Summary

The latest CO2 foam technology reviews were conducted to understand recent research trends in CO2 enhanced oil recovery (EOR). In general, it is expected to improve CO2 sweep efficiency resulting in better oil recovery and prevention of early breakthrough. From CCUS point of views, the delay of gas breakthrough has a significant advantage in underground storage of industry-originated CO2. The reviews highlighted that various types of nano-additives have been investigated to develop further advanced foam technology. Key points to be focused on are how achieving more robust foam stability. Even a conventional CO2 foam generated with surfactant agents might be deteriorated in short period, those additives can extend foam half-life time. As additives, the recent researches have paid attention to nano-particles, polymer, viscoelastic surfactant, etc. The investigation measured half-life, viscosity, and differential pressure in core flood as key performance indicators. In addition, “high temperature (HT)” and “high salinity (HS)” are keywords in their researches. Namely, screening criteria of experimental conditions are aiming to more harsh conditions. However, the reviewed reports have not covered up to our target conditions in typical Middle East region. Thus, we have been concentrating to develop nano-additive enhancing CO2 foam technology in HTHS.
Introduction

Carbon dioxide (CO$_2$) has been used for a promising enhanced oil recovery (EOR) because of expecting miscible displacement whereby single phase oil is achieved by lowering minimum miscibility pressure (MMP). Even immiscible displacement, many advantages are still expected such as oil swelling, oil viscosity reduction, etc. The injection of CO$_2$ into reservoir is not only EOR but also a type of CO$_2$ sequestration. In other word, a series of EOR using CO$_2$ emissions from fossil fuel combustion in various industries: manufacturing and power plant, in particular, is Carbon Capture, Utilization and Storage (CCUS). However, a typical CO$_2$ EOR problem such as poor sweep efficiency makes more recycled CO$_2$ which are originated from carbon capture process, injected into reservoir and produced due to early gas breakthrough. This deteriorates CO$_2$ sequestration efficiency. The unexpected early gas breakthrough is often caused in heterogeneous reservoir consisting of high permeability layers and/or even in thick homogeneous reservoir allowing gravity segregation. To tackle with the technical challenges for improving sweep efficiency, a mobility control technology of injected CO$_2$ has been developed. The CO$_2$ foam technology has gathered interests as a high potential option. More homogeneous gas front can be created by increasing CO$_2$ viscosity in high permeable zone (see Figure 1).

![Figure 1](image_url) Comparison of CO$_2$ EOR versus CO$_2$ Foam EOR from a viewpoint of storing CO$_2$ Emission.

Recent Research Review

The CO$_2$ foam technology was initially patented and suggested in 1950’s (Bond and Holbrook, 1958) and has long research history. This paper reviewed the recent advanced concept. A technical challenge of CO$_2$ foam is to improve foam stability in harsh reservoir condition: higher salinity and temperature because foam is thermodynamically and kinetically unstable in general. The expansion of CO$_2$ foam application criteria can contribute more CO$_2$ sequestration. From a viewpoint of enhancing foam stability, various additives have been evaluated in recent years.

- nanoparticles
- polymer
- viscoelastic surfactant (VES)

Nanoparticles have been investigated to stabilize foam by many researchers (Emrani et al. 2017; Emrani and Nasr-El-Din. 2017; Ibrahim et al. 2017; San et al. 2017; Nazari et al. 2018; Razali et al. 2018; Rognmo et al. 2018).

Emrani and Nasr-El-Din (2017) used two types of nanoparticles such as SiO$_2$ (two sizes: 100 and 140nm) and Fe$_2$O$_3$ (less than 50nm). They evaluated foam stability in the presence of nanoparticles as sensitivity
analyses of pressure ranged from 300 to 800 psi, temperature ranged from 24 to 82°C, and NaCl concentration ranged from 1 to 5wt%. In their work, nanoparticles improved foam half-life at the milder conditions such as 24°C, NaCl 0.1wt%, or 300-400 psi. Ermani et al (2017) conducted another work using silica nanoparticle (140nm) that was not for EOR purpose but hydraulic fracturing utilization to improve mobility control of fracturing fluid. In this case, the performance of nanoparticle-stabilized CO₂ was investigated under the condition of 5wt% NaCl, and temperature of 25 and 121°C. As a result, foam stability could be improved by adding nanoparticle even at high temperature.

Four types of nanoparticles such as hydrophilic/hydrophobic types of SiO₂ (7-12nm), ZnO (less than 100nm), and TiO₂ (less than 25nm) were evaluated by Razali et al (2018) for comparing nitrogen foam half-life time at 110°C. As a result, three types of nanoparticles (two types of SiO₂ and TiO₂) revealed enhancing foam half-life time compared with that of surfactant foam alone. Hydrophilic type of SiO₂ was remarkable, in particular, because its addition showed only increase of half-life time at existence of oil (45°API). They proposed a mechanism of surfactant molecules attaching on the surface of SiO₂ nanoparticles to increase foam stability. The interface between SiO₂ and surfactant formed a steric layer at the lamella structure which could avoid foam shrinkage or expansion (see Figure 2).

In the study by Ibrahim et al (2017), both of SiO₂ nanoparticles and VES were utilized to stabilize CO₂ foam. The foam stability was evaluated through coreflood tests at 65°C and 5wt% NaCl. Addition of nanoparticles increased 6.5 % recovery factor from the baseline of CO₂ foam injection. Both addition of nanoparticles and VES revealed further increase of 7.7 % from the nanoparticles adding case (i.e. 14.2% increase from the baseline).

A physics-based polymer enhanced foam flow model was established by Luo et al (2018). In their theoretical works, polymer additive improved foam stability by increasing viscosity in aqueous phase and disjoining pressure. Small sized polymers existing in foam film can boost foam stability because bonding between certain hydrophobic heads of polymers and surfactant molecules can increase surface elasticity.

Rognomo et al (2018) used silane modified colloidal SiO₂ nanoparticles (23nm) solution for CO₂ foaming purpose. The nanofluids were observed stable up to 25wt% TDS in the existence of mono- and divalent ions and up to 120°C through the static stability tests. The nanofluids revealed less retention compared with surfactant in coreflood tests using homogeneous and water-wet Bentheimer sandstone cores (1-3 darcy, 20-25% porosity).

Nazari et al (2018) focused on polyelectrolyte complex nanoparticles (PECNP). They mixed polymers and dextran sulfate sodium salt. The stability of mixture was confirmed in brine up to 200,000 ppm salinity. The core flooding using PECNP-added CO₂ foam showed the highest pressure drop in two brine concentrations of 34,000 and 67,000 ppm at 40°C.

The polymer enhanced CO₂ foam concept was also used by Ahmed et al (2017). They used a conventional polymer of hydrolysed polyacrylamide (HPAM) and associative polymer. This combination with the associative polymer revealed a significant viscosity enhancement. Their screening was performed by assuming a light crude (43°API), 3wt% NaCl and 80°C. The highest case of polymer-enhanced foam half-life extended twice of polymer free case.
Experiments

Currently, the foam technology has been attracting attention because of mobility control requirement in heterogeneous carbonate reservoirs. Therefore, a research target has been set to cover a typical harsh condition: high temperature (more than 99°C) and high salinity conditions (see Table 1) in Middle East region.

**Table 1** Typical Composition of Seawater and Arab D Formation Water. (Lindlof and Stoffer, 1983)

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<tbody>
<tr>
<td>Seawater</td>
<td>40,000</td>
<td>1,800</td>
<td>8,460</td>
<td>6,580</td>
<td>57,000</td>
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<tr>
<td>Arab D Formation Water</td>
<td>130,000</td>
<td>82,500</td>
<td>16,700</td>
<td>148</td>
<td>230,000</td>
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In our CO₂ foam EOR research (Yonebayshi and Miyagawa, 2017), we are developing useful nano-additives to stabilize CO₂ foam under high temperature and high salinity (HTHS) condition. After foamability/stability screening tests, the screened materials are planned to evaluate its apparent viscosity increase through a slimtube test. The first screening process have already revealed certain enhancement of CO₂ foam stability at HTHS. A typical slimtube apparatus is shown in Figure 3. Sand-or carbonate grain-packed slimtube (inner diameter of 4.7mm and length of 12m) is prepared with a heat jacket. Prior to the slimtube, a small sandpack is set for mixing purpose to create foam from simultaneous injected CO₂ and foaming agent solution (FAS). The foaming situation can be observed through a sight cell between the slimtube and sandpack. To evaluate viscosity increase, differential pressure is monitored during injection. By comparing with baseline case (i.e. water flood and/or CO₂ single injection), a relative effect of CO₂ foam can be understood. Currently, the differential pressure (dP) can be monitored for a whole slimtube; however, the apparatus is being improved to monitor several dPs by section such as inlet-side, middle, and outlet-side. Preparatory slimtube tests are being conducted to optimize the apparatus design: clear variation between foam flood and other cases, nano-additive consumption due to adsorption, mesh size for packed material retention, etc. The preliminary work could increase 4-5 times of viscosity compared with the water flood case under ambient condition. This viscosity increase was estimated 50 times higher than CO₂ sole injection.

![Figure 3 Slim Tube Test Apparatus for Evaluating CO₂ Foam EOR from a Viewpoint of Differential Pressure Increase.](image-url)
Conclusions

- Various additives, such as nanoparticles and polymers, have been investigated to improve foam stability. The investigation were conducted from many perspectives of foam half-life time, viscosity increase, and differential pressure in flooding tests.
- Function of those additives are expected to work at harsh conditions: high temperature and high salinity. However, the recent researches have not been matchable to our target conditions in typical Middle East region yet.
- In our preliminary study, a potential of adding nano-additive was extracted through foamability tests at HPHT conditions and further investigation is necessary to estimate apparent viscosity increase in slimtube tests.

Acknowledgements

The authors would like to thank INPEX management for their permission to publish this paper. We gratefully acknowledge Nissan Chemical Corporation and Hirosaki University for the supply of nano-foaming agents.

References


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