

Article

Stability and Foam Performance Optimization of CO₂-Soluble Foaming Agents: Influencing Factors and Mechanistic Analysis

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Abstract

This study systematically analyzes the influencing factors and optimization strategies of foam stability and performance for CO₂-soluble foaming agents in high-temperature and high-pressure (HTHP) complex reservoir environments. By constructing a HTHP experimental system and utilizing dynamic foam testing, interfacial tension analysis, and microscopic observation of liquid films, the effects of chemical factors (e.g., pH, foaming agent concentration, stabilizer synergy) and physical factors (e.g., temperature, pressure) on foam behavior are investigated. The results show that the nonionic surfactant E-1312 exhibits optimal foam performance in neutral to mildly alkaline environments. The foam performance tends to saturate at around 0.5% concentration. High pressure enhances the foam stability, whereas elevated temperature significantly reduces the foam lifetime. Moreover, the addition of nano-sized foam stabilizers such as silica (SiO₂) can significantly delay liquid film drainage and strengthen interfacial mechanical properties, thereby improving foam durability. This study further reveals the key mechanisms of CO₂-soluble foaming agents in terms of interfacial behavior, liquid film evolution, and foam formation in porous media, providing theoretical guidance and optimization pathways for the molecular design and field application of CO₂ foam flooding technology.

Keywords: CO₂ flooding; CO₂-soluble foaming agents; foam stability; supercritical CO₂



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1. Introduction

With the continuous growth of global energy demand, enhancing oil recovery (EOR) has become a central issue in energy development. CO₂ flooding technology has been widely applied in recent years due to its multiple advantages, including improved recovery efficiency, reservoir pressure maintenance, and greenhouse gas sequestration. However, the rapid breakthrough and fingering of CO₂ in porous media often lead to poor sweep efficiency, becoming a major bottleneck in the application of CO₂ gas flooding technology [1].

To address this issue, foam-assisted oil recovery has emerged as an effective solution. Foam can significantly improve mobility control of gas flooding by increasing gas viscosity and reducing the gas–liquid mobility ratio, thereby mitigating CO₂ fingering and enhancing oil recovery [2]. In particular, the use of CO₂-soluble foaming agents in CO₂ flooding

processes offers distinct technical advantages due to their rapid foaming capability and stability under high-pressure conditions [3].

CO₂-soluble foaming agents possess amphiphilic molecular structures, featuring both hydrophilic groups (e.g., hydroxyl, ether) and hydrophobic groups (e.g., long-chain alkyl). This enables the agents to align directionally at the gas–liquid interface, reduce interfacial tension, and promote foam formation and stability. The HTHP conditions and complex pore structure during CO₂ injection impose higher demands on foam formation and stability. Therefore, systematic research on the behavior of CO₂-soluble foaming agents under multifactorial conditions is of great significance for the efficient application of foam-assisted oil recovery technology. In recent years, optimization strategies in materials science and engineering have exhibited an increasingly pluralistic trajectory. For instance, Der et al. [4] employed a machine learning-based framework to predict multiple outputs simultaneously, thereby optimizing the CO₂ laser cutting quality of fused filament-fabricated ASA thermoplastics; this work underscored the efficacy of data-driven models in capturing intricate parameter interdependencies. Similarly, Ürgün et al. [5] leveraged meta-heuristic algorithms—including genetic algorithms, particle swarm optimization, and the ant-lion optimizer—for the joint minimization of kerf width and depth in PMMA laser cutting, demonstrating the rapid convergence of these methods within highly complex response topologies. Collectively, such studies not only furnish methodological insights—spanning data-centric modeling and intelligent optimization paradigms—but also advance the elucidation of multi-factor coupling phenomena. The present investigation integrates experimental design with mechanistic analysis to establish a physicochemical foundation for the performance optimization of CO₂ foams, while positioning future work to incorporate data-driven models for enhanced predictive capacity.

Nevertheless, challenges such as high temperature and pressure, the high solubility of CO₂, and the influence of minerals and porous media on foam propagation still limit foam stability and performance. Thus, investigating the stability and foam performance of CO₂-soluble foaming agents is crucial for optimizing surfactant design and improving EOR techniques [6,7].

In this study, an experimental system simulating reservoir conditions was constructed to deeply analyze variations in foam performance with different pH levels, concentrations, stabilizer types, temperatures, and pressures. Additionally, the intrinsic coupling of molecular design, interfacial behavior, and liquid film mechanisms is explored, aiming to provide scientific and technical support for engineering applications of CO₂ foam flooding.

2. Experimental Materials and Methods

2.1. Materials

The primary materials used in this study include a series of nonionic surfactants: E-1303, E-1305, E-1306, E-1308, E-1309, E-1310, and E-1312. All reagents were of analytical grade. Simulated formation water was used in the tests. To replicate reservoir conditions, CO₂ gas was utilized under high-temperature and high-pressure (HTHP) experimental settings for foam performance testing. Additionally, nano-sized silica particles (SiO₂) were selected as foam stabilizers for the synergy experiments. All the above chemical materials were provided by Jiangsu Hai'an Petrochemical Factory.

Polyoxyethylene isotridecyl ether (E series) is a non-ionic surfactant formed by polymerizing isomeric tridecyl with different amounts of ethylene oxide (EO) units. Its structural formula is CH₃(CH₂)₁₁CH₂O(CH₂CH₂O)_{*n*}H, where *n* represents the number of EO units and ranges from 3 to 12.

The specific information is shown in Table 1.

Table 1. Chemical structure description of E-series surfactants.

Number	Number of EO Units	Chemical Name	Skeleton Symbol
E-1303	3	Polyoxyethylene (3) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₃ H
E-1305	5	Polyoxyethylene (5) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₅ H
E-1306	6	Polyoxyethylene (6) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₆ H
E-1308	8	Polyoxyethylene (8) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₈ H
E-1309	9	Polyoxyethylene (9) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₉ H
E-1310	10	Polyoxyethylene (10) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₁₀ H
E-1312	12	Polyoxyethylene (12) isotridecyl ether	i-C ₁₃ H ₂₇ O(CH ₂ CH ₂ O) ₁₂ H

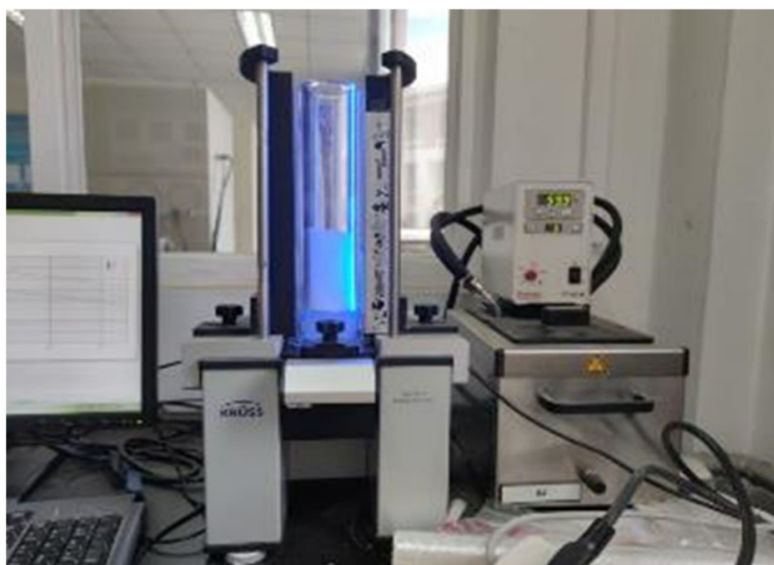
2.2. Equipment and Instruments

2.2.1. Dynamic Foam Analyzer (DFA-100)

The DFA-100 Dynamic Foam Analyzer is manufactured by KRÜSS Scientific Instruments, Germany. This instrument was employed to evaluate the foaming performance of surfactants. The experimental apparatus is shown in Figure 1. During the test, 60 mL of the test solution was injected into the analyzer. CO₂ gas was introduced under a defined gas–liquid ratio to generate foam. The maximum foam volume and foam half-life were recorded, and the Foam Comprehensive Index (FCI) was calculated using the following formula:

$$FCI = 0.75 \times V_{max} \times t_{1/2} \quad (1)$$

where V_{max} is the maximum foam volume (mL), and $t_{1/2}$ is the foam half-life (s).

**Figure 1.** DFA-100 dynamic foam analyzer.

2.2.2. High-Temperature and High-Pressure Visual Foam Analyzer

This experimental instrument was developed by Beijing Vista Technology Co., Ltd. (Beijing, China), with the model number COMT-GZ-5. This analyzer comprises a visual reaction kettle, magnetic stirrer, temperature control module, and CO₂ injection system. It operates up to 30 MPa and 150 °C, allowing real-time observation of foam formation and decay processes. The experimental apparatus is shown in Figure 2.

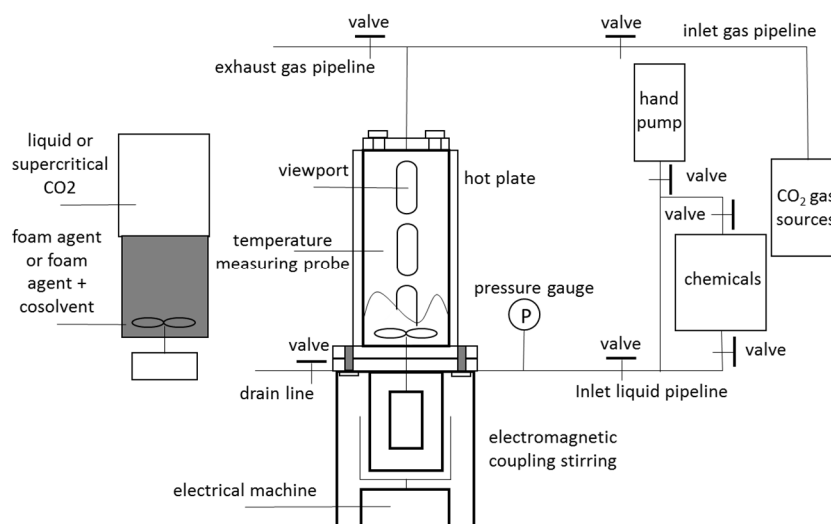


Figure 2. Experimental setup of the HTHP visual foam analyzer.

2.2.3. High-Temperature and High-Pressure Interfacial Tensiometer

This experimental instrument was developed by Beijing Vista Technology Co., Ltd., with the model number COMT-GZ-6. Interfacial tension was measured using the pendant drop method. The instrument supports a wide range of temperatures and pressures (0–70 MPa, room temperature to 200 °C) and features automatic image acquisition and tension calculation.

2.2.4. Foam Film Thickness Measurement Device

The Olympus BX53-P polarizing microscope is a professional-grade polarized light analysis instrument introduced by Olympus Corporation of Japan. An Olympus BX53-P polarized light microscope, combined with a film-holding device, was used to observe film thickness, structural evolution, and molecular arrangement.

2.2.5. High-Temperature and High-Pressure Rheometer

The HAAKE RS6000 high-temperature and high-pressure rheometer is a high-performance rheological analysis instrument developed by Haake GmbH, Germany. A HAAKE RS6000 HTHP rheometer was used to measure the rheological properties of the foam system. It precisely determines viscosity, yield stress, and elastic modulus at different shear rates, temperatures, and pressures, offering theoretical support for evaluating foam stability and its flow behavior in reservoirs.

2.3. Experimental Methods

2.3.1. Foam Performance Evaluation

Foaming ability and stability were assessed for surfactants at temperatures of 35 °C, 50 °C, 65 °C, and 80 °C and pressures of 12 and 16 MPa, with concentrations ranging from 0.1% to 1.0%.

2.3.2. pH Adjustment Experiments

The pH of the foaming solution was adjusted using HCl and NaOH (range 4–10) to investigate the effect of acidic and alkaline environments on the foam performance of E-1312 and anionic surfactants.

2.3.3. Foaming Agent Concentration Experiments

The foam volume, half-life, and FCI of E-1312 were evaluated at different concentrations to clarify the relationship between concentration and foam performance.

2.3.4. Stabilizer Synergy Experiments

Silica nanoparticles (SiO_2) were compounded with E-1312, and their foam stabilization performance under HTHP conditions was assessed using the visual foam analyzer.

2.3.5. Effects of Temperature and Pressure

By adjusting the experimental temperature and pressure, the influence on foam formation and overall performance trends was analyzed.

2.3.6. Liquid Film Thickness Measurement

Liquid films were prepared using the platinum ring method. Film thickness was measured at different time points using a polarized light microscope, and dynamic changes were plotted.

2.3.7. Rheological and Viscoelastic Property Measurements

The rheological properties were measured using a HAAKE RS6000 HTHP rheometer equipped with a coaxial cylinder (Couette geometry) measurement system. Experiments were conducted under isothermal conditions at 80 °C, where the rotor speed or shear stress was precisely controlled by a servo motor while recording the rheological response in real time. The data acquisition software is RheoWin 4 Job Manager, which can generate flow curves (shear rate vs. viscosity) and dynamic viscoelastic spectra (frequency vs. modulus) for comprehensive evaluation of the structural response characteristics and stability of the foam system. The shear rate range was set from 0.1 to 1000 s^{-1} for all measurements.

3. Experimental Results and Discussion

3.1. Comparative Analysis of Foam Performance Among Different Nonionic Surfactants

The nonionic surfactants used in this study include E-1303, E-1305, E-1306, E-1308, E-1309, E-1310, and E-1312, all of analytical grade. Simulated formation water was used in all experiments.

The foam performance of these surfactants was preliminarily evaluated using a DFA-100 dynamic foam analyzer. The results are shown in Figure 3.

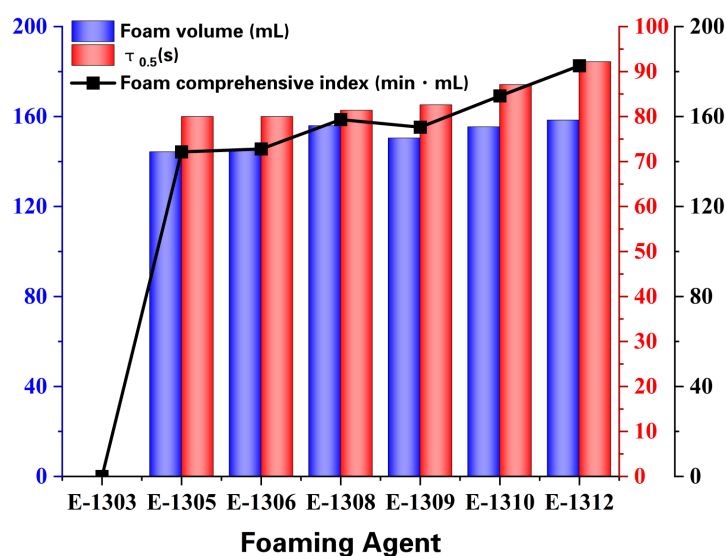


Figure 3. Comparison of foam performance among different nonionic surfactants.

As shown in Figure 3, there are significant differences in the foaming performance of various nonionic surfactants. E-1303 exhibits relatively poor foaming ability and stability, whereas E-1312 demonstrates excellent comprehensive foam performance, characterized by larger foam volume, longer half-life, and the highest Foam Comprehensive Index (FCI). Overall, the data trend suggests that, as the number of ethylene oxide (EO) units increases, foam performance is progressively enhanced, providing a basis for subsequent system optimization.

The foam height generated by E-1312 rapidly reaches a peak and then quickly declines, with the most intense decay occurring within the first 400 s. Eventually, the system becomes dominated by the liquid phase. This indicates that E-1312 has good initial foaming ability but still has room for improvement in structural stability. A more detailed analysis of the time-dependent foam height of E-1312 was conducted using the DFA-100, and the results are shown in Figure 4.

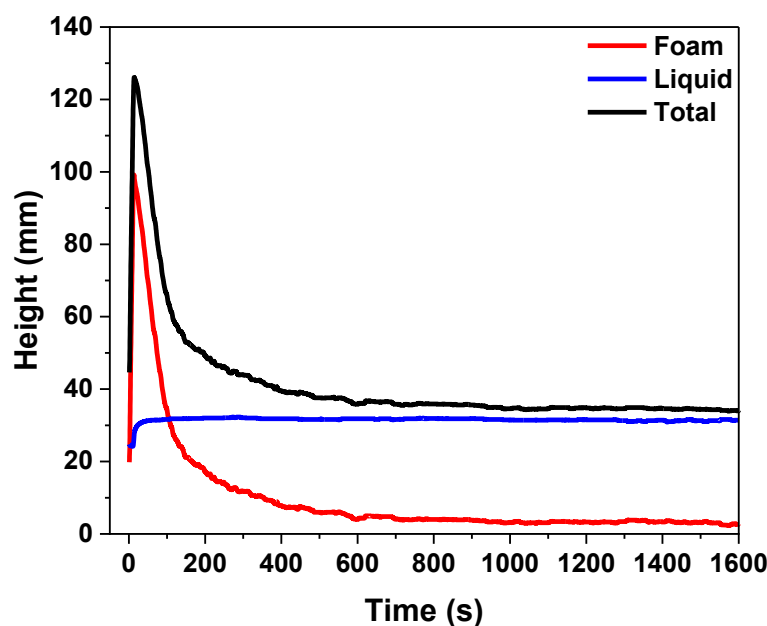


Figure 4. Time evolution of foam height in the E-1312 foaming system.

As illustrated in Figure 4, foam generated by E-1312 forms rapidly, reaching a peak height of 110 mm. This is followed by a sharp decline, especially within the first 400 s. In the stable stage, the foam height remains at a low level (approximately below 10 mm), indicating that the foam structure has largely collapsed. The foam system demonstrates excellent foaming capability in the initial stage, but the foam height drops sharply afterward, suggesting rapid liquid drainage and limited structural stability. The liquid level slightly rises initially and then remains steady, indicating that liquid drainage from the film completes quickly. Ultimately, the entire system is dominated by the liquid phase. This further confirms that, while E-1312 exhibits strong initial foaming ability, its foam stability still requires further optimization.

3.2. Influence of Chemical Factors

3.2.1. Effect of Solution pH

At a temperature of 80 °C, the foam performance of the nonionic surfactant E-1312 under various pH conditions was systematically evaluated using a high-temperature and high-pressure visual foam analyzer. The pH of the foaming solution was adjusted using hydrochloric acid (HCl) and sodium hydroxide (NaOH) to investigate the influence of

acidity and alkalinity on foam generation and stability. The experimental results are shown in Figure 5.

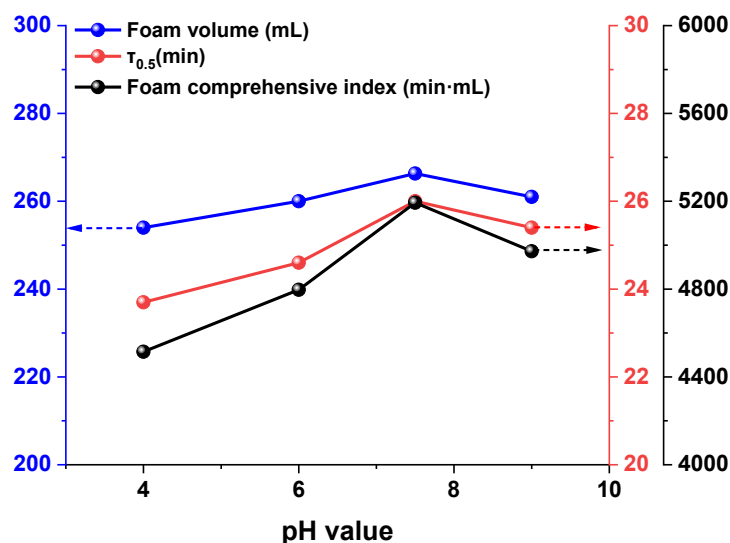


Figure 5. Effect of pH on foam performance of nonionic surfactants (80 °C, 12 MPa).

As shown in Figure 5, E-1312 exhibits the best foam generation and stability under neutral to mildly alkaline conditions ($\text{pH} \approx 8$), with maximum foam volume, half-life, and comprehensive index values. Strongly acidic or alkaline conditions inhibit the interfacial adsorption of the foaming agent, thereby affecting foam performance. Thus, pH is a key chemical parameter for tuning foam properties, and moderate alkalinity facilitates foam optimization.

Nonionic foaming agents show better stability in different pH environments. Since their molecular structure does not contain charged groups, changes in ion concentration (such as H^+ or OH^-) caused by pH adjustment do not significantly affect intermolecular electrostatic interactions. This prevents aggregation or precipitation and contributes to their excellent stability [8,9].

3.2.2. Effect of Foaming Agent Concentration

At a reservoir-representative temperature of 80 °C, the foam performance of E-1312 at different concentrations was evaluated using the HTHP visual foam analyzer. The results are shown in Figure 6.

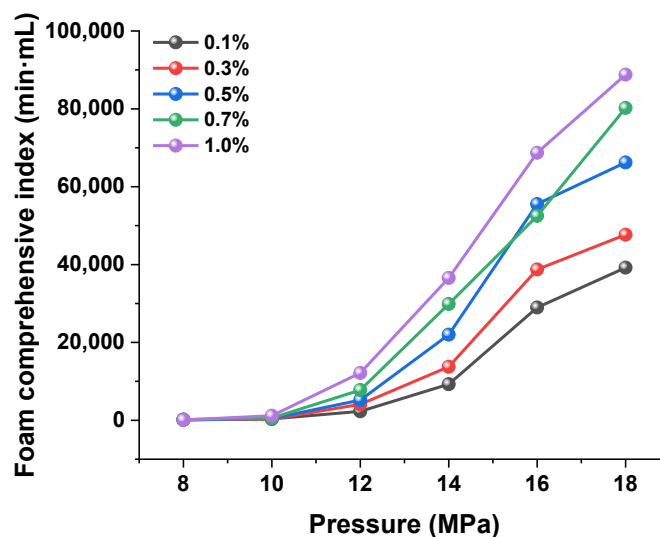


Figure 6. Effect of foaming agent concentration and pressure on foam performance (80 °C).

As seen in Figure 6, the Foam Comprehensive Index (FCI) increased significantly with pressure at all concentrations, indicating that higher pressure is favorable for foam formation and stability. At low pressure (<12 MPa), the performance curves for different concentrations are similar, but at higher pressures, foams with higher concentrations show improved performance.

The concentration of the foaming agent significantly affects foam performance. As the concentration increases, the foam properties improve due to better interfacial adsorption. However, once the concentration exceeds 0.5%, the increase in FCI becomes less pronounced, indicating that the foam performance approaches saturation.

At low concentrations, insufficient adsorption of surfactant molecules at the gas–liquid interface leads to poor foaming efficiency due to inadequate surface coverage and interfacial tension reduction. As the concentration increases, interfacial adsorption density and liquid film thickness also increase, improving foam generation and stability. However, above the critical micelle concentration (CMC), additional molecules form micelles, which contribute little to foam stability [10]. Moreover, excessive concentrations may raise solution viscosity, hindering foam flow and transport, thereby reducing practical usability.

3.2.3. Role of Foam Stabilizers

To extend foam half-life and improve foam stability and persistence, blending suitable types and concentrations of stabilizers with foaming agents is an effective strategy. Stabilizers can modify the physicochemical properties of the system, enhance the mechanical strength of the liquid film, inhibit liquid drainage and bubble coalescence, and significantly improve foam stability.

At 80 °C, the foam performance of E-1312 combined with silica nanoparticles (SiO_2) was evaluated. The results are shown in Figure 7.

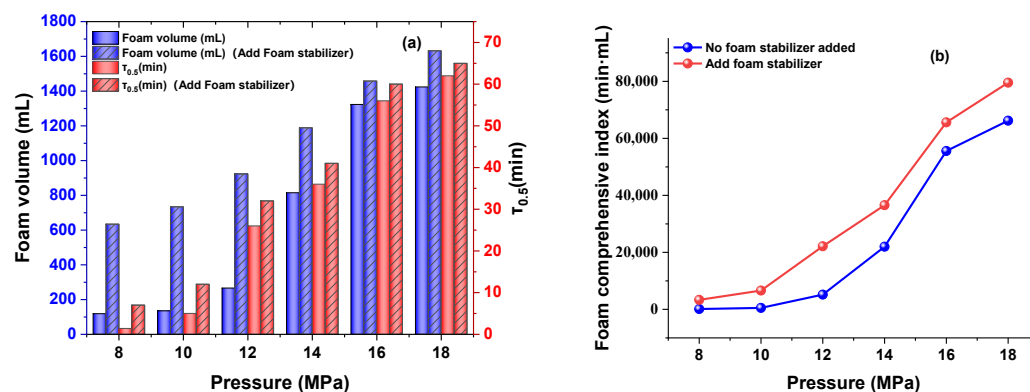


Figure 7. Effect of stabilizers on foam performance. (a) Effect on foam volume and half-life. (b) Effect on comprehensive foam index.

Figure 7 shows that adding SiO_2 significantly enhances foam volume and half-life across all pressure conditions. Its stabilization effect is especially prominent at high pressure, effectively suppressing foam collapse and bubble coalescence, making it a key method for enhancing foam stability.

The surface of silica (SiO_2) is rich in hydroxyl groups ($-\text{OH}$), which can form hydrogen bonds with ether bonds ($-\text{O}-$) or hydroxyl groups in E-1312 molecules, enhancing the mechanical strength of the liquid film. At the same time, the long-chain alkyl group of E-1312 undergoes hydrophobic interactions with partially alkylated hydrophobic SiO_2 and further enhances its adsorption strength at the gas–liquid interface through van der Waals forces. In this process, silica nanoparticles can be adsorbed at the gas–liquid interface to form a physical barrier, and this interfacial adsorption behavior increases the thickness and strength of the liquid film, significantly improving the anti-cracking property of foam; its

high specific surface area and high surface energy make it an effective interface modifier, further improving the stability of the foam [11]. It is worth noting that E-1312 is a non-ionic surfactant with uncharged molecules, and its electrostatic interaction with SiO₂ is relatively weak. However, in high salt environments, the high ionic strength of the solution will produce an ion shielding effect, which may indirectly change the surface charge distribution of SiO₂ particles, thus affecting their interface behavior and adsorption characteristics and ultimately play a role in regulating the stability of foam.

3.3. Influence of Physical Factors

3.3.1. Effect of Temperature

Temperature is a crucial physical factor affecting foam stability, with a complex underlying mechanism. To assess this effect, the foam performance of E-1312 was tested at four temperatures: 35 °C, 50 °C, 65 °C, and 80 °C. The results are shown in Figure 8.

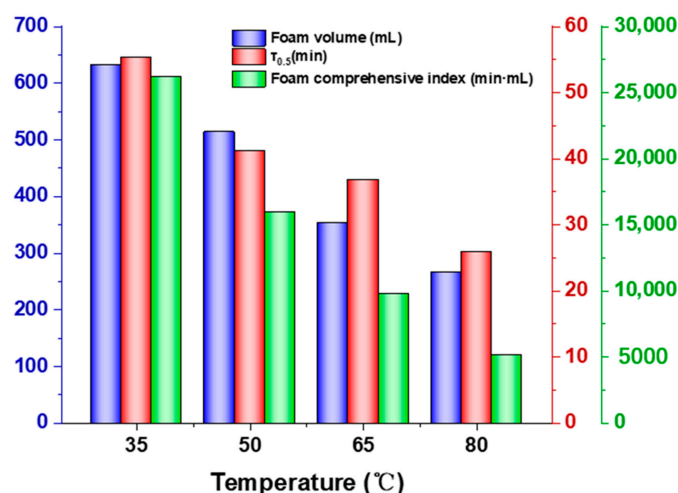


Figure 8. Effect of temperature on half-life, foam volume, and FCI (12 MPa).

As seen in Figure 8, increasing the temperature leads to significant reductions in maximum foam volume, half-life, and FCI. High-temperature environments trigger thermal defoaming, weakening surfactant adsorption at the interface. This reduces the viscosity of the liquid film, making bubbles more prone to coalescence or rupture [12,13]. The enhanced thermal motion of the molecules reduces their residence time at the interface, further diminishing stability.

Moreover, elevated temperatures can accelerate liquid evaporation, which reduces film thickness and strength, thereby undermining foam structure. Increased solute concentrations due to evaporation may also affect surfactant solubility and interfacial activity, further compromising foam stability.

3.3.2. Effect of Pressure

Pressure is another key factor influencing foam formation and stability. The foam performance of E-1312 was systematically tested at 80 °C at various pressures. The results are shown in Figure 9.

Figure 9 demonstrates that, as pressure increases, foam volume, half-life, and FCI all rise significantly, indicating that moderate pressurization promotes foam formation and stability. However, above 16 MPa, the increase in these indices plateaus, suggesting that foam properties approach saturation. Prior research indicates that pressures between 10 and 20 MPa are optimal for bubble generation [14], while excessive pressure may hinder bubble expansion or induce film rupture, adversely affecting long-term stability.

Pressure also influences bubble size distribution. As shown in Figure 10, at 16 MPa, foam bubbles are smaller and more uniformly distributed compared to at 10 MPa. Higher CO₂ solubility at elevated pressure results in denser, more compact foam structures. In contrast, larger, weaker bubbles form under lower pressure, making the foam more prone to collapse.

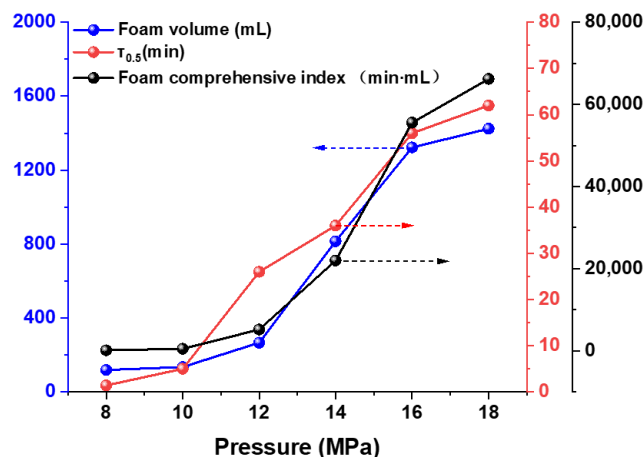


Figure 9. Effect of pressure on half-life, foam volume, and FCI (80 °C).

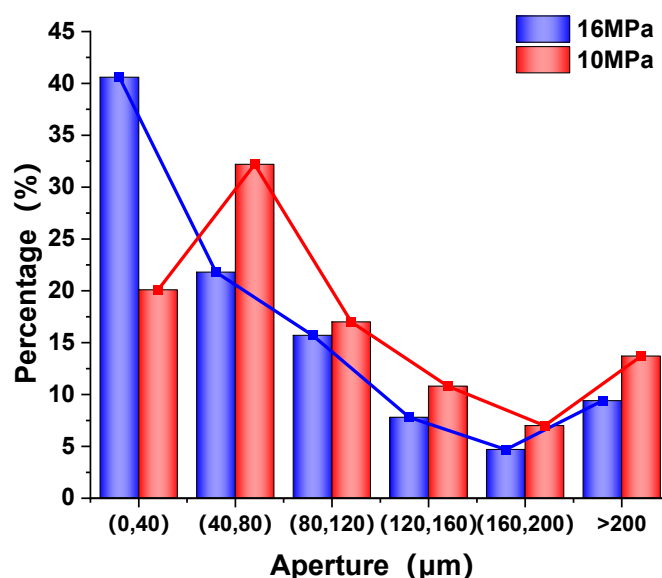


Figure 10. Comparison of bubble size distribution at different pressures.

3.4. Foam Stability and Interfacial Behavior

3.4.1. Liquid Film Thickness and Its Effect on Foam Longevity

Film thickness is a key factor influencing foam stability. Thicker films effectively resist bubble coalescence and rupture, thereby extending foam life. A thick film acts as a strong physical barrier, minimizing direct bubble contact and maintaining internal pressure balance.

During foam formation and stabilization, surfactant molecules form bilayer or multilayer structures that dynamically adjust film thickness to accommodate external conditions [15]. This ensures stability at varying pressures, temperatures, and flow rates. Figure 11 presents microscopic images of foam structure at 10 s, 30 s, 50 s, 70 s, and 90 s.

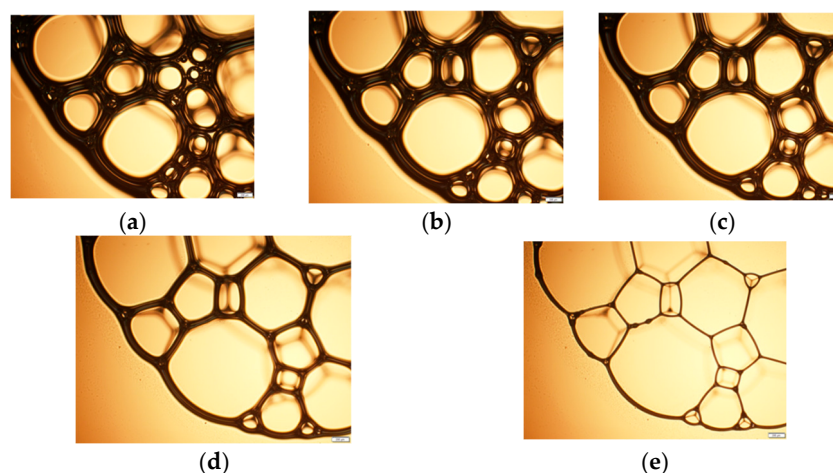


Figure 11. Evolution of foam structure with time and film thickness. (a) 10 s, (b) 30 s, (c) 50 s, (d) 70 s, and (e) 90 s.

Early stage (10–30 s): Figure 11a,b show tightly packed structures with thick films and clear, strong boundaries, indicating good stability and resistance to coalescence. Mid stage (50 s): In Figure 11c, film thinning begins, with smaller bubbles disappearing or merging into larger ones. Late stage (70–90 s): Figure 11d,e show significantly thinner films, simplified structures dominated by large bubbles, blurred boundaries, and signs of rupture. At 90 s, the system is unstable, with frequent coalescence and collapse.

This demonstrates that thicker films delay foam collapse, while thinning due to liquid drainage reduces stability and leads to breakdown.

3.4.2. Liquid Drainage Rate and Interfacial Tension Regulation

Foam stability is highly influenced by liquid drainage from the film. Due to gravity, liquid flows downward, thinning the film and increasing the risk of bubble coalescence and rupture.

As shown in Figure 12, the film thickness exhibits a monotonically decreasing trend over time, indicating that the foam liquid film continues to thin throughout its lifespan after formation. In the initial stage, the film is relatively thick, which helps stabilize the foam. However, as time progresses, continuous liquid drainage leads to a significant reduction in film thickness. By 90 s, the film retains only about 30% of its original thickness, suggesting that the foam system is gradually entering an unstable state, prone to rupture and bubble coalescence.

According to Figure 12, the foam film thickness decreases from approximately 155 μm to 48 μm within 90 s, reflecting a pronounced drainage rate. Simultaneously, the foam images show a clear loosening of the structure, with a reduction in the number of small bubbles and the appearance of film rupture and bubble merging in some areas. This demonstrates that accelerated liquid drainage leads to thinning of the film and weakens its mechanical support for the foam, directly contributing to the decline in foam stability.

Based on the linear regression equation in Figure 12,

$$\text{Film thickness } (\mu\text{m}) = -1.32 \times \text{Time (s)} + 165.50 \quad (2)$$

The average drainage rate is 1.32 $\mu\text{m/s}$, indicating that the film thickness decreases by approximately 1.32 microns per second.

The coefficient of determination (R^2) is 0.9951, indicating an excellent fit and confirming that film thickness decreases in a highly linear fashion over time.

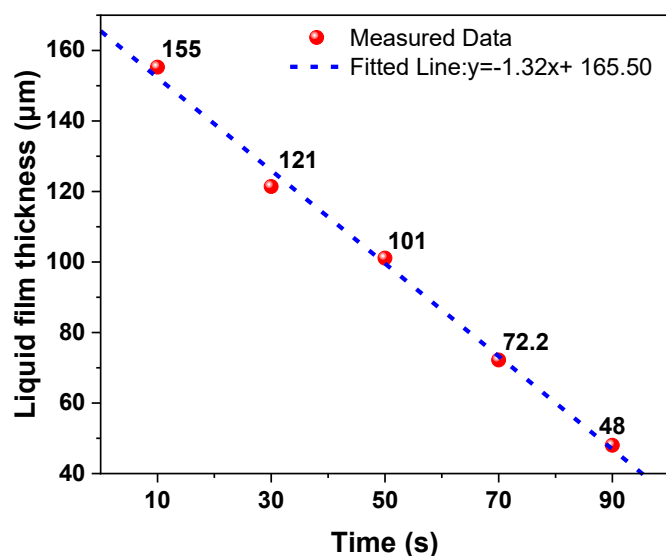


Figure 12. Change in film thickness over time.

Microscopic image analysis of foam evolution shows that, at 10–50 s, bubble size distribution is uniform, many small bubbles are present, and the film is thick and stable. At 70 s, visible bubble coalescence occurs, and small-to-medium bubbles decrease, suggesting the film can no longer sustain individual bubbles. At 90 s, the structure becomes coarser, boundaries blur, and more rupture zones appear—indicating that the foam is in a destabilized phase.

The linear regression of film thickness versus time confirms a steady and continuous drainage process, with a rate of 1.32 $\mu\text{m/s}$. As the film becomes thinner, bubble structures become coarser and foam stability declines significantly, validating that film drainage is a dominant factor influencing foam longevity.

By adjusting pH and salinity, interfacial tension can be reduced, effectively slowing the drainage rate of the liquid film. This delays bubble coalescence and improves foam stability. The results are shown in Figure 13.

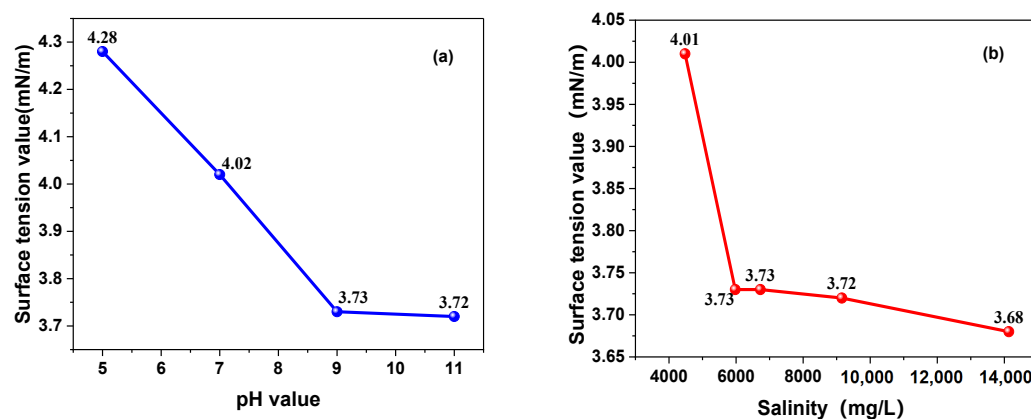


Figure 13. Effect of pH and salinity on interfacial tension. (a) Effect of pH on surface tension. (b) Effect of salinity on surface tension.

As shown in Figure 13a, increasing alkalinity enhances the adsorption capacity of foaming agent molecules at the interface, resulting in a reduction in interfacial tension. This indicates that an alkaline environment is favorable for the action of foaming agents, promoting foam formation and stability. In Figure 13b, under low salinity conditions, the surface tension remains relatively high, suggesting that the activity of the surfactant is inhibited. As salinity increases, ionic shielding effects on the foaming agent structure

enhance its adsorption at the gas–liquid interface. However, at high salinity levels, the surface tension tends to stabilize, indicating a saturation effect. Therefore, adjusting the pH and salinity of the system can further optimize foaming performance and improve foam stability.

The experimental results show that the interfacial tension of CO₂-soluble foaming agent solutions decreases significantly with increasing pH and salinity. The reduction in interfacial tension promotes the formation of a denser adsorption layer at the gas–liquid interface, enhancing interfacial elasticity and effectively inhibiting liquid drainage along the film surface. In conjunction with Figure 14, it is evident that the rate of film thickness reduction over time is closely related to interfacial tension—the lower the tension, the slower the drainage rate, and the longer the liquid film is maintained. Thus, precise regulation of interfacial tension through pH and salinity adjustment is a critical method for controlling film drainage and enhancing foam structural stability.

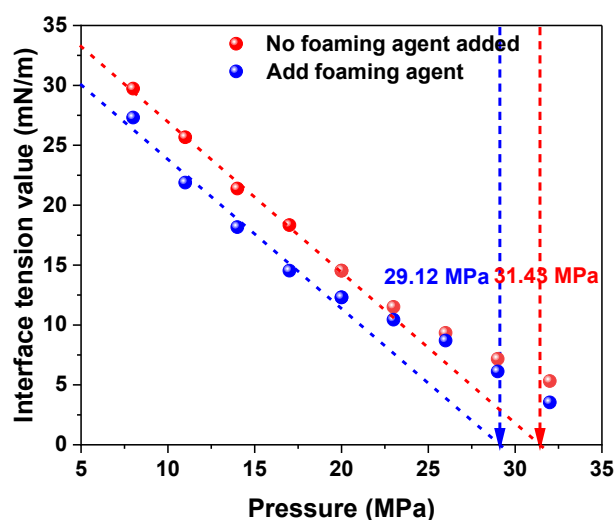


Figure 14. Effect of CO₂-soluble foaming agents on crude oil–CO₂ interfacial tension.

By lowering the gas–liquid interfacial tension, foaming agents not only improve bubble generation efficiency, but also increase the shear resistance of the liquid film. The effect of the gas-soluble foaming agent on the crude oil–CO₂ interfacial tension is shown in Figure 14.

As shown in Figure 14, the addition of foaming agents significantly reduces gas–liquid interfacial tension, especially at high pressure. This enhances bubble formation and improves the elasticity and shear resistance of the liquid film, thereby improving foam stability and flexibility. The surfactant adsorption layer not only lowers surface tension, but also strengthens mechanical resistance against shear stress [16].

As shown in Figure 15, the foaming system exhibits shear-thickening behavior and a high storage modulus, indicating strong structural elasticity and shear resistance. The viscosity and stress remain stable under dynamic conditions, reflecting excellent rheological stability. Thus, surfactants not only reduce interfacial tension, but also enhance interfacial mechanics, significantly improving film strength and foam durability.

Foam stability is governed by multiple factors: chemical composition, physical conditions, and interfacial behavior. The coordinated regulation of these aspects provides a solid foundation for optimizing CO₂-soluble foaming agents in gas flooding applications.

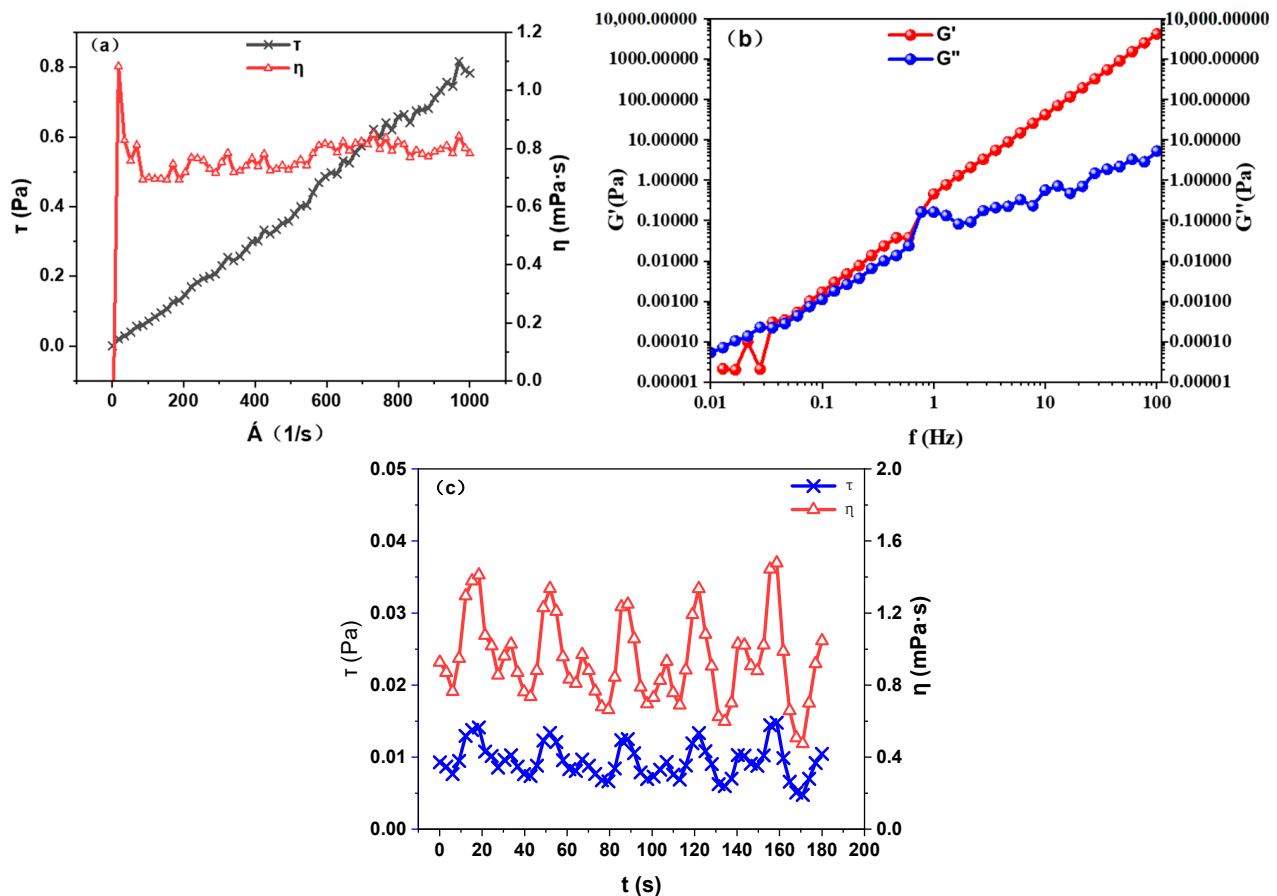


Figure 15. Rheology (a), viscoelasticity (b), and viscosity (c) of the foaming system.

4. Mechanistic Analysis of CO₂-Soluble Foaming Agents

The performance of CO₂-soluble foaming agents in CO₂ gas flooding primarily originates from their unique molecular structure and interfacial behavior. This section provides an in-depth analysis of their mechanisms at the microscopic level to offer theoretical support for improving foam stability.

4.1. Molecular Structure and Gas–Liquid Interfacial Behavior

CO₂-soluble foaming agents typically possess amphiphilic molecular structures, consisting of hydrophilic and hydrophobic ends. This configuration enables spontaneous and orderly adsorption at the gas–liquid interface, forming a compact molecular film. The hydrophilic groups orient toward the aqueous phase, while the hydrophobic groups face the CO₂ gas phase, thereby significantly reducing interfacial tension and providing a kinetic basis for bubble generation and foam formation. During CO₂ injection into porous media, the foaming agents rapidly migrate and align at the interface, enhancing foam generation efficiency and structural stability [17].

4.2. Concentration Control and Foam Generation Efficiency

Foaming agent concentration directly affects foam generation and longevity. At low concentrations, insufficient adsorption at the gas–liquid interface results in slow and unstable foam generation. When the concentration approaches or exceeds the critical micelle concentration (CMC), the foam volume and half-life increase significantly, and stability is greatly enhanced. However, overly high concentrations may lead to micelle formation and increased system viscosity, which can impair foam mobility in the reservoir and limit its practical effectiveness. Therefore, the design of foaming agents should balance interfacial

saturation and rheological properties. A schematic of foam performance variation with surfactant concentration is shown in Figure 16.

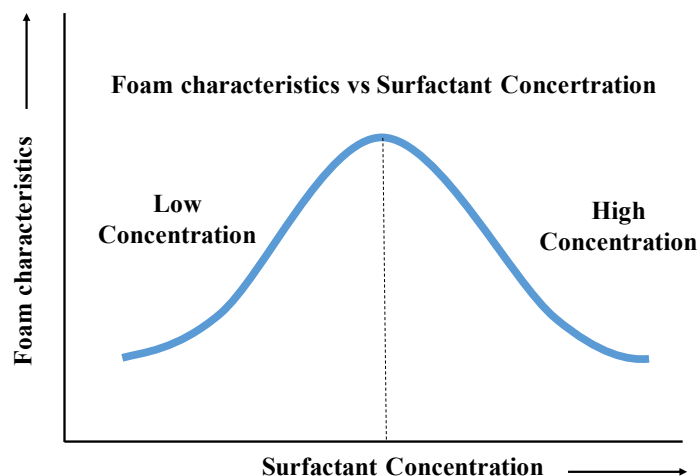


Figure 16. Schematic of foam performance variation with surfactant concentration.

4.3. Foam Formation Mechanism in Porous Media

During CO₂ flooding, foam formation involves three key stages: gas–liquid mixing, interfacial adsorption, and foam aggregation/connection. The foaming agent dissolves in supercritical CO₂ and is injected as a gas-phase slug. Upon encountering the formation water and being constrained by pore throat structures, foam is induced. Subsequently, the surfactant rapidly adsorbs at the interface, forming a stable film that prevents bubble coalescence. Multiple stable bubbles aggregate within the pore space, constructing a uniform and continuous foam network. This effectively controls CO₂ channeling and fingering, improving displacement efficiency.

The diameter of the foam bubbles generated during CO₂ flooding is typically smaller than 200 µm. Such small bubbles offer a higher surface area, which helps increase fluid displacement efficiency [18].

4.4. Critical Role of Film Stability and Interfacial Adsorption

Foam stability largely depends on the liquid film's resistance to rupture, which is influenced by film thickness, interfacial adsorption behavior, and the physicochemical properties of the porous medium. By precisely tuning these factors, the foam system's stability can be significantly enhanced to meet industrial application demands.

Film thickness is a key parameter affecting foam stability. Thicker films offer greater mechanical strength and resistance to external stress or disturbances. However, excessively thick films may hinder foam mobility, reducing transport efficiency in porous media. Through molecular design—adjusting chain length and structural configuration of surfactants—film thickness can be dynamically regulated to achieve an optimal balance between stability and mobility.

The adsorption of foaming agent molecules at the gas–liquid interface is essential to foam stability. These molecules form monolayers at the interface, effectively slowing liquid drainage from bubble walls. Additionally, they prevent bubble coalescence via electrostatic repulsion or steric hindrance effects [19], thereby preserving foam structure integrity [20].

In porous media, film stability is also influenced by pore size, flow rate, and mineral surface properties. Research shows that introducing synergistic enhancers—such as nanoparticles and salts—can significantly improve the mechanical strength of the film. These enhancers interact with the surfactant molecules, enhancing film resistance to rupture and extending foam lifespan [21–24].

4.5. Coupling Between Film Thickness and Foam Stability

The liquid film serves as a critical barrier for maintaining foam structure. The thicker the film, the stronger its shear and rupture resistance. However, excessively thick films may reduce foam flowability. By tuning structural parameters such as surfactant chain length and type of polar groups, film thickness can be dynamically controlled. A properly thick film enhances bubble mechanical stability and buffers against external disturbances, thereby maintaining foam integrity.

4.6. Synergistic Role of Foam Stabilizers

Foam stabilizers such as silica (SiO_2) nanoparticles can anchor at the gas–liquid interface through physical adsorption, enhancing film strength and thickness. As shown in Figure 17. This forms a composite barrier that inhibits bubble coalescence and liquid drainage. The high specific surface area and surface energy of nanoparticles provide excellent interfacial reinforcement, offering long-term foam stability.

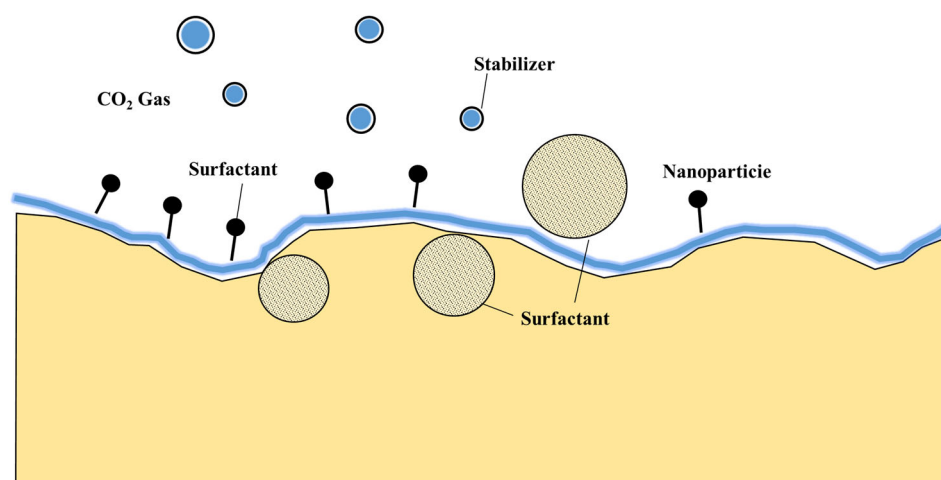


Figure 17. Foam stabilizer and foam longevity.

In summary, the micro-mechanisms of CO_2 -soluble foaming agents encompass multiple interrelated aspects: molecular structure regulation, interfacial adsorption behavior, foam network construction, and film stability control. Together, these mechanisms determine the foam's generation efficiency and stability. By integrating molecular design and additive compounding strategies, foam properties can be precisely tailored—laying a solid foundation for the efficient application of CO_2 -EOR technology in real reservoirs.

5. Conclusions

- (1) The foam stability of CO_2 -soluble foaming agents is strongly dependent on the synergistic effects of chemical factors (such as pH, surfactant type, and concentration) and physical factors (such as temperature and pressure). A moderately alkaline environment, an optimal concentration around 0.5%, and high pressure are favorable for enhancing foam performance, while high temperatures accelerate film drainage and lead to rapid foam decay.
- (2) Incorporating nano-sized foam stabilizers such as silica (SiO_2) enhances the thickness of the liquid film and improves the regulation of interfacial tension. These stabilizers form robust molecular barriers that effectively prevent foam collapse and bubble coalescence, with especially pronounced effects under high-pressure conditions.
- (3) Foam stability is governed by the adsorption capacity of the foaming agent at the gas–liquid interface, the rate of film drainage, and variations in film thickness. The experimental results show that film thickness decreases linearly over time, with an

average drainage rate of 1.32 $\mu\text{m/s}$. Regulation of surface tension—achieved through pH and salinity adjustment—can effectively slow down the drainage process.

- (4) A mechanistic model for foam generation in porous media was developed, incorporating gas–liquid mixing, interfacial adsorption, bubble aggregation, and connectivity. This model reveals the directional migration and structural reorganization behavior of foaming agent molecules under CO_2 flooding conditions.
- (5) For the large-scale application of CCUS-EOR in deep and low-permeability reservoirs, future research needs to systematically explain the synergistic stability mechanism of foam stabilizers in the real reservoir salinity temperature pressure coupled field and accordingly build a multi-functional composite foam system integrating scale prevention (chelating agent/pH buffer), corrosion inhibition (metal ion complex/inhibitor), and thermal shear bistability (thermal stable polymer/nanoparticle synergy). This system has been proven to have excellent stability under supercritical CO_2 and high pressure and high temperature (>2500 m) conditions, and is demonstrating excellent flow control performance in the core displacement experiment of the national major project “CCUS Demonstration Zone in Songliao Basin”, laying a solid material foundation and data support for the industrial promotion of deep shale oil and low-permeability reservoirs.

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