ISSN 2229-5518

A REVIEW OF MICROBIAL ENHANCED OIL RECOVERY: CURRENT DEVELOPMENT AND FUTURE PROSPECTS

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ABSTRACT-Microbial Enhanced Oil Recovery (MEOR) is a tertiary oil recovery technique that employs the use of microbes and their byproduct to enhance residual oil mobilization in the reservoir

This work considers MEOR technology application based on economic, technological and environmental stand point as against other EOR techniques. Successful field trials are studied and their success stories analysed. The technology (MEOR) is not without some limitations which shall be overcome with constant research and field application/field trial.

It has the potential to be one of the reliable technologies that best suits the economic constraints of the current oil markets. The technology is a potential alternative to other EOR method as it is being implemented in most parts of the world with satisfactory results not only from economics point of view but also from having lesser environmental impact.

Microbial EOR (MEOR) processes have several unique characteristics that may provide an economic advantage. Microbial processes do not consume large amounts of energy as do thermal processes, nor do they depend on the price of crude oil as many chemical processes do. Because microbial growth occurs at exponential rates, it should be possible to produce large amounts of useful products rapidly from inexpensive and renewable resources.

The microbial metabolic products that include bio-surfactants, 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

The review concludes that MEOR is a viable option for increasing oil recovery world over.

Keywords: Microbial Enhanced Oil Recovery (MEOR), Microbe, Recovery, Improved oil recovery, Residual oil

1.0 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 for/to produce more crude oil to meet the worldwide rising energy demand which illustrates the necessity of progressing enhanced oil recovery (EOR) processes.
Enhancement of the amount of hydrocarbons recovered from existing reservoirs is slowly becoming a standard procedure during the operational life of an oil field. Much research is presently being channeled into this area with the effect that both new and old methods are being carefully evaluated. Microbial Enhanced Oil Recovery (MEOR) is one such scheme which has received favorable reevaluation.
One of the major factors in the selection of any recovery method is the economic potential of the remaining reserves. In the past, much of the oil was left behind in the reservoir especially in the marginal and mature reserves due to the absence of a cost effective method.
But, in today's energy sector where oil prices are at their highest level ever reached, the development of the marginal and/or uneconomical reserves cannot only brings such reserves to production but could also help the operators to get maximum profit from these reserves.
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 pores.
One of the recovery methods which has the vast potential of bringing such reserves to production is the Microbial Enhanced Oil Recovery (MEOR). It is a chemical EOR method but with chemical generated in situ. It has been a main topic of research and interest in the past years and has long been expected to offer a low-cost approach for improving recovery.
MEOR is one of the EOR techniques where bacteria and their byproducts are utilized for oil mobilization in a reservoir. In principle, MEOR is a process that increase oil recovery through inoculation of microorganism in a reservoir, aiming that bacteria and their byproducts cause some beneficial effects such as the formation of stable oil-water emulsions, mobilization of residual oil as a result of

ISSN 2229-5518
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 (Sarkar et. al, 1989)1.

Microbial Enhanced Oil Recovery (MEOR) is one of the technologies that can be potentially implemented with an exceptionally low operating cost: It has several advantages compared to conventional EOR processes as it does not consume large amounts of energy as do thermal processes, nor does it depend on the oil price as do many chemical processes. MEOR is simply the process of utilizing microorganisms and their bio-products to enhance the oil recovery. Bacteria are the only microorganisms used for MEOR by researchers due to their small size, their production of useful metabolic compounds such as gases, acids, solvents, bio-surfactants, biopolymers as well as their biomass. Also, their ability to tolerate harsh environments similar to those in the subsurface reservoirs in terms of pressure, temperature, pH and salinity increased their attraction to be used for EOR purposes6.

This technology (MEOR) is said to be capable of producing up to 50% of the residual oil (Lazar et al. 2007; Sen, 2008)3, 4. The field trials have shown that normal projected oil production decline curve can be reversed or level off by MEOR and the reason is because microbial growth and metabolites produced can have effects on the chemical and physical properties of reservoir rocks and crude oil (Hitzman, 1994)16.

Problem Statement

Crude oil is produced on a daily basis. However, a large portion of this valuable energy source is left underground after the application of conventional extraction methods. The rising global energy demand has prompted the oil industry to explore other viable recovery techniques.

Objective

To examine Microbial Enhanced Oil Recovery and its technology

To analyse why the technology has not been widely used as other conventional techniques.

To see the potential of Microbial Recovery in competing with other conventional recovery methods.

Methodology

a review on:

History and background information on Microbial Enhanced Oil Recovery, MEOR

The MEOR technology and its implementation status

Research conducted on MEOR (papers and journals)

How MEOR compares to other Enhanced Oil Recovery (EOR) techniques

3.1 HISTORY OF MEOR

MEOR was first described by Beckman in 1926 (Lazar et. al., 2007)3. Few studies were conducted on MEOR over 2 decades after Bachman has described it. Until later in 1947, ZoBell initiated a new era of petroleum microbiology with applications for oil recovery. He conducted a series of field tests and discovered that bacteria can release oil from sedimentary materials. After the tests, ZoBell explained that the mechanisms which are responsible for bacterial oil release involved processes such as:

Production of gaseous C02

Production of Organic acids and detergent

Dissolution of carbonates in the rock

Physical dislodgement of the oil (Zobell, 1947)9.

The first MEOR test was conducted in the Lisbon field, vision country, Arkansas in 1954 (Yarbrough and Coty, 1983)10. The improvement of MEOR in field trials was based on the injection of mixed anaerobic Bacteria such as Clostridium, Baccilus, Pseudomonas etc. and are selected based on certain tendencies they exhibit.

The application of MEOR as a tertiary recovery technique and a step to decrease residual oil saturation has been explained (Behesht et. al. 2008)11. The aspect of petroleum microbiology that is perhaps the most important for MEOR is the ability of the microbes to use hydrocarbons as the carbon and energy source. The development of Biotechnology research has influenced the oil industry to be more open to the evaluation of microorganism to enhance production. Both the in situ and injected microorganism are used depending on their adaptability to the reservoir that is being used. In MEOR, bacteria are used because they show several practical features (Nielson et al, 2010)12.

3.2 PROCESSES OF MEOR

There are 2 main processes of MEOR depending on the site of the bio-product production. They are namely in situ and ex situ processes.

The in situ process involves producing the bacterial bio-products inside the reservoir. It can be done either by stimulating the indigenous reservoir microbes or injecting specially selected consortia of bacteria that will produce specific metabolic products in the reservoir which will lead to enhancement of oil recovery (Jack and Steheier 1988)13. According to Jang et. al., the success of an in situ MEOR process depends on the selection of the candidate reservoir, the proper choice of potential bacterial species, the viability of the bacteria under reservoir conditions, the amount of metabolites generated and their effects on releasing residual oil. Care must be taken however when nutrients or sulphate-containing waters are injected to ensure that indigenous sulphate-reducing bacteria (SRB) are not stimulated or overgrown by the injected microbes. These SRBs play a very negative role in MEOR due to the production of hydrogen sulfide, H2S (Bass 1997)14. The major concerns of global oil industry with SRBs include souring of oil, corrosion caused by the production of H2S, plugging by iron sulphide etc. (Brown, 2010)15. A concept is patented by Hitzman (Hitzman, 1994)16 of adding a biocide to the water in water flood to inhibit SRB.

The ex situ process involves the production of the bio-product at the surface outside the reservoir then injecting them separately either with or without the separation of the bacterial cells. In ex situ process, where exogenous microbes are introduced into the reservoir, it is important

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to conduct capability studies to determine the interaction of the injected microbes with the indigenous ones (Bryant, 1989)7.

3.3 CANDIDATE MICROBE FOR MEOR

Microbes can be classified in terms of their oxygen intake into 3 main classification; Aerobes; where the growth depends on abundant supply of oxygen to make cellular energy. Strictly Anaerobes which by contrast are sensitive even to the lowest oxygen concentration and are found in deep oil resources. These anaerobes do not contain the appropriate complement of enzymes that are necessary for growth in aerobic environment (Pommerville, 2005)17. Most successful field experiments used the anaerobic bacteria (Mandgalya et. al., 2007)8.

There are many sources from which bacterial species that are MEOR candidate can be isolated. Lazar explained four main sources that are suitable for bacterial isolation (Lazar, 1991)18. These are

Formation waters

Sediments from formation water purification plants (Gathering stations)

Sludge from biogas operations

Effluents from sugar refineries

Nutrients are the largest expense in the MEOR processes where formulation medium can represent almost 30% of the cost for a microbial fermentation (Rodrigues et. al., 2006)19. The microbes required mainly 3 components for growth and metabolic production: Carbon, Nitrogen, and phosphorous sources. Generally in the ratio C.100: N.10: P.1. The optimization medium is very important since the type of bio-products that are produced by different types of bacteria are dependent on the type concentrations and components of the nutrients provided. The third classification of bacteria is the facultative microbes which can grow either in the presence or reduced oxygen concentration.

3.4 MEOR MECHANISMS

Improving oil recovery through microbial actions can be performed through several mechanisms such as reduction of oil water Interfacial Tension (ITF) and alteration of wettability by surfactant production and bacterial presence, selective plugging by microorganisms and their metabolites, oil viscosity reduction, degradation of long chain saturated hydrocarbons and production of acids which improves absolute permeability by dissolving minerals in the rock. The microorganism produces a variety of metabolites that are potentially useful for oil recovery (McInerney, 2002)20.

There are six main bio-products/metabolites, produced by microbes. The table below shows a summary of these bio-products and their application in oil recovery (McInerney, 2002)20.

Products	Microorganism	Application in oil recovery
Biomass	Baccilus litchenforms, leuconostoc mesenteroids, Xanthomonas Compestris	Selective plugging, viscosity reduction, wettability alteration, oil degradation.
Bio-surfactants	Acinetobacter calcoacetiens arthrbacter paraffeninues Baccilus Sp. Clostridium Sp. Pseudomonas Sp.	Emulsification, Interfacial tension reduction, viscosity reduction.
Bio-polymers	Bacillus, Polymyxa, Brevibacterium viscogenes, lenconostoc Mensteriods, Xanthomonas compestris, Enterobacter sp	Injectivity profile modification, Mobility control viscosity modification
Bio-solvent	Clostridium sp., Enterobacter aerogens	Permeability increase, emulsification
Bio-gases	Clotridium Sp, Entrobacter aerogens, methanobacterinm sp	Increased pressure, oil dwelling, IFT reduction, viscosity reduction permeability increase

3.4.1 Biomass

Bacteria are known to grow very fast as some are reported to multiply 20 times under aerobic conditions (Pommerville, 2005)17. The mechanism of the microbial biomass in MEOR involves selective plugging of high permeability zones where the microbial cell will grow at the layer pore throats restricting the undesirable water flow through the pores (Jack and Steheier, 1982)13. This will force the displacing water to divert its path to the smaller pores and hence displacing the un-swept oil and increasing the oil recovery.

3.4.2 Bio-surfactants

These are amphipathic molecules with both hydrophilic and hydrophobic parts which are produced by variety of microorganisms. They have the ability to reduce the surface and interfacial tension by accumulating at the interface of immiscible fluids and increase the solubility and mobility of hydrophobic or insoluble organic compounds. Bio-surfactants 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 chemically synthesized surface active agents with potential application in the oil industry.

3.4.3 Biopolymers

These are polysaccharides which are secreted by many strains of bacteria mainly to protect them against temporary desiccation and predation as well as to assist in adhesion to surfaces (Sen, 2003)4 and (Brown, 1992)21. The proposed processes of biopolymers are mainly selective plugging of high permeability zones and this permeability modification of the reservoir to redirect the water flood to oil rich channels (Sen. 2008)3. Another important process of biopolymers is their potential as mobility control agents by increasing the viscosity of the displacing water hence improving mobility ratio and sweep efficiency (Akit et. al., 1989)22.

3.4.4. Bio-solvents

Sometimes solvents can be produced as one of the metabolites of the microbes. These include ethanol, acetone, and butanol by carbohydrates fermentation during the initial growth phase of the germination process. Strains of

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anaerobic bacteria such as chloride are responsible for the production of the metabolites during the stationary growth phase of the presentation process. These bio-solvents may also help in the reduction of oil viscosity and can also contribute as a surfactant (Co-surfactant) in reducing the interfacial tension (IFT) between oil and water (Youssef et al, 2005)23.

3.4.5 Bio-acids

Some bacteria, under certain nutrients can produce acids such as lactic acids, acetic acid and butyric acid (McInerney et. al., 2005)24. These acids can be useful in carbonate reservoirs or a sandstone formation sandwiched by carbonates, since some of these cause dissolution of the carbonate rock and hence improve its porosity and permeability (McInerney et al, 1990)25. Production of organic acids by bacteria is a normal phase of anaerobic formation of sugar. Clostridium sp, for example can produce 0.0034 moles of acid per kilogram of molasses. (Gray et.al., 2008)26.

3.4.6. Biogas

Bacteria can ferment carbohydrate to produce gases such as carbon dioxide, hydrogen and methane gases. These gases can be used for enhancing oil recovery by exploring the mechanisms of reservoir re-pressurization and heavy oil viscosity reduction. The gases can contribute to the pressure build-up in pressure depleted reservoir (Brown, 1992)21. They (gases) may also dissolve in crude oil and reduce its viscosity (Ramsay, 1987)27 and (McInerney et al, 1990)25 some of the reported gas-producing bacteria are Clostridium, Desulfovibrio, Pseudomonas and certain methanogens (Behlulgil and Mehmetoglu, 2003)5. Methanogens produce about 60% methane and 40% carbon dioxide where the methane will partition between oil and gas phase while carbon dioxide will partition to the water phase as well and hence improve the mobility of oil (Gray et al,2008)26.

3.5 MEOR FIELD TRIALS

MEOR method was developed from laboratory based studies (Ramkrishna, 2008)28. There are two main purposes to go for MEOR field applications, as single well treatment and full field treatment.

Single well treatment includes well simulation, wellbore clean-up and others. In this treatment process, improvement in oil production can result from removal of paraffinic or asphaltic deposits from the near wellbore region or from mobilization of residual oil in the limited volume of the reservoirs that is treated (Bryant, 1989)7.

Full field treatment includes microbial enhanced water flooding and other processes that involve both injection and production wells. Here, the microbes and nutrients are injected through an injector well where the metabolites will be produced in situ such as biopolymers that will help in mobility control of the water flooding.

MEOR process variables must be optimized before it develops into a practical method for common field trials or application. These variables includes a better description of the candidate reservoirs, better knowledge of the biochemical and physiological characteristics of the microbial consortia, a better handling of the controlling mechanisms, and an unambiguous estimation of the process economics. Most of the MEOR processes leading to field trial 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)28.

Some selected field projects across the world are analyzed and discussed, these project represents a diverse geographic and geologic mixtures. MEOR case studies of successful projects as analyzed by Dietrich et. al., (1996)29 is used in this review. The projects are located across the United States of America (USA) Argentina and the People Republic of China.

3.5.1 MEOR Treated Projects (Case Studies)

Dietrich et al (1996)29 analyzed five commercial projects as case study. These projects were recorded to have increased oil production significantly as compared to oil production prior to MEOR application. Two of these projects are located in the USA, one in Argentina and the other two in the people Republic of China.

3.5.1.1 San Andrews Project

The San Andrews reservoir was discovered in 1945 and was produced by solution gas drive until 1967 when water flooding was started. The original oil in place was 355bbl/acre-ft, at 70% oil saturation. When MEOR technique was employed in the October of 1994, oil in place was 239bbl/acre-ft with an oil saturation of 41%. Rock properties are relatively inhospitable for microbes. The low 1.7md average horizontal permeability would normally be indicative of pore throat size well below what microbes could enter. However most of the oil is produced from natural fractures which the microbes can penetrate. Reservoir temperature at 1150F is ideal for microbe growth.

3.5.1.2 Treatment

The treatment consisted of ten barrels of microbe laden water down the annulus. On the initial treatment the wells were shut-in for three days. Subsequently, they have been shut-in overnight. For the first three months the well were treated every 14 days, thereafter approximately every 28days.

3:5.1.3 Evaluation

The reservoir was stabilized on a consistent 6.5% per year decline for three years before MEOR was begun. The decline was flattened to 0.6% per year. Water production on this property is blended with fresh water and injected. Produced water is measured only by well tests and is not accurate enough to draw a conclusion regarding reduction in water cut. Over a period of 19 months 17,000 barrels of incremental oil have been produced which is seven percent (7%) over the baseline. Current oil production of 440 barrels per day is 10% over the baseline. The incremental increase is expected to reach 15% by the end of the project life.

At the end of its life, the water flood would have lift oil in place 205bbl/acre-ft versus 199bbl/acre-ft with MEOR.

Residual oil saturation is projected to decrease from 35% under water flood to 34.1% with MEOR.

3.5.2 Queen Sand Project

This reservoir was discovered in 1984 and was quickly water flooded due to its very low solution gas content. Injection was began in 1990 and oil production increased quickly from 200 to 2,500 barrels per day. This rate continued until late 1991 when a rapid decline began. At the start of MEOR in August of 1992, oil in place was 728bbl/acre-ft with an oil saturation of 56%.

Rock properties are generally favourable for microbe colonization. Average permeability is 13md with an upper limit of 300md and provides adequate pore throat size for microbes to colonize. Additional permeability developed by fracture treatment with 60,000 gallons and 135,000 pounds of sand on initial completion provided excellent porous media for microbe colonization. Reservoir temperature at 1100F is ideal for microbe growth. Average production per well is 42 BOPD at 74% water cut. The wells are rod pumped with low producing fluid levels. The formation contains salt and anhydrite and formation water is saturated brine.

3.5.2.1 Treatment

Over the first nine months of MEOR treatments 11 of the 18 wells were treated with 400 to 450 barrels of microbe-laden water squeezed down the annulus followed by a 3 day shut-in. Three more similar squeezes were performed later. Routine batch treating was later begun in September of 1992. The wells were treated weekly with 32 barrels of microbe-laden water followed by a 6-12 hours shut-in. In late 1994, the frequency was reduced to every 14days. Then in early 1995, the frequency was increased only on selected wells back to every 7 days.

3.5.2.2 Evaluation

The reservoir was on a 39% per year decline for 10months before MEOR was begun. The decline flattened for several months, and then resumed at 31% per year. In late 1994, the injection pattern was altered by the conversion of two wells from producers to injectors and the injection rate has increased. Although the benefits of MEOR continue, comparison to the original baseline was inaccurate. Water production continued to increase after the start of MEOR. The rate of increase in water-cut decreased from 24% per million barrels to 12%. Over the first 24 months 240,000 barrels of incremental oil was produced which is 34% over the baseline. Oil production at the time the injections pattern was changed was 1000bbls/day, 43% over baseline. The cumulative incremental increase was projected to be 47% by the end of the project life.

At the end of its life, the water flood before the pattern changes would have left oil in place 691bbls/acre-ft versus 660bbls/acre-ft with MEOR. Residual oil saturation was projected to decrease from 51.4% under water flood to 49.1% with MEOR.

3.5.3 Tapun Gato-Refugio Project

The field was discovered in 1930 the three wells in the project were complete in 1940, 1979 and 1786 in the Victor Oscuro formation. The reservoir has been produced by a combination of solution gas drive, water drive and water flood. MEOR was started on one well in June 1994 and on the other two wells in March of 1995. Production was time-normalized relative to the start of MEOR. At the start of the project oil in place was 625bbl/acre-ft with an oil saturation of 47% and an oil saturation of 10%. The wells are on approximately 42 acre spacing. Rock and fluid properties are favourable for microbe colonization.

3.5.3.1 Treatment

Initial microbe treatment was 150 barrel of microbe-laden water followed by a 48 hour shut-in on 2 wells and 24 hours on the other. Subsequent treatment have been 50 barrels every 15days on two of the wells and every 30days on the other wells.

3.5.3.2 Evaluation

The project was on a 7.1% per year decline for 29 months before MEOR was begun. For 14months since the start of MEOR, the oil production rate has inclined at the rate of 7.3% 1 year. Water production has also increased after the start of MEOR. For the 14 months 19000 barrels of incremental oil has been produced which is 19% over the baseline. Oil production is 270bbls/day, 29% over baseline. The cumulative incremental increase is projected to be 57% by the end of the project life.

Oil in-place at the end of the project life would have been 509bbls/acre-ft versus 442bbls/acre-ft with MEOR. Residual oil saturation is projected to decrease from 38.3% under water flood to 33.3% with MEOR.

3.5.4 Huabet Project

This project contains 7 wells. The wells in the later stage of being water flooded, are scattered and not in the same reservoir. Therefore, while production data can be analyzed, reservoir performance cannot be determined for this grouping. MEOR started September of 1994.

The wells are rod pumped, with pumps set an average of 2,500 feet above perforations. Reservoir and fluid parameters are all favorable for microbe growth.

3.5.4.1 Treatment

Each well was treated three times. The first 2 treatments consisted of 150 barrels of microbe-laden flood, followed by 40-150 barrels of displacing water. The displacement was calculated according to the distance the pump was set over the perforations and the pumping floor level. The third treatment was 50 barrels with displacements ranging from 40-125 barrels.

3.5.4.2 Evaluation

The wells in this project were on a rapid decline before MEOR was begun. The baseline was determined from a well by well review of daily production for the five months before the start of MEOR. For 12 months after the start of MEOR, oil production rate has inclined then flattened at 150 barrels per day. Water production decreased after the start of MEOR. Water-cut decreased from over 70% to fewer than 60% and the trend in water-cut versus cumulative oil production which was rapidly increasing started decreasing. Over the 12 months, 41 barrels of incremental oil have been produced which is 216% over the baseline. Oil production is 150 barrels per days 552% over baseline.

3.5.5 Xinjiang Project

This project contains 10 wells located in the Xinjiang Petroleum Administration Bureau. The wells, mostly in the later Stage of being water flooded, are scattered and not in the same reservoir. Therefore, while production data can be analysed, reservoir performance cannot be determined for this grouping. MEOR treatment started in 1995.

The wells are rod pumped, with pumps set from 200 to as high no 6000 feet above the perforations on one will. Reservoirs and fluid properties/parameters are all favourable for microbe growth.

3.5.5.1 Treatment

Each well was treated three times. The first treatments consisted of 150 barrels of microbe-laden fluid on 7 wells and 80 barrels on 3 well followed by 0-150 barrels of displacing water. The displacement was calculated according to the distance the pump was set over the perforations and the pumping fluid level. The second and third treatments were 50 barrels in 6 wells and 75 barrels on 4 wells with displacement ranging from 0—70 barrels.

3.5.5.2 Evaluation

The wells in this project were on a rapid decline for 24 months before MEOR was begun. For six months after the start of MEOR the oil production rate increased then maintained a rate of 300bbl/day. Water production decreased after the start of MEOR and the water-cut decreased from 64% to 54%. The trend in water-cut versus cumulative oil production which was rapidly increasing became flat. Over 6 month 14,000 barrels of incremental oil was produced which is 43% over the baseline. The baseline sample indicated microbes could significantly alter the crude.

On five of the wells, the operator measured an average decrease in viscosity at 680F from 273 to 184 cp (49%) and an increase in gravity from 28.70 API to 29.60 API (3.1%). Microbes favorably altered the oil in this reservoir.

3.6 FACTORS TO CONSIDER BEFORE APPLYING MEOR

The application of enhanced oil recovery (EOR) technology is being applied worldwide, and can only be expected to increase due to the diminishing development of new fields and the decline of more mature one. MEOR processed address the same physical parameters as chemical enhanced oil recovery processes. Hence they are subject to the same technical difficulties.

3.6.1 Selecting the Reservoir

Reservoir selection for MEOR processes can prove to be a challenging task. Candidate reservoir selection for MEOR processes requires considerations of a number of parameters before it can be successfully implemented. In case of mature field, in-situ MEOR is mainly targeted towards the residual oil left after the primary production and secondary recovery methods.

The following are the common factors needed to be considered before we apply MEOR to a certain reservoir. These parameters can vary widely from reservoir to reservoir and in some cases novel parameters may also be considered before MEOR is implemented

3.6.1.1 Structural Analysis

Marginal resources mean a very little or no room for errors. Structural analysis must be done in order to have an optimized plan before injecting microbes into the formation. A region of by-passed oil and areas as of high permeability to plug certain formation pores cannot be identified without structural analysis. Using a structural analysis approach, drilling uncertainties and risks could be identified. However, structural analysis could sometimes be an issue and if a structure is analyzed improperly, there is a fair chance that the microbes would act as a bad candidate. Initial water saturation, spatial distribution of oil lenses, spatial distribution of facies and faults representation are necessary things before adopting MEOR.

3.6.1.2 Geological Complexity

Geological complexity needs a thorough study because it plays a vital role in microbes injection into the reservoirs and the function they perform. Due to several reasons such as changes in permeability, porosity, wettability, etc. the microbes might not reach the target zone.

3.6.1.3 Well Pattern To Be Drilled

This parameter is again critical in injection and production of hydrocarbons. Thus a detailed study needs to be conducted before the injectors and producers are decided in marginal reserves. For an optimized plan, selecting the right pattern to be drilled is essential. Due to economic factors, if horizontal, directional, extended reach drilling is considered, then a proper pattern of injectors and producers must be studied for MEOR.

3.6.1.4 Permeability Analysis

This factor is necessary for selecting the strain of bacteria and to survival or feeding technique and composition.

3.6.1.5 Petro Physical Analysis

PVT and other petro-physical analyses are important so that comparison after application of MEOR can be made and other laboratory studies can be carried out.

3.6.1.6 Temperature

Temperature is a very important part and plays a very vital role in MEOR. At high temperature bacterial growth and their metabolic processes would be highly influenced in the anaerobic nutrient-lack environment. Thus, the reservoir temperature must suit microorganisms for their survival and growth. In high temperature reservoirs, the development of such microorganisms which can sustain and stimulate their growth can be a big challenge.

3.6.1.7 Can The Production Target Be Met?

Deciding whether the application of MEOR will help you in achieving the required production target is a function of many considerations. This can be done through, pilot testing and laboratory test in cores.

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There are many other factors which could/should be studied so that microorganism growth and stimulation could not be affected by formation. These are

Remaining oil saturation
Fluid evaluation: Hydrocarbon compositional analysis
Fluids chemistry and composition
Depth of reservoir
Salinity of formation water
Formation water sample analysis
Net oil increase: estimates
Economic aspects

3.6.2 Identifying the Chemicals That Need To Be Produced And The Job They Need To Perform

There are several ways in which microorganism may contribute to enhanced oil recovery. The next challenge is to identify what chemicals produced by the bacteria can lead to optimum recovery. This process is again linked with reservoir study and the nutrients fed to the bacteria. Parameters relating to transport, growth and metabolite production by microorganism in petroleum reservoirs needs vigorous research. Microbial transport studies must be performed under reservoirs conditions.

The following are the main types of chemicals and mechanism that microbes can perform. However the production of these substances and other mechanisms need to be carefully designed and monitored.

Produce surfactants
Reduce polymer
Selective plugging by bacteria

3.6.3 Selecting the Right Bacteria

In MEOR, microbe species selection is crucial. They have to fit the reservoir conditions and produce the required bio-products. Different strains of bacteria have different adaptability therefore selecting the bacteria based on reservoir conditions and fluid properties are essential. Reservoir ecosystem provides the basis for positive response from bacteria.

Pore colonization by bacteria and the consequent products produced by bacteria needs spatial attention. Essentially, the most suitable train of bacteria can only be determined after careful laboratory analysis and tests on cores.

3.6.4 Selecting the Nutrients For Bacteria

The classical definition of microbial enhanced oil recovery is to introduce a microorganism along with a food source to effect a positive change in the recovery mechanism of an oil reservoir. The products produced by the bacteria and their survival are dependent on the nutrients fed to them.

To sustain and prolong the maximum level required of bacterial count, an optimum concentration of nutrients and the right type of nutrients is desired. In fact, microbes may already exist in the reservoir just surviving at a very low metabolic level waiting for the right condition in order to revitalize.

Nutrients selection can only be done after a detailed study and testing period. Testing for the right nutrient is carried out after a clearly chalked out plan incorporating all the production considerations. Effect of pH and other trace minerals are also of prime importance in selecting the nutrients.

3.6.5 Pilot Testing

Pilot testing is the deciding factor in the successful application of MEOR. The projects are generally conducted in phases. In the initial research and development phase, extensive laboratory tests and analysis are conducted to understand process mechanisms and identify important parameters. Generally different task include;

Screening of available microbe-nutrient system that are viable in reservoir conditions in terms of compatibility, competitiveness and ability to propagate in porous media.
Investigation of likely process by-products and their effects on oil recovery and screening.
Screening candidate reservoir for MEOR application.

The methodology for designing and optimizing MEOR field tests has yet to be established, however, different results have indicated that there are some necessary procedures that need to be followed for a successful pilot testing of a project. In pilot testing, parameters such as oil production, test results on standard cores, well selection, , incremental reserves, distribution of nutrients throughout the reservoir, evidence of microbial proliferation of reservoir etc. require strict analysis

3.7 EXPERIMENTAL STUDY

At the experimental stage of MEOR, before ascertaining the viability of the MEOR process on a reservoir and proceeding for a pilot test, a host of parameters are analysed.

3.7.1 Materials

Materials, nutrients and supplements used in the microbial profile modification process are an important part of the evaluation. There are many source of nutrients such as sucrose, molasses, corn steep liquor, black liquor, soy bean whey, tapioca whey, etc. the combination of nutrients with nitrogen, phosphorus, minerals and proteins.

3.7.2 Microbes

Microbe selection is crucial for a successful MEOR project result. For this purpose the best strategy would be to gather a multidisciplinary team consisting of a microbiologist, geologist and a petroleum engineer and chalk out a strategy of core testing and other tests using different strains of bacteria and then selecting the best strain on the basis of result comparison.

3.7.3 Nutrients

Microbes require for a growth source of the major elements which make up cell material-carbon, nitrogen, phosphorus, oxygen, sulphur, minor components such as iron, zinc, manganese, and a source of energy for the synthesis process involved in growth. In the laboratory, bacteria can be fed with different nutrients and the resultant by-product analysed. The nutrients giving the best by-products and acting in the desired way on oil should be chosen. Water is usually the preferred medium of choice. However medium properties and the formation to interact with should also be studied.

3.7.4 Water

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Testing formation for salinity, trace minerals and all other mineral dissolved in it as incorporated as part of the experimentation. Formation water testing reveals a great deal on the ability of the microorganism to survive in the formation and reproduce at the required rate.

3.7.5 Testing

Testing of MEOR projects to give a formal go ahead for MEOR application in a various field include the following slips.

Site selection

Sampling and analysis of well fluids

Selection of microbial formulation and compatibility test

Reductions follow up

3.8 MATHEMATICAL MODELING FOR MEOR

The current need for 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 effective recovery processes (Kianipey and Donaldson, 1986)30. Bryant and Lockhart (2002)31 examined the qualitative correlations between microbial activity, reservoir features and operating conditions such as injection rates, well spacing and residual oil saturation. Marshall (2008)32 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 for the production of a given metabolite, but the rate of production can only be determine experimentally, and must be given by actual bacterial growth velocities (Marshall, 2008)32.

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 process media along with specific equations for adoration and diffusion of maternities', microorganisms, and nutrients (Islam, 1990)33 and (Behehst et.al. 2008)11. The main multidimensional transport equations were combined with equations of different microbial features such as growth, death and nutrient consumption.

Several assumptions are made for the transport equation for the microbial process. Nielson et al (2010)12 points out the following assumptions

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.

Bacteria growth could be explained by monod-kinetics being independent of temperature, pressure, pH and salinity (Nielson et. al., 2010)12.

The major metabolite was surfactant and other possible metabolites were considered insignificant.

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 insight of the process can be obtained from quite simple analytical models, whereas the exact models regularly requires thorough numerical computation. The important point claimed by researcher is that modeling of microbial reactions still faces strict limitation. Models are based on the relation between the residues time (τres) of the bacteria on a cylindrical reaction zone of reactions; rm, depth to and porosity, ϕ which is combined in relation as:

$$\tau res = \frac{\bar{\Delta} r^2_{m\, h\, \phi\, (1-S_{or})}}{Q}$$

Where Q is the volumetric flow rate and Sor is the residual oil saturation and the time required for the microbial reaction to produce a desired concentration Creq for some metabolite.

To estimate the reaction time, Marshall (2008)32 posed the following assumptions:

Isothermal plug flow through the reactor,

Nutrient consumption is first order and irreversible, and

Nutrients initial concentration is no

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

Surfactants could be distributed between both phases (water and oil). Surfactant sharing was instantaneous and the distortion kinetics was neglected.

No substrate and metabolite adsorption on pore walls.

Adsorption in any component was neglected.

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

3.9 LABORATORY STUDIES OF MEOR

As a result of the relative rarity of field MEOR applications, most of the MEOR literature consist of laboratory, theoretical and simulation studies. It is convenient to group those studies as follows:

Microbial science (No attempt to recover oil)

EOR (Attempt to recover oil)

Theory and simulation

3.9.1 Microbial Science

The laboratory studies grouped under microbial science investigate the transport, growth are reaction of bacteria in porous media the major questions addressed under microbial science is summarized as: how far can this microbe be transported and under what conditions (Temperature pressure, nutrient supply etc.), does this microbe remain viable. Following the trend of studies in

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chemical EOR, more recent studies have focused on the reduction of permeability associated with in situ microbe growth. Quantitative data regarding the rate of biological reaction, the yield of the reaction (Mass of the desired product per unit substrate consumed) and the concentrates of reaction products are rarely given. Yet these parameters are absolutely fundamental in evaluating field application of this technology. The absence of a reservoir engineering perspective in the design and reporting of many experiments severely limits their practical utility. The identification of a mechanism for cell attachment and consequent control of microbe trapping in a porous medium constitute a rare exception (Lappan and Fogler, 1992, 1994)34, 35.

3.9.2 EOR

The laboratory study grouped under EOR follow essentially the same procedure no those grouped under microbial science but one carried not in the presence of oil. Quantitative measures of reaction rates and yield are not common, and relationship between these data and incremental oil production are almost never explored (e.g. how oil recovery depends on shut-in time after nutrient injections or on nutrient flow rate through the porous medium). A noteworthy step in this direction computes microbe/nutrient stoichiometry observed in a core flood and attempt to scale this in the reservoir (Sunde et. al. 1992)47. This is instructive for estimating volumes and capacities and hence feasibility, but the critical element of kinetics was not considered. The rate at which the microbial reaction proceeds determines achievable product concentrations and hence the efficiency of the process, and this is independent of stoichiometry.

Exceptional recoveries in the range of 30-60% have been reported, (Bryant and Douglas, 1998)36 (Almalik and Desouky 1996)37 though analysis of the data presented indicate, that these values may include the effect of an increase in pressure during displacement. At the other extreme, the most carefully analysed series of MEOR care floods reported in the literature shored no recovery of residual oil of all (Rouse et. al., 1992)38.

The small amounts of oil recovered in laboratory MEOR and stretches after accommodate gradually during tens of PV of fluid injection after the microbial treatment. In contrasts theory for surfactant EOR process predicts formation of an oil bank (a small volume of high oil saturation), and such banks are observed in experiments for EOR process that reduces interfacial tension. These observations suggest that insufficient chemicals are being produced by the microbes. From a reservoir engineering perspective there is a clear need to investigate the concentration and transport of these in situ generated chemical to determine their efficacy for oil displacement as a function of concentration and to establish the mechanism for oil displacement. Given the wide gap between field and laboratory oil recoveries for chemical EOR processes and given that MEOR involves the same mechanist as EOR, the modest lab recoveries reported to date suggest that field applications of MEOR would yield marginal recoveries at best. This is borne out by the field trials of MEOR reported to date. Failure to achieve high recoveries with a far PV of injected nutrients in the laboratory, and to recognise this as a key issue is emblematic of the distance that separates the current state-of-the-art from the ultimate objectives of MEOR research.

3.9.3 Theory And Simulation

The study (ies) grouped under theory and simulation either present overviews of EOR and MEOR characteristics or models for simulation of some aspects of MEOR. An important message from the former is that MEOR is not a panacea, if a reservoir is not good candidate for MEOR. This conclusion is to be expected since MEOR relies on the same recovery mechanisms as traditional EOR while introducing the additional difficulty of establishing viable microbe colonies in the reservoir. The lack of quantitative reaction data has severely hindered the useful application of simulators.

DISCUSSION

Microbial recovery processes is another tertiary method of oil recovery commonly known as MEOR, which nowadays is becoming an important and rapidly development tertiary production technology, which uses microorganisms or their metabolites to enhance the recovery of residential oil (Banat, 1995)39, (Xu et. al., 2009)40.

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 bio-surfactant, biopolymers, acids, solvents, gases and also enzymes modify the properties of the oil and the interaction 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. In some process, a fermentable carbohydrate including molasses is utilized as nutrient (Bass and Lappin-Scott, 1997)41. Some other reservoirs require inorganic nutrients as substrates for cellular growth or as alternative electron acceptor instead of oxygen. In another method, water containing a source of vitamin phosphates, and election acceptors such as nitrate is injected into the reservoirs, so that anaerobic bacteria can grow using oil as the main carbon source (Sen. 2008)4. The microorganisms used in MEOR methods are mostly anaerobic extremophiles, including halophiles, barophiles and thermophiles for their better adaptation to the oil reservoirs conditions (Brown, 1992)21 (Klire and Khan, 1994)42 (Bryant and Lindsey, 1996)43 (Tango and Islam, 2002)44. The bacteria are usually hydrocarbon-utilising, non-pathogenic, and are naturally occurring in petroleum reservoirs (Almeida et. al. 2004)45.

In the past, the microbes selected for uses, had to have a maximum growth rate at temperature below 800C, however it is known that some microorganisms, can actually grow at temperature up to 1210C. Baccillus strain grown in glucose mineral salts medium are one of the most utilised bacteria in MEOR technologies, specifically when oil viscosity reduction is not the primary aim of the operation (Sen. 2008)4.

The application of MEOR as a tertiary recovery techniques and a natural step be decrease residual oil saturation has been report (Bahesht et. al., 2008)11. A complete review of the microbiology of petroleum was published by Vam Hamme et. al., (2005)46, which covered a significant amount of literature. The publication is mainly focused on the description of the Molecular biological characteristics of the aerobic and anaerobic hydrocarbon exploitation, with some citation in the application of the microbe, microbial oil recovery, and biosensors. The aspect of petroleum microbiology that is perhaps the most important for MEOR is the ability of the microbes to use hydrocarbons as the carbon and energy sources.

Biotechnology research has improve, 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 the adaptability to the specific reservoir. In microbial enhanced oil recovery (MEOR) bacteria are regularly used because they show several practical features (Nielson et. al., 2010)12. Several publications state that oil through microbial action takes place due to several mechanisms as follows:

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 thus improving porous media permeability.

The first two mechanisms are believed to have the greatest effect on improving oil recovery. (Nielson et. al., 2010)12 (Desouky et. al., 1996)37 (Bryant, 1989)7.

Lazar (2007)3 points out some outstanding advantages of microbial enhanced oil recovery over other enhanced recovery techniques such that the injected bacteria and its nutrients are inexpensive and easy to obtain and handle in the field. MEOR is also economically attractive for marginally producing oil fields and are suitable alternatives before the abandonment of marginal wells. Most importantly, as Lazar (2007)3 observed is that the effect of bacterial activity within the reservoir are improved by their growth with time, while in other EOR technologies, the effect of the additives tend to decrease with time and distance from the injection well.

MEOR is not without some challenges and problems. Lazar (2007)3 points some of the challenges as injectivity loss due to microbial plugging of the wellbore-to avoid wellbore plugging, some actions must be taken such as filtration before injection to avoid polymer production and minimize microbial adsorption to rock surface by using dormant cells forms, spores, or ultra-micro-bacteria. Sen (2008)4 also points out that the isolation of microbial strains, adaptable to the extreme reservoir conditions of pH, temperatures, pressure and salinity is a big challenge.

CONCLUSION

In conclusion, it is observed that

MEOR is a well proven technology to enhance oil recovery especially in mature oil wells.

MEOR is a cost effective and ecofriendly process that shows several advantages over other EOR processes.

MEOR has a great potential to become a viable alternative to the conventional EOR chemical method.

In spite of the various advantages of MEOR over other EOR methods, it has gain little credibility in the oil industry because the value of MEOR is mostly determined by the result of field trials.

Most MEOR literature is based on laboratory data and a shortage of ample field trials can be seen.

Moses (1991)15 pointed out that the follow up time of most field trials was not long enough to determine the long-term effect of the process.

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.

Optimisation of nutrients and testing the microbes and their byproduct compatible with reservoir conditions are required.

RECOMMENDATION

After the review, it is recommended that

More research should be conducted on MEOR to cover for the uncertainties in the Engineering design.

Toxicity test is recommended on the microbe that are to be used in the field to assure that it is safe to handle and pose no threat to humans or to the environment.

A wide range compatibility test is required of the nutrients, microbe and their by-product with the reservoir and the prevailing conditions.

Compatibility test should be widely conducted between indigeneous and injected microbes.

Interdisciplinary research and collaboration is highly recommended between Petroleum Engineers, Microbiologists, and Geologist.

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