The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2021

Volume 15, Pages 88-98

ICBAST 2021: International Conference on Basic Science and Technology

Review on Microbial Enhanced Oil Recovery and Controlling Its Produced Hydrogen Sulfide Effects on Reservoir and Transporting Pipelines

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Abstract: Using viable microbial cultures within hydrocarbon reservoirs so as to enhancement of oil recovery through metabolic activities is exactly what we recognize as Microbial enhanced oil recovery (MEOR). In similar with many other process in industries, there are some cons and pros following with MEOR. The creation of sulfides such as hydrogen sulfide as a result of injecting the sulfate-containing seawater into hydrocarbon reservoirs in order to maintain the required reservoir pressure, leads to produce and growth of Sulfate Reducing Bacteria (SRB) approximately near the injection wells, turning the reservoir into sour, however SRB is not considered as the only microbial process stimulating the formation of sulfides. Along with SRB, thermochemical sulfate reduction or thermal redox reaction (TSR) is also known to be highly effective at resulting in having extremely concentrated zones of $H2$S in the reservoir fluids eligible to cause corrosion. Owing to extent of the topic, more information on formation of $H2$S are going to be put finger on. Besides, confronting the undesirable production of sulfide species in the reservoirs can lead to serious operational, environmental and financial problems in particular the transporting pipelines. Consequently, conjuring up reservoir souring control strategies on the way production of oil and gas is the only way to prevent possible damages in terms of environment, finance and man power which requires determining the compound's reactivity, origin and partitioning behavior. This article is going to provide a comprehensive review on progress made in this field and the possible advent of new strategies in this technologically advanced world of petroleum industry.

Keywords: Corrosion, Hydrogen sulfide, NRB, Reservoir souring, SRB

Introduction

Deployment of microorganisms in purpose of enhancing oil recovery is not considered as a newly developed assessment in this field (Rashedi, 2014; Chilingarian et. al., 1989; Patel et. al., 2015; Nmegbu, 2014). In 1926, the effect of bacteria on mineral oil were tested and reported by Beckmann, consequently he observed the high efficiency of bacterial enzymes in order to be used for enhance oil recovery methods (Chilingarian et. al., 1989; Zobell, 1973; Nerurkar et. al., 2012). In oil microbiological studies, six principles were targeted respectively: Beginning of the rebirth of organic compounds in sediments and oils, the degradation of hydrocarbons, hydrocarbons enhanced recovery from reservoirs, modification of hydrocarbon products at initial production or reproduction, reduction of disturbing microorganisms and eventually biological purging of product or crude oil (Rashedi, 2014; Zobell, 1973). Putting effort into enhancing oil recovery in microbial way is done by injecting sulfate-containing seawater into reservoir for maintaining the requiring pressure of oil reservoirs in order to recover oil from depleted wells (Ekemini et. al., 2019; Basafa et. al., 2019; Nmegbu et. al., 2014). Regarding the injection of seawater, resuscitation of thiosulfate into sulfide could be expecting in the reservoirs (Little, 2013). H2S is a toxic, corrosive, hazardous and explosive gas, procreating remarkable operational and health risks which makes those in charge of enhancing oil recovery unable to avoid financial and environmental damages (Kögler et. al., 2021).

The idea behind this biological damage could be announced the creation and spread of SRB known as sulfate-reducing bacteria which by making physical and chemical changes at oil in reservoirs, increases the production of oil along with some unwanted influences on reservoir leading to souring which has no outcome except acidifying the atmosphere dominant over the reservoir and corrosion of transporting pipelines (Rashedi, 2014). As a matter of fact, the reduction of sulfate to sulfide is the main cause of chemically and biologically mediated reactions resulting in formation of various reduced sulfur compounds, consequently the souring of reservoir takes place (Holubnyak et. al., 2011; Basafa et. al., 2019; Patel et. al., 2015; Quraishi et. al., 2021).

Along with sulfides, other species such as Sulfite, Thiosalts and polysulfide are all along with sulfide in reservoir (Basafa et. al., 2019). The average oxidation state of these Sulfur species only ranges between Sulfate-Sulfur (+ 6) and Sulfidic-Sulfur (− 2) which means they are usually referred to as intermediate sulfur species (fig.1) (Basafa et. al., 2019; Little, 2013). As is obvious, these intermediate sulfur species could affect the treatment approaches for soured reservoirs due to having implications in microbial and chemical process. Appearing in different oxidation–reduction is what can be done by reduced sulfur species leading to react with other species in reservoir (Basafa et. al., 2019; Little, 2013).

As a result, in order to get by these possible damages, some strategies must be used to reduce and finally stop the extent of sulfide species. In this paper, some of the most effective strategies to stop spreading the sulfide are going to be reviewed and discussed which are expected to be using biocides, NRB and a newly researched way, using molybdate as Inhibitor of biogenic hydrogen sulfide produce by Sulfate-Reducing Bacteria (SRB) (Al-Tamimi et. al., 2017).

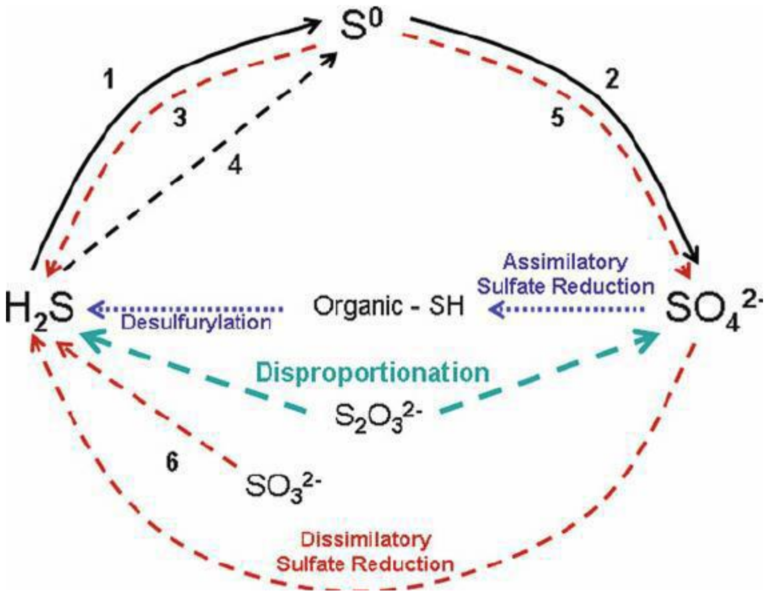

Figure 1. The biological sulfur cycle with roles of bacteria identified. Solid lines indicate aerobic reactions, dashed lines indicate anaerobic reactions, and dotted lines indicate both aerobic and anaerobic activity (Barton et. al., 2017).

Controlling these harmful process requires knowing some primitive information about souring and consequently corrosion like their being a function of pressure, pH, composition and reservoir temperature, hence while the conditions at reservoir changes within unit operations and other reasons, these specific compounds could degrade to corrosion leading to turning up of some problematic situation such as health and manpower hazards, equipment's damage and decline of effectiveness of produced water and other treatment systems (Basafa et. al., 2019; Ibrahem et. al., 2012)

In this case, the injection of nitrate into an oil reservoir to boost the growth of nitrate reducing bacteria (NRB), could be considered as a cost-effective and ordinary strategy to inhibit microbial sulfate reduction by several mechanisms (Kögler et. al., 2021). Besides, employment of biocides, chemical compounds used to disinfect, decontaminate and sterilize materials (Surfaces or objects) in order to eliminate microbiological degradation processes, as an inhibitor is getting common in oil industries (Okoro, 2014). As stated earlier, another inhibition method exists known as Inhibition of microbial sulfate reduction by molybdate which has received much less intention in compare with the other strategies even with having more advantages in various fields related to reservoirs (Jesus et. al., 2015). The objective of this study is to evaluate the efficiency of implementing the stated souring control strategies in different situation in purpose of managing the activity of sulfur reducing bacteria (SRB) and other process namely TSR so as to prevent the taking place of corrosion with transporting pipelines and other supplements used to get to oil and gas and The reader is directed to recent reviews discussing these topics (Gieg et. al., 2011; Jesus et. al., 2015; Sugai et. al., 2015).

Discussion

Reservoir Souring and Thermochemical Sulfate Reduction

The highly concentrated Aggregation of hydrogen sulfide present in many oil and gas fields is thought to levitate from the oxidation of petroleum hydrocarbons by sulfate-reduction reactions occurring at temperatures above 250C. However sulfate derived from seawater or the dissolution of solid calcium sulfide is able to be reduced by a great amount of chemical and organic compounds known as polar aromatic, saturated hydrocarbons and alcohols (Lin et. al., 2020; Goldstein et. al., 1991). This thermal-related reaction is known as thermochemical sulfur reduction(TSR) considered to be responsible for bulk of these reduction-related reactions leading to get the reservoirs soured, significantly in deep and high temperatures (Goldstein et. al., 1991). Thermochemical Sulfate Reduction is fully known in the field and experiments have been led to survey the reactions engaged with this process, any possible products, and the impact of temperature, various types of oxidants, the presence of different sulfur species and metal cations, and the effect of pH on the rate of Thermochemical Sulfate Reduction (Goldstein et. al., 1991; Basafa et. al., 2019; Singhapetcharat et. al., 2018).

Besides Thermolysis aquathermolysis of aromatic thiophene-type organosulfur compounds similar to thiophene and aliphatic organic sulfides such as tetrahydrothiophene in heavy oil are also in ability to produces H_2S. The amount of H_2S produced by thermal way of decomposition of oil is symmetric to the sulfur content of the oil and is usually measured at a number less than 5% in reservoir (Basafa et. al., 2019). The most available sulfur species present at bitumen are sulfide, Polysulfide, Thiols, disulfides, benzothiophenes, dibenzothiophenes and thiophenes while disulfides and Thiols are the most reactive ones, on the other hand the Benzothiophenic compounds are considered as the most stable (Basafa et. al., 2019; Barton et. al., 2017; Nourani et. al., 2007; Sugai et. al., 2015). Some oxidative and reductive dissolution of metal sulfides under specific circumstances like acidic atmosphere may lead to production of sulfate ions and naturally H_2S during employment of steam injection and water flooding as an asset to enhance the pressure of reservoir (Basafa et. al., 2019).

Oxidative dissolution reaction:

$$MS + 4H_2O + xO \rightarrow M^{2+} + SO_4^{2-} + 8H^+ + xR \quad (1)$$

Reductive dissolution reaction:

$$MS + 2H^+ + yR \rightarrow M^{2+} + H_2S + yO \quad (2)$$

The MS in all Oxidative dissolutions and Reductive dissolutions is indicator of sulfide mineral where M is coined the metal base, O and R are oxidized and reduced compounds in the redox reaction, respectively. The acidic components all come from the injection of water or the bio degradation of injected biocides and scale inhibitors and corrosion. Pyrite and pyrrhotite, known as some Iron sulfides, are common metal sulfide minerals associated with reservoirs forming under reducing conditions (Basafa et. al., 2019; Li et. al., 2011)

How things get done is that Pyrite is oxidized to sulfate and hydrogen reduces the pH of the environment surrounding. When PH values are lower than 7, Pyrite oxidation by dissolved oxygen may produce Tetrathionate and sulfate on the contrary, at higher pH values, more than 7, thiosulfate and sulfite are considered as the major reaction products (Basafa et. al., 2019; Goldstein et. al., 1991; Lin et. al., 2020; Correia et. al., 2021). The most favorable decomposition reactions for pyrite at low pH values to be exact less than 7 and under reducing conditions, generating H_2S are (Okoro et. al., 2015):

$$FeS_2 + 2H^+ \rightarrow Fe^{2+} + H_2S + S^0 \quad (3)$$

$$FeS_2 + 4H^+ + 2R \rightarrow Fe^{2+} + 2H_2S + 2R \quad (4)$$

Under some conditions, pyrite is turned into sulfate and sulfide, as, in the presence of an oxidant, it is become to elemental sulfur (Okoro et. al., 2015):

$$FeS_2 + 4\ OH^- \rightarrow 13Fe_3O_4 + 116S2- + 16\ SO_4^{2-} + 2H_2O \quad (5)$$

$$FeS_2 + 2O \rightarrow Fe^{2+} + 2S_0 + 2O \quad (6)$$

Sulfate Reducing Bacteria (SRB)

The turning up of SRB, is considered as a common problem during the injection of sea water into reservoir in order to increase the pressure of reservoir as a known method of enhanced oil recovery. SRB are anaerobic microbes having most accompaniment with microbial corrosion, reservoir plugging, deterioration of product quality, and decrease in the permeability of pores of underground petroleum reservoirs (Okoro et. al., 2015; Little, 2013). They are diverse groups of anaerobic microbes present everywhere and zero in on producing $H2S$ by using sulfate ion as the final electron receiver although enormous amount of different organic matters such as format, acetate, propionate, pyruvate, lactate, butyrate and ethanol can play the role as the electron donors for SRB (Little, 2013; Naresh et. al., 2015; Tatar, 2018). An outstanding amount of these bacteria, by using $H2$ or some organic compounds are able to reduce nitrate, sulfite, thiosulfate and fumarate (Little, 2013). The following reaction was assumed to occur in the reservoir into which the water containing the SRB was injected (Suga et. al., 2020):

$$C_2H_5OH + 12\ SO_4^{2-} \rightarrow CH_3COO^- + 12\ HS^- + 12\ H^+ + H_2O \quad (7)$$

These bacteria have already departed from diverse zones including seawater containing a compactness of 25 mM. However, the amount of seawater's oxygen is above thermocline ranges from 5 to 10 ppm, anaerobic microbes settled at anaerobic microniches stay alive until the return of formation's normal conditions (Little, 2013; Ibrahem et. al., 2015).

If the rate of aerobic breathing at the biofilm is more than the rate of oxygen infiltration, the biofilm-iron area can turn into anaerobic and embark on creating an opportunity for production of sulfide species with help of sulfate reducing bacteria (Little, 2013). In fact, metabolic activity of SRB causes the accumulation of sulfide near the iron species. Due to studies done in the recent years, many mechanisms have been found to be related to SRB detrimental activities: Cathodic Depolarization due to Dehydrogenase enzyme, anodic Depolarization, formation of iron sulfides, sulfide-induced stress cracking or hydrogen blister. These reactions are discussed to be involved in sulfate reducing bacteria process (Little, 2013; Jesus et. al., 2015):

$$4\ Fe \rightarrow 4\ Fe^{2+} + 8\ e^- \quad (8)$$

$$8\ H_2O \rightarrow 8\ H^+ + 8\ OH^- \quad (9)$$

$$8H^+ + 8e^- \rightarrow 8\ H \quad (10)$$

$$SO_4^{2-} + 8H \rightarrow S2- + 4H_2O \quad (11)$$

$$Fe_2+ + S^{2-} \rightarrow FeS \quad (12)$$

$$4\ Fe + SO_4^{2-} + 2H_2O_3 \rightarrow Fe\ (OH)_2 + FeS + 2OH^- \quad (13)$$

These reactions are known as Cathodic Depolarization, stating that sulfate reducing bacteria omit the accumulated hydrogen's hydrogenase (Hase+) at cathode (Little, 2013). In 1985, Hamilton studied $H2S$ reduction as a cathodic reaction and the role of FeS as a low hydrogen overvoltage. Afterwards, it was revealed that Desulfovibrio which doesn't form hydrogenase (Hase+) as a result of Cathodic Depolarization, can stimulate the corrosion rate (Hamilton et. al., 1985).

Regarding the investigation done in field of SRB corrosion, sulfate reducing bacteria mostly have been based on Desulfovibrio although it was revealed that the presence of Desulfobacterium is dominant at a marine environment and grows faster than Desulfovibrio species (Little, 2013).

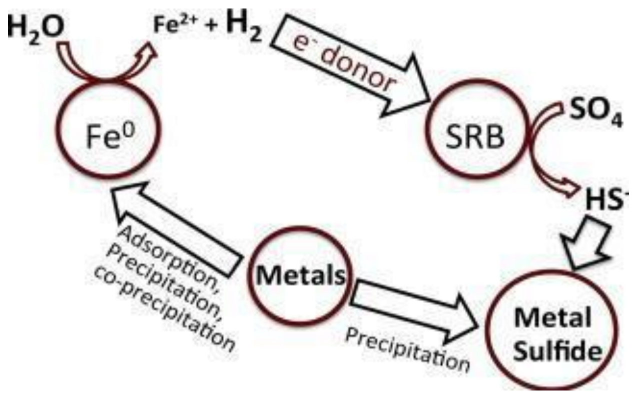

Figure 2. A general overview of SRB and other process involved in.

As a result, the SRB's blemishing activities to the reservoir and environment along with drilling equipment has to be stopped in the most proportional ways due to studies have been done during recent years. As far as the microbial enhanced oil recovery method keeps on going, the production of SRB is expected to be continued so taking advantages of MEOR method could be feasible by prompting big changes on the way controlling SRB activities (Basafa et. al., 2019; Ekemini et. al., 2019; Ibrahem et. al., 2015).

Sulfur Chemistries and The Catalyzers

When the reservoir fluids flow from injection well to production well, production of intermediate sulfur species could be expecting owing to microbial and chemical reactions occurring at reservoir (Basafa et. al., 2019). What makes these compounds complex is their dependence over some factors like PH, Temperature along with the presence of other sulfur species, metals, and microorganisms (Chen et. al., 2018).

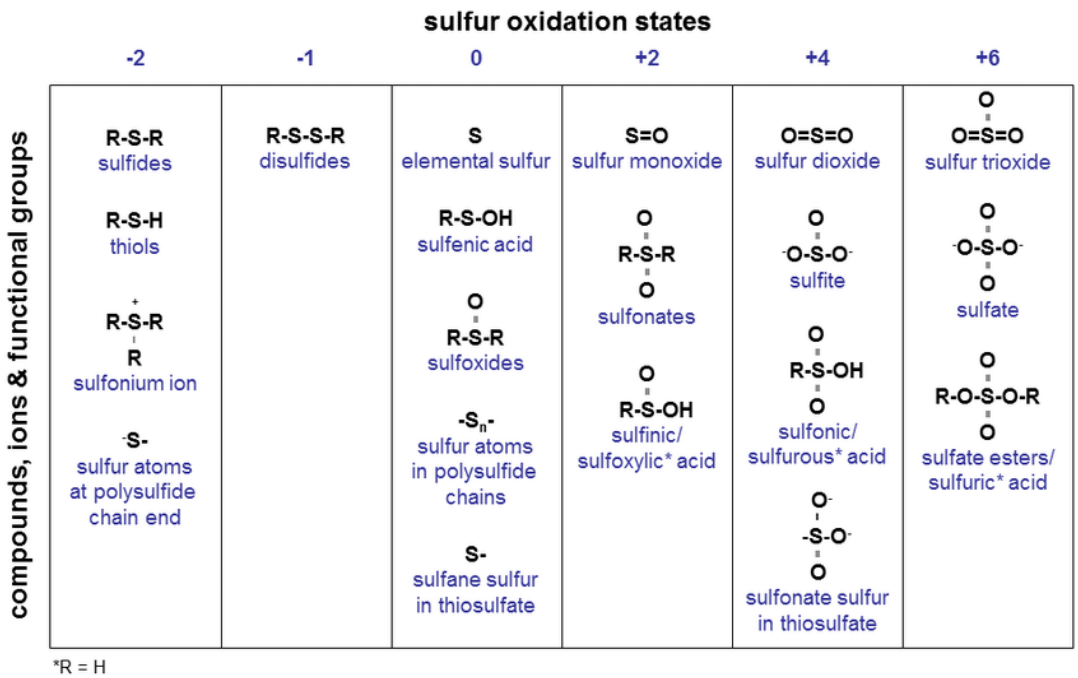

Figure 3. Most common inorganic and organic sulfur compounds ions and functional group

In terms of chemical views, these compounds are divided into three major groups; the first group are rich in acidic properties and include Carbonyl sulfide, Aryl, Carbon disulfide and Thiols (Rabbani, 2010). The second group is chemically neutral however they are not stable at high temperatures and this group has been made up of Sulfur and Polysulfur (Rabbani, 2010). The third group not only is neutral but also have shown resistance and stability at high temperatures. Thiophene is an example compound of the last discussed group. Major parts of these compounds under redox conditions, produce H2S like the reaction of Thiocarbamat and reduction of Thioter (Rabbani, 2010):

$$RCS_2R + 3H_2O \rightarrow RCO_2H + 2H_2S + ROH \quad (14)$$

$$RSR \rightarrow 2RH + H_2S \quad (15)$$

Non-organic sulfur compounds mostly flash around as Insoluble metal or soluble sulfate. There are some incomplete redox reactions involving H_2S, sulfur dioxide, or even sulfate which are likely the reason why the sulfur oxyanions are generated in places with low temperature. Partial re oxidation of H_2S to sulfur may occur in some aerobic environments, where molecular $O2$ is present, and in high temperature anaerobic environments, excess sulfate may act as the role of the oxidant. Intermediate sulfur species are able to be reduced to sulfide. Some of the sulfate reducers can reduce the sulfur compounds like sulfite, Thiosalts and sulfur (Rabbani, 2010, Basafa et. al., 2019; Hiorth et. al., 2007). Electrochemical detection and Ion chromatography with a glassy carbon electrode chemically modified with palladium particles have shown the highly potential ability to catalyze sulfide oxidation over vast potential and pH ranges and thus, could discover dissolved ions in all aqueous solutions.

Hydrogen Embrittlement in Pipelines Transporting Sour Hydrocarbons

In order to achieve a good integrity management, knowledge of damage mechanisms is very important. In the recent years many studies have been done on hydrogen embrittlement (HE) and how effects on load carrying steel. As ASTM F2078 states, HE is defined as "a permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either externally applied or internal residual stress". However, the interaction of Hydrogen with metals under stress is very complex and many different mechanisms are proposed (Gabetta et. al., 2018; Nmegbu et. al., 2014). Diffused Hydrogen, for instance, not only can be associated to embrittlement but also to enhanced ductility. Three conditions are required to cause cracking - potentially developing to failure: presence of water solution, Tensile stresses and material susceptibility (Gabetta et. al., 2018). In particular, the first two i.e. the nature of the flow wetting the pipe wall and the working factors of line pipe material when in service, commonly act as triggers for cracking, while the root cause remains the line pipe material susceptibility (Gabetta et. al., 2018; Nmegbu, 2014). Don't forget that the presence of H_2S and other sulfur species in hydrocarbons can be in charge of the general and localized corrosion. Laminations are a significant threat to the integrity of the pipeline and due to the presence of H_2S in the fluid, it is reported several laminar features (Gilliland, 1976).

In presence of wet H_2S in the fluid, however, it is possible to observe blisters. From blisters, cracks may propagate in the steel. An estimate of crack growth rate for these defects can be useful to assess the integrity of pipelines. H_2S has a great tendency to react with minerals rich in iron such as siderite ($FeCO_3$), hematite (Fe_22O_3), and magnetite (Fe_3O_4) as shown in the coming part (Hosseini noosheri, 2016):

$$FeCO3 + H2S \rightarrow H2O + CO2 + FeS \quad (16)$$

$$Fe22O3 + 3H2S \rightarrow 3H2O + FeS2 + FeS \quad (17)$$

$$Fe3O4 + 4H2S \rightarrow 4H2O + FeS2 + 2FeS \quad (18)$$

As a matter of fact, Temperature, pressure, and pH influence the solubility of iron-rich minerals. So, that changes the amount of adsorbed hydrogen sulfide which has no outcome expect the reservoir souring and corrosion following with transport pipes embrittlement (Gilliland, 1976; Hosseini noosheri, 2016; Anon, 1988).

Souring Control Strategies and Treatments

Underestimating the spontaneous process leading to formation of H_2S and other intermediate sulfur species following with reservoir souring and other hazardous consequences like environmental, human and financial problems, can be considered as irreparable mistake in long term. Putting finger on seeking effective solutions in recent years, has ended up with some highly effective strategies to anticipate and stop the reservoir from destructive souring anymore. Controlling the microbial oilfield souring activities is done by several a number of various methods.

One of the most common ways of controlling the reservoir souring is injection of biocides to the top side and injection water mostly known as biocides treatments. The efficiency of biocides has been proved in both studies and operations. The possible obstacles on the way using the biocides are considered as high costs of using, the rate of toxic and eventually its efficiency at operational environments.

What is exactly done by biocides is inhibition of microbial growth and activity special in those reservoirs where souring is bounded to the zone surrounding the injecting well. The determination of these compounds effects at reservoir environment due to the sulfate reducing bacteria's desire to grow in biofilm environment and formation's matrix is extremely tough thus, biocide compounds are hardly able to contact them. Besides, another trouble flashing around in biocide treatment is the SRB's resistivity against the biocides during injecting the biocides (Rabbani, 2010; Hubert et al). As the surveys demonstrate, it could be inferred that deployment of these compounds is not usually considered cost-effective and has no outcome except wasting time and energy (Rabbani, 2010; Udosoh et. al., 2020). In order to make sure that the biocides efficiency is in the most proportional way, some qualitative tastings are required to be done (Little, 2013). By normal water treatments, the reduction of bacteria to less than 1000 at m liter could be possible in (Table 1).

Morris and his colleagues gathered comprehensive information from 33 places of natural gas stations about biocides and corrosion inhibitors (Little, 2013; Berben et. al., 2017) (Table 2). In the coming tables, normal water treatments and the active biocides and the numbers they have been used are respectively going to be shown in coming tables.

Table 1. Conventional water treatments.

Suggest	Technical Information	Precautions	Operating Range	Water Imptrovement
	-	-	-	Oxidizing biocide
Injecting from some various points.	PH, amount of ammonia FE and MN. Temperature of water.	-	PH 6.5 to 7.5 evacutaions restrictions approved By EPA.	Chlorine.
2.5 times more effective than chlorine for controlling mud	PH, amount of Ammonia FE and MN. Temperature of water	Very volatile compounds	PH to 8.7 restrictions approved By EPA	Chlorine dioxide
-	-	-	-	Non-oxidizing biocide
Can be used at water no minerals	Suspended solids	Needs to fine sieve	Low flow	Ultraviolet light

Table 2. Active biocide components and the number of their usages

Active component	Number of uses
Glutaraldehyde	9
Quarter ammonium compounds (QAC)	3
Acrolein	1
Isothiazolin	1
Diamine acetates (Cocodiamine)	1
Carbamates	1
Methylene-bis-thiocyanate	1

According to Table 1, glutaraldehyde is a non-oxidizing biocide providing the cell's death by cell proteins denaturation (Little, 2013). Glutaraldehyde is soluble in water and insoluble in oils and is incompatible with alkaline substances or strong acids. Quaternary Ammonium compounds are able to dissolve the lipid and lead to cells vitals leak (Little, 2013). As an effective inhibitor, Quaternary Ammonium compounds form some protective films on inner surface and reduce the contacts with oxidizers. The rate of efficiency has a direct relation to consumption and the local conditions. The major usages of these compounds are at closed systems like extraction tubes and gas-liquid separators. Acrolein is a carbon compound including aldehyde and vinyl (Little, 2013). The biocide activity is resulted from both. As the researches indicate, vinyl is the most reactor and toxic. Acrolein is effective removal of sulfide which creates complex reactions and sulfuric compounds with H_2S and metal sulfides (Little, 2013; Gabetta et. al., 2018). Isothiazoline is a complex compound containing nitrogen and oxygen, mostly used at industrial complexes such as water-cooled air-conditioning systems and oil reservoir injecting systems however Isothiazoline gets inactive by H_2S thus is not effective at sour environment.

Diamine acetates have 2 Amine groups. The experiments done in purpose of determining the efficiency have shown the inefficiency of Diamine acetates at controlling microbial corrosion at fluids and on surface of carbon steel (Little, 2013). Biocides are highly hazardous to oilfield workers and the environment involved in and is hard to inject very deep into reservoir, making the treatment of SRB distant from all injection well challenges (Basafa et. al., 2019; Haiyan et. al., 2020).

An alternative treatment for reservoir souring is nitrate injecting at the injection well or at the production well in the produced water. In contrast with the biocide treatment, nitrate is able to flow readily into an oil-bearing formation, consequently shift the corrosive microbial activity from SRB to nitrate reducing bacteria (NRB). The idea behind injecting nitrate-containing seawater is to stimulate nitrate-reducing bacteria in charge of reduction of nitrate to nitrite (Basafa et. al., 2019). Based on researches done on nitrate and nitrite's effect on SRB, the general activities of sulfur reducing bacteria (SRB) stops while the density of nitrite reaches to a level of 2 ppm whereas a density of nitrate above 100 ppm had no remarkable impact on the growth rate of SRB (Rabbani, 2010) [figure 4]. Due to instability of nitrite behavior as a result of potential difference of redox occurred after adding nitrate to sulfate reducing bacteria (SRB) containing seawater (Rabbani, 2010). More importantly, the SRB are very sensitive to redox leading to their habitant only available in reduction environments. The ways the NRB is able to effect on SRB are divided into two ways: 1- direct inhibition as in presence of nitrate, 2- indirect inhibition based on difference at redox potential. Chemical reaction of nitrite with H_2S demonstrates that the high value of nitrite to nitrate, is considered necessary in order to have optimal inhibition sulfate-reducing-bacteria (SRB) in sour hydrocarbon reservoirs in particular at the time the formation's PH is close to 7 or even less than 7 (Rabbani, 2010; Fan et. al., 2018).

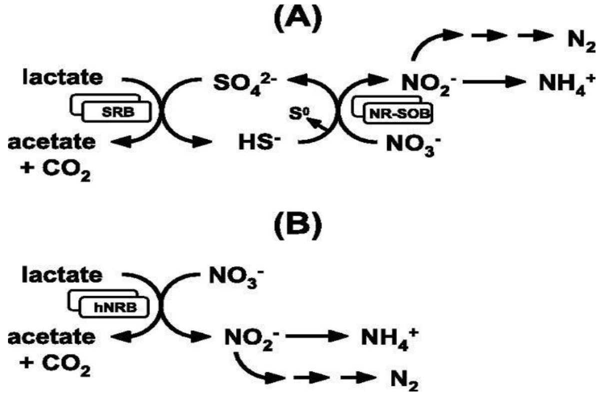

Figure 4. Impact of nitrate on the oil field sulfur cycle.

In comparison with other two strategies for controlling reservoir souring, using molybdate as an inhibitor to activity of sulfate-reducing bacteria, is less expensive along with having no significant side effects to subsurface environment, besides, most biocides are non-specific and cannot be used to stop sulfate reducing bacteria (SRB) if the growth of other microbial species is desirable. (Kögler et. al., 2021; Chilingar et. al., 1985). Deployment of Molybdate as a particular inhibition was first done by Peck in 1959 and already applied to prevent microbial sulfide genesis in sediments yet in recent years, its function as inhibitor to sulfate-reducing bacteria has been tested and proved. Molybdenum is an important chemical element for biological systems, including the anaerobic sulfate-reducing bacteria (Kögler et. al., 2021). It is used by these microbes in the synthesis of enzymes in charge of catalyzing reduction reactions, and it plays a key role in carbon, nitrogen, and sulfur cycles although the high concentration of molybdenum could be harmful for the environment due to its effect on development of microorganism (Kögler et. al, 2021). Looking over how this process is done, reveals that the molybdate ion can operate as a functional analog sulfate that can move into the bacteria so as to make it deprived of sulfur reducing compounds while the process of cellular respiration is being executed (Kögler et. al., 2021). Therefore, this acts as an ion specific metabolic inhibitor that limits sulfate reduction while is toxic to these microorganisms (Kögler et. al., 2021). In the studies done earlier, the most efficiency of molybdate has been proved to be resulted at 0.04 to 0.2 mM to fully stop the growth of pure cultures of SRB in a culture medium low in sulfate 5 mM (480 mg L-1) (Kögler et. al., 2021; Guo et. al., 2015).

Conclusion

The presence of intermediate sulfur species within the reservoir formed as a result of detrimental microbial activities may lead to operational, personnel, financial and environment irreparable damages. Not only do these sulfur compounds form toxic and corrosive compound of H_2S, but also impress the total reactivity and quality of the existing fluids in reservoir. Needless to say that as the rate of these corrosive and souring compounds rise in the reservoirs, the cost of final product decreases. In order to prevent more harms on the way microbial enhanced oil recovery scientists have come to obtain the ability to control the Phenomenon of reservoir souring resulting in corrosion by various strategies. Sulfate-reducing bacteria (SRB) is targeted as the common enemy of all strategies designed for coming over the activity of SRB and as stated earlier although the utilization of both biocides and nitrate-reducing bacteria have put the process of controlling the reservoir souring in a highly advanced way, but the comparisons between using molybdate and biocides and NRB as inhibitors to activity of SRB has brought out an awareness to the operators using these strategies as their inhibitors. Molybdate has been less impressed by the operators unlike its being cost-effective and providing less side effects.

Above all, the mentioned souring control strategies are all rich in pros and cons which made the able to be used at different and proportional circumstances compatible with the atmosphere dominant over the reservoir. On the whole, all available techniques in order to detect and get by the activity of SRB and other factors must be deployed in order to prevent further disorders in reservoirs leading to souring and corrosion and the production which is going to be delivered to the markets. All these methods must be done quick and reliable due to the rapid changes that could occur during the analysis of sulfur species.

Acknowledgements or Notes

The authors declare that they have no known financial source or personal relationships that could have appeared to influence this information reported in this paper.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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To cite this article:

Haratian, A. & Emami Meybodi, S. (2021). Review on microbial enhanced oil recovery and controlling its produced hydrogen sulfide effects on reservoir and transporting pipelines. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 15*, 88-98.