

Development of Microbial Consortia and Its Impact on Reservoir Engineering

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Abstract

We emphasize the importance of microbiology in modern reservoir engineering as well as its interaction with other reservoir components and engineering fundamentals. Underground hydrocarbon and water reservoirs are unique deep-subsurface ecosystems and are characterized by extreme conditions, including high temperatures and pressures, high salinity levels, and an anaerobic gas content with considerable diversity of physiologically distinct microorganisms present in these reservoirs. Clearly, the development of microbial consortia and the activities of these communities have a substantial influence on reservoir environments, consequently exerting a significant impact on reservoir performance studies. The formation of Hydrogen Sulfide (H_2S) in petroleum reservoirs through the activity of anaerobic microorganisms (specifically, Sulfate-Reducing Bacteria, SRB) is known as biogenic souring of reservoirs. Microbial Enhanced Oil Recovery (MEOR) involves the action of microbes by reacting with a substrate to form metabolites to recover a part of the remaining oil in the reservoir after primary and secondary recoveries. Since Geologic Carbon Storage (GCS) is designed for long-term CO_2 sequestration, containment of the storage formation is the most important aspect; therefore, any microbiological impact on the integrity of the overlying formations is of particular interest. Methanogenesis and H_2S formation are cited as among the challenges of Underground Hydrogen Storage (UHS). Current technological developments provide excellent opportunities for microbiological monitoring of reservoirs and production facilities, enabling the timely implementation of effective mitigation measures.

Introduction

Reservoir Engineering (RE) is defined as the application of scientific principles to fluid flow through porous media during the development and production of hydrocarbon and geothermal reservoirs. The goal is to achieve higher economic recovery. However, this definition does not encompass all areas of RE responsibility. The injection of CO_2 for long-term sequestration (Geological Carbon Storage, GCS) and H_2 for temporary storage (Underground Hydrogen Storage, UHS), before energy conversion in geological formations, is a process designed, conducted, and monitored using long-term petroleum reservoir engineering experience and physical and numerical modelling tools to predict storage and exploration performance. Field measurements and monitoring methods, developed within the domain of reservoir science and engineering, are used to calibrate and validate these tools.

Figure 1 illustrates the fundamental components of modern RE, depicting an injection-production process within a hydrocarbon reservoir. Water coexists with oil and/or gas in a porous geological medium within hydrocarbon reservoirs. The RE originates from the Darcy equation [1], which is pivotal to comprehending and modelling the flow of water in porous media. Over time, the Darcy equation has undergone a process of generalization, resulting in its current ability to encompass the flow of oil and gas in porous media under various boundary conditions. This development has been accompanied by stronger incorporation of petrophysics. When considered alongside the Darcy equation, hydrodynamics forms the basis of RE (I in Figure 1). The second pillar of RE involves studying thermodynamics (II in Figure 1) and examining how the phases and compositions of fluids change in geological media when the Pressure (P) and Temperature (T) are altered by disturbances to the natural equilibrium of

the reservoir caused by injection and/or production. Incorporating the Equations of State (EoS) into RE is imperative to account for the impact of pressure and temperature variations within the reservoir. This approach should also consider the salinity of the formation

brine and the composition of any injected fluids. The fundamentals are frequently combined with geochemistry, taking into account alterations in mineral compositions.

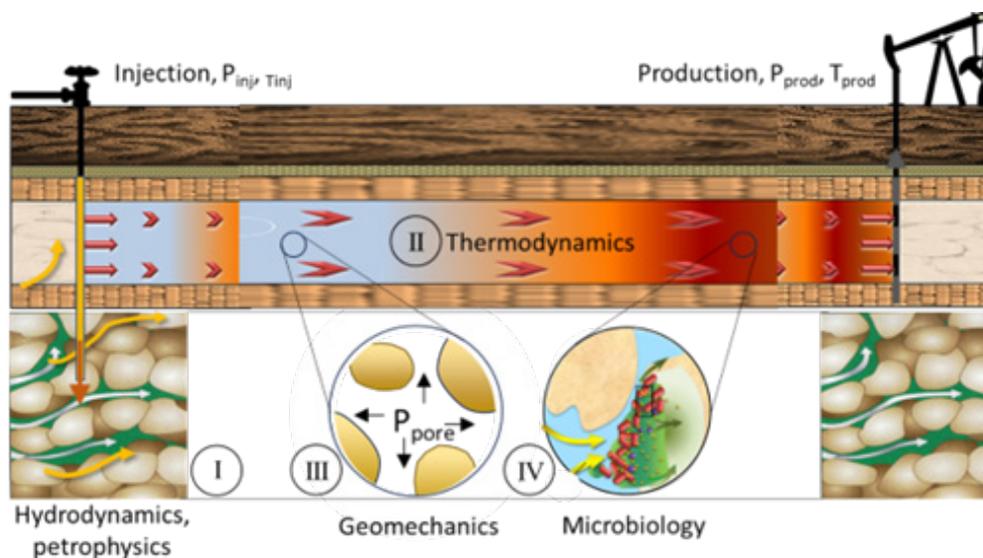


Figure 1: Fundamental pillars of reservoir engineering (inj: injection; prod: production).

Changes in P and T can substantially influence the geomechanical equilibrium of geological formations. Variations in pore pressure (P_{pore}) resulting from fluid production or injection lead to shifts in geological stresses, which can induce fracturing, for example. This, in turn, directly influences the flow dynamics within the reservoir. Integrating geomechanics (III in Figure 1) into Reservoir Engineering (RE) is particularly significant in geological storage projects involving continuous and/or cyclic injection and production.

The challenges posed by microbes and their development as microbial consortia in reservoir habitats have been recognized since the establishment of the oil industry in the mid-19th century. Sulfate-Reducing Bacteria (SRB), for example, have been identified as the cause of H_2S formation in reservoirs and surface facilities, which raises health and safety concerns. Although studies attempting to mitigate this issue have failed to deliver a definitive solution, they have underscored the importance of microbiology (IV in Figure 1) in reservoir and production studies. Beckmann [2] suggested that the development of microbial consortia could assist in recovering residual oil in reservoirs. This idea paved the way for the subsequent development and implementation of Microbial Enhanced Oil Recovery (MEOR), which is one of the most well-known Enhanced Oil Recovery (EOR) methods. Using geological formations for the permanent storage of CO_2 (Geological Carbon Storage, GCS) or the temporary storage of H_2 (Underground Hydrogen Storage, UHS) has led to a better understanding of the importance of incorporating microbiology into reservoir studies (e.g., [3,4]). Despite these advancements, microbiology remains one of the most disregarded yet pivotal fundamentals of RE.

This overview study emphasizes the importance of microbiology in modern RE, as well as its interaction with other RE components and factors. It should be noted that the cited studies are just a few recent examples chosen to demonstrate how microbiology is applied in various domains of RE.

Microbiology of Hydrocarbon Reservoirs

Underground hydrocarbon and water reservoirs are unique deep-subsurface ecosystems. They are characterized by extreme conditions, including high temperatures and pressures, high salinity levels, and an anaerobic gas content. In recent decades, a significant number of studies have drawn attention to the considerable diversity of physiologically distinct microorganisms present in these reservoirs [5-7], advancing our understanding of subsurface microbial consortia and their functions. Clearly, the activities of these microorganisms substantially influence reservoir environments and therefore have a significant impact on reservoir performance studies.

As might be expected, the petrophysical and thermodynamic conditions of reservoirs can either enhance or limit microbiological habitats and life. Reservoirs with temperatures higher than 80 °C exhibit less or no microbial activity, as indicated by a lack of biotransformation [8]. Depth can serve as a criterion when an estimation of reservoir temperature is necessary. In general, effects on microbial growth, such as changes in biomolecular conformation, are not expected to occur below 500 bar unless there is a sudden change in pressure. This is considerably higher than the pressure in conventional hydrocarbon reservoirs [9]. Various studies confirm the importance of permeability to bacterial movement in porous media [10,11]. Although microorganisms have various geometries,

a general scale of 1-5 μ m can be reasonably assumed for bacteria. This dimension is crucial for low-permeability cores with narrow pore throats. Thus, low-to very low-permeability reservoirs (e.g., less than 10mD) are not necessarily hospitable environments for bacteria. Recent studies on reservoir microbiology and related applications, such as MEOR, have shown that Halanaerobiales bacteria are present and active in reservoirs with extremely high salinities of up to 220g/L [12].

Microbial Interactions in the Reservoirs

The importance of considering microbial activity in RE has become clearer over time, partly due to technological developments. Samples of reservoir fluids can be taken either at the wellhead or, if necessary, within the wellbore, to reveal the effects of pressure and temperature [13]. These samples are then characterized for their microbiological activity in a specialized laboratory. In this laboratory, the presence, number, physiological state, and morphology of microbial consortia and microorganisms are determined using microscopy and other analytical tools and methods. These include direct enumeration of specific bacterial groups using microscopy (e.g., Fluorescence in Situ Hybridization [FISH]). Alternative methods (e.g., qPCR and DGGE) entail the direct extraction of genetic material from cells (DNA/RNA) [14]. Subsequently, the amplified DNA is subjected to high-throughput sequencing. The use of BLAST analyses for microbial sequences facilitates the identification of microorganisms. This information can then be used to solve related challenges and mitigate risks of the following tasks of RE, as given in the following examples:

Biogenic souring (H₂S) management

The formation of hydrogen sulfide (H₂S) in petroleum reservoirs through the activity of anaerobic microorganisms (specifically, Sulfate-Reducing Bacteria, SRB) is known as biogenic souring of reservoirs. This process poses a significant risk to the petroleum industry, as H₂S is highly toxic, flammable, and corrosive, causing severe damage to reservoirs and associated surface facilities. SRB are also one of the most important sinks for hydrogen. SRB use hydrogen as an electron donor to reduce sulfate to hydrogen sulfide (H₂S) and often compete with other microorganisms for the available hydrogen.

For SRB, this is an energy-creating process that depends on the presence of volatile fatty acids or other carbon sources. If water is injected into the reservoir, for example, for producing more oil, there is a higher chance of biogenic souring if the water used for injection and/or formation contains sulfate and/or carbon sources like organic acids. This major technical risk exists in all water injection processes if the thermodynamic conditions allow and the microbiological composition of formation water and/or injection water contains SRBs. For its mitigation, specific attention is given to the concept of nitrate injection (mostly as calcium-nitrate) for the mitigation of reservoir souring. There are already some examples available for the use of nitrate in oil fields reporting mixed positive effects on corrosion and souring [15,16]. However, using nitrates cannot solve the problem completely, as they also exhibit side effects such as Microbially Induced Calcite Precipitation (MICP), which can

block pores, reducing permeability and thus the flow of its contents. The use of other mitigation agents, such as molybdate, is currently being investigated [17]. Anaerobic microbial corrosion, which is caused by interactions in reservoirs and corrosion by-products, as well as bacterial growth, can significantly reduce permeability. This process produces solids, such as iron sulfide or oxides, which block flow paths. Bacteria, such as SRB, also form biofilms and contribute to the production of hydrogen sulfide [18].

SRB are present in almost all types of reservoir habitats. Although they are obligate anaerobes, they can also be found in oxygenated environments in a dormant state. They are now well recognized for their involvement in Microbially Induced Corrosion (MIC) as well. Microbial corrosion depends on the formation of a biofilm on the attacked surface, which provides favorable conditions for the development of microbial consortia, including SRB. MIC is a major concern in the oil and related industry [19,20].

Microbial Enhanced Oil Recovery (MEOR)

The extraction of oil from geological formations is governed by natural physical principles. Consequently, a significant portion of the oil remains in the reservoir after primary depletion. This residual oil can account for 40 to 95 percent of the original oil in situ. After waterflooding, Enhanced Oil Recovery (EOR) processes are applied to produce the remaining oil. There have been many attempts to categorize EOR methods, including thermal, gas, and chemical methods [21,22]. However, one method stands alone in all classifications: Microbial Enhanced Oil Recovery (MEOR).

MEOR stands for an EOR technology alongside thermal, gas, and chemical methods and involves the action of microbes by reacting with a substrate to form metabolites to recover a part of the remaining oil in the reservoir after primary and secondary recoveries. In ex situ MEOR, as a general application, a microbial metabolite resulting mostly in a biopolymer or biosurfactant is prepared in an industrial facility, is transported, and injected into the field. In in situ MEOR, metabolites are generated in the reservoir as a reaction of the injected substrates with targeted microbial consortia living in the reservoirs or injected from the surface.

From a pragmatic RE point of view, the ideal way forward for an MEOR application is to investigate the reservoir microbiology, isolate the microbes, and catalog them according to their EOR capabilities. Such catalogs are published periodically; however, they always need to be reviewed as new bacteria appear in newly studied fields. A recent collection is provided by [23]. Most of the bacteria are used for ex situ MEOR to produce biosurfactants and biopolymers. Some others, which are mainly used for in situ MEOR, are grouped under the name fermentative bacteria. Currently, in situ or ex situ MEOR is applied in many fields worldwide as a cost-effective, easy-to-apply technology for recovering more oil from reservoirs [24].

In EOR fluid injection applications, including MEOR, it is crucial to prevent ex situ bacteria from entering the formation via the injected fluids and accumulating near the wellbore. Conversely, it may be imperative to impede the action of in situ bacteria on the biosurfactants or biopolymers introduced for EOR treatments,

thus diminishing their efficacy. In such cases, the utilization of a screened biocide directed against the targeted bacteria is strongly recommended. Consequently, the implementation of routine sampling, testing, and analysis is imperative to facilitate timely intervention and avert substantial harm. The dosage of the biocide and oxygen scavenger (if deemed necessary) must also be accurately determined to prevent under- or overdosing.

Another noteworthy type of microbial interaction in oil and gas reservoirs is the fermentation of organic matter to produce hydrogen. This process, referred to as dark fermentation, occurs in the absence of light and can utilize a diverse array of organic substrates, including waste products and refined sugars. Nevertheless, the economic controversy of the process is rooted in the low yield of hydrogen produced by bacteria when they are used to break down organic compounds [15,16,25].

Microbial implications in GCS and UHS

As a short-term solution for addressing the greenhouse effect and climate change, anthropogenic CO₂ is injected into deep geological formations rather than being released into the atmosphere. This process, widely referred to as GCS, utilizes Depleted Hydrocarbon Reservoirs (DHR), saline aquifers, and occasionally salt caverns. The presence of active microbiological life in these reservoirs is contingent upon the existence of favorable thermodynamic and petrophysical conditions. However, the impact of CO₂ on subsurface microbial communities remains a subject of limited research. A low-pH, high-CO₂ environment may favor some species and harm others. In environments where there is a significant reduction of CO₂, the injection of CO₂ may stimulate microbial consortia that reduce CO₂ to methane (CH₄). In other reservoirs, the injection of CO₂ could cause a short-term stimulation of iron (III)-reducing communities. An enhanced activity and quantity of the microbial population after five months of CO₂ storage in saline aquifer indicated that the in-situ consortium was able to adapt to the extreme conditions of the deep biosphere and to the extreme changes of these anthropogenically modified conditions [26]. From an operational perspective, the formation of biofilms can alter the effective permeability of storage and confining formations. Given that GCS is designed for long-term CO₂ sequestration, containment of the storage formation is of paramount importance; consequently, any microbiological impact on the integrity of the overlying formations is of particu-

lar interest. Microbially Induced Calcite Precipitation (MICP) is a sustainable technology or natural process that utilizes biochemical pathways to generate calcium carbonate cement barriers, thereby sealing leakage zones in geological formations [27]. New research initiatives are underway to ascertain the potentially beneficial or unfavorable biological side effects of CO₂ sequestration (e.g., [3]).

Depending on the duration of storage and demand, a range of UHS options can respond to the cyclic process. The utilization of porous media structures, including deep aquifers, depleted oil and gas reservoirs, and salt caverns, has been demonstrated to accommodate substantial volumes. Recent studies indicate that microbiology should be considered from the beginning in such UHS operations. Homoud RA et al. [4] highlighted that, in addition to the H₂S impurity, which has been a subject of concern in UHS, CH₄ formation due to methanogenesis is another issue in UHS. Consequently, all endeavors are focused on preserving the high purity of the stored hydrogen. A numerical study revealed that the utilization of non-reactive cushion gases, such as nitrogen, instead of CO₂, results in a reduction of H₂S generation and an enhancement of hydrogen containment conditions. This reduction in H₂S generation and improvement in hydrogen containment conditions, in turn, minimize hydrogen dissolution and pyrite reactivity. The methanogenesis has been observed to result in substantial hydrogen loss, with reductions of up to 50% in in situ hydrogen volume. This decrease in hydrogen volume, in turn, lowers the effectiveness of hydrogen storage, thereby highlighting the need for preliminary microbial assessment and judicious cushion gas selection. The authors further concluded that it is imperative to investigate the impact of pressure and temperature on geochemical and microbiological reactions and to analyze microbial growth rates. The acquisition of comprehensive data in these areas is essential for enhancing our comprehension of the lifecycle of microbes in hydrogen storage environments. Moreover, [28] observed that SRB present in salt caverns consume H₂, which is accompanied by a significant pH increase. This phenomenon leads to a decline in activity over time. This self-limiting process of pH increase during sulfate reduction is advantageous for H₂ storage in low-buffering environments, such as salt caverns.

Table 1 provides a broad overview of the relevance of microbiology to reservoir engineering based on various applications.

Table 1: Broad overview of the relevance of microbiology to reservoir engineering based on various applications.

Effect	Impacts on EOR/GCS/UHS	Reference
Wettability alteration	A transition in wettability from oil/intermediate to water-wet, resulting from the formation of a biofilm, has the potential to enhance oil recovery. This effect should also be considered in UHS.	Alkan et al. [29,30]; Boon et al. [31]
Rock dissolution	The generation of organic acids, which have the capacity to dissolve the carbonates present within the reservoir rock, can exert a significant influence on the original petrophysics, particularly porosity and permeability. Despite the paucity of empirical research conducted on this subject, the impact on oil recovery can be measured.	Kögler et al. [32]

Generation of bio-H ₂ Methanogenesis	The H ₂ generation through dark fermentation in the DHRs is claimed to be a safe and climate-friendly option, but with low economic prospects. While methanogenesis can function as a carbon sink, sequestering carbon in biomass or new stable compounds, it can also reduce the volume of CO ₂ stored and alter the mobility of supercritical fluids in GCS. Methanogenesis is regarded as unsuitable for UHS, efforts are focused on maintaining the high purity of stored hydrogen.	Alkan et al. [15,16]; Sampaio et al. [25] Tyne et al. [33]; Homoud et al. [4]
Pressurization	The gases produced (primarily CO ₂) due to microbial activity have the potential to increase pressure within the formation, either in a local or a global sense. An increase in pore pressure leads to an increase in driving energy and potential for the gases to dissolve into the oil, thereby increasing its mobility.	Alkan et al. [24]; Alkan et al. [15,16]
Biodegradation	The efficacy of injected biosurfactants and biopolymers in EOR is diminished by in situ microbes. The utilization of a carefully selected biocide is strongly suggested in order to adequately address this issue.	Castro-Dominguez et al. [34]
Clogging	The straining of biomass in small pore throats may block high-permeability zones, helping to diversify the EOR fluid into other pores and recover more oil. This could also help block pores in confining formations within GCS and UHS systems, thereby decreasing leakage.	Gaol et al. [35]; Eddaoui N [36]; Landa-Marbán et al. [27]
Microbially Induced Corrosion (MIC)	Corrosion induced by microbes is associated with the formation of biofilms, which can lead to substantial damage to industrial equipment or infrastructure, resulting in significant economic and environmental challenges.	Javaherdashti R [37]; Procópio, L. [20]
H ₂ S generation	The issue gives rise to HSE concerns in EOR, GCS, and UHS. Its assessment and the negative effects are well documented, yet a definitive mitigation solution remains lacking.	Hagar et al. [38]; Alkan et al. [15,16]

Conclusion

Although reservoir engineering has long survived without the support of microbiology, this has resulted in misinformation and failed decisions, particularly with regard to risk assessments and mitigations. Technological advances and developments in associated domains have converged to elevate microbiology to a pivotal role within the RE framework, complementing disciplines such as hydrodynamics, thermodynamics, and geomechanics. This is particularly relevant given the expanding range of applications of RE in various subsurface energy initiatives, including oil recovery technologies, transforming remaining hydrocarbons into viable energy sources after depletion, and reducing risks in geological carbon and hydrogen storage projects. Whereas MEOR represents a favorable application of microbiology with the cultivation of microbial consortia through the injection of substrates into the reservoir, biogenic souring remains the predominant challenge to be dealt with using microbiological science and technology. Concerns pertaining to matters that have the potential to either diminish or disrupt reservoir performance, whether through the production or storage of energy, must be addressed by the implementation of mitigation measures aimed at restoring optimal conditions. In the context of microbial factors, it is imperative to address these factors by incorporating the principles and methodologies of microbiological science and technology. It is of particular importance to direct attention towards injectors and wells that undergo frequent stimulation and workover operations. These wells probably provide conditions favorable for the development of microbial consortia. Recent technological advancements have rendered effective microbiological monitoring of reservoirs and

production facilities a viable prospect. This, in turn, facilitates the timely implementation of effective mitigation measures.

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