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On the benefits of desulfated seawater flooding in mature hydrocarbon fields

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HIGHLIGHTS

- Desulfation can still be beneficial after years of untreated seawater injection.
- Souring is better mitigated with desulfation than nitrate treatment.
- Desulfation enhances oil recovery while reducing watercut.
- Produced water re-injection is more viable with desulfation.
- The environmental footprint of oil production is decreased with desulfation.

GRAPHICAL ABSTRACT

ABSTRACT

Removal of sulfate from the injection seawater (desulfation) in hydrocarbon reservoirs is a Modified Salinity Water (MSW) flooding method that mitigates microbial reservoir souring, improves oil recovery, and enables produced-water re-injection (PWRI). Aside from the Improved Oil Recovery (IOR) effect, desulfation results in a cleaner production of oil through enabling PWRI and reducing the environmental impacts associated with reservoir souring and nitrate treatment. However, whether desulfation is still beneficial for mature fields, after years of the injection of untreated seawater, is a valid common concern. In such cases, sulfate concentration inside the reservoir has already increased due to years of untreated seawater injection. The high sulfate concentration inside the subsurface reservoir before desulfated water flooding may render desulfation pointless. The present study investigates the potential benefits of desulfation after around 20 years of untreated seawater injection in a sector of an oil field in the Danish North Sea. The results show that depending on the cessation of production point in time and the efficiency of residual oil saturation reduction of MSW flooding, desulfation results in a significant increase in oil production. Even if improving oil recovery is no longer a priority, modification of injected seawater would still help reduce the amount of water required to support a given oil production rate. Moreover, desulfation is considerably more effective than nitrate treatment in mitigating microbial reservoir souring. Furthermore, the possibility of scale formation is decreased considerably due to desulfation, which further encourages PWRI.
1. Introduction

A challenge associated with flooding subsurface hydrocarbon reservoirs with untreated seawater is microbial reservoir souring. Mainly due to the lower temperature of the injection water, compared to that of a deep reservoir, along with the high concentration of sulfate (SO$_4^{2-}$) in the injection water, a suitable situation is created for Sulfate Reducing Bacteria (SRB) to reduce sulfate and produce hydrogen sulfide (H$_2$S), which is a corrosive and hazardous gas with detrimental direct and indirect environmental effects (Al-Janabi, 2020; Mahmoodi et al., 2023; Mahmoodi and Nick, 2022; Mitchell et al., 2021). One mitigation strategy for microbial reservoir souring is the addition of nitrate ions (NO$_3^-$) to the injection water, which mitigates souring through various mechanisms (Agrawal et al., 2012; Eckford and Fedorak, 2002; Jahanbani Veshareh and Nick, 2019; Marietou, 2016; Qi et al., 2022; Veshareh et al., 2021; Xue and Voordouw, 2015). Nitrate treatment is, however, associated with some challenges, including environmental concerns regarding the disposal of nitrate/nitrite into the sea after production from production wells (Carrey et al., 2021). As an alternative solution, desulfation (the removal of sulfate from the seawater before injection) may be an effective solution in mitigating souring through limiting sulfate as a nutrient for SRB$^1$ (Krebs et al., 2019; Pedenaud et al., 2012; Vance and Thrasher, 2005).

On the other hand, despite previous experiments on Stevns Klint outcrop chalk, which suggested that increasing sulfate concentration could improve oil recovery (Austad et al., 2008; Strand et al., 2006a; Strand et al., 2006b; Yousef and Ayirala, 2014; Zhang et al., 2007; Zhang and Austad, 2006), recent laboratory experiments on actual reservoir chalk core samples suggest that reducing sulfate concentration of seawater for flooding hydrocarbon chalk fields significantly improves oil mobilization and reduces the residual oil saturation (Mokhtari et al., 2023). Moreover, hydrocarbon extraction operations are usually associated with the production of a co-produced water stream, which originates from both in-situ formation brine and injected seawater (Bergfors et al., 2020; Lee and Neff, 2011). The co-produced water can be produced in large volumes especially by approaching the last stages of the production life (Azizov et al., 2021; Bakke et al., 1996). Infrastructure limitations on offshore platforms lead to subsequent treatments and disposal of the produced water. Marine disposal is the most common approach for produced water management despite being environmentally unfavorable (Farajzadeh, 2004). An environmentally friendly and economically preferably disposal method is re-injecting the produced water back to the reservoirs with the aim of both pressure maintenance and produced water management (Kabyl et al., 2020). However, produced water re-injection may lead to a considerable injectivity decline (Hsi et al., 1994; Sharma et al., 1997). This is due to the restriction of the flow path in both facilities and porous media caused by the deposition of inorganic/organic substances present in the produced water (Azizov et al., 2021). Among mineral phases, iron sulfide derivatives (Fe$_x$S$_y$) with an affinity to organic species are accounted as major constituents in the structure of mixed organic-inorganic deposits (schmoo or sludge) (Eroini et al., 2015; Romaine et al., 1996). These deposits induce clogging and corresponding injectivity loss in the produced water reinjection system. Besides, other inorganic components, such as sulfate-based scales (specially BaSO$_4$ and SrSO$_4$), can also contribute to the formation and precipitation of schmoo-type deposits. The formation of iron sulfides and sulfate-bearing mineral scales during PWRI$^2$ is positively correlated with the sulfate content of the injected water. Iron sulfide scaling also depends on the severity of microbial souring in the reservoir. Therefore, desulfation of injected water can help reducing the load of biologically induced (e.g., Fe$_x$S$_y$) and sulfate-based scales and thus improve the potential of PWRI.

Although the benefits of desulfation have already been shown in each of the above-mentioned topics, whether desulfation is still beneficial after years of high-sulfate seawater injection (i.e., in mature water-flooded fields) is of paramount concern. This study demonstrates the influence of desulfation on improving oil recovery and decreasing water cut, microbial reservoir souring mitigation, and produced water re-injection possibilities in a sector of an oil field in the Danish North Sea after around 20 years of untreated seawater injection.

2. Method

Here, the three modeling approaches that are coupled and utilized for this study are introduced:

- Modified Salinity Water (MSW) flooding is commonly modeled by assigning a new set of permeability curves to the MSW-oil system obtained from core flooding experiments. As the current sector model is located in the capillary transition zone, the method described by HosseinizadehSadat et al. (2022b) is applied in reservoir simulations for switching among relative permeability curves of MSW$^-$-oil, SW$^-$-oil, or FW$^-$-oil, along with the concept and formulation of hysteresis and the procedure for simulating MSW flooding in the presence of the hysteresis effect.
- A non-isothermal multi-component bio-chemical model has been coupled with the reservoir simulations and simulate microbial reservoir souring in subsurface reservoirs (Mahmoodi et al., 2023; Mahmoodi and Nick, 2022). The microbial pathways and the Monod-equation-based governing laws and input values to compute their kinetics are taken from Cheng et al. (2016), whose work has been validated against the experimental data of Engelbrektson et al. (2014). The effect of temperature on the growth rates of bacteria has been added to the model (Hosseininooshiri et al., 2017; Leroy et al., 2012; Rosso et al., 1995). The input compositions of formation brine and seawater were set to resemble the case of this study based on the work of Mahmoodi et al. (2023). Partitioning of H$_2$S among the three phases in different pressure and temperature conditions has been considered in the model through interpolating between the data-points from the work of Burger et al. (2013). Notably, although a microbial guild can comprise various strains of microorganisms with various specifications, only one microbial strain for each of the functions (sulfate reduction, nitrate/nitrite reduction, and nitrate/nitrite reduction sulfate oxidation) has been assumed in this study (Cheng et al., 2018). Biofilm generation inside the porous media has been neglected in this work, but it can have an effect on the flow properties and bioavailability (IJa confusion et al., 2019; Sanderlin et al., 2013).
- PHREEQC geochemistry simulator version 3 (Parkhurst and Appelo, 2013) has been applied for implementing the numerical simulations related to the interactions of mineral species and approximating the precipitation intensity of the target scale forming phases (i.e., Fe$_x$S$_y$, BaSO$_4$, SrSO$_4$). Phreeqc.dat was employed as the thermodynamic database for conducting the chemical simulations and quantifying the precipitation values (Kermani et al., 2023).

A sector of a chalk hydrocarbon field in the Danish North Sea has been selected to investigate the effect of desulfation at the beginning of 2024, after around 22 years of untreated seawater injection, on oil recovery, microbial reservoir souring and nitrate treatment, and re-injection possibilities. The history matched sector model assumes that the sector injection possibilities in a sector of an oil field in the Danish North Sea after around 20 years of untreated seawater injection.

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$^1$ Sulfate Reducing Bacteria.
$^2$ Produced Water Re-Injection.
$^3$ Modified Salinity Water.
$^4$ Sea Water.
$^5$ Formation Water.
comprises 3 horizontal production wells and 2 horizontal injection wells in between them (Fig. 1). The middle production well is the target of this study for analyses. The black oil reservoir model had already been created in the commercial reservoir simulator Eclipse 100 and history matched against field production data (Hosseinzadehsadati et al., 2024).

Initial and operational parameters as the inputs of the reservoir model are described in Table 1. A scenario with no desulfation has been set to be the base case for studying the Improved Oil Recovery (IOR) effect of MSW flooding. Two different values of residual oil saturation ($S_{or}$) reduction of 2.5% and 7% compared to the original $S_{or}$ have been set to represent the maximum and minimum possible effect of MSW flooding on oil recovery assuming MSW. Notably, it has been assumed that souring and nitrate treatment has no effect on the flow field, since the simulation results show that the sulfate consumed through souring is far from enough to make a difference in terms of MSW flooding. For microbial growth rates, two values, hereafter referred to as medium and low effective growth rate cases, corresponding to $1 \times 10^{-4.3}$ and $1 \times 10^{-4.5}$ correction factors, respectively, multiplied by the maximum specific growth rates of microorganisms ($\mu_{\text{max}}$) from Cheng et al. (2016) have been considered. This is done due to the combined effect of thermal, mixing, and chemical processes that cause the microbial reactions to happen at lower effective rates in large-scale (grid-scale) compared to batch and small-scale experiments (Mahmoodi et al., 2023). Three different scenarios of (i) no desulfation with cessation of nitrate treatment in 2024, (ii) no desulfation with a continuous nitrate treatment, and (iii) desulfation with the cessation of nitrate treatment in 2024 have been investigated for both medium and low microbial growth rates. For studying produced water reinjection possibility, the scale formation potential for three of the above-mentioned scenarios has been investigated for two cases: (i) mixing the produced water with the seawater whenever water production rate is lower than water injection rates and (ii) assuming no seawater is mixed with the produced water and the whole injection water has the composition of the produced water. A series of batch chemical simulations were simulated having the predicted physicochemical properties of the produced water from 2024 to 2060 to predict the potential of scale formation.

Fig. 1. The studied sector model geometry, unstructured mesh, dimensions, and initial fluid saturations. The middle production well is the target studied well.
Table 1
Initial and operational parameters as the inputs of the reservoir model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial reservoir pressure</td>
<td>282 atm (4150 psi) to 316 atm (4650 psi)</td>
</tr>
<tr>
<td>Initial reservoir temperature</td>
<td>76.67 °C (170 °F)</td>
</tr>
<tr>
<td>Injection seawater temperature</td>
<td>15.56 °C (60 °F)</td>
</tr>
<tr>
<td>Injection rate</td>
<td>Left 1303.7 m³/d (8200 STB/d)</td>
</tr>
<tr>
<td></td>
<td>Right 1589.9 m³/d (10,000 STB/d)</td>
</tr>
<tr>
<td>Production bottom-hole pressure</td>
<td>Left 176.9 atm (2600 psi)</td>
</tr>
<tr>
<td></td>
<td>Middle 156.5 atm (2300 psi)</td>
</tr>
<tr>
<td></td>
<td>Right 108.9 atm (1600 psi)</td>
</tr>
<tr>
<td>Permeability</td>
<td>Range 0.001 md to 7.25 md</td>
</tr>
<tr>
<td></td>
<td>Mean 0.84 md</td>
</tr>
<tr>
<td>Porosity</td>
<td>Range 10 % to 42 %</td>
</tr>
<tr>
<td></td>
<td>Mean 25 %</td>
</tr>
<tr>
<td>Saturation range</td>
<td>Oil 0.06 to 1</td>
</tr>
<tr>
<td></td>
<td>Water 0 to 0.94</td>
</tr>
<tr>
<td></td>
<td>Gas 0 to 0.93</td>
</tr>
</tbody>
</table>

3. Results and discussion

The benefits of sulfate removal from injected seawater have been investigated through several simulation cases, the most notable of which have been summarized in the following.

3.1. Watercut and oil recovery

Fig. 2 depicts normalized cumulative oil production and watercut (%) for three cases, the case of no desulfation (base case) and the cases with 2.5 % and 7 % percent of $S_y - S_x$ reduction as the minimum and maximum possible IOR effect of MSW flooding.

Based on Fig. 2A, for the case of maximum oil recovery, cumulative oil production increases by 5.2 %, 11.0 %, and 13.0 % in 2040, 2050, and 2060, respectively, compared to the case of no desulfation. For the case of minimum oil recovery, cumulative oil production increases by 3.1 %, 6.1 %, and 6.9 % in 2040, 2050, and 2060, respectively, compared to the case of no desulfation. This means that at the very least, which is the case of cessation of production in 2040 and the minimum increase in oil recovery, a 3.1 % of higher cumulative oil production is predicted, which is a considerable amount.

Based on Fig. 2B, compared to the case of no desulfation, for the case of maximum oil recovery, watercut decreases by 11.2 %, 4.3 %, and 1.5 % in 2040, 2050, and 2060, respectively. For the case of minimum oil recovery, watercut decreases by 5.7 %, 1.8 %, and 0.4 % in 2040, 2050, and 2060, respectively. Hence, even if IOR is not the priority, MSW flooding still helps reduce the amount of water required for a given oil production rate. This will benefit the environment thanks to reduced use of chemicals and a reduced water handling energy footprint. In other words, the environmental effect of per unit energy produced is decreased, and this decrease happens long before the current plan for cessation of production, which is in 2043.

It is worth noting that one could look at MSW flooding from another perspective. Untreated seawater flooding, due to the higher sulfate content compared to the formation water, has a reduced oil recovery effect, which can be mitigated by desulfated water flooding of the high-sulfate saturating water porous medium.

3.2. Microbial reservoir souring mitigation

Fig. 3 represents sulfate concentration in the produced water (ppm) and $H_2S$ concentration in the produced gas phase (ppm) for six cases. For each of the two values of medium and low microbial growth rates, three scenarios of (i) no desulfation with cessation of nitrate treatment in 2024 (base case), (ii) no desulfation with continuing nitrate treatment (50 mg/l of nitrate added to the injection seawater), and (iii) desulfation in 2024 with cessation of nitrate treatment at the same time have been studied to allow a comparison between the effect of nitrate treatment and desulfation after 2024. Only the case of maximum IOR effect of MSW flooding has been considered for souring studies since the change in flow patterns does not have a considerable impact on souring. Moreover, continuing nitrate treatment after 2024 in case of desulfation did not show a considerable effect. Therefore, this scenario is not included in the results here.

Fig. 3A represents a comparison between field data and simulation results on the sulfate concentration profile in the produced water for the two different maximum effective growth rates. The reasons why sulfate concentration in the produced water has been used to match the history instead of hydrogen sulfide concentration in the produced gas have been explained in Mahmoodi et al. (2023). Fig. 3A shows that, based on the field data, both assumed growth rates for microbial activities and any value in between them could possibly be the case. However, no value higher than the medium effective growth rate case is acceptable for this sector since higher growth rates would cause a faster drop of sulfate production profile, which does not match the history of data. It is worth mentioning that in the same field, different sectors show different effective growth rate values to match the history based on the flow properties and the mixing efficiency.

As shown in Fig. 3B, for the case of low effective growth rate, seawater desulfation results in a 18.6 %, 47.6 %, and 64.2 % decrease in hydrogen sulfide concentration in the produced gas in 2040, 2050, and 2060, respectively, opposed to the effect of continuous nitrate treatment, which results in a 16.3 %, 26.6 %, and 33.3 % decrease in hydrogen sulfide concentration in the produced gas in 2040, 2050, and 2060, respectively. For continuous nitrate treatment, on the other hand, a decrease of 3.7 %, 4.9 %, and 9.4 % is predicted in hydrogen sulfide concentration in the produced gas in 2040, 2050, and 2060, respectively. This suggests desulfation as a considerably more efficient method in mitigating reservoir souring compared to a continuous nitrate treatment. The results also show that this effect will happen early enough to make a considerable difference before the plan for cessation of productions.

Furthermore, nitrate treatment is associated with environmental concerns about produced water disposal. The presence of nitrate and nitrite, which is produced by Nitrate Reducing Bacteria (NRB) through heterotrophic nitrate reduction to nitrite, in the produced water calls for extra treatment before disposal to reduce its toxicity. Desulfation, on the other hand, is not associated with such concerns. Furthermore, in case of nitrate treatment with no desulfation, since still different kinds of microorganisms grow in the porous media and tubulars, biofilm generation can cause problems in terms of blocking flow channels (bio-clogging).

3.3. Produced water re-injection

The three cases with low effective growth rate have been studied for the potential of sulfide/sulfate-bearing scales formation in the backflow co-produced water, the results of which are presented in Figs. 4 and 5. In Fig. 4, the produced water has been mixed with sea water with appropriate mixing fractions to reach the desirable flow rate for the re-injection process. In the chemical simulations, pyrite (FeS$_2$) has been selected to be investigated as the representative of FeS$_2$ scales. This is because when pyrite precipitates, the other forms of iron sulfide like mackinawite (FeS) remain thermodynamically undersaturated, according to the results of the chemical model.

In Fig. 4A, rough values of the predicted pyrite (FeS$_2$) precipitation in

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6 The percentage of water in the produced liquids.

7 Improved Oil Recovery.

8 Nitrate Reducing Bacteria.
Fig. 2. (A) Normalized cumulative oil production and (B) normalized watercut.

Fig. 3. (A) Sulfate concentration in produced water and (B) H₂S concentration in produced gas.

Fig. 4. (A) FeS₂ scale formation potential, (B) BaSO₄ scale formation potential, and (C) SrSO₄ scale formation potential for the case of mixing produced water with appropriate amount of seawater.
the produced water (mixed with sea water) are demonstrated for three cases. As shown, desulfation of injected seawater shows a great impact on diminishing the load of iron sulfide scales in contrast to the other two cases. Desulfation leads to an approximately 19%, 46%, and 67% reduction of iron sulfide precipitation during PWRI in 2040, 2050, and 2060, respectively, in contrast to the influence of sea water injection with nitrate treatment which results in a reduction of 12%, 26%, and 33% in pyrite precipitates during PWRI in 2040, 2050, and 2060, respectively. The iron content present in the produced water is directly proportional to the souring severity, from which biologically induced corrosion in the PWRI cycle originates. More souring activity results in the presence of more hydrogen sulfide, iron, and corresponding FeS phases in the produced water. This is why the load of iron sulfide precipitation is high when non-desulfated nitrate-free sea water is injected. It should be pointed out again that mixing fractions of produced water with sea water was determined based on the produced water and precipitation is high when non-desulfated nitrate-free sea water is injected.

It should be pointed out again that mixing fractions of produced water with sea water was determined based on the produced water and sea water injection rates in the period of 2024 to 2060. The portion of water with sea water was determined based on the produced water and precipitation is high when non-desulfated nitrate-free sea water is injected.

Based on Fig. 5A, no significant change is seen for iron sulfide precipitation during PWRI when individual produced water is considered in contrast to the case that produced water is mixed with sea water to reach the required injection flow rate (compare Fig. 5A with Fig. 4A). According to Fig. 5B, for BaSO$_4$, the precipitation reduces in time until eliminated in 2050. Apart from desulfation effect, the incompatibility between the produced water and sea water is not an issue anymore when the individual produced water is considered. This is why BaSO$_4$ precipitation amount reaches zero in 2050. Similarly, in the period between 2024 and 2050, the precipitation of SrSO$_4$ is reduced in the non-mixing case in contrast to the mixing case (compare Fig. 5C with Fig. 4C). This is also related to the incompatibility issue present in the mixing case. In 2060, no substantial difference is observed between the precipitation value of SrSO$_4$ in mixing and non-mixing cases. This can be attributed to the mixing fraction of produced water to sea water which is higher in 2024 and reduces over time as more produced water is extracted.

All in all, sea water desulfation presents a considerable advantage for long term PWRI over nitrate treatment. Desulfation makes the environmentally preferable re-injection method more feasible by diminishing the content of some major problematic components negatively affecting the injectivity during PWRI.

Another noticeable aspect of PWRI is that the produced water contains DOC$^9$, which is a nutrient for microorganisms. If this dissolved DOC exists in the (re)injected water, due to its higher availability to the microbial community compared to the carbon partitioned from the hydrocarbon phases inside the reservoir, it can increase microbial growth if the injected water is not desulfated. This is, therefore, another reason for why desulfation is necessary in case of PWRI.

4. Environmental implications

Fig. 6 illustrates the environmental implications associated with the removal of sulfate from the injection seawater.

As shown in this study, aside from the IOR effect of MSW flooding, desulfation is an effective tool against reservoir souring. Therefore, a reduction in hydrogen sulfide production compared to the common nitrate treatment is expected. Other than the hazards directly associated with hydrogen sulfide, it leads to increased corrosion in the tubulars, higher use of chemicals for H$_2$S scavenging and corrosion inhibition, and thus higher consumption of materials (Rathnayake et al., 2019; Wang et al., 2022). More importantly, H$_2$S scavengers and corrosion inhibitors increase the toxicity of the produced water (Knudsen et al., 2002; Rye

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$^9$ Dissolved organic carbon.
et al., 2004). Moreover, the addition of excessive amounts of nitrate to injection water for souring mitigation results in the presence of unconsumed nitrate and nitrite in the produced water. Added chemicals and an increased nitrate or nitrite concentration calls for costly treatment of the produced water before it is discharged into the sea, as they may impact marine and terrestrial ecosystems (Carrey et al., 2021; Lee et al., 2009; Wang et al., 2022; Zou et al., 2021). Desulfation, however, can reduce the need for produced water treatment without the risk of nitrate or nitrite presence in the produced water. Furthermore, desulfation reduces the total amount of produced water, which means less water to treat and discharge. Desulfation will also enhance the possibility of PWRI, which will ideally eliminate the need for the discharge of produced water to the sea and avoiding the costly treatment. Finally, MSW flooding could be used as a method to reduce the amount of water injected to maintain a specific oil production rate. This benefits the environment due to the reduced use of chemicals and the reduced water handling energy footprint.

Last but not least, the elephant in the room, the possible increase in negative emissions from the production of extra oil, needs to be discussed. Basically, this article demonstrates the reduction of the environmental footprint per barrel oil produced, i.e., per unit energy produced. Whether the amount of cumulative produced oil until the end of life of the reservoir is increased or limited to the current predictions by the operator and governor, however, is their decision and out of the scope of this article. On the other hand, considering current efforts globally and specifically in Denmark, there is a chance that by the time the extra oil is being produced, CCS technologies have progressed enough to make it a net-zero emission energy source (Bonto et al., 2021).

5. Conclusions

Seawater desulfation had been shown to be beneficial in terms of improving oil recovery, mitigating microbial reservoir souring, and enabling produced water reinjection. However, this study investigates whether desulfation is still beneficial after years of untreated seawater injection. The following conclusions are made based on the results presented in this study:

- Desulfation is still an effective mitigation strategy for souring, with a more considerable effect compared to a continuous nitrate treatment.
- Desulfation can still considerably improve oil recovery and reduce watercut.

- The risk of produced water reinjection decreases after some years of desulfated water injection.
- Desulfation is an environmentally positive practice due to enabling produced water re-injection and avoiding the negative environmental impacts associated with souring and nitrate treatment.

Hence, it is wrong to assume that desulfated seawater flooding after years of untreated seawater flooding is ineffective. However, each case should be studied separately. The utilized sector model assumes there are no fractures between injection and production wells that act as shortcuts, something that has been demonstrated to speed up injection water breakthrough in other parts of the field. Scaling up of the demonstrated results to full field level would therefore need to take these heterogeneities into account, which ipso facto would further accelerate any benefits of sulfate removal.

5.1. Caveats and future work

There are several simplifying assumptions in the models used for this study that can be improved in the future. The temperature of the injection SW is assumed to be constant. However, in reality, there is some seasonal changes in the temperature of the injection SW.

The MSW flooding model assumes that only the imbibition curve is salinity-dependent and changes during MSW injection (Hosseinzadehsadati et al., 2022a). This assumption is due to lack of data specific to chalk, the case of this study. Moreover, the water weakening effect caused by sulfate adsorption has not been taken into account in this study. Instead, the rock compaction table is utilized to capture pore volume changes during pressure depletion (Hosseinzadehsadati et al., 2023; Hosseinzadehsadati et al., 2022b). Furthermore, Langmuir isotherms were used instead of a complex and computationally expensive surface complexation model to capture sulfate adsorption. The microbial model also simplifies the formation of biofilm by assuming 10 times slower advection for the microorganism. A better match against the history of the data for the microbial souring model may be obtained by acquiring the detailed composition of the injected lift gas and considering several microbial strains that can be active in different parts of the field with different temperatures, salinities, and the concentrations of the nutrients. For the PWRI model, the possibility of scale formation has been predicted based on the equilibrium state of the solution. However, a scaling model that considers the kinetics of scale formation will be more accurate, especially in the cases where scale formation is slow. Moreover, such a model needs to be first tuned using analogous cases. Finally, an economic study may be conducted to consider the detailed costs and benefits of desulfation for this field using full-field simulations and considering the number of platforms on which

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10 Carbon Capture and Storage.
desulfation facilities should be installed. Doing an economic study for a single sector will be misleading since desulfation facilities are not generally installed per well but per platform, which is connected to several wells. Generally, it is expected that desulfation will be more capital intensive compared to nitrate treatment from the souring mitigation point of view. However, a more efficient souring mitigation will reduce the costs of scavenging the hydrogen sulfide in the produced fluids. It is the same story from the point of view of IOR and PWRI, where desulfation adds upfront costs and saves money in the future. All in all, a proper economic study together with full-field simulations is necessary.

CRediT authorship contribution statement

A. Mahmoodi: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. S.B. Hosseinizadehsadati: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. H.M. Kermani: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. H.M. Nick: Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Azizov, I., Dudek, M., 2013. On the partitioning of hydrogen sulfide from the point of view of IOR and PWRI, where desulfation adds upfront costs and saves money in the future. All in all, a proper economic study together with full-field simulations is necessary.


