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Microbial enhanced oil recovery, a critical review on worldwide implemented field trials in different countries

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ABSTRACT

In recent years that reaching oil price to its minimum amount has become a critical issue in petroleum industry, microbial enhanced oil recovery (MEOR) is a main topic of interest in energy researches as an environment-friendly and low operating cost treatment technology. Accordingly, it could be considered as an adequate alternative for conventional EOR techniques. The significant positive impact of MEOR technology in enhancement of oil recovery is established in both sandstone and carbonate reservoirs with different flow characteristics implemented all over the world. Unfortunately, in spite of its enormous benefits, MEOR is still not widely under investment due to lack of sufficient data. This paper presents the fully detailed update of MEOR field trials which exclusively investigates the field history performance of MEOR in different countries. This investigation includes 47 field trial cases in 21 countries in which the corresponded technologies, reservoir/formation names, microorganisms, nutrients and specific effects of each case are totally illustrated. Furthermore, microbial bioproducts and screening criteria parameters are widely demonstrated. A unique categorization of MEOR biosurfactants is also presented. In addition, different set of carried out experiments on biosurfactants along with their effects on IFT and residual oil recovery are examined. In fact, this review confirms the creditability of MEOR which creates strong perspectives to move toward more investment on this method.

1. Introduction

Typically, 35–55% of crude oil is left behind in the reservoir after primary and secondary recoveries [1] which should be extracted by different improved or enhanced oil recovery techniques such as miscible gas injection, polymer flooding and thermal EOR methods [2].

In recent years that the oil price has declined to its minimum value, selection of the optimal recovery method is significantly influenced by economical issues. Consequently, development of cost effective technologies which bring maximum oil reserves to production is a main topic of interest in today's energy researches [2]. Microbial enhanced oil recovery is potentially a low-priced technique in which different microorganisms and their metabolic products are convinced to exploit the remaining trapped oil in the reservoir [2]. MEOR is widely applicable in sandstone [3] and carbonate [4,5] reservoirs with light/heavy crude oil [6,7] and low/mid and high permeabilities [8,9]. Satisfactory results of implemented field trials lead to the fact to contemplate MEOR as an adequate alternative for other IOR/EOR technologies [10].

The concept of employing microorganisms to accomplish maximum oil recovery was first proposed by Beckham [11] who established the possibility of utilizing bacterial enzymes in oil recovery [12]. In 2007, Saikrishna Maudgalya et al. [13] investigated the success or failure of 407 reported MEOR field trials in sandstone and carbonate reservoirs where the tremendous positive results were a great establishment on applicability of this technique. In 2014, Biji Shibulal et al. [12] presented a review on thermophilic spore-forming bacteria as resistant microorganisms to very extreme oil reservoir conditions.

Development of sufficiently accurate models to simulate salinity, mobility control, temperature, produced bioproducts and other needed parameters is extremely vital to choose the best reservoir candidates for MEOR process which contributes to maximum ultimate recovery [14,15]. In fact, complexity of proposing a comprehensive model to interpret all aspects of MEOR is a critical issue [16]. In 2015, Jay Patel et al. [16] reviewed the twelve published models with different approaches to interpret MEOR processes.

In 2007, Lazar et al. [17] presented a review on world experience of MEOR field trials during the last 40 years. In his study, different technologies, microorganisms and nutrients utilized in each country as well as the corresponded positive or negative impact on the incre-

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Table 1
MEOR processes classification (adapted from [19]).

MEOR process	Production problem	Type of used microorganism
Well stimulation	• Formation damage • Low oil relative permeability	• Generally surfactant, gas, acid and alcohol producers
Waterflooding	• Trapped oil due to capillary forces	• Generally surfactant, gas, acid and alcohol producers
Permeability modification	• Poor sweep efficiency channeling	• Microorganisms that produce polymer and/or copious amounts of biomass
Wellbore cleanup	• Paraffin problems • Scaling	• Microorganisms that produce emulsifiers, surfactants and acids • Microorganisms that degrade hydrocarbons
Polymer flooding	• Unfavorable mobility ratio • Low sweep efficiency	• Microorganisms that produce polymers
Mitigation of coning	• Water or gas coning	• Microorganisms that produce polymer and/or copious amounts of biomass

Table 2
Advantages and disadvantages of MEOR technology (adapted from [2,10,17,20–25]).

Advantages	Disadvantages
• Economically efficient • Low injection cost of microbes and nutrients • Low expenses and complexity of facilities set up • Low energy consumption required for microbial metabolic activities • Considerably efficient in sandstone and carbonate reservoirs • Microbial metabolic activities enhancement along with time, as opposed to other EOR additives • Low environmental pollution • Obtaining better results due to occurrence of multiple mechanisms at the same time • Possibility of applying to both light and heavy crude oils	• Corrosion of equipment as a result of aerobic bacteria activities • Limited applications in offshore platforms in view of requirement of much sugar as anaerobic bacteria activities • Complexity of developing a comprehensive model to interpret all aspects of MEOR process • Toxicity of microbes due to existence of specific heavy metal ions • Microorganisms tolerance limitationsin regard to reservoir conditions

mental oil production were introduced, but there was no information about reservoir/formation name and detailed effects of each case. Moreover, the related information of all cases of each country was presented together without any specification of each case. In the present study, the fully detailed updated MEOR field trial cases are presented which includes 47 field trial cases in 21 different countries. In this investigation, the technologies, reservoir/formation name, microorganisms, nutrients and fully detailed effects of each specific case carried out in each country are exclusively presented.

2. MEOR processes

MEOR processes are basically involved with two categories of in-situ and ex-situ mechanisms. In in-situ mechanism, generation of certain kinds of products such as gases, acids, biopolymers, etc. occurs by stimulation of different indigenous bacteria under appropriate reservoir conditions [2]. In contrary, ex-situ mechanism involves the selective removal of generated bioproducts from surface by microbial metabolic activities to be finally injected to the reservoir [2,18]. Table 1 presents different MEOR processes along with their production problems and type of utilized microorganisms.

It should be noted that MEOR has some advantageous over conventional EOR methods which make them to be contemplated as a remarkable option for investment in petroleum industry. On the other hand, some constrains such as process complexity and microorganism survival limitations could be regarded as the reasons for lack of investment on this technique. To illustrate different aspects of this issue, MEOR advantages and disadvantages are listed in Table 2.

3. Microbial bioproducts

3.1. Bioproducts full specifications

In MEOR, a variety of drastically beneficial metabolites are produced by microorganisms which finally increase the ultimate oil recovery [26]. There are specific approaches in which propagation of microbial bioproducts significantly affect the physical properties of reservoirs including porosity, permeability and wettability as well as fluid characteristics such as viscosity, IFT, etc. [10]. Generally, the bioproducts could be classified into seven major groups as biosurfactants, biopolymers, gases, acids, solvents, biomass and emulsifiers. Biosurfactants have a significant impact on wettability alteration as a result of their potential in lowering surface and interfacial tensions. Biopolymers could aid in enhanced oil recovery by permeability and viscosity reduction which leads to mobility ratio alteration. Gases are produced by some specific kinds of bacteria which contribute to re-pressurization of the reservoir and finally enhancement of oil recovery. Acids and solvents have an enormous potential to dissolve different parts of rock which results in porosity and permeability improvement and consequently reduction of the entrapped oil. Biomass could be much efficient in improvement of oil recovery by selectively plugging the porous media which finally channels the floodwater towards available oil. Oil emulsification could be achieved under production of emulsifiers by a wide variety of microorganisms where stable emulsions with hydrocarbon (commonly oil in water) are formed [16]. Table 3 shows a full list of generated bioproducts by different microorganisms along with their major effects, production problems and best reservoir candidates for MEOR process. It shall be noted that among all of the bioproducts, biosurfactants have been much more attracting to be investigated by many researchers as a consequence of their enormously beneficial properties including biodegradability, stability, low toxicity and specifically the considerable impact on wettability alteration which significantly enhances the ultimate oil recovery.

In this regard, the brief introduction and detailed classification of biosurfactants as well as the relevant conducted experiments are demonstrated in the next two following sections.

3.2. Biosurfactants

3.2.1. Biosurfactants classification

Biosurfactants are one of the metabolic products of microbial enhanced oil recovery which have potentially significant effects on surface and interfacial tensions, emulsification, solubility, etc. [29].