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A Brief Review On The Science, Mechanism And Environmental Constraints Of Microbial Enhanced Oil Recovery (MEOR)

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Abstract: MEOR is involved in the third phase of oil recovery namely tertiary phase to lift heavy oil from reservior which do not flow on its own to surface.This technique uses micro organisms to retrieve additional oil from existing wells, thereby enhancing the petroleum production of an oil reservoir. Selected natural microorganisms are introduced into oil wells to produce harmless by-products, such as slippery natural substances or gases, all of which help propel oil out of the well. Because these processes help to mobilize the oil & facilitate oil flow, they allow a greater amount to be recovered from the well. The microbial processes proceeding in MEOR include well bore clean up to remove mud and other debris blocking the channels where oil flows through, well stimulation that improve the flow of oil from the drainage area into the well bore and enhanced water floods to increase microbial activity by injecting selected microbes and sometimes nutrients. From the engineering point of view, MEOR is a system integrated by the reservoir, microbes, nutrients and protocol of well injection. The present study deals with the exploration of science and mechanism of MEOR. Also the impact of environmental factors such as temperature, pressure, pore size/geometry, pH (surface charge, enzymatic activity) and oxidation potential on microbial communities for oil recovery are presented.
Key words: Review, Science, Mechanism ,Environmental Constraints, Microbial Enhanced Oil Recovery (MEOR).

Introduction

Microbial Enhanced Oil Recovery (MEOR) is a biological based technology consisting in manipulating function or structure, or both, of microbial environments existing in oil reservoirs. The ultimate aim of MEOR is to improve the recovery of oil entrapped in porous media while increasing economic profits. MEOR is a tertiary oil extraction technology allowing the partial recovery of the commonly residual two-thirds of oil, thus increasing the life of mature oil reservoirs.

MEOR is a multidisciplinary field incorporating, among others: geology, chemistry, microbiology, fluids mechanics, petroleum engineering, environmental engineering and chemical engineering. The microbial processes proceeding in MEOR can be classified according to the oil production problem in the field:

- *well bore clean up* removes mud and other debris blocking the channels where oil flows through;
- *well stimulation* improves the flow of oil from the drainage area into the well bore; and
- *enhanced water floods* increase microbial activity by injecting selected microbes and sometimes nutrients From the engineering point of view, MEOR is a system integrated by the reservoir, microbes, nutrients and protocol of well injection

Types Of MEOR

MEOR is used in the third phase from a well,known as tertiary oil recovery Recovering oil usually requires two to three stages which follows.

Stage1: Primary Recovery -12% to 15% of the oil in the well is recovered without the need to introduce other substances into the well.

Stage2: Secondary Recovery- the oil well is flooded with water or other substances to drive out an additional 15% to 20% more oil from the well.

Stage3: Tertiary Recovery- this stage may be accomplished through several different methods, including MEOR, to additionally recover up to 11% more oil from the well.

Advantages can be summarised as follows:

- Injected microbes and nutrients are cheap; easy to handle in the field and independent of oil prices.
- Economically attractive for mature oil fields before abandonment.
- Increases oil production.
- Existing facilities require slight modifications.
- Easy application.
- Less expensive set up.
- Low energy input requirement for microbes to produce MEOR agents.
- More efficient than other EOR methods when applied to carbonate oil reservoirs.
- Microbial activity increases with microbial growth. This is opposite to the case of other EOR additives in time and distance.
- Cellular products are biodegradable and therefore can be considered environmentally friendly.

MEOR disadvantages

- The oxygen deployed in aerobic MEOR can act as corrosive agent on non-resistant topside equipment and down-hole piping
- Anaerobic MEOR requires large amounts of sugar limiting its applicability in offshore platforms due to logistical problems
- Exogenous microbes require facilities for their cultivation.
- Indigenous microbes need a standardized framework for evaluating microbial activity, e.g. specialized coring and sampling techniques.

- Microbial growth is favoured when: layer permeability is greater than 50 md; reservoir temperature is inferior to 80 ^{0}C, salinity is below 150 g/L and reservoir depth is less than 2400m.

The environment of an oil reservoir

Oil reservoirs are complex environments containing living (microorganisms) and non living factors (minerals) which interact with each other in a complicated dynamic network of nutrients and energy fluxes. Since the reservoir is heterogeneous, so do the variety of ecosystems containing diverse microbial communities, which in turn are able to affect reservoir behaviour and oil mobilization[2][3][4][6].

Microbes are living machines whose metabolites, excretion products and new cells may interact with each other or with the environment, positively or negatively, depending on the global desirable purpose, e.g. the enhancement of oil recovery. All these entities, i.e. enzymes, extracellular polymeric substances (EPS)[9][10] and the cells themselves, may participate as catalyst or reactants. Such complexity is increased by the interplay with the environment, the later playing a crucial role by affecting cellular function, i.e. genetic expression and protein production.

Despite this fundamental knowledge on cell physiology, a solid understanding on function and structure of microbial communities in oil reservoirs, i.e. ecophysiology, remains inexistent.

Environmental constraints

Several factors concomitantly affect microbial growth and activity. In oil reservoirs, such environmental constraints permit to establish criteria as to assess and compare the suitability of microorganisms. Those constrains may not be as harsh as other environments on Earth. For example, connate brines salinity is higher than that of sea water but lower than that of salt lakes. In addition, pressures up to 20 MPa and temperatures up to 80 °C, in oil reservoirs, are within the limits for the survival of other microorganisms.

Some environmental constraints creating selective pressures on cellular systems that may also affect microbial communities in oil reservoirs are:

Temperature

Enzymes are biological catalysts whose function is affected by a variety of factors including temperature, which at different ranges may improve or hamper enzymatic mediated reactions. This will have an effect over the optimal cellular growth or metabolism. Such dependency permits to classify microbes according to the range of temperature at which they can grow. For instance: psychrophiles (<25 °C), mesophiles (25-45 °C), thermophiles (45-60 °C) and hyperthermophiles (60-121 °C). Although such cells optimally grow in those temperature ranges there may not be a direct relationship with the production of specific metabolites.

Pressure

Direct effects

The effects of pressure on microbial growth under deep ocean conditions were investigated by ZoBell and Johson in 1949. They called barophilic to those microbes whose growth was enhanced by increasing pressure. Other classification of microorganisms is based on whereas microbial growth is inhibited at standard conditions (piezophiles) or above 40 MPa (piezotolerants). From a molecular point of view, the review of Daniel shows that at high pressures the DNA double helix becomes denser, and therefore both gene expression and protein synthesis are affected.

Indirect effect

Increasing pressure increases gas solubility, and this may affect the redox potential of gases participating as electron acceptors and donors, such as hydrogen or CO_2.

Pore size/geometry

One study has concluded that substantial bacterial activity is achieved when there are interconnections of pores having at least 0.2µ diameter. It is expected that pore size and geometry may affect chemotaxis. However, this has not been proven at oil reservoir conditions.

pH

The acidity of alkalinity has an impact over several aspects in living and non living systems. For instance:

Surface charge

Changes in cellular surface and membrane thickness may be promoted by pH due to its ionization power of cellular membrane embedded proteins. The modified ionic regions may interact with mineral particles and affect the motion of cells through the porous media.

Enzymatic activity

Embedded cell proteins play a fundamental roll in the transport of chemicals across the cellular membrane. Their function is strongly dependent on their state of ionisation, which is in turn strongly affected by pH.

In both cases, this may happen in isolated or complex environmental microbial communities. So far the understanding on the interaction between pH and environmental microbial communities remains unknown, despite the efforts of the last decade. Little is know on the ecophysiology of complex microbial communities and research is still in developmental stage.[13][14][15].

Oxidation potential

The oxidation potential (Eh, measured in volts) is, as in any reaction system, the thermodynamic driving force of anaerobic respiration, which takes place in oxygen depleted environments. Prokaryotes are among the cells that have anaerobic respiration as metabolic strategy for survival. The electron transport takes place along and across the cellular membrane (prokaryotes lack of mitochondria). Electrons are transferred from an electron donor (molecule to be oxidised anaerobically) to an electron acceptor (NO_3, SO_4, MnO_4, etc.). The net Eh between a given electron donor and acceptor; hydrogen ions and other species in place will determine which reaction will first take place. For instance, nitrification is hierarchically more favoured than sulphate reduction. This allows for enhanced oil recovery by disfavouring biologically produced H_2S, which derives from reduced SO_4. In this process, the effects of nitrate reduction on wettability, interfacial tension, viscosity, permeability, biomass and biopolymer production remain unknown.

Electrolyte composition

Electrolytes concentration and other dissolved species may affect cellular physiology. Dissolving electrolytes reduces thermodynamic activity (aw), vapour pressure and autoprotolysis of water. Besides, electrolytes promote an ionic strength gradient across cellular membrane and therefore provides a powerful driving force allowing the diffusion of water into or out to cells. In natural environments, most bacteria are incapable of living at aw below 0.95. However, some microbes from hypersaline environment such as Pseudomonas species and Halococcus thrive at lower a_w, and are therefore interesting for MEOR research.

Non-specific effects

They may occur on pH and Eh. For example, increasing ionic strength increases solubility of nonelectrolytes ('salting out') as in the case of dissolution of carbon dioxide, a pH controller of a variety of natural waters.

Biological factors

Although it is widely accepted that predation, parasitism, syntrophism and other relationships also occur in the microbial world, little is known in this relationships on MEOR and they have been disregarded in MEOR experiments.

In other cases, some microorganisms can thrive in nutrient deficient environments (oligotrophy) such as deep granitic and basaltic aquifers. Other microbes, living in sediments, may utilise available organic compounds (heterotrophy). Organic matter and metabolic products between geological formations can diffuse and support microbial growth in distant environments

MEOR mechanism

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

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

- *Beneficial effects*. Biodegradation of big molecules reduces viscosity; production of surfactants reduces interfacial tension; production of gas provides additional pressure driving force; microbial metabolites or the microbes themselves may reduce permeability by activation of secondary flow paths.
- *Detrimental effects*. Biologically produced hydrogen sulphide, i.e. souring, causes corrosion of piping and machinery; consumption of hydrocarbons by bacteria reduces the production of desired chemicals
- *Beneficial or Detrimental*. Permeability reduction can be beneficial in some cases but detrimental in others. Negatively, microbial metabolites or the microbes themselves may reduce permeability by activation of secondary flow paths by depositing: biomass (biological clogging), minerals (chemical clogging) or other suspended particles (physical clogging). Positively, attachment of bacteria and development of slime, i.e. extracellular polymeric substances (EPS), favour the plugging of highly permeable zones (thieves zones) leading to increased sweep efficiency.

MEOR strategies

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

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

MEOR agents	Microbes	Product	Possible MEOR application
Biomass, i.e. flocks or biofilms	Bacillus sp.	Cells and EPS (mainly exopolysaccharides),	Selective plugging of oil depleted zones and wettability angle alteration
	Leuconostoc		
	Xanthomonas		
Surfactants	Acinetobacter	Emulsan and alasan	Emulsification and de-emulsification through reduction of interfacial tension
	Bacillus sp.	Surfactin, rhamnolipid, lichenysin	
	Pseudomonas	Rhamnolipid, glycolipids	
	Rhodococcus sp.	Viscosin and trehaloselipids	
	Arthrobacter		

Biopolymers	Xanthomonas sp.	Xanthan gum	Injectivity profile and viscosity modification, selective plugging
	Aureobasidium sp.	Pullulan	
	Bacillus sp.	Levan	
	Alcaligeness sp.	Curdlan	
	Leuconostoc sp.	Dextran	
	Sclerotium sp.	Scleroglucan	
	Brevibacterium		
Solvents	Clostridium, Zymomonas and Klebsiella	Acetone, butanol, propan-2-diol	Rock dissolution for increasing permeability, oil viscosity reduction
Acids	Clostridium	Propionic and butyric acids	Permeability increase, emulsification
	Enterobacter		
	Mixed acidogens		
Gases	Clostridium	Methane and hydrogen	Increased pressure, oil swelling, reduction of interfacial section and viscosity; increase permeability
	Enterobacter		

Grounds of failure

- Lack of holistic approach allowing for a critical evaluation of economics, applicability and performance of MEOR is missing.
- No published study includes reservoir characteristics; biochemical and physiological characteristics of microbiota; controlling mechanisms and process economics.
- The ecophysiology of microbial communities thriving in oil reservoirs is largely unexplored. Consequently, there is a poor critical evaluation of the physical and biochemical mechanisms controlling microbial response to the hydrocarbon substrates and their mobility.
- Absence of quantitative understanding of microbial activity and poor understanding of the synergistic interactions between living and none living elements. Experiments based on pure cultures or enrichments are questionable because microbial communities interact synergistically with minerals, extracellular polymeric substances and other physicochemical and biological factors in the environment.
- Lack of cooperation between microbiologists, reservoir engineers, geologists, economists and owner operators incomplete pertinent reservoir data, in published sources: lithology, depth, net thickness, porosity, permeability, temperature, pressure, reserves, reservoir fluid properties (oil gravity, water salinity, oil viscosity, bubble point pressure, and oil-formation-volume factor), specific EOR data (number of production and injection wells, incremental recovery potential as mentioned by the operator, injection rate, calculated daily and total enhanced production), calculated incremental recovery potential over the reported time.

- Limited understanding of MEOR process economics and improper assessment of technical, logistical, cost, and oil recovery potential.
- Unknowns life cycle assessments. Unknown environmental impact.

Trends

- Wellbore microbial plugging and consequent lost of injectivity (clogging).
- Dispersion of components necessary to the target.
- Control of indigenous microbial activity.
- Mitigation of unwanted secondary activity due to competitive redox processes such as sulphate reduction, i.e. control of souring.
- Microbial paraffin removal.
- Microbial skin damage removal.
- Water floods, where continuous water phase enables the introduction of MEOR.
- Single-well stimulation, here the low cost makes MEOR the best choice.
- Selective plugging strategies.
- MEOR with ultramicrobes.
- Genetically engineered MEOR microorganisms able to survive, grow and produce metabolites at the expense of cheap nutrients and substrates.
- Application of extremophiles: halophiles, barophiles, and thermophiles.
- Artificial neural network modelling for describing in situ MEOR processes.
- Competition of exogenous microbes with indigenous micro flora, no understanding of microbial activity.

Ventures working in MEOR

Private sector	**Public sector**
Rawwater Engineering Company Ltd	Durham University
Oppenheimer Biotechnology, Inc.	CSIRO
Titan Oil Recovery, Inc.	Sultan Qaboos University
Yara International ASA	TERI
Circle T Sales and Service Inc.	DOE
GloriOil Ltd.	Mississippi State University
StatoilHydro ASA	RIPI
Environmental BioTechnologies, Inc.	ASP
ONGC-IRS	Norwegian University of Science and Technology
Rogaland Research	
COREC	
DuPont Sustainable Solutions (DSS)	
CIPR	

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