chang et al., 1991). Additional development of MEOR mathematical models is essential because none of the present models account for all of the variables involved in microbial growth. For instance, wettability modification and changes in interfacial tension (IFT) are two vital variables of microbial growth which are ignored in previous models. Moreover, some important physico-chemical features such as surfactant and polymer adsorption, and the effects of salinity and polymer viscosity on the mobility of the aqueous phase are ignored in these models. Finally, all of them are limited to transport in porous media. Simulation efforts to consider the effect of various parameters on the efficiency of MEOR using the current deficient models may not lead to successful results in the field (Behesht et al, 2008).

Surfactant production and adsorption, salinity effects, adsorption of microorganisms, reduction of interfacial tension, and wettability changes were taken into account in a MEOR model presented by Behesht et al. (2008). In this work, polymer was also injected in order to reduce permeability of the porous media and to increase the viscosity of the displacing water. The use of these two techniques resulted in an increase of oil recovery. Behesht et al., (2008) developed a three-dimensional multi-component transport model in a two-phase oil-water system. The model accounted for the effects of dispersion, convection, injection, growth and death of microbes, and accumulation of microbial debris. For the first time, effects of both porous media wettability modification from oil wet to water wet and the reduction of interfacial tension (IFT) on the relative permeability and capillary pressure curves were included in a MEOR simulation model. Transport equations were considered for the bacteria, nutrients, and metabolite in the matrix, reduced interfacial tension on phase trapping, surfactant and polymer adsorption, and the effect of polymer viscosity on mobility of the aqueous phase. The model was used to simulate the effects of parameters such as: flooding time schedules, washing water flow rate, substrate concentration, permeability, polymer and salinity concentration on the recovery of original oil in place (OOIP) in a hypothetical reservoir (Behesht et al., 2008).

Several methods were used to model relative permeability changes as a function of interfacial tension. Nielsen et al. (2010) used a correlation between surfactant concentration and interfacial tension (Nielsen et al., 2010). Usually, a reduction of interfacial tension decreases residual oil saturation affecting the relative permeability curve endpoints, but it also straightens the relative permeability curves approaching full miscibility (Coats, 1980; Al-Wahaibi et al., 2006). Nielsen et al. (2010) investigated three methods: (1) capillary number and normalized residual oil saturation correlations; (2) Coats interpolation between relative permeability curves; and (3) interpolation of factors of Corey type relative permeability curves (Coats, 1980; Green and Willhite, 1998). They recommend the third method, in which more parameters can be estimated in order to obtain a better fit with experimental data. Moreover, different distributions of surfactant between phases, the effect of bacterial growth rate, and the effect of injection concentrations of substrate and bacteria were considered as well. The saturation curves with specific MEOR characteristics were stated mutually with the oil recovery curves. Nielsen et al. (2010) developed a mathematical model describing the process of microbial enhanced oil recovery. The one-dimensional isothermal model comprised dislocation of oil by water containing bacteria and substrate as energy source. The bioproducts were both bacteria and metabolites. In the situation of MEOR modeling, a novel approach was partitioning of metabolites between the oil and the water phases. The partitioning was considered by a distribution coefficient. The portion of metabolite transferred to the oil phase was termed as vanishing so that the total amount of metabolite in the water phase was reduced. The metabolite produced was biosurfactant that reduced the oil–water interfacial tension, which resulted in oil mobilization. Different methods of incorporating surfactant-induced reduction of interfacial tension into models were also investigated. Reactive transport models were used to describe convection, bacterial growth, substrate consumption, and metabolite production, where the metabolite was a surfactant. The model was based on two-phase flow comprising five components; oil, water, bacteria, substrate, and metabolite/surfactant. The water phase comprised water, bacteria, substrate, and metabolite. The following assumptions were used in this model (Nielsen et al. 2010):

- Fluid flow was one-dimensional.
- The microorganisms were anaerobic bacteria, and they were injected into the reservoir. It was assumed that there was no local microorganism in the reservoir.
- Bacterial growth rate could be explained by Monod-kinetics being independent of temperature, pressure, pH, and salinity (Nielsen et al. 2003).
- The major metabolite was surfactant and other possible metabolites were considered insignificant.
- Surfactant could be distributed between both phases (water and oil). Surfactant sharing was instantaneous and the distribution kinetics was neglected.
- Adsorption of any component was neglected
- No substrate and metabolite adsorption on pore walls.
- Partial flow function was exploited, because capillary pressure was considered negligible.
- Negligible diffusion and chemotaxis.
- Isothermal method with incompressible flow.
- No volume change on mixing.

Therefore, the transport equation for each component was given as (Nielsen et al. 2010):

$$\frac{\delta}{\delta t}\left(\phi\sum_{j=1}^{n_p} w_{ij}.\rho_j.s_j\right)+\frac{\delta}{\delta x}\left(v\sum_{j=1}^{n_p} w_{ij}.\rho_j.f_j\right)=\phi q_i \tag{2}$$

where j is the phase, i is the component, n_p is the number of phases, ω_{ij} are component mass fractions in phase j, v is the linear velocity, ρ_j is the phase density, f_j is the fractional flow function of phase j, x is the length variable, t is the time, φ is the porosity, and q_i is the source expression for component i also comprising the reaction terms.

Growth rate expressions for microorganisms are regularly the Monod- expression based on the Michaelis–Menton enzyme kinetics and Langmuir expressions for heterogeneous catalysis (Islam, 1990; Chang et al., 1991; Nielsen et al., 2003).

The relative permeability curves for oil k_{ro} and water k_{rw}, and the Corey correlations were used (Lake, 1989). Moreover, the capillary number N_{ca} (ratio of viscous to capillary forces) are applied, which depend on changes in interfacial tension σ.

11. Challenges in MEOR

In spite of the various advantages of MEOR over other EOR methods, MEOR has not gained credibility in the oil industry because the value of MEOR can only be determined by the results of field trials. MEOR literature is mainly based on laboratory data and a shortage of field trials can be seen in this field. Also, because of reservoir heterogeneity, it is so difficult to extrapolate laboratory results into what is to be expected in the field or predict what will happen in a new field based on the results obtained from another field. Furthermore, few of the tests explain the mechanisms of oil recovery or offer a reasonable analysis of the application outcome. In addition, as Moses (1991) pointed out, the follow-up time of most field trials was not long enough to determine the long-term effects of the process. Finally, the precise mechanisms of in-situ MEOR operations are still unclear. Thus more research is required in this field (Xu & Lu, 2011).

12. Conclusion

MEOR is a cost effective and eco-friendly process that shows several advantages over other EOR processes. MEOR has great potential to become a viable alternative to the traditional EOR chemical methods. Although MEOR is a highly attractive method in the field of oil recovery, there are still uncertainties in meeting the engineering design criteria required by the application of microbial processes in the field, which has led to its current low acceptance by the oil industry. Therefore, a better understanding of the MEOR processes and its mechanisms from an engineering standpoint are required; as well as the systematic evaluation of the major factors affecting this process such as reservoir characteristics and microbial consortia, to improve the process efficiency.

13. References

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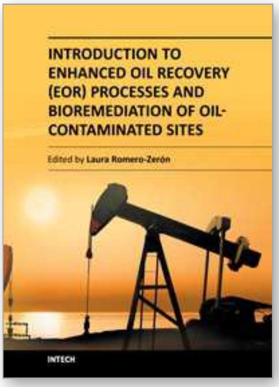

Introduction to Enhanced Oil Recovery (EOR) Processes and Bioremediation of Oil-Contaminated Sites

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This book offers practical concepts of EOR processes and summarizes the fundamentals of bioremediation of oil-contaminated sites. The first section presents a simplified description of EOR processes to boost the recovery of oil or to displace and produce the significant amounts of oil left behind in the reservoir during or after the course of any primary and secondary recovery process; it highlights the emerging EOR technological trends and the areas that need research and development; while the second section focuses on the use of biotechnology to remediate the inevitable environmental footprint of crude oil production; such is the case of accidental oil spills in marine, river, and land environments. The readers will gain useful and practical insights in these fields.