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Impact of Eco-Friendly Drilling Additives on Foaming Properties for Sustainable Underbalanced Foam Drilling Applications

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ABSTRACT: Underbalanced foam drilling stands out as a drilling technique acclaimed for its capacity to enhance safety and efficiency in operations. Utilizing foams as drilling fluids offers several benefits over traditional methods, including lower density, diminished formation damage, and augmented borehole stability. However, the persistent challenge of sustaining foam stability in demanding conditions, particularly amid elevated water salinity and alkaline environments, remains a critical issue. Current literature lacks comprehensive insights into foam stability under such specific circumstances, raising concerns about the practicality of numerous reported foaming agents in field applications. This study aims to fill this knowledge void to align with industry standards. With a heightened focus on sustainability due to mounting environmental considerations, the research explores the use

of an eco-friendly surfactant, ammonium alcohol ether sulfate (AAES). Additionally, the investigation delves into the impact of environmentally friendly drilling additives-polyanionic cellulose (PAC), carboxymethyl cellulose (CMC), and starch-on the stability of bulk foam under mildly alkaline conditions. Employing a dynamic foam analyzer, diverse foam properties of AAES foams were assessed, encompassing stability, foamability, and bubble structure. The results demonstrated that the optimal concentrations of the tested additives, in the order of PAC > CMC > starch, significantly prolonged the half-life of the AAES foam bubbles. The introduction of PAC and CMC additives elevated the viscosity of AAES foaming solutions, enhancing the liquid retention within the foam structure. In contrast, starch addition exerted no influence on the solution viscosity and did not impede liquid drainage, although it did reduce bubble coalescence. Furthermore, the PAC- and CMC-based AAES foams manifested as considerably wetter foams with a rounded bubble structure, while the starch-based AAES foam exhibited a dry foam characterized by a distinct polyhedral bubble structure. These findings offer valuable insights into the potential application of the AAES surfactant in foam drilling, showcasing its efficacy in improving foam stability and contributing to the evolution of eco-friendly drilling practices.
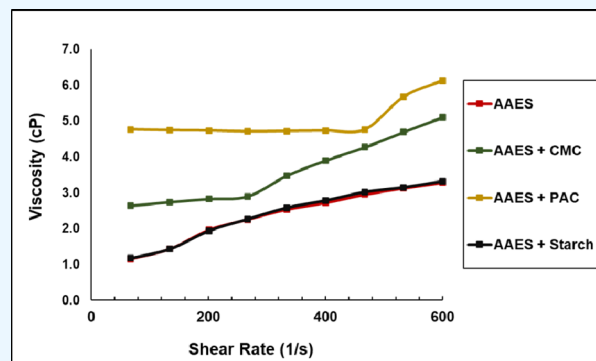
1. INTRODUCTION

Foam has emerged as a valuable and versatile fluid in the field of drilling wells. With its unique properties and characteristics, foam finds extensive application in enhancing underbalanced drilling operations. Foam is a two-phase system consisting of gas bubbles dispersed in a liquid phase, typically water or oil.[1] The use of foam in drilling wells offers several advantages. First, foam provides excellent hole stability by reducing the influx of formation fluids and minimizing the risk of wellbore collapse.[2] Additionally, foam acts as a barrier to prevent the loss of drilling fluids into permeable formations, thereby minimizing formation damage.[3] Foam's low density and high viscosity allow for efficient transport of drilled cuttings to the surface, resulting in improved hole cleaning. Furthermore, the use of foam facilitates the control of formation pressures, enhancing safety and well control during drilling operations.[4] Foam can also be tailored to specific drilling conditions by adjusting its density, viscosity, and stability. Overall, the application of foam in drilling wells has proven to be highly

beneficial, improving drilling efficiency, reducing costs, and ensuring optimal wellbore integrity.[5] Foam can be characterized through different parameters including foam stability, structure, and drainage behavior.

Foam stability is a critical characteristic of foaming systems and pertains to the changes in foam volume or height over time following its formation. This stability is influenced by various parameters, including pressure, temperature, pH, surfactant concentration, and salts.[2] The foam stability can be quantified by evaluating the foam bubbles' half-life (H_o)

which represents the duration upon which the foam volume decreases to half its initial value due to foam decay.

The structure of foam can be classified into different categories based on the amount of liquid present: dry foam and wet foam. In dry foam, the gas bubbles take on a polyhedral shape with distinct edges, whereas in wet foam, the bubbles are more spherical and stable.[6] A thin layer called a thin film or lamella forms between two adjacent bubbles. The point of connection among three approaching bubbles is known as plateau borders (PBS).[7] However, foam is inherently unstable and has the potential to separate into gas and liquid phases due to its high surface energy.[8] Literature has identified three primary phenomena that contribute to the instability of foam: liquid drainage, coarsening, and bubble coalescence.[7,9] The process of liquid drainage plays a significant role in the degradation of foam, reducing its liquid content, which determines the thickness of the film.[10] This process is driven by gravity and capillary pressure, where the capillary pressure transfers liquid from the foam film to the plateau borders, while gravity drains the liquid from the network of plateau borders.[11] Bubble coarsening occurs when gas diffuses through the liquid film due to a pressure difference, leading larger bubbles to grow while smaller ones tend to disappear.[12] Bubble coalescence refers to the breaking of adjacent films. To mitigate these phenomena, various chemical additives, primarily surfactants, are employed to enhance foam stability by increasing liquid viscosity and establishing a network of connections between films to minimize liquid drainage and coarsening.[13]

Tracking a typical foam drainage curve, it passes through three distinct phases.[15] Phase I (transient drainage) represents the initial rapid drainage in a static foam column. Phase II (steady drainage) shows a linear relationship between drainage volume and time due to the balance between gravitational and opposing forces. Phase III (drying) occurs as more liquid drains, increasing viscous and capillary forces, although gravity remains the primary driver. Coarsening and coalescence mechanisms, while facilitating drainage, also contribute to foam degradation throughout Phase III.[10,14] Foam liquid drainage can be analyzed in terms of the drained liquid volume over time to interpret the foam stability. Foam liquid stability (FLS) is a critical factor that needs to be considered when evaluating the stability of foam and its ability to retain liquid and control drainage. FLS determines how well the foam can hold onto liquid and influences the degree of dryness of the foam. The drainage half-life time ($t_{FLS50\%}$) signifies the time it takes for 50% of the liquid to drain out of the foam structure. Therefore, a higher $t_{FLS50\%}$ value indicates better stability of the foam system, as it suggests that the foam can retain more liquid within its lamella film and minimize liquid drainage.

Foam formulations typically incorporate surfactants to reduce surface tension between gas and liquid, facilitating the creation of more stable foam.[6] Anionic surfactants have been utilized in foam-based underbalanced drilling.[16] These surfactants are well-regarded for their ability to produce stable and effective foams, which is a critical factor in improving drilling performance. Based on the literature review, commonly employed anionic surfactants include sodium dodecyl sulfate (SDS),[17] alpha olefin sulfonate (AOS),[18,19] and cetyltrimethy-lammonium Bromide (CTAB)[20] for drilling foams. Another promising secondary surfactant, ammonium alcohol ether sulfate or alcohol ethoxy sulfate (AES), was introduced by Memon et al.,[21] demonstrating excellent foam properties and

stability. However, it is noteworthy that the pH of foaming solutions using these surfactants was not adequately addressed in the reported studies. pH plays a vital role in foaming stability by influencing the balance of double-layer repulsive forces and, consequently, the stability of the equilibrium thickness of the liquid film.[17]

Unstable foam in foam drilling poses several challenges including weak structure, high drainage, and low viscosity. This directly affects the foam's ability to transport solids and leads to poor hole cleaning, impacting drilling operations.[22] In contrast, stable foams offer consistency and predictable rheological properties.[19] Unstable foams can cause segregation, free liquid presence, and two-phase flow, resulting in pressure fluctuations, formation damage, and well control problems.[23,24] Addressing unstable foam is essential for successful foam drilling.

When designing a foam system for drilling applications, the main concern is maintaining stability in challenging drilling environments while remaining compatible with water-sensitive formations. To qualify as a suitable foam system for underbalanced drilling, certain criteria must be met. These standards include ensuring sufficient stability to transport cuttings to the surface, maintaining a mildly alkaline pH range of 9.5−10.5, and withstanding the salts that may enter the wellbore from the formation due to underbalanced conditions, such as saline water.[25−27] These field standards provided by the International Association of Drilling Contractors (IADC) are not clearly met in the current literature, which questions the practicality of the reported foaming agents when it comes to field applications. Such a gap raised the motivation to this study for continued research on drilling foams in a typical drilling environment and shaped the objective of this research.

Hence, the aim of this investigation was to analyze the resilience of foam in high pH conditions, a research aspect that has garnered limited focus in the current literature. To thoroughly evaluate the stability of the foam in a saline environment, a synthetic water formulation comprising a combination of monovalent and divalent salts was utilized. In line with commitment to environmental sustainability, this study explores the utilization of green and biodegradable surfactant and additives in the formulation of drill foam, aiming to develop eco-friendly alternatives. Furthermore, this study aims to examine the influence of drilling additives commonly employed in conventional drilling fluid formulations on the stability of bulk foam under mildly alkaline conditions. By rigorously examining these factors, we seek to enhance our understanding of foam stability and contribute to the advancement of eco-friendly drilling practices.

2. MATERIALS AND METHODS

2.1. Materials. *2.1.1. Foaming Agent.* Ammonium alcohol ether sulfate (AAES), provided by the APChem company, was utilized as the foaming agent in the tested foam systems. It has been used in foam applications in the literature. For instance, a study on surfactant screening to generate strong foam with formation water and crude oil was conducted.[21] The study reported AAES as a promising foaming agent with excellent foam properties and foam stability. It can also be used as a secondary surfactant, compatible with anionic and nonionic surfactants. AAES is an anionic surfactant that exhibits a high biodegradability. Structurally, it consists of a hydrophobic alkyl chain linked to an ethoxylated sulfate group. The hydrophobic alkyl chain confers lipophilic properties to the surfactant,

facilitating its interaction with hydrophobic substances and solubilization of hydrophobic substances. The surfactant's anionic charge is derived from sulfate (SO_4) groups present within its structure, which dissociate in aqueous solutions, yielding sulfate ions (SO_4^{-2}). This anionic nature enables AAES to effectively reduce the surface tension of water and form stable mixtures with polar and nonpolar compounds.

2.1.2. Gas Phase. Air was chosen as the gas phase for experimentation due to its widespread usage in foam drilling applications in the field.[28]

2.1.3. Liquid Phase. A synthetic seawater solution was prepared by combining ACS-grade salts, namely, sodium chloride, calcium chloride, sodium sulfate, sodium bicarbonate, and magnesium chloride. This synthetic seawater had a total salinity of 67.70 g/L and contained both mono- and divalent cations. The specific composition of the synthetic seawater can be found in Table 1. In foam drilling aWhether is this head

Table 1. Mineral Compositions of Synthesized Seawater

#	composition	synthetic sea water (g/L)
1	Na_2SO_4	6.34
2	$NaHCO_3$	0.16
3	$CaCl_2 \cdot 2H_2O$	2.39
4	$MgCl_2 \cdot 6H_2O$	17.64
5	NaCl	41.17
total dissolved solids (TDS) − g/L		67.70

lever or not. Please check.pplications, it is crucial to minimize the potential corrosion of the drilling equipment. To achieve this, it is recommended that a slightly alkaline drilling fluid. Therefore, a pH buffer solution containing 5 M potassium hydroxide (KOH) was utilized to adjust the pH of the prepared foaming solutions within the range of 9−10. This adjustment helps create an environment that is conducive to foam drilling and reduces the risk of equipment corrosion.

2.1.4. Drilling Additives. Polyanionic cellulose (PAC) (*Type: anionic*) with a commercial name of PAC-R and carboxymethyl cellulose sodium salts (*Type: anionic*) were purchased from Sigma-Aldrich Chemicals Co. Starch sample (*Type: nonionic*) was purchased from Oren Hydrocarbons Pvt. Ltd.

2.2. Sample Preparation. The foaming solutions were prepared by dissolving the surfactant (i.e., AAES) in water using a volumetric flask and a magnetic stirrer. The desired concentration of the drilling additives was then added to the solution. Then, the pH of the solutions was adjusted to the range 9−10 by adding droplets of 5 M KOH solution. The solutions were thoroughly mixed for several hours to ensure homogeneity before the foaming tests.

2.3. Foaming Testing. Foaming properties were evaluated using the Dynamic Foam Analyzer (DFA 100) under standard conditions of 25 °C and atmospheric pressure. To perform the measurements, a 50 mL foaming solution was injected into a glass column through a syringe. The column was equipped with prisms for visualizing the foam structure and a calibration grid for measuring the bubble size. Positioned between a linear LED panel and a line sensor, the column enabled the measurement of the foam height and volume. Gas (either air or nitrogen) was introduced from the bottom of the column using porous filter paper with pore sizes ranging from 16 to 50 μm. The DFA 100 software analyzed the number of bubbles,

bubble size, and foam volume decay over time. The experiments were conducted in triplicate, and the average values were reported. Figure 1 depicts a schematic representation of the DFA 100 apparatus employed in this research.
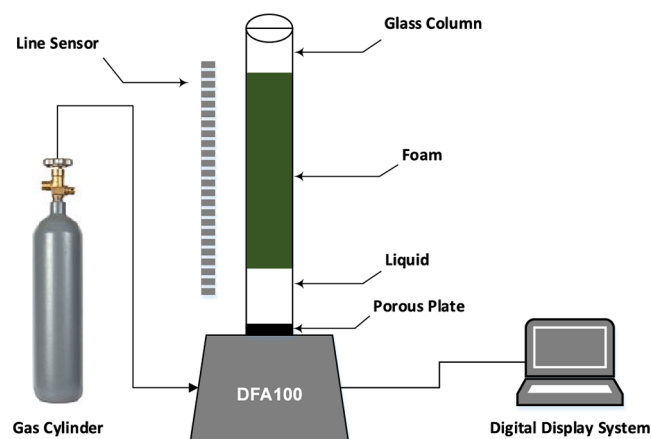

Figure 1. A schematic illustration of the foam analyzer DFA 100 employed for assessing foam properties.

2.4. Viscosity Measurements. The viscosity of the base liquid plays a vital role in determining the bulk foaming properties in foaming systems.[29] In this study, the viscosity of the AAES liquid solutions used for generating foam was assessed using an Anton-Paar Rheometer at ambient conditions. The measurements encompassed a range of shear rates and ambient conditions to obtain a thorough understanding of the viscosity profile. These precise measurements provide valuable insights that contribute to a deeper comprehension of the foaming process and aid in the optimization of the foaming system performance.

3. RESULTS AND DISCUSSIONS

3.1. Impact of Drilling Additives on Foaming. Different foam types can be employed in underbalanced drilling operations, including stable foam and stiff foam. Stable foams consist of surfactants, salts, and corrosion inhibitors in the liquid phase, with minimal influence on liquid phase viscosity.[2] On the other hand, stiff foams incorporate polymers and stabilizers in addition to these additives. While stiff foams share similarities with aqueous foams in terms of structure, their stability varies depending on the type of stabilizer used. In this study, the effects of drilling additives, namely, polyanionic cellulose (PAC), carboxymethyl cellulose (CMC) polymers, and starch, on foaming stability were examined. These additives were specifically chosen for their environmentally friendly characteristics as they are derived from renewable and natural sources.[30−32]

3.1.1. Drilling Additive (I): Polyanionic Cellulose (PAC). PAC has been widely employed in various studies as both a viscosifier and a foam stabilizer.[33−35] It offers cost-effectiveness as an additive for water-based drilling fluids and exhibits a notable resistance to salts. PAC serves multiple functions, including thickening, controlling rheology, suspending solids, and reducing filtrate.[36] Moreover, it is recognized as an environmentally friendly polymer that maintains its effectiveness across a broad spectrum of pH environments.[32]

Foam Stability. Within the scope of this investigation, varying concentrations of the PAC sample were introduced into AAES (0.5 wt %) foaming solutions to assess their influence on the bulk properties of foam. PAC samples, spanning concentrations ranging from 0.5 to 3 g/L, were added into the AAES solutions in the presence of SW in addition to a pH buffer, allowing for adjustment of the solution within the mildly alkaline range of approximately 9.5.

The stability of the generated AAES foams was examined in Figure 2, demonstrating the effects of incorporating PAC. The
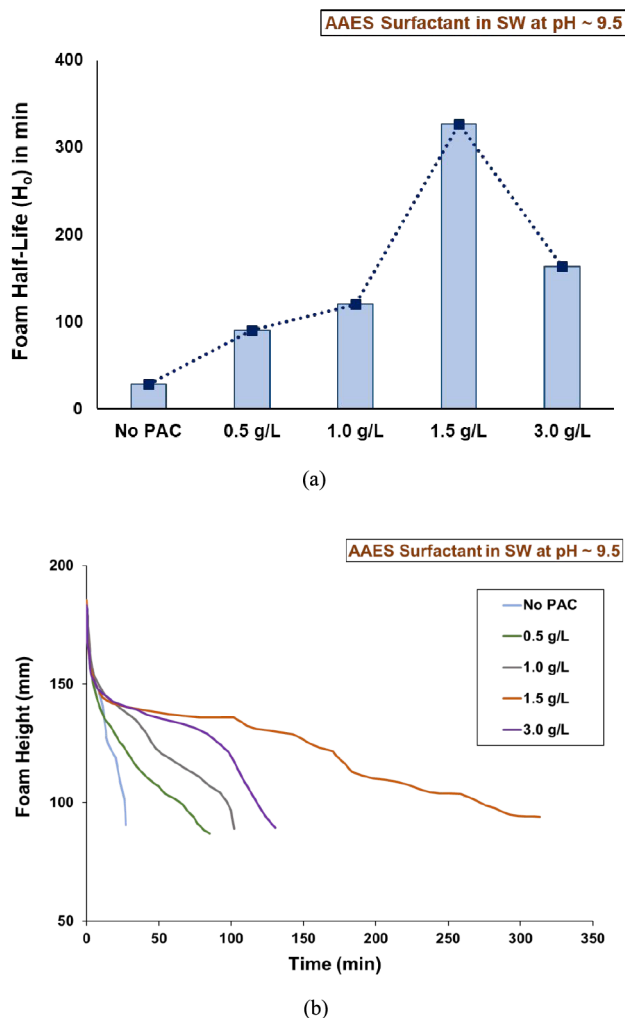

(a)

(b)

Figure 2. Evaluation of foam stability in an AAES-based foaming solution with varying concentrations of PAC polymer, depicted in terms of (a) bubbles' half-life and (b) foam height over time (captured at each system's respective half-life).

results from the experiment, shown in Figure 2a, showed that when PAC was added to the AAES foaming solution at a concentration of 0.5 g/L, the foam's half-life was extended by three times. Furthermore, it was noted that the addition of 1 g/L of PAC slightly extended the half-life of the bubbles. However, when the PAC concentration was increased to 1.5 g/L, a substantial prolongation of the foam's half-life was observed, surpassing 300 min. In contrast, the foam stability unexpectedly decreased by nearly 2-fold when the PAC amount was doubled to 3 g/L.

The observed effects can be explained by the interplay between the PAC and the foaming solution. At a PAC concentration of 0.5 g/L, a 3-fold increase in the foam's half-life suggests that PAC has a positive impact on foam stability. This effect can be attributed to the adsorption of PAC molecules onto the bubble surfaces. The PAC molecules form a protective layer that hinders coalescence and drainage, reducing the interaction between adjacent bubbles and inhibiting the merging process. This barrier effect prevents the formation of larger bubbles and promotes the retention of smaller, more stable bubbles within the foam structure, leading to a prolonged half-life. Such a positive impact of PAC on foam stability was also noticed in previous studies.[37,38] When the PAC concentration was further increased to 1.0 g/L, there was only a minimal extension in foam stability. This suggests that the additional amount of PAC was insufficient to create a significant improvement in the formed barrier and stabilize the foam significantly further.

However, at a PAC concentration of 1.5 g/L, a significant improvement in the foam stability was observed. This suggests that a higher PAC concentration allows for a more effective interaction between PAC and the foaming solution, resulting in enhanced foam stabilization. The increased PAC concentration likely provides a greater number of PAC molecules available for adsorption onto the bubble surfaces, forming a thicker and more robust protective layer. This layer further inhibits coalescence and drainage, leading to improved foam stability and a longer half-life.

Surprisingly, doubling the PAC concentration to 3 g/L led to a considerable reduction in foam stability by 2-fold. This outcome suggests that an excessive PAC concentration disrupts the foam structure, potentially causing excessive stabilization and hindering normal drainage and coalescence processes. Consequently, the foam becomes less stable, exhibiting a shorter half-life. This could be due to saturation of the available bubble surfaces with PAC molecules. This suggests that to achieve optimal foam stability, careful optimization of the PAC concentration is essential to strike a balance between stabilization effects and potential disruptions to foam structure, ensuring optimal foam performance in practical applications.

Analyzing the foam height decay curves over time (Figure 2b) revealed that the AAES-based foam exhibited a rapid decrease in stability over time. However, the addition of PAC polymer resulted in a slower rate of reduction in foam half-life. Notably, PAC concentrations of 0.5 and 1.0 g/L displayed a similar rate of decrease in foam height. The results indicate that the concentration of 1.5 g/L yielded the lowest gradient of decrease, thereby resulting in the longest foam half-life.

Liquid Drainage. The graphs in Figure 3 show how liquid drains from an AAES foam structure at different concentrations of PAC over time as well as the corresponding drainage half-life ($t_{FLS50\%}$). The observed results indicate that PAC has a noticeable influence on the gradient of liquid drainage from AAES foam. The PAC concentration of 1.5 g/L had the slowest rate of drainage compared to other concentrations. Moreover, adding PAC to AAES foam delays liquid drainage across all PAC concentrations, with the most significant delay occurring at 1.5 g/L that started after 30 s (see Figure 3a). This suggests that, at this concentration of PAC, the foam possesses a greater capacity to retain liquid. The results in Figure 3b support these findings by demonstrating that a PAC concentration of 1.5 g/L leads to the longest drainage half-life. This suggests that the foam, at this specific concentration, has a slower rate of liquid drainage and the capability of forming
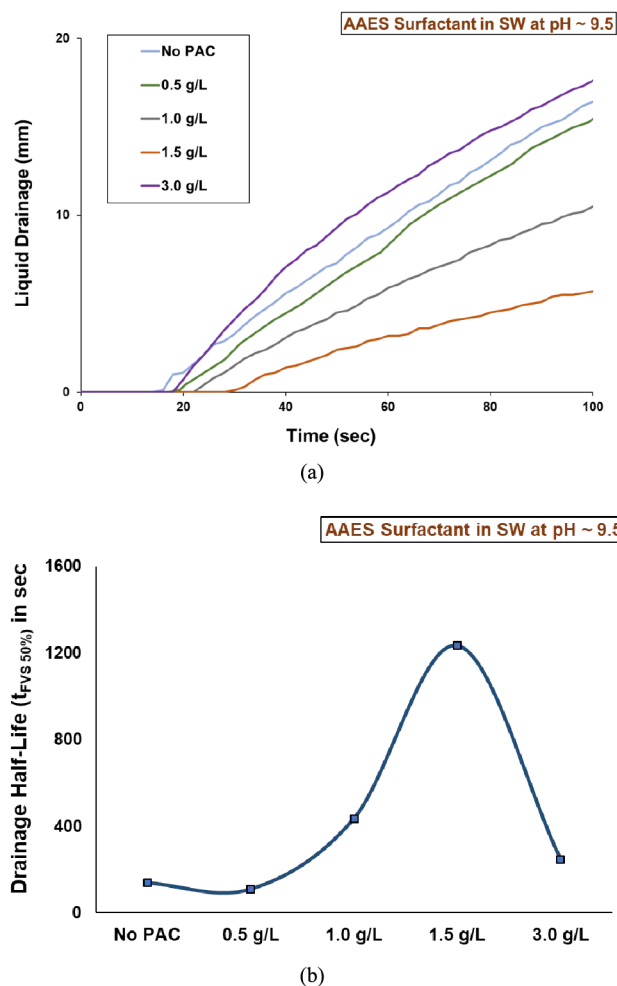
Figure 3. Liquid drainage of AAES foam at different PAC concentrations including (a) drained liquid volume over time and (b) drainage half-life.
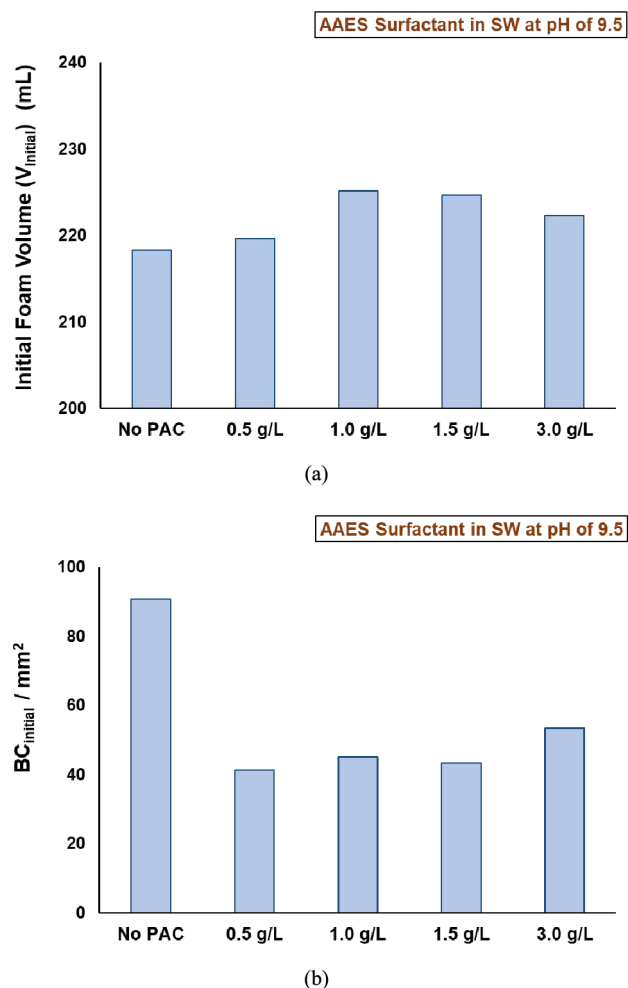

Figure 4. Foamability of AAES foam at different PAC concentrations including (a) initial foam volume $V_{Initial}$ and (b) initial bubble count $BC_{Initial}/mm^2$.

bubbles that last for a longer time. Consequently, the stability of the foam is enhanced.

Foamability and Bubbles' Structure. Figure 4 illustrates the initial volume ($V_{Initial}$) and initial bubble count ($BC_{Initial}/mm^2$) of AAES foams under varying concentrations of PAC. The results demonstrate that the introduction of PAC to the foam systems leads to a marginal increase in the initial foam volume compared to the basic case without PAC (see Figure 4a). However, the analysis reveals that this increase in $V_{Initial}$ is not statistically significant, reaching a maximum of 3% at a PAC concentration of 1.5 g/L. Therefore, it is inconclusive to assert a direct relationship between the PAC concentration and foamability of the system based on this marginal increase in $V_{Initial}$.

Conversely, the $BC_{Initial}$ for all tested PAC-AAES foams is consistently lower than that of the reference AAES foam (without PAC), as depicted in Figure 4b. This intriguing finding suggests that the presence of PAC exerts a polymeric effect by forming a thicker liquid film between the bubbles, as measured per unit area in square millimeters. This phenomenon can be attributed to the molecular characteristics of PAC, which enable it to enhance the stability and strength of the liquid lamella. As a result, fewer bubbles are formed within the same area, leading to a lower bubble count.

This observation is substantiated by the visual evidence provided in Figure 5, which exhibits captured images of the foam bubbles at different time intervals. These images clearly demonstrate a distinct change in the appearance of the foam bubbles at early time intervals (1 and 5 min). Notably, one can speculate from the captured images that the PAC-AAES foams exhibit a lower bubble count compared with the reference case at all time intervals. The effect becomes more pronounced as the PAC concentration increases, particularly at a PAC concentration of 1.5 g/L. In these cases, the bubbles retain their spherical shape for a longer duration, indicating a higher liquid content within the lamella between the bubbles due to the enhanced viscoelastic properties of the films resulting from the addition of PAC.

3.1.2. Drilling Additive (II): Carboxymethyl Cellulose (CMC). CMC is a commonly used additive in drilling engineering due to its versatile properties and numerous applications.[39] CMC is a water-soluble polymer derived from cellulose, and it possesses excellent rheological properties, high viscosity, and exceptional fluid loss control capabilities.[40] In drilling fluids, the CMC polymer acts as a viscosifier, providing the required thickness and stability to prevent well collapse and maintain hole integrity. This study aimed to evaluate the influence of varying CMC concentrations on the bulk
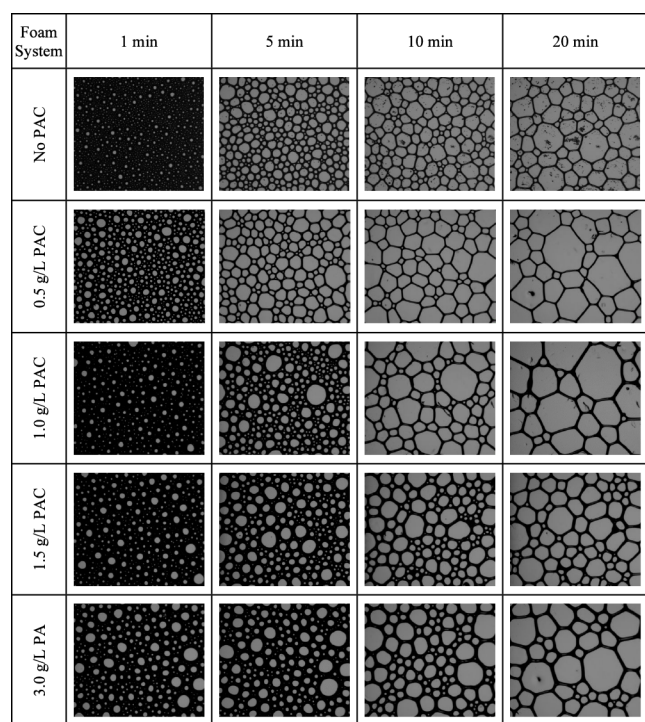
Figure 5. Captured images of bubble structure of AAES foam at different time intervals for different PAC concentrations (foam bubbles are in gray while the liquid film is in black).

Figure 6. Evaluation of foam stability in an AAES-based foaming solution with varying concentrations of CMC polymer, depicted in terms of (a) bubbles' half-life and (b) foam height over time (captured at each system's respective half-life).

properties of the AEES foam. The CMC concentrations tested in the experiment encompassed a range from 1.0 to 12.0 g/L.

Foam Stability. Figure 6a illustrates the impact of introducing CMC on the stability of the AAES foams. The findings indicate a steady and progressive enhancement in the half-life of the foam bubbles as the CMC concentration increased up to 6.0 g/L. Such gradual increase in bubbles' half-life can be attributed to the properties of CMC, such as its ability to interact with the surfactant molecules in the foam solution thereby the bubble coalescence is reduced. However, doubling the CMC concentration did not further enhance foam stability. Therefore, it is suggested that a concentration of 6.0 g/L of CMC is optimal for AAES foam in the presence of air and SW. Beyond this limit, increasing the CMC concentration does not provide significant additional benefits. This could be due to the saturation of available binding sites on the foam interface.

In Figure 6b, the foam half-life curves for CMC-AAES foams demonstrate a noticeable decrease in the gradient of the decline in foam height with increasing CMC concentrations. This indicates a longer duration of foam integrity and stability. This trend is observed up to a concentration of 6.0 g/L CMC, beyond which, at a concentration of 12.0 g/L CMC, the foam height decline follows a similar gradient as that of the 6.0 g/L CMC concentration, indicating no further improvement. This reinforces the notion that higher concentrations of CMC do not significantly enhance stability compared to the optimal concentration of 6.0 g/L. Overall, the observations in Figure 6a,b highlight the concentration-dependent effect of CMC on foam stability with an optimal concentration of 6.0 g/L.

Furthermore, it was observed that the optimal concentration of CMC is comparatively higher than the optimal concentration of PAC to maximize the AAES foam stability. This can be attributed to several factors, including the molecular weight,
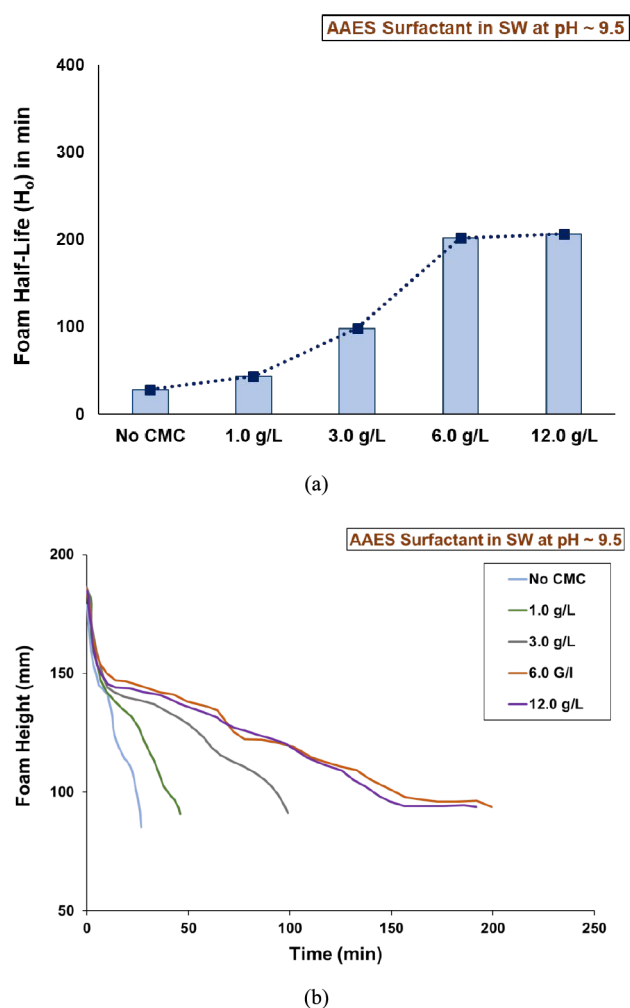
structure, solubility, and hydration properties of the respective polymers. The tested CMC has a relatively lower molecular weight compared to PAC. Polymers with higher molecular weight tend to exhibit increased chain entanglement and stronger interactions with water molecules, resulting in higher viscosity at lower concentrations. Thus, the lower molecular weight of the CMC may necessitate a higher concentration to achieve comparable viscosity levels. In addition, the structural and chemical compositions of the polymers play a crucial role in their viscosity-building capabilities. CMC is a cellulose derivative modified with carboxymethyl groups, and PAC is derived from cellulose through chemical modification of cellulose fibers. These structural differences lead to variations in their interactions with water and the formation of a three-dimensional network. Consequently, the ability of the polymer to build viscosity at different concentrations can be influenced by these structural disparities. Lastly, the solubility and hydration characteristics of the polymers affect their ability to interact with water molecules and form a viscous solution. PAC exhibits favorable solubility and hydration properties. However, due to its lower solubility and slower hydration kinetics, CMC may require higher concentrations to attain comparable viscosity levels.

Liquid Drainage. The results presented in Figure 7 demonstrate the effect of varying CMC concentrations on
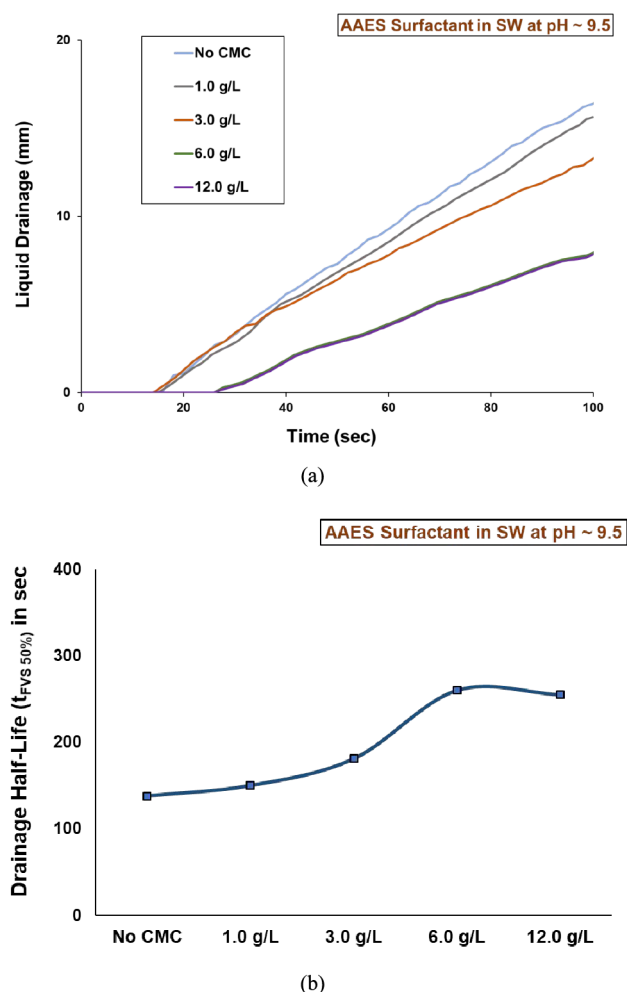

(a)

(b)

Figure 7. Liquid drainage of AAES foam at different CMC concentrations including (a) drained liquid volume over time and (b) drainage half-life.

the rate of liquid drainage from AAES foam and the corresponding drainage half-life ($t_{FLS50\%}$). The graphs show that different CMC concentrations result in different gradients of liquid drainage. Notably, both the CMC concentrations of 6.0 and 12.0 g/L demonstrate nearly identical lowest drainage gradients, suggesting a higher liquid content in the foam and a reduced rate of liquid drainage (see Figure 7a). This leads to an extended half-life of the bubbles. These findings are further supported by Figure 7b, which illustrates that increasing the CMC concentration prolongs the drainage half-life of the AAES foam. Specifically, the 6.0 g/L CMC concentration demonstrates the highest drainage half-life, almost identical to that of the 12.0 g/L CMC concentration. This suggests that CMC polymer foam at a concentration of 6.0 g/L exhibits an enhanced capacity to retain liquid within its structure, contributing to improved foam stability. These observations highlight the hydrophilic nature of the CMC polymer and its favorable interactions with the liquid phase, which enable the foam to retain liquid and enhance stability. In the light of this, the concentration of 6.0 g/L of CMC shows the most favorable balance among surface activity, viscosity, and viscoelasticity, resulting in optimal foam stability and a longer foam half-life.

Foamability and Bubbles' Structure. Figure 8 illustrates the initial volume of foam and bubble count after foaming at
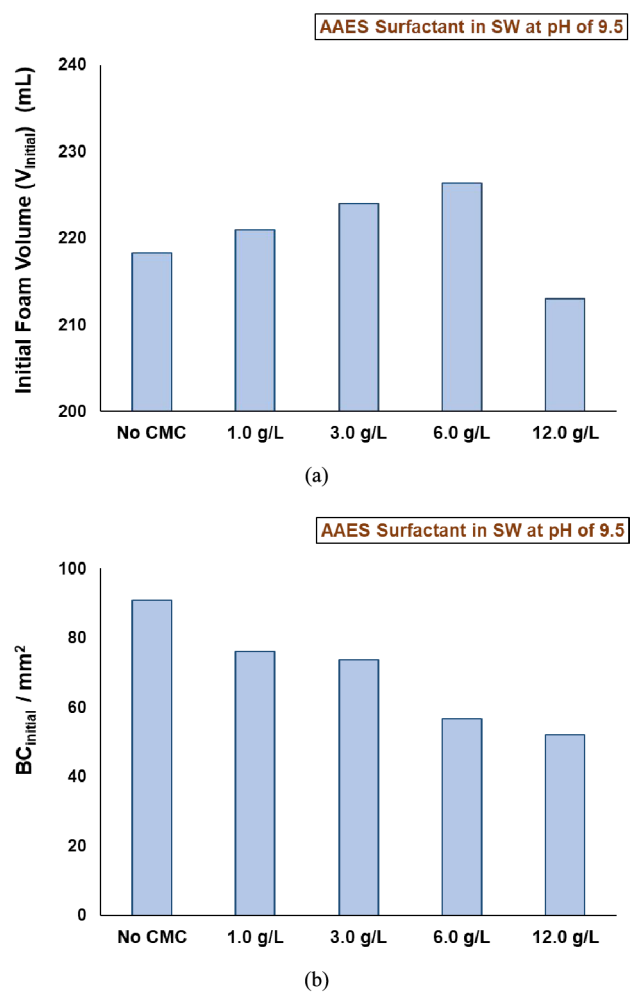

(a)

(b)

Figure 8. Foamability of AAES foam at different CMC concentrations including (a) initial foam volume $V_{Initial}$, (b) initial bubble count $BC_{Initial}/mm^2$.

different concentrations of CMC. A slight upward trend was observed in the initial foam volume ($V_{Initial}$) with increasing CMC concentration, up to a CMC concentration of 6.0 g/L. However, unexpectedly, the foam volume substantially decreased when the CMC concentration was raised to 12.0 g/L, dropping below the reference case (see Figure 8a). These observations can be explained by the influence of the CMC on foam stability and bubble formation. At lower CMC concentrations, the presence of CMC molecules enhances the foam stability by strengthening the liquid films between the bubbles. This results in an increase in the initial foam volume as more bubbles can be accommodated within the foam structure. However, at higher CMC concentrations (12.0 g/L), a different phenomenon occurs. The excessive concentration of CMC molecules leads to an increased viscosity of the liquid phase, impeding the efficient formation and stabilization of bubbles. This higher viscosity restricts the mobility of liquid films, making it more difficult for bubbles to coalesce and grow. As a result, the initial foam volume decreases, deviating from the trend observed at lower CMC concentrations.

The addition of CMC to the AAES foams also resulted in a notable decrease in the initial bubble count compared to that

of the reference case without any polymer (see Figure 8b). This reduction in bubble count became increasingly significant at CMC concentrations of 6.0 and 12.0 g/L. Moreover, the bubbles exhibited a prolonged rounded appearance at these concentrations, as observed in Figure 9. The presence of a
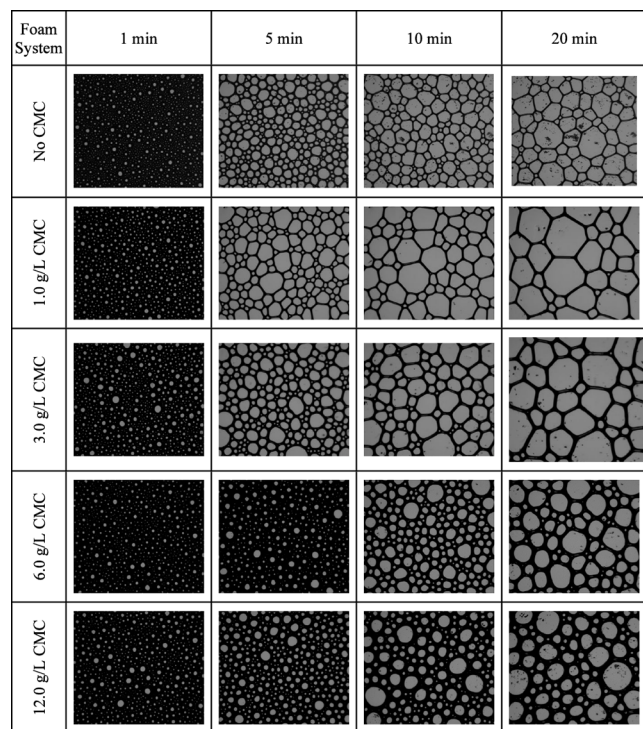

Figure 9. Captured images of bubble structure of AAES foam at different time intervals for different CMC concentrations (foam bubbles are in gray while the liquid film is in black).

thicker lamella between the foam bubbles in these cases allowed for greater liquid retention compared to lower CMC concentrations at the same time lapse. This suggests that the addition of CMC introduces a higher viscosity to the liquid phase, resulting in the formation of a thicker lamella. This enhanced viscosity hinders the coalescence and mobility of bubbles, leading to a lower bubble count. Additionally, the thicker lamella allows for greater liquid retention, contributing to the rounded appearance of the bubbles and the prolonged maintenance of this shape.

3.1.3. Drilling Additive (III): Starch. Starch, a complex carbohydrate derived from plant sources like corn, wheat, and potatoes, finds widespread use across various industries, including drilling engineering.[30] Within the field of drilling engineering, starch serves primarily as a fluid-loss control agent in drilling fluids, playing a crucial role in minimizing the loss of drilling fluid into the drilled formation.[30] As drilling fluid is injected into the wellbore, it forms a protective filter cake on the wellbore walls, preventing the escape of fluid. Starch facilitates the formation of a thin and impermeable filter cake, effectively reducing fluid loss and ensuring that the drilling fluid maintains its desired properties.[41] Additionally, starch is often favored in drilling operations due to its environmentally friendly attributes and biodegradability. It can be readily decomposed by natural processes, thereby minimizing its impact on the environment. In this study, the impact of varying

concentrations of starch ranging from 1.0 to 4.0 g/L was tested on the bulk properties of AAES foam.

Foam Stability. Figure 10a presents the impact of starch addition on the stability of the AAES foams. The introduction
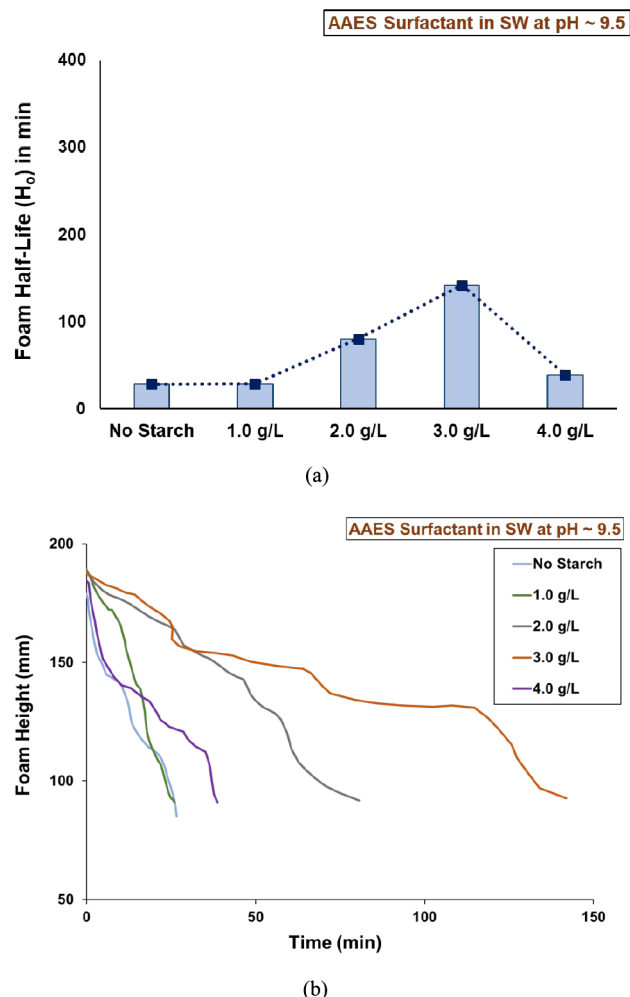

Figure 10. Evaluation of foam stability in an AAES-based foaming solution with varying concentrations of starch polymer, depicted in terms of (a) bubbles' half-life and (b) foam height over time (captured at each system's respective half-life).

of 1.0 g/L starch did not noticeably enhance the foam's half-life. However, doubling the starch concentration to 2.0 g/L significantly improved the bubbles' half-life, reaching nearly three times the value of the starch-free reference case. Further increasing the starch concentration to 3.0 g/L led to the maximum observed foam stability, with a foam half-life exceeding 140 min. However, surpassing this concentration limit, specifically at 4.0 g/L, resulted in a reduction of the foam's half-life by approximately 100 min. Additionally, the pure AAES foam exhibited a rapid decline in foam height, whereas the use of starch mitigated the rate of the foam volume decrease (Figure 10b). The concentration of 3.0 g/L demonstrated the lowest decline gradient, followed by the concentration of 2.0 g/L. Notably, the addition of starch at concentrations of 1.0 g/L and 4.0 g/L did not significantly enhance the foam height decline gradient compared to the starch-free reference case.

These observations can be explained by the interactions between starch and the foam system. Starch acts as a stabilizing agent due to its ability to adsorb onto the gas−liquid interface, forming a protective layer that hinders bubble coalescence and prolongs the half-life of the foam. The improvement in foam stability with an increasing starch concentration up to 3.0 g/L can be attributed to the greater availability of starch molecules for adsorption at the interface, leading to enhanced film formation and stabilization. However, beyond the optimal concentration of 3.0 g/L, an excess of starch may disrupt the delicate balance of the foam system, resulting in a reduced stability and a decrease in foam half-life. The observed reduction in the rate of foam height decline with starch addition is consistent with the protective film formed by starch, which slows the coalescence of the bubbles within the foam structure, thereby preserving the foam volume. The concentration of 3.0 g/L stands out as the most effective among the tested concentrations, providing the longest foam half-life and the highest level of stability.

Liquid Drainage. Figure 11 displays the liquid drainage rate from the AAES foam structure over time at various starch concentrations along with the corresponding drainage half-life ($t_{FLS50\%}$). The results reveal that different starch concentrations in the solution did not lead to significant variations in the

Figure 11. Liquid drainage of AAES foam at different X-Gum concentrations including (a) drained liquid volume over time and (b) drainage half-life.

gradients of liquid drainage. The lowest drainage gradient was observed at a starch concentration of 3.0 g/L compared to the other cases with different starch concentrations (Figure 11a). This narrow range of changing liquid drainage gradients suggests that the addition of starch did not effectively slow down the liquid drainage in the AAES foam system. These findings support the notion that the impact of starch on the foam structure primarily stems from the adsorption of starch onto the foam bubbles and the delay in film rupture between drops/bubbles due to the Ostwald ripening effect, rather than directly affecting the rate of liquid drainage from the foam structure. This observation is consistent with the measurements presented in Figure 11b, which demonstrate that starch did not yield a significant difference in the drainage half-life across all of the tested concentrations.

It is important to highlight that under mildly alkaline testing conditions, starch was not completely dissolved but rather dispersed in the AAES solution. This dispersion can be attributed to the interaction between starch and surfactant molecules as well as the structural changes induced by the alkaline conditions. Starch is composed of long chains of glucose molecules held together by hydrogen bonds.[42] In the presence of an ionic surfactant solution (e.g., AAES), where positively charged cations are present, the surfactant molecules are attracted to and interact with the negatively charged sites on the starch molecule. This interaction may have resulted in the formation of complexes between starch and surfactant, causing starch to aggregate and suspend instead of dissolving. Additionally, the alkaline conditions at high pH levels further affect the solubility of starch. The hydroxide ions present in the alkaline solution can disrupt the hydrogen bonds within the starch structure, leading to structural changes such as swelling or gelatinization.[43] These changes make starch less soluble and more likely to form a dispersion rather than dissolve completely. This condition may have influenced the ability of starch to significantly improve the liquid drainage rate of AAES foams.

Foamability and Bubbles' Structure. Figure 12 depicts the impact of different starch concentrations on the initial volume of foam and bubble count following the foaming process. When 1.0 g/L starch was added to the AAES system, there was an approximate 6% increase in the initial foam volume. However, as the starch concentration increased from 1.0 g/L to 4.0 g/L in one-gram increments, the initially generated foam volume decreased (see Figure 12a). This can be attributed to the presence of suspended starch particles in the base liquid solution, which increases the solids content within the liquid film and consequently reduces the initial foam volume.

Moreover, there were no significant discrepancies observed in the initial bubble count among the tested foams with varying starch concentrations compared to the starch-free foam (see Figure 12b). This finding is further supported by the visual evidence presented in Figure 13, which demonstrates that the bubble structure of the starch-based foams closely resembled that of the reference case without starch. Furthermore, the images clearly indicate that the starch-based foam bubbles turned into a polyhedral structure so rapidly, suggesting a drier foam, where a significant amount of liquid had drained out of the foam structure. In contrast, the PAC and CMC-based foams exhibited distinct bubble characteristics in terms of their appearance.

3.2. Impact of Liquid Base Viscosity on Foaming. The viscosity of the tested AAES liquid solutions with different
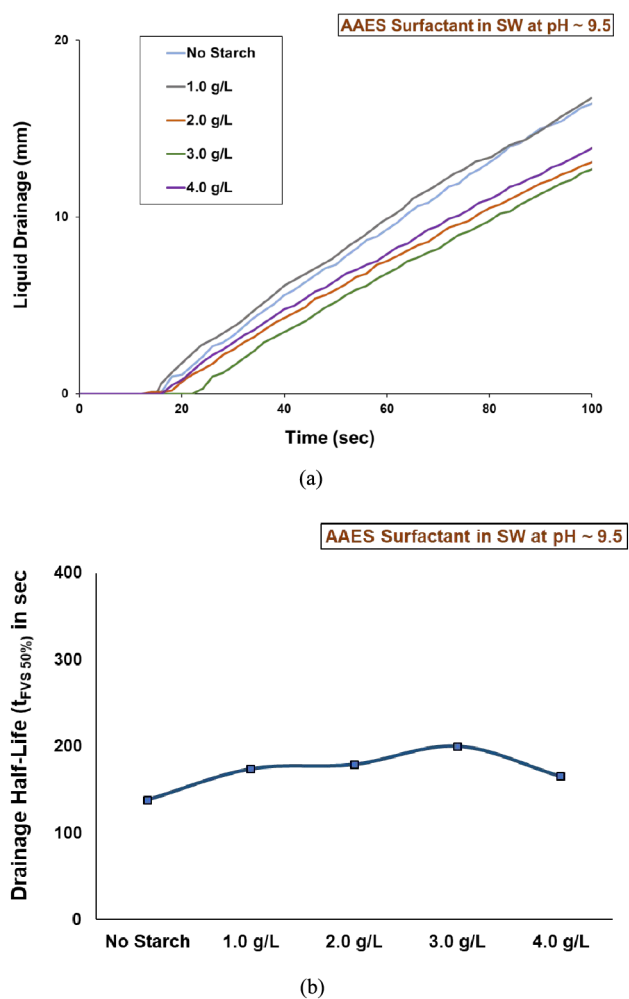
AAES Surfactant in SW at pH of 9.5

(a) Initial Foam Volume $V_{Initial}$ (mL) vs starch concentration (No Starch, 1.0 g/L, 2.0 g/L, 3.0 g/L, 4.0 g/L)

AAES Surfactant in SW at pH of 9.5

(b) $BC_{Initial}$ / mm^2 vs starch concentration (No Starch, 1.0 g/L, 2.0 g/L, 3.0 g/L, 4.0 g/L)
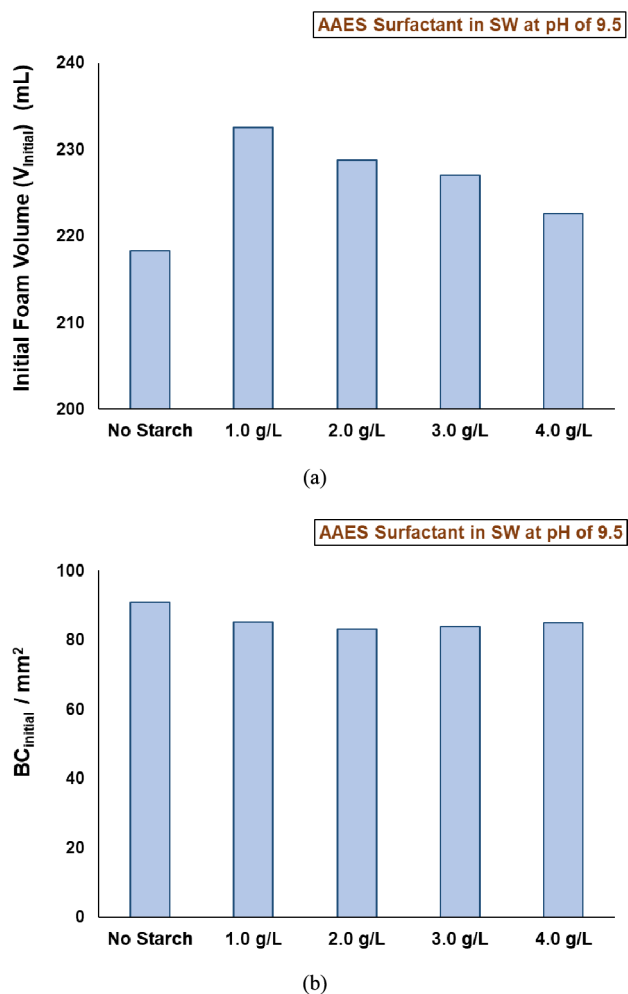
Figure 12. Foamability of AAES foam at different starch concentrations including (a) initial foam volume $V_{Initial}$, (b) initial bubble count $BC_{Initial}/mm^2$.

Figure 13. Captured images of bubble structure of AAES foam at different time intervals for different starch concentrations (foam bubbles are in gray while the liquid film is in black).

Figure 14. Viscosity measurements of the tested AAES liquid base solutions under ambient conditions.

drilling additives, including PAC, CMC, and starch, was evaluated at their respective optimal concentrations (Figure 14). The results demonstrated that the starch-AAES foaming solution exhibited viscosity at different shear rates (ranging from 60 to 600 s^{-1}) comparable to that of the reference solution containing only AAES surfactant. Conversely, the addition of PAC and CMC significantly increased the viscosity of the AAES liquid solution, with PAC-AAES solution exhibiting the highest viscosity.

These viscosity observations align with the findings from the foaming testing stage discussed earlier. It was observed that both PAC and CMC enhanced foam stability, as indicated by the longer bubbles' half-life, compared to starch at their respective optimal concentrations. The disparities in foam stability can be attributed to the molecular structures and interactions of the drilling additives with the surfactant system. PAC and CMC possess long, flexible chain structures with high molecular weights, promoting their affinity for surfactant molecules due to their polar and hydrophobic regions. This enables their effective adsorption onto the air−water interface, creating a cohesive and elastic film that stabilizes the foam. Furthermore, the presence of CMC and PAC polymers increases the viscosity and elasticity of the liquid films between the bubbles. The higher viscosity hinders liquid drainage from the films, preventing foam collapse. The enhanced elasticity
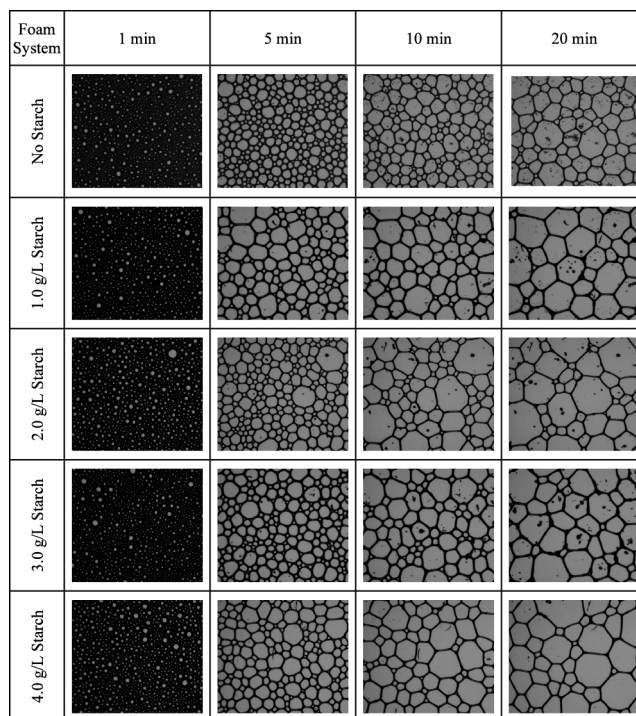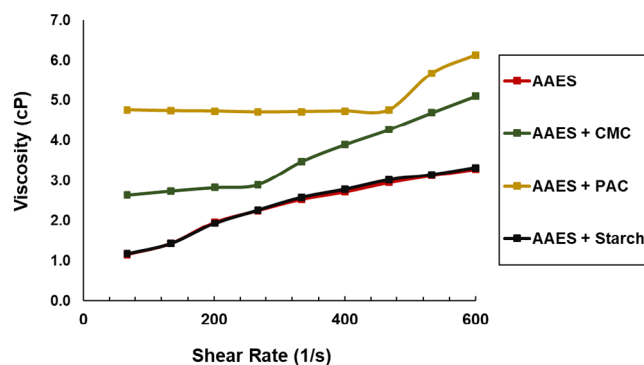
enables the films to withstand mechanical stresses and resist bubble coalescence, resulting in a more stable foam compared with starch-AAES foam, which exhibited no significant difference from the starch-free AAES solution. Moreover, the PAC-AAES system demonstrated the highest foam half-life, surpassing the CMC-AAES foam, owing to its greater increase in solution viscosity when added to the AAES solution. This increase in viscosity contributed to higher foam stability with a prolonged half-life, exceeding 300 min for PAC-AAES and approximately 200 min for CMC-AAES.

The addition of drilling additives, specifically PAC and CMC, to AAES solutions had a positive impact on both the viscosity and foam stability. The molecular properties and interactions of these agents played a critical role in stabilizing the foam structure by both slowing liquid drainage and delaying bubble coalescence. This resulted in an extended foam half-life and maintained the integrity of the liquid films between bubbles. In contrast, starch was found to be a less

effective additive for AAES foam compared with PAC and CMC. Although starch improved foam stability by adsorbing onto the bubble/liquid interface, it did not contribute to reducing liquid drainage from the foam structure, leading to lower foam stability.

It is crucial to acknowledge the intricacies involved in evaluating foam characteristics, which are profoundly influenced by diverse variables, such as testing conditions, surfactant type, water composition, and surfactant concentration. To the authors' knowledge, the utilized surfactant, particularly under mildly alkaline conditions (pH = 9.5) with a specific salt mixture in synthetic seawater, lacks prior exploration in literature. Given the potential for divergent outcomes arising from these variations, careful consideration must be given to the context in which the study is situated.

Furthermore, the foaming method employed plays a pivotal role, with different techniques, including shaking, rotational, or injection methods, yielding significantly distinct results. This study addressed this challenge by employing a state-of-the-art dynamic foam analyzer, providing a standardized benchmark for future comparisons across various foaming systems. Consequently, the authors recommend either reproducing the presented data or conducting comparative analyses with other studies. To enhance the scientific rigor and significance of such comparisons, it is imperative to meticulously replicate the experimental setup specifications and components of the foaming system, including the water type and pH environment. This approach ensures a basis for reasonable comparisons and contributes to the establishment of scientific coherence in the evaluation of foam characteristics.

4. CONCLUSIONS

In this study, foaming properties including foam stability, foamability, and bubble structure of ammonium alcohol ether sulfate (AAES) were examined using a state-of-the-art dynamic foam analyzer (DFA 100) under ambient conditions. The study aimed to assess the potential of the AAES surfactant as a viable foaming agent for foam drilling in typical drilling environments by analyzing foam properties at elevated pH levels. Additionally, the impact of drilling additives, specifically polyanionic cellulose (PAC), carboxymethyl cellulose (CMC) polymers, and starch, on the bulk characteristics of AAES foams was considered. The key findings of the study can be summarized as follows:

1. The foam's half-life was significantly extended by using an optimal concentration of PAC (1.5 g/L) compared to CMC (6.0 g/L). PAC foam lasted more than 300 min, whereas CMC foam lasted approximately 200 min.

2. The stability of AAES-starch foams was improved by adding starch, even when it was dispersed rather than dissolved. The longest half-life (140 min) was achieved with a starch concentration of 3.0 g/L.

3. Increasing the PAC concentration did not result in a significant increase in foam volume. CMC initially increased foam volume, but at 12.0 g/L, it dropped below the volume of CMC-free foam. Starch addition increased foam volume by approximately 6%, but higher concentrations had the opposite effect.

4. The introduction of PAC and CMC reduced the number of bubbles, leading to a wetter foam with thicker lamella and higher liquid retention due to increased viscosity.

5. Starch addition influenced foam structure by adsorbing onto bubbles and delaying film rupture, resulting in a drier foam with a polyhedral structure. However, it did not effectively slow down liquid drainage.

The novelty of this research project is rooted in the evaluation of a novel surfactant's compatibility with saline water within high-pH environments, replicating conditions encountered in underbalanced foam-drilling scenarios. Currently, the literature lacks substantial insights into foam stability under such specific conditions, raising questions about the practicality of many reported foaming agents. This study aims to address this gap, potentially redefining industry standards for field applications. Furthermore, it places a strong emphasis on sustainability by exploring the use of eco-friendly foaming agents and additives, as well as the substitution of precious freshwater with more readily available seawater, reflecting contemporary concerns about resource conservation.

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A.G. contributed to formal analysis, investigation, data curation, and writing—original draft. S.E. contributed to conceptualization, methodology, and writing—review and editing. A.F.I. contributed to resources and writing—review and editing.

Notes
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■ NOMENCLATURE

AAES	ammonium alcohol ether sulfate
$BC_{Initial}$	initial bubble count per mm^2
PAC	polyanionic ellulose
CMC	carboxymethyl cellulose
FLS	foam liquid stability
FVS	foam volume stability
Ho	foam half lifetime
PAC	polyanionic cellulose
$t_{FLS50\%}$	foam drainage half-life time
UBD	underbalanced drilling
$V_{initial}$	Initial oam olume

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