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Invited review

Advances and challenges in foam stability: Applications, mechanisms, and future directions

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Abstract:
Foam has wide applications in oil and gas resource development, environmental engineering, and chemical industries due to its favorable rheological properties and interfacial characteristics. However, foam stability is influenced by a complex interplay of external and intrinsic factors, including surfactant type, gas-to-liquid ratio, temperature, and pressure. The combined effects of these factors can significantly alter foam characteristics, with each influencing the other in ways that can either enhance or destabilize foam. This research investigates these factors in detail, exploring how they interact to impact foam stability and how their optimization can enhance foam performance for various applications. The study delves into the role of interfacial tension in foam stability, highlighting how surfactant properties, gas composition, and liquid characteristics contribute to foam formation and stability. The study also reviews advancements in foam technology, particularly in oil production, CO_2 storage, environmental pollution management, and the creation of novel materials, while examining strategies for boosting foam stability under extreme conditions. Findings indicate that the gas-to-liquid ratio, surfactant type, temperature, and pressure all play key roles in foam stability, and fine-tuning these parameters can lead to significant improvements in foam performance. In harsh environments, maintaining foam stability presents substantial challenges. This research further proposes methods to enhance foam stability. Foam technology demonstrates broad potential in fields like oil recovery and wastewater treatment, where optimized foam stability can improve both reservoir recovery and treatment efficiency. This review summarizes the latest advancements in foam stability research, providing valuable insights for the further development of foam technology.

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1. Introduction

Foam is widely used in sectors such as oil and gas development, environmental remediation, chemical processing, and construction materials (Orujov et al., 2025). By dispersing gas within a liquid, foam exhibits unique properties like low density, high surface area, favorable flow characteristics, and robust suspension capabilities, making it crucial in many industrial applications. For example, foam enhances oil recovery (Wang et al., 2023a), improves geologic carbon storage (Guo and Aryana, 2019), aids in wastewater management and soil restoration (Liu et al., 2024), and serves as a lightweight material in construction and packaging (Tran et al., 2022).

Foam stability is essential for its practical use, and interfa-

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cial tension plays a central role. Surfactants reduce interfacial tension, facilitating foam formation and stability (Yu and Kanj, 2022). However, foam stability is influenced by additional factors such as the gas-to-liquid ratio, foam structure, and external conditions (Bhatt et al., 2023). Understanding the relationship between interfacial tension and foam stability is therefore crucial for improving foam performance in various applications.

Recent advancements in foam technology have focused on improving stability to meet the demands of industries like oil recovery and environmental protection. Despite progress, challenges remain. External factors like temperature, pressure, and liquid composition significantly influence foam stability, particularly in complex multiphase systems. Achieving long-term foam stability under high pressure and temperature remains a major challenge (Yekeen et al., 2018; Zhan et al., 2022). In oil recovery, foam instability can hinder oil displacement and reduce recovery efficiency, while in CO_2 storage, instability may compromise containment integrity. These challenges highlight the need for methods to enhance foam stability under extreme conditions.

This study explores the primary factors influencing foam stability and investigates methods to optimize foam performance for various applications. It reviews advancements in foam creation, stability enhancement strategies, and techniques for improving foam performance in challenging environments. The findings suggest that adjusting composition and processing conditions can significantly enhance foam stability and versatility. This review aims to offer insights for advancing foam technology and provide practical guidance for its applications.

2. Foam concept and characteristic

2.1 Definition and classification

Foam is a distinct dispersion where the liquid serves as the continuous phase and the gas as the dispersed phase. Bubbles are inherently unstable from a thermodynamic perspective. When foam collapses, the total surface area of the liquid decreases significantly, thereby lowering the system energy. Generally, completely pure liquids do not foam; stable foams typically require at least two components. Solutions containing surfactants in water are particularly prone to forming foam. In geologic applications, the foaming system often includes a foaming agent, a foam stabilizer, and various functional additives (Kumar and Mandal, 2017; Majeed et al., 2021; Hosseini et al., 2021).

Foams can be categorized based on various parameters. Primarily, by their composition, they can be grouped into gas-liquid, gas-solid, and liquid-solid foams, with gas-liquid being the most prevalent (Malysa et al., 2005). In terms of stability, foams are classified as either stable or unstable. Stable foams maintain their bubble structure over extended periods, whereas unstable foams tend to burst or coalesce easily. By bubble size, foams are divided into micro, medium, and large categories. Micro foams have a small bubble diameter, typically under 100 µm, while large foams have a bubble diameter exceeding 1 mm (Hunter et al., 2008; Larmignat et al., 2008). Additionally, foams can be distinguished as water-based or oil-based, depending on whether they form in a water or oil phase (Wang et al., 2023b). These different classifications aid in enhancing the performance and functionality of foams in diverse applications.

2.2 Structure and characteristic

A foam is a porous assembly made up of numerous bubbles, where each bubble consists of a gas core encased by a liquid film. The spatial arrangement of these bubbles may be uniform or irregular, and their size, shape, distribution, and concentration significantly influence the macroscopic attributes of the foam. To achieve the lowest energy state, bubbles typically assume a spherical shape to minimize the surface area of the liquid film, thus reducing surface energy (Yang et al., 2007). In foams with low liquid content, the bubbles often take on polyhedral shapes, known as dry foam. Conversely, in foams with high liquid content, the bubbles are generally spherical and are referred to as wet foam. Wet foam tends to be more stable under similar conditions due to its higher liquid content and thicker liquid film (Gowida et al., 2024; Moradpour et al., 2024). The size of the bubbles also plays a role, as larger bubbles have thinner liquid films, which impacts the foam's stability and longevity. Fig. 1 illustrates the structure of the foam. In Fig. 1(a), the schematic of wet foam with a spherical bubble structure is shown, where the bubbles are densely packed with a thicker liquid film. This type of foam is typically more stable due to the higher liquid content, which helps to maintain the integrity of the foam structure. In Fig. 1(b), the polyhedral structure of the liquid drainage process is depicted, illustrating how liquid drains from the foam under the influence of gravity. This drainage causes the foam to lose stability over time, leading to the formation of dry foam. Finally, in Fig. 1(c), dry foam is shown, where the bubbles have a polyhedral shape and are separated by thinner liquid films. Dry foam is less stable and more susceptible to collapse due to its lower liquid content. This sequence of schematics effectively demonstrates the transition from wet to dry foam and highlights the role of liquid drainage in altering the foam structure.

Foam typically exhibits a lower density because the majority of its volume is composed of gas, rendering it lighter than the corresponding liquid phase and allowing it to float on the liquid's surface (Das et al., 2024). Furthermore, foam possesses an exceptionally large specific surface area, which expands as the number of bubbles increases, thereby providing more surface area for adsorption, reactions, or heat transfer (Inagaki et al., 2015). The excellent thermal insulation of foam is attributed to the gas within the bubbles, which, due to its low thermal conductivity, results in poor heat transfer, making foam highly valuable as an insulating material (Wang et al., 2023c). The elasticity and compressive strength of foam are influenced by the bubble size, the thickness of the liquid film, and the foam's structure. Foams with higher densities tend to have better compressive properties, allowing them to deform without bursting under external forces (Tan et al., 2005). The fundamental properties of foam, such as

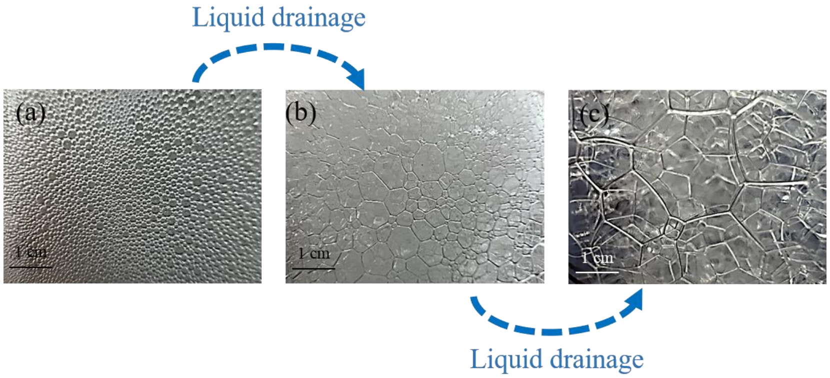

Fig. 1. Diagram of the foam structure. (a) wet foam with a spherical structure, (b) polyhedral structure of the liquid drainage process and (c) dry foam with a polyhedral structure.

density, viscosity, and stability, can be fine-tuned by adjusting factors like the preparation method, surfactant type, concentration, and gas-liquid ratio, offering significant flexibility for various applications (Fujii et al., 2016). Foam also displays non-Newtonian fluid behavior, with its viscosity varying with the shear rate, enabling it to adapt to different flow conditions (Du et al., 2018). Additionally, the liquid film in foam has wettability and adsorption properties, which can alter the physical characteristics of surrounding gas or liquid molecules, making it widely applicable in industrial processes such as cleaning, separation, and reaction enhancement (Chowdhury et al., 2022). In summary, foam's low density, extensive specific surface area, superior thermal insulation, and favorable rheological properties have made it a versatile material in numerous industries.

2.3 Foam stability parameter

The important indicators of foam stability mainly include foam quality, foam liquid holdup, foaming volume, half-life and other parameters (Bathe et al., 2018). Foam quality refers to the volume of gas contained in unit volume of foam under certain pressure and temperature conditions, which is usually represented by Γ. Specifically, the relationship between gas volume V_G and liquid volume V_L in foam and foam volume V_F can be calculated by (Abdelgawad et al., 2022):

$$\Gamma = \frac{V_G}{V_G + V_L} = \frac{V_G}{V_F} \tag{1}$$

Related to the foam quality is the foam liquid holdup, which describes the content of liquid volume in the unit volume of foam, usually expressed by H_L, as shown (Ellman et al., 1990):

$$H_L = \frac{V_L}{V_G + V_L} = \frac{V_L}{V_F} \tag{2}$$

Foaming volume refers to the total volume of foam generated by a certain amount of liquid and gas under certain conditions. The bubble volume reflects the interaction between gas and liquid, as well as the degree of dispersion of bubbles in the liquid. Half-life is another key parameter to measure the foam stability. It refers to the time it takes to break half the volume of foam or separate half the liquid from a certain volume of foam (Kim et al., 2007; Derikvand and Riazi, 2016). The analysis of these parameters can comprehensively evaluate the foam stability and its performance in different applications.

3. Interfacial tension concepts and measurement

3.1 Definition and mechanism

Interfacial tension is the force per unit length that arises from molecular interactions at the boundary between different phases, such as liquid and gas, liquid and solid, or two immiscible liquids (Drelich et al., 2002). This force causes the liquid to minimize its surface area by contracting at the interface (Claesson et al., 1996; Tangparitkul et al., 2023). Interfacial tension significantly influences various physical properties, including the fluidity and wettability of liquids, foam stability, droplet formation, and droplet movement. The development of interfacial tension is mainly due to the intermolecular forces within the liquid (Gong et al., 2022). While the attraction between molecules inside the liquid is relatively uniform, at the interface, there are imbalanced forces from the adjacent phase (e.g., gas or solid) due to the molecular asymmetry. Near the interface, liquid molecules tend to move inward, leading to a contraction effect that generates tension (Feller et al., 1995). For a liquid-gas interface, the weak attraction from gas molecules causes the liquid surface to contract. At a liquid-solid interface, the wettability is determined by the attraction between the liquid molecules and the solid surface. Interfacial tension is influenced by the liquid physical properties, as well as by temperature, pressure, and the presence of additives or surfactants (Mirchi et al., 2015; Minakov et al., 2024). Surfactants can adsorb at the interface, altering the molecular arrangement and reducing interfacial tension, which enhances wettability and foam stability (Yekeen et al., 2019). In many applications, controlling interfacial tension is essential for achieving specific functional properties of the liquid, such as foam formation, emulsification, and lubrication (Langevin, 2000; Zhang et al., 2023).

3.2 Measurement techniques

(1) Wilhelmy plate method

The wilhelmy plate technique, introduced by Wilhelmy, is a straightforward, clear, and dependable experimental approach. It is well-suited for determining the interfacial tension between liquids and solids and is extensively utilized in research on liquid surface tension and wettability, as illustrated in Fig. 2. This method entails vertically submerging a flat plate with a known area into a liquid, where the liquid adheres to the plate's surface, creating adhesive forces between the plate and the liquid. A high-precision force sensor measures this force, and the interfacial tension (γ) is subsequently calculated using the force (F), the plate's perimeter (L), and the contact angle of the liquid (θ), according to (Daniel et al., 2023):

$$\gamma = \frac{F}{L\ \cos\theta} \tag{3}$$

This method does not require density data and can be used to measure both liquid-liquid interfacial tension and gas-liquid surface tension. However, it is essential that the liquid adequately wets the plate, ensuring that the contact angle is zero.

(2) Capillary rise method

The capillary rise method is one of the more commonly used and relatively fundamental techniques. In this method, a capillary tube is placed into a liquid, causing the liquid to rise along the tube wall. Once equilibrium is reached, the liquid ceases to rise. Through mechanical analysis, it can be determined that the upward force exerted by the liquid interface is equal to the downward force of the liquid (Dang-Vu and Hupka, 2005; Kim et al., 2020):

$$\gamma = \frac{1}{2}(\rho - \rho_g) g h r_0 \cos\theta \tag{4}$$

where r_0 is the radius of the capillary tube, h is the height of the liquid rise in the tube, and ρ_g is the density of the gas.

The capillary rise method is suitable for measuring interfacial tension. It is particularly accurate for low-viscosity liquids that easily rise within the tube, making it one of the most precise methods for direct interfacial tension measurement. However, variations in the choice of the reference horizontal plane may introduce errors. To minimize such errors, Sugden (1921) used a third tube to calibrate the liquid level baseline.

(3) Pendant drop method

The pendant drop method determines surface tension by suspending a liquid droplet in another phase and analyzing its shape. This method relies on the morphology of the droplet, which is typically captured through photography or high-resolution imaging (Hansen and Rødsrud, 1991; Saad et al., 2011). By analyzing the droplet's contact angle or shape, the interfacial tension can be calculated, as shown in Fig. 2.

The pendant drop method is a widely used and practical technique for measuring interfacial tension:

$$\frac{-\dfrac{\mathrm{d}^2 r}{\mathrm{d}z^2} + \dfrac{1}{r}\left[1 + \left(\dfrac{\mathrm{d}r}{\mathrm{d}z}\right)^2\right]}{\left[1 + \left(\dfrac{\mathrm{d}r}{\mathrm{d}z}\right)^2\right]^{3/2}} = \frac{p_0 - \Delta\rho g z}{\gamma} \tag{5}$$

where r is the radial position or the droplet's radius in the vertical (axial) direction, z is the height when the droplet's apex is taken as the origin, p_0 is the pressure at the suspension point, $\Delta\rho$ is the density difference between the two phases, and g is the gravitational acceleration. By solving this differential equation, the droplet shape can be determined, allowing for the calculation of interfacial tension.

Although the pendant drop method is more complex to operate and its data processing is more challenging compared to other interfacial tension measurement methods, it has several advantages: it does not require strict wetting conditions for the sample, is not affected by contact angle, introduces minimal disturbance to the system, and has a broad measurement range (Berry et al., 2015).

(4) Rotating drop method

The rotating drop method is capable of measuring ultra-low interfacial tension by analyzing the shape of a rotating droplet, as illustrated in Fig. 2 (Esfandiarian et al., 2022). In this method, a sample tube is filled with a high-density liquid, followed by the addition of a lower-density liquid to be measured. Under the influence of centrifugal force, gravity, and interfacial tension, a deformed droplet is formed and imaged during rotation (Song and Springer, 1996; Liu et al., 2011). The interfacial tension, , can be estimated using the following expression for elongated droplets ($L/D \geq 4$):

$$\gamma = \frac{1}{4}\omega^2 D^3 \Delta\rho \tag{6}$$

where ω is the angular velocity, D is the short-axis diameter of the droplet, and L is the long-axis diameter of the droplet. In practical applications, uncertainties in droplet volume and limitations in rotational speed can affect the accuracy of interfacial tension measurements, but these can be mitigated using appropriate modeling and correction techniques (Popinet, 2018).

3.3 Influence on foam stability

The effect of gas-liquid interfacial tension on foam stability is complex, as its magnitude directly influences foam generation, morphological maintenance, and decay processes. Overall, one cannot simply state that higher interfacial tension gives rise to more stable foam, or that lower interfacial tension gives rise to greater foam stability; rather, a full consideration of many different aspects (such as bubble film mechanical properties, liquid drainage rate in the film, resistance of the bubble film to disturbances, etc.) is needed to properly discern its effect on foam stability. When interfacial tension is relatively low, less energy is required to form a foam, and bubbles can persist more easily. Low interfacial tension also reduces capillary pressure in the bubble film, thereby slowing liquid drainage in the bubble film. This reduces the likelihood of film thinning occurring rapidly, which contributes to the long-term stability of the foam. However, if interfacial tension is too low, the bubble film becomes extremely soft, and without enough mechanical strength, is more easily perturbed and ruptured, or baseline bubble coalescence occurs. Additionally, low interfacial tension can potentially shorten the Marangoni effect and thus reduce the bubble film's self-healing ability, which reduces foam stability (Zeng et al., 2020; Xu et al., 2023). When

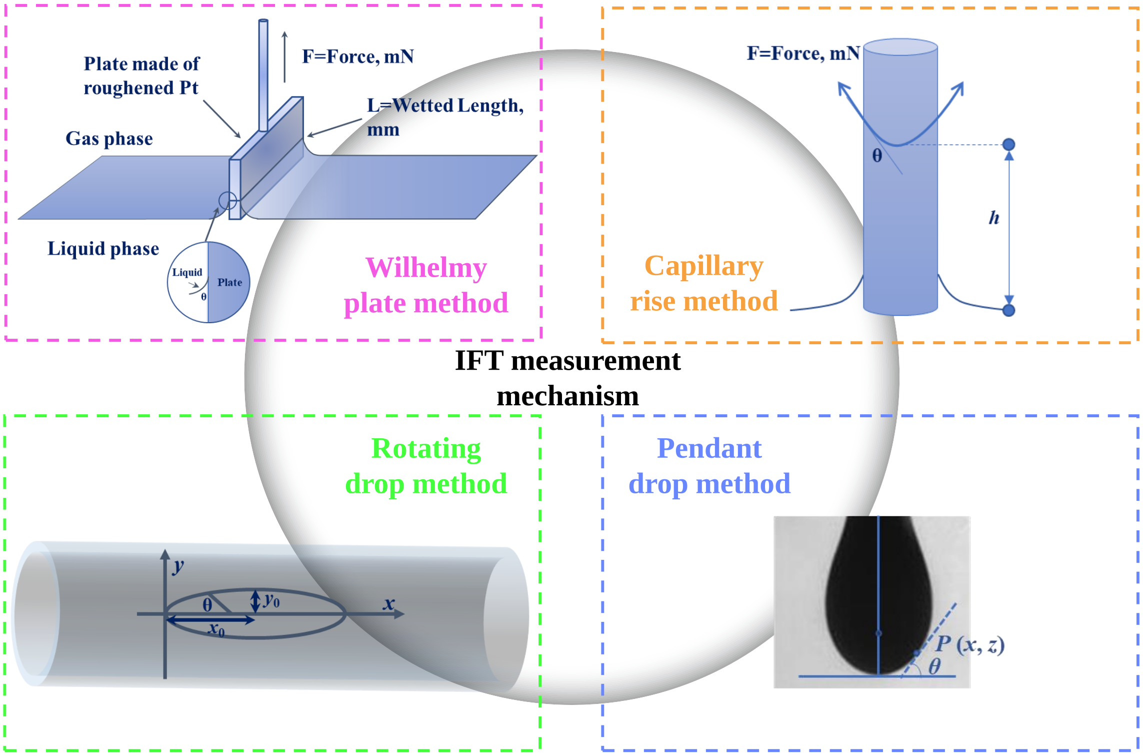

Fig. 2. Schematic of the interfacial tension measurement.

gas-liquid interfacial tension is relatively high, some aspects of foam stability may be increased. Increased interfacial tension increases the tensile strength of the bubble film, thus reducing its chance of rupture due to external mechanical disturbances (e.g., shear forces, bubble collisions, etc.). Higher interfacial tension can also promote surface recovery ability, meaning the film can recover more readily and efficiently when subjected to minor damage, and this may also assist in foam stability. On the other hand, excessively high interfacial tension can have adverse effects. Increased interfacial tension causes an increase in capillary pressure in the bubble film, promoting liquid drainage. As liquid drainage occurs, the liquid film becomes thinner and at some point will reach the critical thickness for rupture, and thus overall foam stability will be reduced. There is a significant amount of literature that indicates that foam stability does not monotonically increase or decrease with increasing interfacial tension or decreased interfacial tension, but rather the foam stability exists within an optimal range or paradigm. Within this optimal range, sufficient mechanical strength exists in the bubble film while ensuring the rate of liquid drainage is adequately decelerated, and both contribute to foam stability. An example of what may be considered as an optimal condition, adding a reasonable amount of surfactant reduces interfacial tension while creating a stable interfacial adsorption layer that contributes to the bubble film resistance to disturbances and slows the rate of liquid drainage, while also increasing the rate or efficiency of forming bubbles, whilst increasing foam stability significantly. (Wang et al., 2023b)

Interfacial tension plays a critical role in foam stability, as it determines the ease with which gas bubbles are stabilized by the surrounding liquid. The molecular interactions at the gas-liquid interface are primarily influenced by the surfactant properties, such as hydrophobicity and charge. Hydrophobic surfactants tend to aggregate at the interface, reducing interfacial tension and promoting foam formation. On the other hand, charged surfactants can alter the electrostatic repulsion between bubbles, further stabilizing the foam. The balance between these interactions governs the foam's stability, with variations in surfactant properties leading to differing degrees of foam durability and resistance to drainage.

4. Factors affecting foam stability

4.1 External factor

(1) Temperature

In general, an increase in temperature tends to destabilize foam. This effect is primarily due to two main factors. First, temperature changes significantly influence the interfacial characteristics of the foam, such as its viscoelastic properties, oil-water interfacial tension, and the behavior of surfactants at the interface. As the temperature rises, the kinetic energy of surfactant molecules increases, which impedes their adsorption at the gas-liquid interface. This leads to higher interfacial tension and a decrease in the viscoelastic modulus, both of which negatively affect foam stability (Mohammadi et al., 2024). Second, higher temperatures reduce the viscosity of the foam system, thereby accelerating the drainage of liquid from the foam film and decreasing the overall stability. Additionally, at elevated temperatures, the increased molecular thermal motion within the film speeds up the coarsening process and liquid drainage, further compromising the film's stability (Chaudhry et al., 2024). The temperature rise also enhances gas mobility, leading to faster changes in bubble size and alterations in the foam's microstructure.

(2) Pressure

Generally, pressure is positively correlated with foam stability. When the pressure in the system is increased, the pressure of the gas phase is also increased, lowering the interfacial tension, which results in reduced surface energy required to form a foam and increased foaming capacity (Tran et al., 2022). Additionally, an increase in pressure, in general, extends the half-life for draining the foam system significantly. At an increased pressure, the density difference between the internal and external phases of the foam is decreasing. This reduces the tendency of the foam to drain due to gravitational segregation. In addition, higher pressure decreases bubble diameter and yields a denser foam structure which maximizes the liquid film surface area and minimizes thickness and drainage rate which increase foam stability (Aronson et al., 1994).

(3) Salinity

The variations in electrolytes in the formation and high salinity of formation water is an important factor in foam stability and significantly influences surfactant adsorption behavior at the interface. At lower electrolyte concentrations, counterions shield the ionic head of the ionic foaming agent, which weakens intermolecular repulsion at the liquid film surface and results in increased adsorption of the foaming agent molecules (Sun et al., 2023). This increased adsorption results in the tighter packing of the molecules, which increases the water-holding capability of the liquid film, decreases gas permeability through the film, and ultimately increases foam stability. However, at too high electrolyte concentrations, foam stability starts to decrease. High concentrations of electrolytes compress the electrical double-layer structure of the hydrophilic groups of ionic foaming agents, which reduces repulsion pressure.

(4) pH value

The pH value is one of the major external factors influencing foam stability. Changes in pH affect the charge state, dissociation, and/or molecular structure of surfactants, altering their interfacial behavior and, consequently, foam stability. In acidic conditions, the hydrophilic groups of ionic surfactants tend to undergo protonation, which reduces electrostatic repulsion at the interface. This leads to a looser molecular arrangement, weaker liquid film strength, and reduced foam stability (Wilde and Clark, 1996). In contrast, under alkaline conditions, high pH facilitates the dissociation of surfactants, increasing charge density at the gas-liquid interface. This, in turn, enhances the electrostatic repulsion within the electrical double layer at the interface, contributing to the stabilization of liquid foam.

(5) Crude oil

In practical scenarios, the interaction between foam and crude oil significantly influences foam creation, stability, and movement through porous materials (Chen et al., 2018). Generally, the oil phase exhibits a potent defoaming effect, particularly when it is dispersed into droplets or spreads over the liquid film's surface. This occurs because the hydrocarbons in the oil phase attach to the gas-liquid interface, altering the molecular layer's structure and weakening the liquid film. Additionally, some foaming agents dissolve into the oil, further reducing their effective concentration. One study provides a key insight by demonstrating that oil destabilizes foam by affecting the stability of foam films, which is critical for the displacement efficiency in enhanced oil recovery. Specifically, oil can enter and disrupt the thin liquid films that form the foam structure, resulting in foam coarsening, and reducing its mobility control capability (Farajzadeh et al., 2012). However, it has been shown that the presence of oil, especially lighter hydrocarbons, can disrupt the foam, though the effect is mitigated when heavier oils with higher viscosity and density are present, allowing foam to remain more stable (Osei-Bonsu et al., 2015).

(6) Gravity

Gravity also plays an important role in foam stability, primarily by draining liquid from the foam. Under the influence of gravity and capillary forces, the liquid film between bubbles gradually thins, leading to bubble coalescence. A decrease in liquid phase saturation causes foam instability. Gravity drives liquid downward, drying the foam and making the foam solution more unstable (Audebert et al., 2019). In contrast, foams are more stable in microgravity environments, where the absence of gravity suppresses liquid drainage, allowing more uniform liquid distribution. This contributes to ticker, more stable films between bubbles. Additionally, spherical bubbles contribute to a more stable foam structure.

4.2 Intrinsic factor

(1) Liquid viscosity and density

The viscosity of the liquid phase plays a crucial role in foam stability (Wei et al., 2022). Higher viscosity increases the resistance to relative movement between bubbles, making coalescence more difficult and thereby enhancing foam stability. Additionally, high viscosity slows the drainage of liquid from the foam film, extending foam's lifespan. During foam generation, higher viscosity contributes to the formation of a more stable liquid film, making the bubbles more durable. However, excessive viscosity may impact foam mobility and generation efficiency (Wilde and Clark, 1996; Wang et al., 2023b). The density of the oil also significantly affects foam stability (Yu and Kanj, 2022). A higher density reduces the rising velocity of bubbles, increasing their retention time in the liquid phase, thereby improving foam stability. Moreover, high-density liquid phases usually exhibit higher interfacial tension, strengthening the foam film. However, excessive density may accelerate liquid drainage, which is unfavorable for long-term foam stability (Kim et al., 2003). In contrast, a low-density oil phase accelerates bubble generation but also makes bubbles more prone to rupture, leading to decreased foam stability.

Oil phases with high viscosity and density generally provide better foam stability, but a balance between foam generation and mobility must be maintained to ensure operational feasibility. In practical applications, optimizing the viscosity and density combination of the oil phase through experiments, combined with the selection of appropriate surfactants, can achieve optimal foam performance to meet the needs of different application scenarios.

(2) Gas type

The type of gas used significantly influences foam stability in oil and gas recovery. Common gases used in foam generation include N_2, CO_2, air, natural gas, and flue gas. N_2 is widely applied in foam flooding due to its high compressibility, good foam stability, low cost, and chemical inertness. N_2 foam is resistant to dissolution and rupture, effectively preventing gas breakthrough, improving sweep efficiency, and enhancing oil recovery (Davarpanah and Mirshekari, 2020; Rezaei et al., 2021). CO_2, with its high solubility, can reduce crude oil viscosity (especially at pressures above the minimum miscibility pressure – MMP), improve recovery and sweep efficiency, and support carbon capture, utilization and storage efforts to reduce greenhouse gas emissions (Aryana et al., 2014; Guo and Aryana, 2018; Guo and Aryana, 2019; Song et al., 2024). However, CO_2 foam suffer from poor stability and higher costs, requiring optimized formulations of surfactant to enhance performance (Xu et al., 2016; Issakhov et al., 2022). Air, due to its low cost, is often used as a gas source, but its high oxygen content poses safety and corrosion risks. Natural gas (mainly methane) has moderate solubility and stability, is readily available, economically viable, and easy to operate (Xu et al., 2018; Lai et al., 2021). Flue gas combines the high oil displacement efficiency of CO_2 with the stability of N_2. The addition of stabilizers can enhance foam performance, but due to its complex composition, its effects on oil displacement agents must be carefully considered (Li et al., 2017; Sun et al., 2020).

Overall, gas type has a significant impact on foam stability in subsurface applications. By optimizing gas selection and tailoring foam formulations, foam stability and displacement efficiency can be effectively controlled to meet the demands of different reservoir conditions, as well as storage and production requirements.

(3) Surfactant type

Foaming agents can be categorized by molecular structure into anionic, cationic, nonionic, and amphoteric surfactants. A single foaming agent often cannot meet multiple performance requirements, so two or more agents are typically combined to enhance foaming performance and reduce application costs. The properties of compound surfactants typically surpass those of individual surfactants, as intermolecular interactions generate synergistic effects. Additionally, the effective dosage of a surfactant mixture is often lower than that required for a single surfactant, contributing to improved cost-effectiveness.

The concentration of surfactants also significantly influences foam stability. Surfactant molecules align at the oil-gas interface, creating an adsorption layer that reduces interfacial tension and bolsters foam stability. The organization and dynamic behavior of surfactants at the interface contribute to the viscoelastic properties of the liquid film, thereby better resisting external disruptions and stabilizing the foam. Generally, foam stability rises with increasing surfactant concentration, up to the critical micelle concentration (CMC). After reaching the CMC, additional surfactant does not enhance foam stability (Majeed et al., 2020). Since no more surfactant can adhere to the film surface beyond the CMC; instead, surplus surfactant molecules aggregate in the liquid, forming micelles. Studies have demonstrated that below the CMC, the strength of the foam improves as the surfactant concentration increases.

(4) Bubble size

The size and distribution of bubbles also determine foam stability. In general, stable foam consists of smaller, spherical bubbles, whereas unstable foam consists of larger, polygonal bubbles (Magrabi et al., 1999). Spherical bubbles have lower surface energy, uniform interfacial tension distribution, and a closely packed arrangement, all of which contribute to forming a stable foam structure (Malysa et al., 2005). In contrast, larger bubbles experience uneven interfacial tension, non-uniform liquid film thickness, and loose packing, which create stress concentration points and accelerate liquid drainage, leading to an unstable foam structure. Therefore, foam stability is closely related to bubble size and shape, with small spherical bubbles being more favorable for stable foam formation (Gupta et al., 2007; Wang et al., 2018).

Ostwald ripening is an important mechanism contributing to foam instability, particularly over extended time scales (Weaire and Hutzler, 2001). Ostwald ripening is driven by local pressure differences between bubbles and involves the diffusion of gas across lamellae from smaller to larger bubbles. This leads to gradual growth of larger bubbles at the expense of shrinkage, and eventual disappearance, of the smaller ones. The process is influenced by gas solubility, interfacial tension and diffusivity, and results in bubble coarsening, an increase in average bubble size, and ultimately foam collapse (Kabalnov, 2001). Surfactants can slow Ostwald ripening by strengthening interfacial films and limiting gas exchange between adjacent bubbles. Additives, such as polymers and nanoparticles, may also reduce the gas diffusion across lamellae and reinforce foam structure, thereby slowing coarsening effects and extending foam half-life (Guo and Aryana, 2016).

(5) Nanoparticles

Nanoparticles significantly influence foam stability due to their unique interfacial effect as well as their small size. Nanoparticles can adsorb at the gas-liquid interface of bubbles, forming a dense particle layer. This irreversible adsorption enhances the mechanical strength and elasticity of the interfacial film, preventing bubble rupture and coalescence, thereby significantly improving foam stability (Yekeen et al., 2018; Zhang et al., 2021). Additionally, non-adsorbed nanoparticles can form layered structures within the liquid film, creating a three-dimensional network that effectively reduces bubble shrinkage and coalescence, further enhancing foam stability (Hunter et al., 2009). The size, shape, and surface properties of nanoparticles play a crucial role in foam performance. For instance, smaller particles more easily form a dense adsorption layer at the interface, while specific shapes (such as plate-like or rod-like structures) can further strengthen the mechanical stability of the interface (Gonzenbach et al., 2006). Compatibility experiments between surfactant and nanoparticles are a pre-requisite to optimizing foam stability. The concentration of particles is also a key factor; an appropriate increase in concentration can cover more gas-liquid interfaces and enhance foam stability (Shojaei et al., 2021). However, ex-

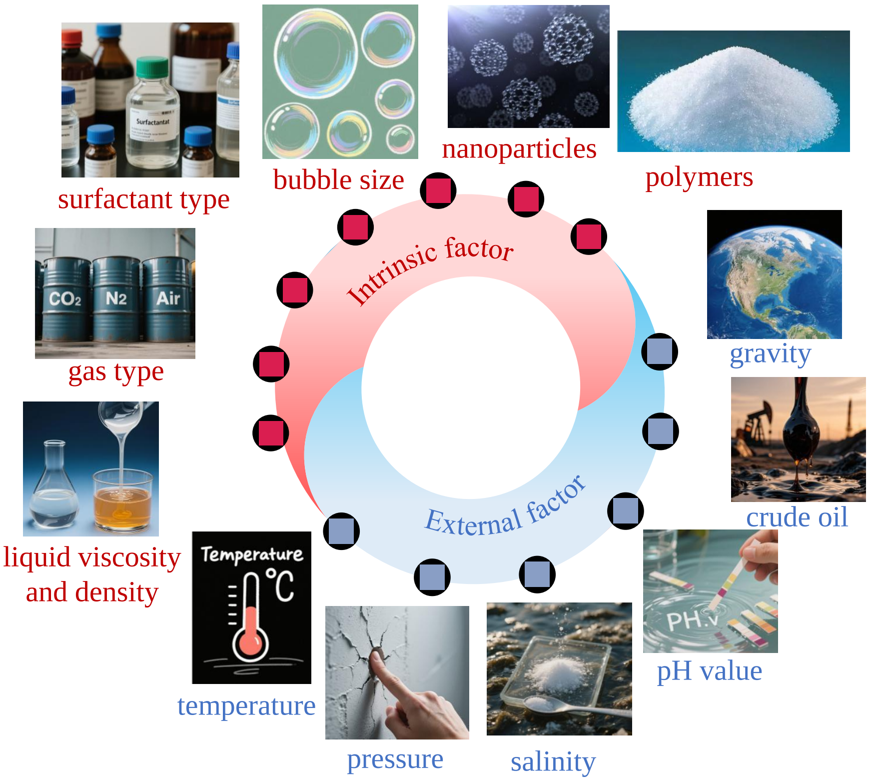

Fig. 3. Key factors influencing foam stability.

cessively high concentrations may lead to particle aggregation in the liquid phase, which can reduce stability. In subsurface applications, the proper selection of nanoparticles presents opportunities not only for enhancing foam performance but also for addressing environmental and operational challenges. For instance, recent research has shown that silica nanoparticles can significantly enhance CO_2 foam stability in tough reservoir conditions, including high temperature and salinity, increasing CO_2 storage by over 300% compared to standard methods without nanoparticles. This breakthrough provides a sustainable solution for both enhanced oil recovery and carbon capture, utilization, and storage applications (Rognmo et al., 2020).

(6) Polymers

Polymers have been widely used to enhance foam stability through several key mechanisms (Jin et al., 2019). First, polymers increase the viscosity of the liquid phase, significantly slowing liquid drainage and thereby extending foam lifespan. Second, polymer molecules can adsorb at the gas-liquid interface, forming elastic interfacial films that strengthens mechanical integrity and resist rupture from external disturbances. Third, certain polymers exhibit strong viscoelastic behavior, generating elastic recovery forces within the liquid film that resist bubble coalescence and collapse. Additionally, polymers can act synergistically with surfactants to further reduce interfacial tension and stabilize the interfacial film.

(7) Ionic liquids

Ionic liquids, which consist of organic cations and organic or inorganic anions, can substantially improve foam stability by changing the surface behavior of surfactant molecules (Hanamertani et al., 2018). Ionic liquids affect the surface properties and micellization of surfactants through electrostatic interactions, hydrophobic effects, and hydrogen bonding, thus altering the physicochemical characteristics of the surfactant system and the structure of micelles in aqueous environments. Fig. 3 summarizes the key factors influencing foam stability, catergorized as intrinsic and external factors. Intrinsic factors include surfactant type, bubble size, nanoparticles, polymers, and gas type, while external factors involve liquid viscosity, temperature, pressure, salinity, pH value, gravity, and crude oil. These factors collectively influence foam properties.

5. Application research in different fields

5.1 Oil and gas field development

(1) Enhanced oil recovery

Gas injection is a commonly used enhanced oil recovery technique in oil and gas field development. However, due to unfavorable mobility ratios, gas injection often faces issues such as gas channeling and viscous fingering, leading to low gas utilization and significantly reduced oil displacement efficiency, especially in heterogeneous and low-permeability reservoirs (Aryana and Kovscek, 2012; Guo and Aryana, 2019). These limitations restrict the applicability of single gas injection techniques under complex reservoir conditions.

To address these challenges, foam flooding has emerged as a viable solution. Foam flooding enhances oil recovery by reducing gas mobility and optimizing gas distribution within the reservoir. Due to its high apparent viscosity, foam can lower the water-oil mobility ratio, improve the water absorption profile, and increase resistance to flow in high-permeability zones, ultimately increasing the sweep efficiency of the oil-bearing formation (Zhang et al., 2015; Guo and Aryana, 2018).

A major research focus in foam flooding technology is the enhancement of foam stability under reservoir conditions. Stable foams can maintain their structure for longer durations, enhancing their effectiveness in displacing the resident fluid. Therefore, understanding and optimizing the factors that influence foam stability have significant theoretical and engineering implications for foam-based subsurface applications. Recent studies have shown that foam generation and sweep efficiency in fractured reservoirs can be significantly improved by employing foam as a mobility control agent, with foam reducing gas mobility by over 200 times compared to traditional methods. This approach addresses gas channeling and improves oil recovery, particularly in fractured systems, by enhancing areal sweep and delaying gas breakthrough (Fern et al., 2016). Kovscek and Bertin introduce an innovative scaling model for foam mobility in heterogeneous porous media, showing that foam-bubble size and its distribution across varying permeability zones play a critical role in controlling gas mobility. This approach highlights how foam can preferentially enter lower permeability zones, improving gas sweep and diversion in reservoirs with significant heterogeneity. The mobility control mechanism is enhanced by foam's ability to reduce gas velocity in high-permeability regions while facilitating more uniform distribution in low-permeability regions, thus overcoming traditional mobility challenges in gas injection processes (Bertin and Kovscek, 2003; Cai et al., 2021).

Foam exhibits non-Newtonian fluid behavior, which is characterized by viscosity changes with shear rate. This rheological property is particularly beneficial in porous media as it enables foam to adapt to varying flow conditions. At low shear rates, increased viscosity reduces foam drainage and improves displacement efficiency. At high shear rates, decreased viscosity facilitates flow through the pore networks. This adaptive behavior is crucial for optimizing foam performance in the complex flow environments characteristic of subsurface reservoirs (Sorbie et al., 1989).

(2) Drilling fluids

Foam drilling fluid is a lightweight system characterized by low density and high suspension capacity, making it very beneficial under drilling conditions. Relative to traditional drilling fluids, foam drilling fluid is especially effective in reducing wellbore pressure, thereby reducing the risk of formation fractures or blowouts. Foam drilling fluids are particularly well-suited for drilling in low-pressure, fragile, or highly fractured formations. Due to its high apparent viscosity and suspension potential, foam effectively transports cuttings to the surface, minimizing bottom-hole deposition and the risk of stuck pipe. These characteristics make foam drilling fluids highly effective in high-angle wells, horizontal wells, and complex geologic environments (Chen et al., 2023). Foam stability is critical to its performance as drilling fluids. A stable foam can maintain its structure under high-temperature and high-pressure conditions, preserving its ability to transport cuttings and resist foam collapse. Moreover, improved foam stability reduces the risk of liquid phase invasion into the formation, thereby helping to protect hydrocarbon-bearing formations during drilling operations.

(3) Well acidizing

Foam is widely used in acidizing treatments to improve the effectiveness of the treatment while reducing the operational risks. In standard acidizing treatments, acid tends to preferentially flow through high-permeable pathways, leading to uneven acid distribution and reduced effectiveness of the treatment. When foam acid is used, its high apparent viscosity restrict channeling, promoting more uniform acid distribution through formations with heterogeneous permeabilities. This improves acid coverage and contact with the target zones. In addition, foam acid has a low liquid-phase fraction, which helps minimize corrosion of downhole formation and wellbore equipment, thus extending operational lifespan. Foam stability is a key factor in acidizing performance. A stable foam acid can maintain its structure under high-temperature and/or high-pressure conditions, thereby improving acid distribution and contact in the subsurface (Garrouch et al., 2017). Foam systems should be designed to be morphology-adaptable (i.e., capable of adjusting in response to reservoir conditions). Improved foam stability under thermal and shear stresses is particularly important for deep acidizing applications in carbonate rock with high-temperature conditions.

(4) Hydraulic fracturing

Foam fluids are important in hydraulic fracturing operations vis-a-vis oil and gas wells in low pressure, low permeability formations, as well as for oil and gas wells in areas of water scarcity. Compared to traditional water-based fracturing fluids, foam-based fracturing fluids have, in general, lower density, higher apparent viscosity, and less liquid phase. These characteristics reduce the dependence on formation pressure during fracture initiation and help minimize formation damage. In addition, foam also has excellent proppant transport properties due to its unique rheological behavior. Its high viscosity supports proppant suspension and facilitates uniform distribution through complex fracture networks. This leads to improved proppant penetration into the network and enhanced fracture conductivity, ultimately contributing to increased hydrocarbon recovery, even in complex formations. Foam fracturing fluid performance is often tied to foam stability. Under operational temperature and pressure conditions, most foams have a limit to their stability. Stable foams maintain high apparent viscosity under operational conditions and resist collapse while effectively transporting proppants throughout the network (Agwu et al., 2018). Stable foam can also delay ionic interactions that may lead to formations clamping or pinching, promoting more efficient fracture propagation and fluid distribution.

(5) Carbon sequestration

Foam shows considerable promise for carbon sequestration due to its ability to control CO_2 mobility, suppress gas channeling, and enhance CO_2 storage capacity in geologic formations. In heterogenous reservoirs, foam tends to preferentially enter higher-permeability channels, suppressing gas mobility and diverting CO_2 into medium- and low-permeability zones. This leads to a more uniform distribution of the injected CO_2 and improves overall reservoir storage capacity (Guo and Aryana, 2018). An innovative aspect of foam-assisted CO_2 sequestration is the ability of foam to significantly reduce the migration of CO_2 into the override zone, thereby preventing rapid segregation. The use of foam enhances both the sweep efficiency of CO_2 and the residual trapping, which improves the long-term sequestration effectiveness. Additionally, foam's ability to modify the gas flow profile is especially beneficial in fractured or faulted reservoirs, as it can potentially block high-permeability zones and increase the amount of CO_2 stored in the formation (Rossen et al., 2024). These characteristics are especially important for reservoir with faults or significant fracturing where the regeneration of the foam in the event of a potential leak may contribute to long-term storage security (Guo and Aryana, 2019; Prasad et al., 2023). Careful selection of the surfactant mixtures in foam systems is critical to foam strength and longevity in high-temperature and high-pressure conditions.

5.2 Environmental engineering

(1) Wastewater treatment

Foam offers significant advantages in the treatment of wastewater containing oil and toxic heavy metals. The flotation method, also known as foam extraction, utilizes foam to separate suspended solids and dissolved contaminants. This technique involves introducing an inert gas into a liquid containing surfactants, transforming the gas into foam. Due to differences in physiochemical interactions, target substances such as oil droplets or metal ions preferentially adsorb onto the foam surface. The foam is then removed, thereby extracting the target substances from the liquid phase. In wastewater treatment, this principle is applied to remove heavy metal ions from the wastewater (Du et al., 2024).

By optimizing foam stability, the adsorption capacity of pollutants at the foam interface can be enhanced, thereby improving removal efficiency. For instance, a stable foam structure favors the adsorbent capture and separation of oil particles; in the treatment of heavy metal wastewater, foam stability enhances the retention time of heavy metal ions interacting with active surfaces for improved removal rates. In addition, research has shown that different foam stabilizers and processing conditions had a significant impact on the removal efficiencies of suspended solids, oils, and heavy metals from wastewater, including the potential for development of an effective and environmentally friendly approach to wastewater treatment (Sun et al., 2021).

(2) Soil remediation

Foam has been applied to remediate soils contaminated with non-aqueous phase liquids (NAPLs), heavy metals and organic contaminants (Vu and Mulligan, 2023; Orujov et al., 2025). In addition to the physical displacement of the contaminants, foam facilitates remediation through its penetration into the porous medium and the adsorption of contaminants onto the gas-liquid interface. This process separates the contaminants from the soil particle surfaces in-situ, followed by their extraction into the foam phase and subsequent recovery through a central treatment process. One of the main advantages of foam-based remediation is its low liquid content compared to conventional remediation methods, which significantly reduces the risk of secondary pollution. Furthermore, foam can penetrate complex pore networks, enabling the removal of contaminants from deeper soil layers that might otherwise be inaccessible to traditional remediation approaches (Wang et al., 2023). Foam stability can also be adjusted to optimize performance across various soil types and contamination profilers. In the case of heavy metals, chelating agents and surfactant can be incorporated into the foam formulation to enhance the efficiency of metal ion capture (Mulligan and Wang, 2006; Vu and Mulligan, 2023). These operational advantages, including efficient contaminant removal, adaptability and environmental impact, highlight foam remediation technology for soil decontamination, especially where rapid and efficient recovery of subsurface pollutants is required.

(3) Waste gas treatment

Foam can effectively eliminate toxic gases from industrial emissions, including SO_2, NO_x, and volatile organic compounds. The process relies on the foam film's ability to adsorb and solubilize gaseous pollutants into the liquid phase, thereby facilitating their removal. Foam stability is important, as a stable foam provides an interfacial area and longer residence time, both of which enhance pollutants removal. By modifying foam characteristics, such as surfactant type, gas-liquid ratio, and liquid-phase additives, it is possible to tailor foam system for treating a wide range of emissions at various concentrations. For example, adding oxidizing agents to the foam can the adsorption and chemical conversion of sulfur containing gases. In high-temperature gas treatment, thermal stability of the foam becomes an important consideration. Heat-resistant surfactants have been developed to prevent foam collapse and maintain performance under elevated temperatures. Foam systems are also adaptable to humid or compositionally complex gas streams, offering a versatile solution for diverse industrial applications (Bhaskaran et al., 2023). In summary, foam-based technologies offer potentially cost-effective, environmentally friendly, and flexible approach to industrial gas pollution control.

(4) Ecological restoration

Foam is an effective tool in ecological restoration, especially in the context of pollution in marine and freshwater environments. Through the adsorption properties of foam films, pollutants including NAPL spills and chemical solvents can be effectively recovered before they cause harm to aquatic ecosystems. In field applications, the physicochemical characteristics of different water bodies, such as salinity, pH, and temperature, can influence foam performance. For example, high seawater salinity can affect the stability of some foam systems while low salinity freshwater can support foam generation and retention. Therefore, it is important to adjust the foam formulation based upon site-specific environmental conditions to optimize foam performance and remediation effectiveness (Jacob et al., 2018). Foam-based cleanup strategies provide the ability to remove contaminated material quickly in complex aquatic environments while minimizing secondary pollution that may be associated with other traditional chemical cleaning methods, making it a sustainable and highly effective tool in ecological restoration.

5.3 Chemical and materials engineering

(1) Foam materials preparation

Foam materials including foamed plastics, foamed concrete, and foamed glass, are increasingly used in applications such as construction, packaging, and automotive parts, in large part due to their advantageous properties, including light density, thermal insulation, and sound absorption. Among these properties, foam stability is a key determinant of material performance based on the pore configuration and structure in foam materials, which in turn impact mechanical strength thermal conductivity, and other functional characteristics. A stable foam structure enables the development of foam material that combine high mechanical strength with low weight (Peng et al., 2023). Furthermore, foam materials that enhanced stability tend to have superior thermal resistance, making them suitable for energy-efficiency uses in buildings and thermal management in automotive applications. Current research provides a strong foundation for further optimization of foam material formulations, with potential uses across multiple industries.

(2) Catalyst supports preparation

Foam structures improve reaction efficiency in catalytic applications due to their high porosity and large surface area, which improve contact between reactants and active catalytic sites to enhance reaction rates. The active surface area of the catalyst plays an important role in determining overall reaction efficiency in catalytic processes in most industrial settings (Karim et al., 2021). The porous nature of foam structures provides an ideal dispersion of catalyst material, allowing reactants to access the active catalyst surface more homogeneously, which leads to more efficient and consistent catalytic performance. Under high-temperature and high-pressure conditions, foam stability directly affects foam's ability to maintain its structure and catalytic function. Therefore, optimizing the stability of the foam materials is important. During foam preparation, factors such as foam material composition, pore structure and the type or amount of surfactant utilized in the formulation of foam materials, can be tailored to improve the foam's thermal and mechanical. These optimizations extend catalyst lifetime and enhance reaction stability under harsh reaction conditions (Tran et al., 2022).

(3) Coatings and adhesives

Foam is used in coatings and adhesives as a thickening, filling, and modifying agent and can have a significant effect on their rheological properties, adhesion characteristics, and bonding strength. The use of foam can improve characteristics such as thickness, leveling, and uniformity in coatings, making coatings and adhesives generally easier to work with and more effective in covering large surface areas and adhering to uneven surfaces. Foam stability plays a role in the efficacy of coatings and adhesives; a stable foam structure prevents phase separation and loss of adhesion over time, thus helping to preserve bonding and adhesion durability of the coating or adhesive layer (Mohd Sabee et al., 2022). The selection and optimization foam stabilizers are crucial for improved thermal and corrosion resistance. Heat-resistant foam stabilizers allow for coatings and adhesives to retain excellent performance characteristics in high heat environments, and foam stabilizers with corrosion resistance properties will retain durability characteristics in extreme environments such as humid or acidic-alkaline environments (Chattopadhyay and Webster, 2009).

6. Challenge and future trend

6.1 Application and challenge

Foam has been used in wide range of applications (or industries), supported by a considerable body of research. However, several key challenges remain. One major challenge is bridging the gap between theoretical understanding and practical applications. While numerous academic studies have examined foam stability and rheology (many under well-controlled laboratory conditions), translating these findings to complex industrial settings remain difficult. In particular, uncertainties related to large-scale production and implementation, field variability, and operational constraints, continue to hinder the application of laboratory-derived knowledge. Another challenge is understanding foam stability at extreme conditions, such as high temperature, pressure, or salinity. In many foam systems, surfactants degrade at high temperatures, leading to foam destabilization. Similarly, high-pressure or high-salinity environments can alter the physicochemical properties of the solution, limiting their performance. These issues are directly relevant in applications such as deep well operations and wastewater treatment, where harsh environments affect foam stability (Tran et al., 2022).

6.2 Future research direction

Addressing the current challenges associated with foam applications requires targeted research across several key areas. First, there is a need for the development of new surfactants with enhanced stability under extreme conditions. Many of the existing surfactants are often not able to maintain foam stability at high temperature, pressure, and salinity conditions. Given the ongoing and anticipated exploration of resource availability and recovery in extreme environments (e.g., Arctic drilling), surfactants designed specifically for thermal, pressure, and salinity resistance are needed to improve foam stability. Second, combining experimental work with molecular simulations via multiscale modeling approaches may provide opportunities to deepen the understanding foam behavior. Such approaches can reveal microscopic mechanisms underlying foam stability and provide theoretical understanding for the design of novel and resilient foam systems. Multiscale and interdisciplinary frameworks, comprising molecular, mesoscopic, and macroscopic numerical and physical experimental programs, can bridge the gap between laboratory research and filed applications and lead to significant design improvements and broader field applications. Third, the development of low-cost and environmentally friendly foam systems is an important direction for future research. Given foam's value in environmental protection and resource extraction and utilization, future formulations should prioritize sustainability without compromising performance. Applications in wastewater treatment, oil and gas extraction, and sustainability-driven sectors will benefit from foams that are both effective and ecologically responsible.

Emerging technologies also play an increasingly important role in foam development. Nanoparticles, for instance, are studied for their ability to improve foam properties by improving the elasticity and mechanical strength of liquid films. In the coming years, nanoparticle-based foam systems are likely to be optimized for specific applications, such as improving foam performance in extreme conditions encountered in oil recovery. Similarly, functional polymers, particularly those with stimuli-responsive properties, are being developed to further enhance foam stability by reducing drainage and improving foam resilience. Additionally, ionic liquids, which offer low volatility and high stability, are anticipated to be a key area of development for creating more stable and long-lasting foams. Breakthroughs in these areas may lead to the creation of foams that can withstand harsh operational environments, opening new possibilities for industries such as resource recovery and geologic storage of sequestered carbon and energy carriers.

7. Conclusions

(1) The impact of interfacial tension on foam stability reveals a multifaceted interaction. When interfacial tension is too high, it can enhance the mechanical strength of the foam film but may also accelerate liquid drainage. Conversely, excessively low interfacial tension decelerates liquid film drainage but may lead to weaker films that are more susceptible to rupture. In real-world applications, achieving optimal foam stability often involves managing interfacial tension within an appropriate range. This is done by adding surfactants that balance film elasticity and the rate of liquid film drainage, ultimately resulting in more stable foam systems.

(2) The stability of foam is impacted by a variety of external and internal elements. Externally, higher temperatures tend to decrease stability, whereas increased pressure improves it. The levels of salinity and pH can alter the adsorption of surfactants, crude oil can degrade the foam's structure, and gravitational forces can hasten drainage, ultimately causing the foam to break down. Internally, the viscosity, density, and surface tension of the liquid phase play a role in the rate at which the foam drains. The type and solubility of the gas phase influence the foam's structure, while the type and concentration of surfactants are crucial for both foam formation and its resistance to rupture. Additives such as polymers or nanoparticles can further improve foam stability.

(3) The stability of foam is essential in various sectors such as oil and gas extraction, environmental remediation, and the chemical industry. In the context of petroleum engineering, it enhances the extraction of oil and gas by minimizing gas channeling and improving sweep efficiency. In environmental applications, foam stability can greatly enhance the efficiency of pollutant removal, contributing to improve ecological outcomes. In materials science, foam is utilized for synthesizing and optimizing lightweight and functional materials, improving product performance in various practical applications.

The future of foam research lies in advancing stability, adaptability, and sustainability. Achieving these goals will require interdisciplinary collaboration across material science, chemical engineering, environmental science, and computational modeling to enable the development of next-generation foam systems capable of performing under increasingly demanding operational environments.

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Conflict of interest

The authors declare no competing interest.

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