

AQUEOUS-BASED FOAM FLUIDS FOR UNDERBALANCED DRILLING APPLICATIONS

BY

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*Dedicated to my beloved family for their continued love and support through my life
journey.*

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LIST OF ABBREVIATIONS

AAES	Ammonium alcohol ether sulfate
BC_{initial}	Initial bubble count
CMC	Carboxymethyl Cellulose Sodium
DI	De-ionized
FLS	Foam liquid stability
FQ	Foam quality
FVS	Foam volume stability
FW	Formation water
H₀	Initial foam height
PAC	Polyanionic cellulose
ppg	Pound per gallon
SW	Sea water
t_{FLS 50%}	Foam drainage half-life time
t_{FVS 50%}	Foam half-life
TDS	Total dissolved solids
UBD	Underbalanced drilling
V_{Initial}	Initial Foam Volume
Xgum	Xanthan gum

ABSTRACT

Full Name : Ahmed Hamdy Hasan El Sayed Gowida
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Underbalanced drilling (UBD) has gained recognition as an effective alternative to conventional overbalanced drilling, addressing various operational challenges. UBD is widely utilized across multiple fields globally due to its ability to enhance rates of penetration (ROP), minimize formation damage, and reduce circulation losses, particularly in depleted and fractured formations. Foam, as a low-density drilling fluid, has become prominent in UBD due to its superior rheological properties, notably its cutting-carrying capacity. However, maintaining foam stability in high-salinity and alkaline environments, typical of downhole conditions, remains a significant challenge. This study focuses on developing a new drilling-foam formulation using eco-friendly foaming agents and additives, investigating its performance under elevated pressure and temperature conditions.

The experimental study was divided into three phases: first, screening and selecting surfactants based on their compatibility with high salinity water and mildly alkaline environments, utilizing seawater as a base liquid for the foaming solutions for the first time in drilling foam applications to overcome the scarcity of fresh water resources; second, evaluating the selected surfactants' foaming properties, including stability and rheology

under varying conditions such as surfactant concentration, water type, pressure, temperature, and foam quality; and third, assessing the impact of additives (polymers and clay solids) on foam stability, rheology, hydrocarbon tolerance, and yielding behavior, and comparing these formulations against a commercial drilling foam blend.

Among the tested surfactants, the eco-friendly foaming agent Ammonium Alcohol Ether Sulfate (AAES) showed significant tolerance to high salinity in mildly alkaline environments, making it a promising candidate for UBD applications. Key findings include that AAES demonstrated notable tolerance to high salinity and mildly alkaline conditions. Gas pressure variations significantly impacted foam stability and viscosity up to 60°C, with temperature becoming the predominant factor beyond this threshold. Polymers such as Polyanionic cellulose (PAC), Carboxymethyl Cellulose Sodium (CMC), and Xanthan gum (Xgum) substantially enhanced foam stability and viscosity, with PAC showing the most significant improvement. Clay solids, particularly Saudi bentonite, improved foam stability and viscosity. A blend of PAC and bentonite outperformed commercial blends, yielding higher viscosity, stability, and yield point. Additionally, the incorporation of PAC or bentonite increased foam resistance to hydrocarbon contamination. The study concludes that an eco-friendly polymer combined with locally sourced Saudi bentonite clay enhances the performance of AAES foam, demonstrating significant potential for UBD applications and surpassing the performance of existing commercial blends.

ملخص الرسالة

الاسم الكامل: أحمد حمدي حسن السيد جويده

عنوان الرسالة: السوائل الرغوية على أساس مائي لتطبيقات حفر الآبار بضغط تحت التوازن.

التخصص: هندسة البترول

تاريخ الدرجة العلمية: مايو ٢٠٢٤

حفر الآبار بضغط تحت التوازن (UBD) قد اكتسب اعترافاً كبديل فعال لطرق الحفر التقليدية بضغط فوق التوازن، حيث يعالج مختلف التحديات التشغيلية. يتم استخدام UBD على نطاق واسع في مجالات متعددة عالمياً نظراً لقدرتها على تعزيز معدلات الحفر (ROP)، وتقليل الأضرار التي تلحق بالطبقات، وتقليل فقدان سائل الحفر، خاصة في الطبقات ذات الضغوط المنخفضة والمستهلكة والتي يوجد بها انشاقات ذات نفاذية عالية. أصبح الرغوة، كسائل حفر منخفض الكثافة، بارزة في UBD بفضل خصائصها اللزوجة المرتفعة، لا سيما قدرتها على حمل الصخور المحفورة. ومع ذلك، يبقى الحفاظ على استقرار الرغوة في البيئات عالية الملوحة والقلوية، وهي ظروف مماثلة لما يوجد أسفل البئر، تحدياً كبيراً. يركز هذا البحث على تطوير تركيبة جديدة لرغوة الحفر باستخدام عوامل رغوية ومضافات صديقة للبيئة، مع التحقق في أدائها تحت ظروف الضغط ودرجة الحرارة المرتفعة.

تم تقسيم الدراسة التجريبية إلى ثلاث مراحل: أولاً، فحص واختيار المواد الفعالة بناءً على توافقها مع الماء عالي الملوحة والبيئات معتدلة القلوية، باستخدام مياه البحر كسائل أساسي لتكوين الرغوة لأول مرة في تطبيقات رغوة الحفر للتغلب على ندرة موارد المياه العذبة؛ ثانياً، تقييم خصائص الرغوة للمواد الفعالة المختارة، بما في ذلك الاستقرار واللزوجة تحت ظروف متغيرة مثل تركيز المادة الفعالة المسببة للرغوة، الضغط، درجة الحرارة، وجودة الرغوة؛ وثالثاً، تقييم تأثير المضافات (البوليمرات والمواد الصلبة الطينية) على استقرار الرغوة، ولزوجتها، وتحمل الهيدروكربونات، ومقارنة هذه التركيبات مع مزيج رغوة حفر تجاري.

من بين المواد الفعالة المسببة للرغوة التي تم اختبارها، أظهر عامل الرغوة الصديق للبيئة أمونيوم إيثار سلفات الكحول (AAES) تحملاً كبيراً للملوحة العالية في البيئات معتدلة القلوية، مما يجعله مرشحاً واعدًا لتطبيقات UBD. تشمل النتائج الرئيسية أن AAES أظهر تحملاً ملحوظاً للملوحة العالية والبيئات معتدلة القلوية. طبقاً للنتائج فإن تأثيرات تغيرات ضغط الغاز كانت كبيرة على استقرار الرغوة ولزوجتها حتى 60 درجة مئوية، مع ظهور درجة الحرارة كعامل رئيسي بعد هذا الحد في التحكم بخصائص الرغوة. البوليمرات مثل PAC و CMC و Xgum عززت بشكل كبير من استقرار الرغوة ولزوجتها، مع إظهار PAC لأكبر تحسن. المواد الصلبة الطينية، وخاصة البنتونيت سعودي المصدر، حسنت من استقرار الرغوة ولزوجتها. مزيج من PAC والبنتونيت تفوق على الخلطات التجارية، محققاً لزوجة أعلى، واستقراراً في تركيبات الرغوة. بالإضافة إلى ذلك، زيادة مقاومة الرغوة للتلوث بالهيدروكربونات عند إضافة PAC أو البنتونيت. خلصت الدراسة إلى أن بوليمراً صديقاً للبيئة، مع الطين البنتونيت المستخرج محلياً في السعودية، يعزز من أداء رغوة AAES، مما يظهر إمكانية كبيرة لتطبيقات UBD ويتفوق على أداء الخلطات التجارية الموجودة.

CHAPTER 1

INTRODUCTION

1.1 Background

Drilling oil and gas wells involves the injection of a drilling fluid into the borehole to circulate the drilled cuttings out to the surface. In addition to hole cleaning, the drilling fluid is used to provide hydrostatic pressure to balance the formation pore pressure (Sloan et al. 1975). Overbalanced drilling (OBD) is considered the most conventional drilling technique in which the hydrostatic pressure of the drilling fluid is kept larger than the pore pressure of the formation. Conversely, underbalanced drilling (UBD) is a non-conventional drilling operation where the hydrostatic pressure of the drilling fluid is maintained below the formation pore pressure . Many advantages can be attained by UBD approach such as higher rate of penetration (ROP), minimal formation damage, minimized fluid losses especially in depleted and highly fractured formations (Salimi et al. 2010; Liang et al. 2017).

Among the low-density fluids that are used for achieving UBD conditions is foam. Foam is basically a complex dispersion of large volume of gas phase into a small volume of continuous liquid phase (Smith 1996). Foam system, in nature, is considered thermodynamically unstable unlike the conventional liquid drilling fluids (Ramadan et al.

2003a). Foam as a drilling fluid has become more popular for UBD activities due to its rheological behavior that promotes desirable properties for the drilling operation, i.e., cutting carrying capacity (Meng et al. 1996a).

It is generally accepted that the foam stability and viscosity are affected by adding some other materials (Chen et al. 2007a). These materials may include surfactants to lower the surface tension of the liquid to facilitate foaming, polymers to enhance the viscosity, stabilizers to improve the foam stability (Wang 2014a). However, drilling-foam stability and rheology are still not sufficiently investigated and understood to mitigate the risk and costs associated with foam drilling. These risks are associated to the degree to which the foam rheology and stability can be estimated under harsh conditions to provide an adequate hydraulic design of the drilling operation.

1.2 Problem Statement

Based on the literature review, foam is recognized as a promising fluid for underbalanced drilling operations. Numerous studies have explored various drilling foam formulations with different components. However, when these formulations are evaluated against industry standards, it becomes evident that many studies lack crucial information regarding the impact of salts and pH levels on these systems. Some research has only considered the effects of individual salts, such as monovalent ions (e.g., Na^+) or divalent ions (e.g., Ca^{+2}). In field applications, however, formation brine is expected to enter the wellbore under underbalanced conditions. This brine contains a mixture of salt ions, not just single ions, raising concerns about the compatibility of the foaming system under these conditions.

Additionally, the reaction of the foaming system with the inclusion of hydrocarbons into the wellbore is not well addressed. These key points remain inadequately covered in existing literature.

1.3 Research Objectives

The main objective of this research is to develop a new drilling foam formulation, preferably using either eco-friendly and local Saudi materials that can be used in harsh drilling environment provided with full foam system characterization and fulfilled the recommendations of the industry standards. First, a set of foaming agents of different types would be tested to evaluate their compatibility with high saline water as well as mildly alkaline medium. This is to decide the potential candidates for effective underbalanced drilling foams. Second, full characterization of the bulk foam properties would be provided at both ambient and evaluated pressure and temperature conditions to assess the foam bulk properties of the selected foaming agents. Third, the impact of suggested additives would be evaluated to assess their impact on the foam properties including a set of eco-friendly polymers as well as local Saudi solid clays. All the foams generated in the study will be assessed in terms of foam stability, and foam rheology under elevated conditions of pressure and temperature. A commercial drilling foam blend is used to establish a baseline for comparison and to verify the performance of the potential drilling foam candidates for field applications. To do so, the following tasks are planned:

- Different foam agents would be screened at ambient conditions for their effectiveness in high saline medium at high pH environment.

- Optimization and foam characterization of the proposed foaming agents at elevated conditions of pressure and temperature.
- Investigate the effect of adding different polymers on the foam stability and rheology.
- Investigate the effect of adding different solid clays on foam stability and rheology.
- Investigate the synergetic impact of the polymers and clays on foam bulk properties and hydrocarbon tolerance.
- Verify the proposed foaming formulations by comparing their performance against a successfully used field commercial drilling foam blend.

1.4 Thesis Proposal Organization

The structure of the thesis proposal is briefly described as follows:

Chapter 1 introduces the thesis by providing background information on underbalanced drilling using foam, followed by the problem statement and thesis objectives.

Chapter 2 offers a literature review on foam characterization and drilling foam systems, including experimental studies and field cases. It also identifies research gaps that require further investigation.

Chapter 3 describes the proposed experimental methodology, detailing the materials, experimental setup, and procedures used to investigate the foam systems.

Chapter 4 presents and discusses the results obtained in the study.

Chapter 5 summarizes the study's findings and outlines future research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 Underbalanced Drilling (UBD) Technology

Underbalanced drilling (UBD) is a non-conventional drilling operation where the hydrostatic pressure of the drilling fluid is maintained below the formation pore pressure. UBD technology has shown several advantages over the conventional overbalanced drilling methods (Shadravan et al. 2009). Thus, it is adopted as an alternative technique to effectively minimize the drilling-induced formation damage, improve the productivity of wells, eliminate the loss of circulation, increase the rate of penetration, and enhance the drilling performance (Shadravan et al. 2009). UBD technique has the potential to be applied in many downhole cases such as naturally fractured formations, depleted reservoirs, hard formations, high permeability vuggy carbonates and formations with high permeability unconsolidated or consolidated sands (Salimi et al. 2010; Liang et al. 2017).

2.2 UBD Advantages

Many advantages can be attained by applying UBD technology as described below.

Minimize Formation Damage

Drilling the borehole with low-density fluid that achieves UBD conditions would eliminate the positive pressure difference that is the main cause of the invasion of the solids and fluid into the formation and hence introduce a positive skin and formation damage (Ashraf et al. 2020).

Increase the Rate of Penetration

Hard rocks can cause low rate of penetration (ROP) and intend to increase drilling time, and hence results in higher drilling costs. In UBD, the rate of penetration could be 10 times higher than the conventional drilling (Shi et al. 2018). The increase of ROP is attributed to the reduction in the confined strength applied to the rock due to the lower bottom-hole circulating pressure (Muqeem et al. 2006). Consequently, the rock is broken more easily under the bit action and reduces operation cost by reducing the drilling time and prolonging the bit the life (Fattah et al. 2010).

Eliminate Differential Sticking and Loss of Circulation

Differential sticking takes place when the drillstring comes to rest against filter cake deposited onto the surfaces of the drilled formation due to the overbalanced conditions (Qutob 2004). In UBD, the hydrostatic pressure is less than formation pressure and hence no filter cake build-up. Thus, the conditions for differential sticking are reduced.

Eliminate Loss of Circulation

Under conventional overbalanced-drilling conditions, the hydrostatic head of the drilling fluid may increase to the point where the formation fracture pressure is exceeded. As a result, the drilling fluid may flow into the induced fractures leading to loss of circulation. The situation may become much worse in case of having naturally fractured zones, low-

pressure, or high permeability reservoirs where it would be more costly to drill overbalanced since expensive drilling fluids would be lost downhole (Qutob 2004). On the other hand, the potential for lost circulation may be reduced by applying UBD whereby large volumes of the drilling fluid can be saved and the need to expensive Lost circulation material (LCM) additives can be avoided (Leslie et al. 2002).

2.3 UBD Drilling Fluid Systems

A wide variety of low-density drilling fluid systems have been deployed to maintain well in underbalanced condition. These fluid systems include gas (e.g., air or nitrogen), mist, foam, and gasified liquid or aerated mud (see Figure 1). These systems vary in the gas volume fraction and the corresponding equivalent circulating density (ECD) ranges they can provide as listed in

Table 1 (Fattah et al. 2010; Guo and Liu 2011; Ojha et al. 2014; Porter et al. 2018).

Table 1 – UBD drilling fluid systems: typical ECD ranges, description, and potentials for application.

Fluid System	Equivalent Density (ppg)	Description	Application Potentials
Air / Nitrogen	0.01 – 0.1	Gas as the fluid medium. No liquid intentionally added.	Extremely low formation pressure Hard Formations Not suitable in case of water influx zones
Mist	0.1 – 0.3	Fluid medium with liquid entrained in a continuous gaseous phase. Typical mist systems have less than 2.5% liquid content	Wet formations but little water influx high annular velocity
Foam	0.3 – 6.9	Two-phase fluid medium with a continuous liquid phase generated from the addition of liquid, surfactant, and gas. Typical foams range from 55% to 97.5% gas	Larger annular spaces vs air drilling Water-bearing formations
Aerated Fluid	4 - 7	Fluid medium with a continuous liquid phase to lower the hydrostatic head.	Weak formations with subnormal pressures (6 to 8 ppg equivalent mud weight)

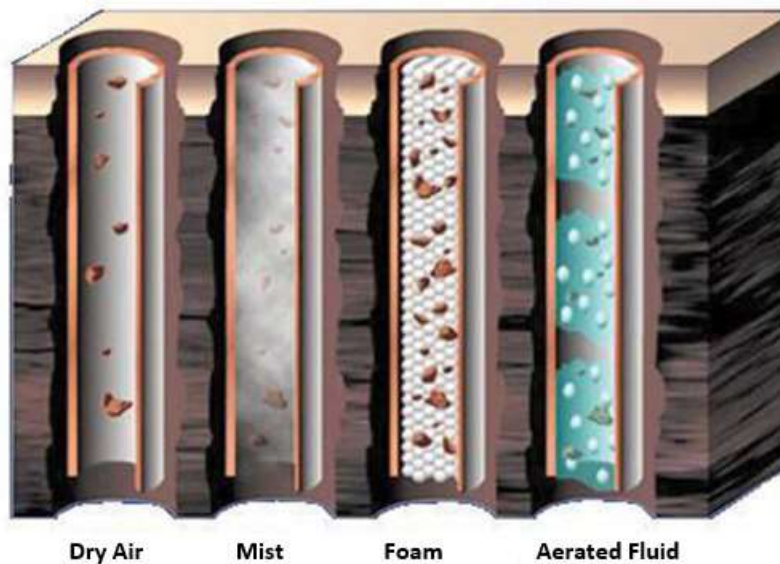


Figure 1 – A schematic representing the common UBD fluid systems (Porter et al. 2018)

2.3.1 Air Drilling

The application of air/gas drilling was introduced in the 1950s (Lavrov 2016). In particular, dry air is the most economical type of fluid drilling since it does not involve any chemicals which reduces the costs. Air drilling can accomplish the maximum rate of penetration due to the lowest specific weight of the dry air (Guo and Liu 2011). Additionally, high annular velocity in air drilling enhances hole cleaning. For effective hole cleaning, adequate air volume is usually required to achieve an annular velocity of 1000 ft per minute annular velocity, this is as a rule of thumb in practice (Okpobiri and Ikoku 1986; Guo and Rajtar 1995). This technique is restricted to zones where there is a considerable water influx in addition to the inherent possibility to downhole explosions especially in case of having natural gas influx (Fattah et al. 2010).

2.3.2 Mist Drilling

In mist drilling, compressed air or gas is pumped as a continuous phase into the borehole with a liquid such as oil or water. The mixing of liquid into the gas stream leads to the generation of mist/unstable foam. It is usually used when the rock formation starts to produce an amount of water (10 to 100 bbl/hr) during the air drilling program (Ojha et al. 2014). The addition of the liquid would saturate the cuttings which would help avoid the formation of mud rings on the wall surfaces of the drilled zones and hence prevent pipe sticking. It also can eliminate the risk of mud ring formation. Characteristics of mist-drilling can be summarized as follows (Wilkes et al. 1998):

- Similar to air drilling, but with the addition of liquid.
- Minimizes downhole fire potential

- The cutting removal rate is governed by annular velocities of fluids.
- Reduces the formation of mud rings.
- High volumes required (30% - 40% more than dry air drilling).
- Pressures are generally higher than dry air drilling.
- Incorrect air/gas-liquid ratio can lead to an abrupt increase in pressure

2.3.3 Aerated Drilling

Aerated drilling has been utilized in drilling purposes since the mid of 1930s (Lyons 2009). It involves adding compressed air into viscosified fluid or mud. The encapsulation of the compressed air into the drilling fluid leads fluid volume expansion to ultimately lower the fluid hydrostatic pressure without significantly changing the properties of the drilling fluid (Guo and Rajtar 1995). This is to eliminate the fluid loss, minimize the formation damage, and increasing the ROP (Kitsios et al. 1994; Porter et al. 2018). The mechanism of cuttings transport in the aerated fluid is based on the lifting and carrying capacity of mud fluid. Being unstable fluid, the aerated mud is not recommended for deep formations beyond 2000 m (Meng et al. 1996). Otherwise, annular flow will occur at the top section of the drilled well thereby the air will blow out losing its ability of carrying liquid and cuttings. This may promote the potential for pipe sticking as a result (Rehm et al. 2012).

2.3.4 Foam Drilling

Foam has been successfully introduced as a viable alternative with promising properties for UBD operations. Foam is typically composed of gas, liquid, and foaming agent, known as surfactants. It is defined as the dispersion of gas in a continuous liquid phase, stabilized by surfactant (Ojha et al. 2014). The gas-phase can be nitrogen, air, carbon dioxide, or

natural gas while the liquid phase could be either water for aqueous-based foams or diesel/hydrocarbon oil for non-aqueous drilling foam systems. It is characterized by high viscosity that promotes its carrying capacity and low density to achieve underbalanced conditions (Fattah et al. 2010). Foam drilling eliminates the potential formation damage that can be addressed by the conventional overbalanced method (Guo and Ghalambor 2006). Having good inherent viscosity in nature as well as fluid-loss control properties makes foam systems an attractive drilling medium inhibiting the fluid loss, formation damage and effective hole cleaning as well (Fattah et al. 2010). Hence, foam as a drilling fluid has been considered to be the scope of this study and more details on the foam chemistry and characterization would be discussed in the following sections.

2.4 Drilling Foam Fundamentals

In this section, more information is described on drilling foam chemistry, rheology and characterization reported in the literature experimental studies in addition to some field applications.

2.4.1 Foam Chemistry

Foam structure can be described as two main sections based on the liquid fraction: dry and wet foam. In the dry foam section, the bubbles of gas-phase are polyhedral and have well-defined edges, while wet foam the bubbles are more spherical and stable (Eren 2004). Thin-liquid film, known as lamellae, is normally formed between the gas bubbles. Plateau borders (PBS) defines the resulted interspace upon the approaching of three gas bubbles

(Zhou et al. 2020). Any four PBs are connected by a node as schematically depicted in Figure 2.

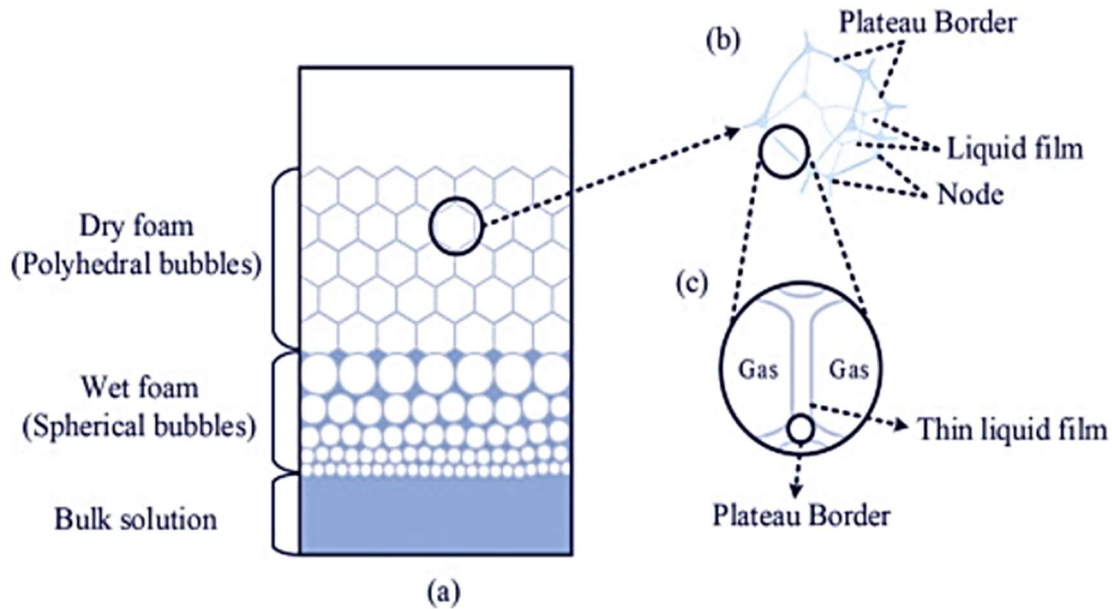


Figure 2 – Foam structure schematic (Zhou et al. 2020).

Foam is considered thermodynamically unstable and potentially separates into gas and liquid phases due to the high surface energy (Pitois et al. 2005). Literature reported three major phenomena which limited the stability of foam: liquid drainage, coarsening, and bubble coalescence (Angarska et al. 2007; Lioumbas et al. 2015). Liquid drainage plays a substantial role in the foam decay process, it decreases the liquid content of the foam, which governs the thickness of the lamella film (Saint-Jalmes 2006). It is driven by gravity and capillary pressure, where the capillary pressure drains the liquid content from foam film to plateau borders then gravity drains the liquid out of the plateau borders (Lioumbas et al. 2015). The mechanism of bubble coarsening is started when the gas diffuses through the

liquid film due to pressure difference. As a result, the large bubbles tend to become larger and the small ones tend to vanish (Zhou et al. 2020). Bubble coalescence refers to the rupture of two neighboring films. To overcome these phenomena, several chemical additives, mainly surfactants, are used to improve foam stability by increasing the liquid viscosity and developing a chain network between films to limit the liquid drainage and coarsening (Angarska et al. 2007).

2.4.2 Foaming Surfactant Fundamentals

Surface-active agent known as surfactants are amphiphilic compounds composed of a hydrophobic tail (non-polar) and a hydrophilic head group (polar) that modify the surface and interfacial properties amongst immiscible mediums (Belhajj and Al-Mahdy 2014). These molecules are oriented at the interface based on their affinity to the respective mediums. Typically, the hydrophobic tail (nonpolar hydrocarbon chain) has an affinity for the nonpolar media while the hydrophilic head has an affinity for polar media (aqueous solution, mainly water). At dilute surfactant concentrations, the surfactant molecules are oriented at the interface surface, forming a monolayer that provides an expanding force acting against the normal interfacial tension due to the adsorption of the surfactant at the interface. Therefore, surfactants have the potential to lower interfacial tension as the surface free energy is reduced (Schramm 1994). At higher surfactant concentrations, the aqueous solution tends to form micelles, which are organized on self-assemble molecular structures. Generally, micelles are oriented where the tail group cluster in the interior of the micelles, while the head parts interact with the aqueous medium through dipole-dipole or ion-dipole interactions (Schramm et al. 2000). Surfactants are classified depending on

their moiety head group into four classes as shown in . The description of these classes is summarized in Table 2.

Table 2 – Summary of surfactant classes.

Class	Definition	Examples	Ref.
Anionic	The hydrophilic part is negative when the molecule dissociates. Molecules are sensitive to salinity and zeta potential of the reservoir matrix (positive-charged: limestone)	Sodium dodecyl sulfate (SDS) Alpha-olefin sulfonate (AOS)	(Levitt et al. 2009)
Cationic	The hydrophilic part has a positive charge when the surfactant molecule dissociates. Molecules are sensitive to the salinity and zeta potential of the reservoir matrix (negatively charged: sandstone and clay).	Cetyltrimethylammonium bromide (CTAB) Dodecyl trimethylammonium chloride (DTAC)	(Xue et al. 2015)
Nonionic	The hydrophilic part has no net charge. Molecules are insensitive to changes in salinity.	Ethoxylates	(Chen et al. 2014)
Amphoteric/ Zwitterionic	The hydrophilic part has both negative and positive charges. The ionic character depends on the pH of the solution. Molecules are sensitive to the salinity and zeta potential of the reservoir matrix.	Betaine salts	(Kamal et al. 2015)

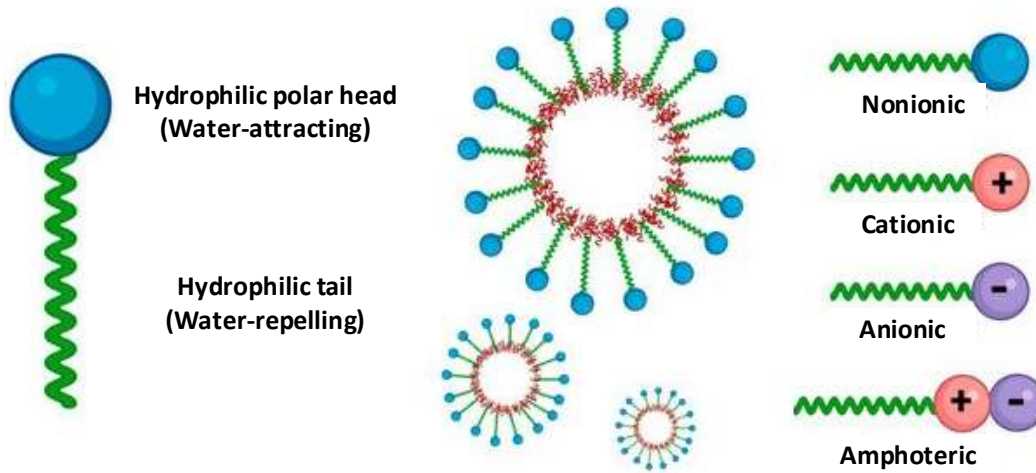


Figure 3 – Surfactant Classification based on their moiety head group.

2.4.3 Foam Characterization

Foam can be characterized by describing its quality, texture, stability, foamability and rheology as discussed below.

Foam Quality

Foam quality is a key parameter for macroscopic description of foam structure. It is defined as the ratio of the gas phase volume (V_{gas}) to the total foam volume ($V_{\text{gas}} + V_{\text{liquid}}$) as stated in Equation (2-1)

$$FQ = \frac{V_{\text{gas}}}{V_{\text{gas}} + V_{\text{liquid}}} \times 100\% \quad (2-1)$$

The required FQ is ranged between 52% and 95 % (Guo and Liu 2011). At low FQ (wet foam), the number of bubbles is less and far apart with insignificant interaction, resulting in low viscosity. On the other hand, at high FQ (dry foam), bubbles are more with

significant interaction, resulting in high viscosity (Ramadan et al. 2003b). Figure 4 shows the effect of the foam quality on the relative viscosity of the foam system. Based on the literature, there is no solid conclusion on what the foam quality value for stable foam is. Okpobiri and Ikoku (Okpobiri and Ikoku 1986) observed that foam became unstable at a quality of 94%, for shear rates below 5000 sec^{-1} . Beyer et al. (Beyer et al. 1972a) found that the foam collapsed to slug at liquid volume at a foam quality of 98%.

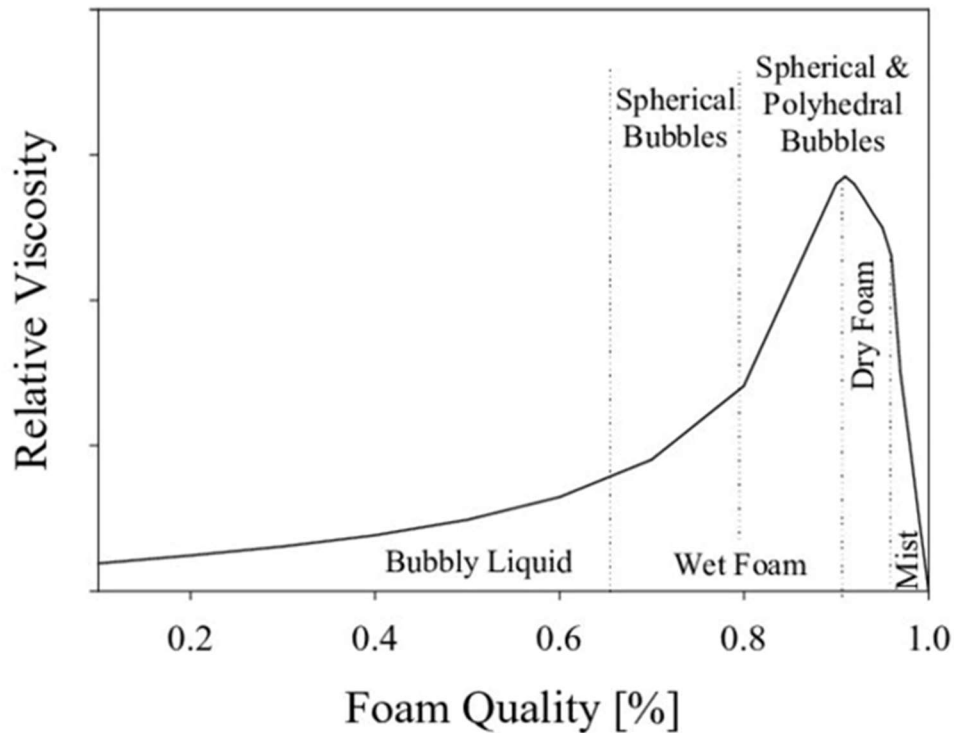


Figure 4 – Relative viscosity vs foam quality for aqueous-based foams systems (Ramadan et al. 2003).

Foam Texture

The foam texture refers the size and distribution of the bubbles. The foam bubble diameter was found to be in the range of 10 μm to 1mm (Den Engelsen et al. 2002). Foam is defined as fine-textured when the bubble size is small, while it is defined as coarse texture when the bubble size is large (Eren 2004). Fine-textured bubble leads to higher viscosity due to the increase of the interfacial area and thinner films and hence high flow resistance is achieved. The viscosity tends to be higher when the bubble size distribution is narrow, and bubbles are homogenous (Harris 1989a). Generally, Foam texture is affected by multi parameters such as concentration of surfactant, type of surfactant, pressure, injection rate, and liquid content.

Foam Stability

Foam stability is defined as the change of foam height or volume with respect to time, immediately after foam generation. Foam stability is generally affected by several parameters, i.e., pressure, temperature, solution salinity, pH of the liquid solution, type of surfactant, surfactant concentration, etc. (Ramadan et al. 2003; Ismail et al. 2013). Foam stability is basically estimated by either measuring the rest time of the bubbles or by measuring the half-life of the generated foam. The rest time of the bubbles studies the duration of existence of the bubbles that coalescence at the interface between the liquid and gas (Ghosh 2004). While foam half-life refers to the time at which foam volume has been reduced to 50% of its initial value (Kamal 2019a). When the foam is generated, there will be a potential for liquid to flow downward due to the force of gravity that destabilized the foam. An increased surface and bulk viscosity do not always increase the stability of

the foam. However, the viscous solution sometimes hinders foamability (Wang 2014). Bulk viscosity does not directly impact the film stabilization. They rather work as resistances to the film thinning and rupturing processes (Belhajj and Al-Mahdy 2014).

Aqueous-Based Foam Rheology

Generally, fluids are classified as Newtonian or non-Newtonian depending on their response to the applied shear stress. Drilling foam as two-phase mixture of gas and liquid are considered as non-Newtonian fluid in most of cases where its viscosity varies with the shear rate (Akhtar et al. 2018). Commonly accepted conclusions from the previous studies, are that low quality aqueous foams exhibit Newtonian flow property while at high qualities, they exhibit shear thinning and yielding (non-Newtonian behavior) due to development of bubble structure (Heller and Kuntamukkula 1987; Prud'home and Khan 1996). Moreover, A common observation from these studies is that polymer addition increases the rigidity of foam structure by increasing the viscosity of the liquid lamellae. This creates stiff and highly viscous foams that are stable for an extended duration (Sinha et al. 2019). The relationship between the shear rate and stress or viscosity can be described using one of the rheological models; Power-Law, Bingham, and Herschel-Bulkley models (Yield Power Law).

Power-Law Model.

This model was basically derived based on two variables parameters; consistency index, K and flow behavior index, n. those parameters are used to relate shear stress to the shear rate as stated in (Firoze 2017).

$$\tau = K\gamma^n \quad 2-2)$$

The apparent viscosity (η) is described as the ratio of shear stress to shear and is given by:

$$\eta = K\gamma^{n-1} \quad 2-3)$$

When the flow behavior index (n) is less than 1, then the fluid is defined as a shear-thinning (Pseudoplastic) fluid. The shear thinning or Pseudoplastic is a phenomenon in which the fluid viscosity decreases with increasing shear rate. When n is equal to 1, the power-law model behaves the Newtonian model where the viscosity is independent of shear rate and shear stress. The fluid behaves shear-thickening (dilatant fluid) when the n is more than 1.

Bingham Plastic Model.

Bingham plastic model is the most common model used in the drilling industry. Bingham's plastic model was derived based on two parameters include yield stress (τ_y) and plastic viscosity (μ_p) of the fluid. Initially, the fluid resists flowing till the shear stress goes beyond a certain value. Then, the fluid begins to flow, showing a linear Newtonian fluid behavior between shear stress and shear rate [75]. The shear stress-shear rate relationship is expressed as:

$$\tau = \tau_y + \mu_p\gamma \quad 2-4)$$

While the apparent viscosity is given as:

$$\eta = \frac{\tau_y}{\gamma} + \mu_p \quad 2-5)$$

Herschel-Bulkley Model.

It is also known as the yield power-law model. Initially, the fluid does not flow until the shear stress goes above the yield stress. Then, the fluid starts to flow, showing power-law fluid behavior (Chhabra and Richardson 1999). The shear-stress-shear rate relationship is expressed as:

$$\tau = \tau_y + K\dot{\gamma}^n \quad 2-6)$$

where the apparent viscosity is given as:

$$\eta = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \quad 2-7)$$

Foam rheology has been investigated by numerous experimental studies (Cawiezel and Niles 1987; Harris 1989b; Martins et al. 2000; Lourencq 2002; Chen et al. 2007b). however, the rheological behavior of foam still not fully understood. The great effort is mainly due to conflicting-observations that have been reported in many cases. It is agreed that foam rheology depends on different factors and the reported experimental results considerably vary when all these parameters are not controlled (Akhtar et al. 2018).

When foam sample was tested using a shearing coaxial rheometer or when flowing into a pipe, wall slip phenomena was found to have an effect on the measurements. This has been observed by many studies (Raza and Marsden 1967; Beyer et al. 1972b; Patton et al. 1983; Enzendorfer et al. 1995). A careful experimental procedure should therefore be followed to consider the wall slip effect. It is also experienced in several studies that plug foam may

occur upon flow in a pipe where the foam would flow only by slip at the wall with no shear (Beyer et al. 1972b; Thondavadi and Lemlich 1985).

Based on the literature, some common conclusions can be drawn in the light of the existent experimental investigation on drilling foams. Foam is usually described as a pseudoplastic fluid either with or without yield stress. Most frequently, the foam rheological behavior follows power-law (Raza and Marsden 1967; Thondavadi and Lemlich 1985; Enzendorfer et al. 1995). However, some other foam systems follow Bingham plastic law (Khan et al. 1988), or Herschel-Bulkley law (Calvert and Nezhati 1986; Harris 1989c; Burley and Shakarin 1992). There is no clear consensus on foam rheological behavior, this is due to all the different parameters that play a role and that are not always examined.

2.5 Aqueous-Based Drilling Foam Systems

A key factor in the design of any drilling foam system is basically how to maintain its properties, i.e., stability and rheology, under the harsh drilling environment and be compatible with the properties of the drilled formations, i.e., water-sensitive clays. Therefore, there are common criteria that need to be satisfied for any foam system to be a promising candidate in practice for UDB operations (IADC UBD Committee 2005; API-RP-92U 2008; Sepulveda et al. 2008). These criteria may include:

- It must exhibit foam height ranges from 350 to 550 mL and half-life of 8 - 10 min.

These properties measure the system's foaming ability and resultant foam stability.

The foam should maintain enough stability to carry the cuttings along the way up to the surface.

- It is recommended to have the water treated to make mildly alkaline, maintaining the pH in the range of 8.5-10.5.
- The foam system should effectively withstand oil-field brine, or other common contaminants that may flow into the wellbore as an influx due to the underbalanced conditions.
- Foam can be affected by low alkalinity and high salinity of the system, so control should be taken to maintain those characteristics values within the range explained above (adding soda ash and/or diluting).
- Foam should be thermally stable (up to 120 °C) and maintain its stability under different pressure conditions representing drilling of different hole-sections.
- The fluid must be compatible with common additives such as scale and corrosion inhibitors,
- Preferably, the fluid should be recyclable to minimize fluids and chemical usage.

2.5.1 Typical Drilling Foam Formulation

Foam systems can be classified into two main categories based on the system components. These are stable foam and stiff foam. Stable foam composes of the liquid phase, gas phase and foaming agent or a surfactant. While stiff foam is a foam system that contains some other chemicals in addition to the surfactant. Typical drilling foam formulation contains (Guo and Liu 2011; Guo and Meng 2021):

Gas Air, nitrogen or natural gas can be used. Air is the lowest cost available gas phase however it is corrosive to the downhole equipment due to its oxygen content which also promotes downhole explosions in case of any ignition. The usage of natural gas is also restricted gas concentration because it is flammable. Nitrogen preferably replaces air and natural gas because it is inert, non-corrosive and usually achieves the highest foam-system stability as compared to other gases. However, it may impose additional costs in case of using membrane-generated nitrogen. The gas content ranges 55% - 97%

Liquid Water (fresh or brine) may be used for aqueous-based foam system while oil, diesel, or mineral oil are used for non-aqueous foam.

Surfactant Foaming agent is added to prolong the stability of the generated foam.

Polymer Polymers are added as a viscofying agent to increase the viscosity of the foam to 35 – 155 cP. It may also be used for lubrication purposes to reduce the friction factor. Moreover, it may help chemically stabilize the wellbore.

pH Controller It is recommended in practice to maintain the pH of the drilling fluid to be at 8 – 10.5. Some chemicals may be added to the foam solution to adjust the pH value of the medium such as soda ash (Na_2CO_3), sodium hydroxide (NaOH), potassium hydroxide (KOH) (Otitigbe 2021).

Corrosion Inhibitor It is commonly added to the foam system in case of using air as a gas phase. Anionic inhibitors are more recommended due to its compatibility with foaming agents unlike the cationic inhibitors that tends to destabilize the foam system.

Shale Inhibitor According to the shale reactivity, chemicals may be added to create a sealing coat between the formation and the drilling fluid to avoid the formation from being saturated with water especially with water-sensitive clays.

2.5.2 Summary of Previous Experimental Studies

Many studies in the literature have experimentally investigated different drilling-foam systems for UBD applications using different components, i.e., surfactants, polymers, stabilizers, etc. Table 3 summarizes the aqueous-based drilling-foam systems and the testing conditions reported in the literature experimental studies that have provided information on the additives they used.

In the light of the reviewed literature, most of the studies have been conducted at ambient conditions which may introduce confusion about the performance of the foam system under in-situ conditions. As foam circulates in a wellbore, its flow properties change due to temperature and pressure. Increase in temperature at constant pressure affects the viscosity of the base liquid, and hence affecting the foam viscosity (Ramadan et al. 2003b; Chen et al. 2005). Major change in the foam rheology and stability is also expected due to pressure change. Increase in pressure would compress the gas bubbles and affect the foam quality and viscosity (Akhtar et al. 2018). In addition, the majority of the previous studies did not report information on the performance of the investigated drilling-foams at high pH conditions, which is highly recommended in drilling practice to avoid corrosion. Moreover, the stability of the drilling-foam systems should be tested against formation influxes, i.e., brine and oil. However, it is fairly covered in the reported studies. This highlights the need

to investigate the drilling foam performance at conditions that mimics that downhole harsh drilling environment and its compatibility with downhole influxes.

Therefore, the main objective of this research is to develop a new drilling foam formulation, preferably using either eco-friendly and local Saudi materials that can be used in harsh drilling environment provided with full foam system characterization and fulfilled the recommendations of the industry standards. This would help provide more comprehensive understanding on the drilling-foam system at typical downhole drilling environment. Besides, it is substantial for hydraulic and hole cleaning optimization, improvement of operational safety, cost control. And for mitigating the risks associated with the application of foam drilling.

Table 3 – Summary of the experimentally investigated aqueous-based drilling foam systems in the literature and the testing conditions.

Ref.	Formulation	Testing Conditions		Foam Quality	pH	Salt Tolerance
		Pressure	Temperature			
(Martins et al. 2000)	<i>Surfactant:</i> Kasey Colombia – Halliburton (0.5%) <i>Gas phase:</i> air	Ambient conditions		60 – 95%	✗	✓
(Suradi et al. 2015)	<i>Surfactant:</i> sodium dodecyl sulfate (anionic) <i>Gas phase:</i> air <i>Polymer:</i> Xanthan gum <i>Stabilizer:</i> styrene methacrylate	Ambient conditions		-	✗	✓
(Chen et al. 2005)	<i>Surfactant:</i> Weatherford KLEAN-FOAM (0.25%, 0.5% v/v and 1% v/v) <i>Gas phase:</i> Air <i>Polymer:</i> Hydroxyl-ethylcellulose polymer (Weatherford KLEАНVISH HEC)	25 psig	24 °C	70%, 80% and 90%	✗	✗
(Chen et al. 2007b)	<i>Surfactant:</i> commercial surfactant 1% <i>Gas phase:</i> Air <i>Polymer:</i> hydroxylethylcellulose (HEC)	Ambient conditions		70%, 80% and 90%	✗	✗

(Liu et al. 2010)	<i>Surfactant:</i> Quick Foam (AQF-2, Zone Sealant 2000) <i>Gas phase:</i> nitrogen <i>Foam stabilizer:</i> HC-2 <i>Viscosifier:</i> Xanthan, Guar Gum, Hydroxy Ethyl Cellulose (HEC), and Dris Pac <i>Weighting Material:</i> Barite, hematite, CaBr ₂ , CaBr ₂ -barite	120 psig	25 °C	80%	✗	✗
(Ismail et al. 2013)	<i>Surfactant:</i> sodium dodecyl sulfate (anionic), cetyltrimethylammonium bromide (cationic), T×100 (non ionic), and n-alkyl betaines (amphoteric). <i>Gas phase:</i> Nitrogen <i>Polymer:</i> Xanthan gum, hydroxyethyl cellulose, guar gum, and carboxymethyl cellulose	Ambient conditions		-	✓	✓
(Saxema et al. 2014)	<i>Surfactant:</i> Anionic surfactant SDS - cationic surfactant CTAB <i>Gas phase:</i> Nitrogen <i>Polymer:</i> nonionic polymer HEC	Ambient conditions		70 – 90%	✗	✗

(Saxena et al. 2017)	<i>Surfactant:</i> Anionic surfactant SDS <i>Gas phase:</i> Nitrogen <i>Polymer:</i> nonionic polymer HEC	Ambient conditions		75 - 88%	✗	✗
(Akhtar et al. 2018)	<i>Surfactant:</i> Anionic foaming agent (Howco Suds™) 2% <i>Gas phase:</i> Nitrogen	120 psig	25 °C	> 94%	✗	✗
(Yang et al. 2019)	<i>Surfactant:</i> The anionic foaming agent AD300 was provided by Aoda Petrochemical Co., Ltd. (Shandong, China) <i>Gas phase:</i> Nitrogen Foaming solution containing 0.4 wt. % AD300 and 0.3 wt.% foam stabilizer <i>Foam stabilizer:</i> (NH ₂ -SiO ₂ -12C) Janus particles	-	280 °C	80%	✗	✓
(Sinha et al. 2019)	<i>Surfactant:</i> anionic foaming agent (Howco Suds™) <i>Gas phase:</i> Nitrogen <i>Polymer:</i> (POLYPAC-R) powder,	1000 psi	24 – 149 °C	45 – 75%	✗	✗
(Obisesa et al. 2021)	<i>Surfactant:</i> an anionic surfactant (Howco-Suds) 2% <i>Gas phase:</i> Nitrogen	Ambient conditions		40 – 65%	✗	✓

* **pH** indicates whether the study investigated the effect of pH on foam stability or not

** **Salt Tolerance** indicates whether the study investigated the effect of salts on foam stability or not

CHAPTER 3

EXPERIMENTAL WORK

This chapter presents the detailed experimental work and methodology conducted in this research. The experimental study was divided into three main phases as follows:

- Phase 01: Screening of a set of selected surfactants and assess their compatibility with high salinity water as well as a mildly alkaline environment. And based on that select the suitable surfactant that is compatible with such conditions and produce clear solution without any suspensions and precipitation.
- Phase 02: Evaluating the foaming properties of the selected surfactants in terms of foam stability and rheology considering different conditions, i.e., surfactant concentration, water type, pressure, temperature and foam quality.
- Phase 03: Investigating the impact of additives, i.e., polymers and clay solids, on the foam stability and rheology as well as hydrocarbon tolerance and yielding behavior. This phase also includes Verify the proposed foaming formulations by comparing their performance against a successfully used field commercial drilling foam blend.

The materials used, and the planned procedures for the experiments are described in the following sections.

3.1 Materials

Foaming Agent A family of surfactants would be used as foaming agent for the proposed drilling foam systems. Some of these surfactants have been used in previous studies however their performance was not investigated at typical harsh drilling environment. While the others are not previously used for UBD applications based on the reported studies in the literature. The suggested surfactants for investigation, are listed in Table 4. These surfactants were selected based on the following criteria:

1. The surfactants should be commercially available.
2. The surfactants should be newly introduced to drilling foam research.
3. The surfactants should be compatible with high-salinity water (i.e., Synthetic seawater).
4. The surfactants should be water-soluble at mildly alkaline medium.

Additives A set of additives are used to promote the bulk foam properties, i.e., polymers including Polyanionic cellulose (PAC) with the commercial name of PAC-R, carboxymethyl cellulose sodium salts (CMC), and xanthan gum (X-gum) and clay solids (Saudi bentonite, vermiculite, and perlite). **Commercial Blend** A commercial drilling-foam blend has been used for comparison purposes. The collected blend has been successfully used in many field applications of foam drilling in US and China.

Gas Phase Nitrogen (N_2) was selected for the gas phase due to its widespread use in foam drilling applications (Rehm et al. 2013). **Liquid Phase** Di-ionized water (DW) and a synthetic seawater (SW): DW sourced from Ultrapure Milli-Q (18.2 M Ω cm at room

temperature) water system. A SW solution was prepared meticulously using ACS-grade salts resulting in a SW with a total salinity of 67.70 g/L, encompassing both monovalent and divalent cations as listed in Table 5. To mitigate potential corrosion risks to drilling equipment, a slightly alkaline environment is recommended. Thus, a pH buffer solution incorporating 5M Potassium Hydroxide was used to adjust the pH of the foaming solutions within the range of 9 to 10, crucial for creating a conducive environment for foam drilling while minimizing equipment corrosion. **Dead Crude Oil** to evaluate the hydrocarbon tolerance of the developed drilling-foams.

Table 4 – List of the suggested surfactants to be investigated for drilling-foam systems.

Index	Surfactant	Type
1	Ammonium Alcohol Ether Sulfate (AAES)	Anionic
2	C14-16 Alpha Olefin Sulfonate (AOS)	Anionic
3	Petrostep S-13 C-HA (C13- 3PO Sulfates)	Anionic
4	Duomeen TTM	Cationic
5	Cocoamido Propyl dimethyl betaine	Zwitterionic
6	Cocamido propyl Hydroxysultaine	Zwitterionic
7	Armavis	Zwitterionic
8	(Petrostep LME 50) betaines	Zwitterionic
9	Petrostep MME 50	Zwitterionic
10	PETROSTEP CG-50	Zwitterionic
11	Amorgel O	Nonionic at high pH
12	Ethomeen C/12	Hybrid
13	Ethodumeen T/13	Hybrid

Table 5 – Mineral compositions of the synthesized seawater.

Component Index	Composition	Synthetic Sea Water (g/L)
1	Na ₂ SO ₄	6.34
2	NaHCO ₃	0.16
3	CaCl ₂ .2H ₂ O	2.39
4	MgCl ₂ .6H ₂ O	17.64
5	NaCl	41.17
Total dissolved solids (TDS) – g/L		67.70

3.2 Foaming Sample Preparation

The foaming solutions were formulated by dissolving the foaming agent in SW using a volumetric flask and magnetic stirrer. Considering the common practice in foam applications, where surfactant concentrations typically range from 0.4 to 2 wt.% (Griffith et al. 2022). Moreover, (Gowida et al. 2024). The desired concentration of additives was then incorporated into the solution. To achieve the recommended pH range of 9-10 for foam drilling applications, droplets of a 5M KOH solution were added, and the solutions were meticulously mixed for several hours to ensure homogeneity before commencing the foaming tests.

3.3 Experimental Setup

Three main equipment have been used in this study in order to evaluate the bulk foam properties of the developed foam systems.

3.3.1 Dynamic Foam Analyzer (DFA 100)

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 bubble size. Positioned between a linear LED panel and a line sensor, the column enabled the measurement of foam height and volume. Nitrogen Gas was introduced from the bottom of the column using a 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 5 depicts a schematic representation of the DFA 100 apparatus employed in this research.

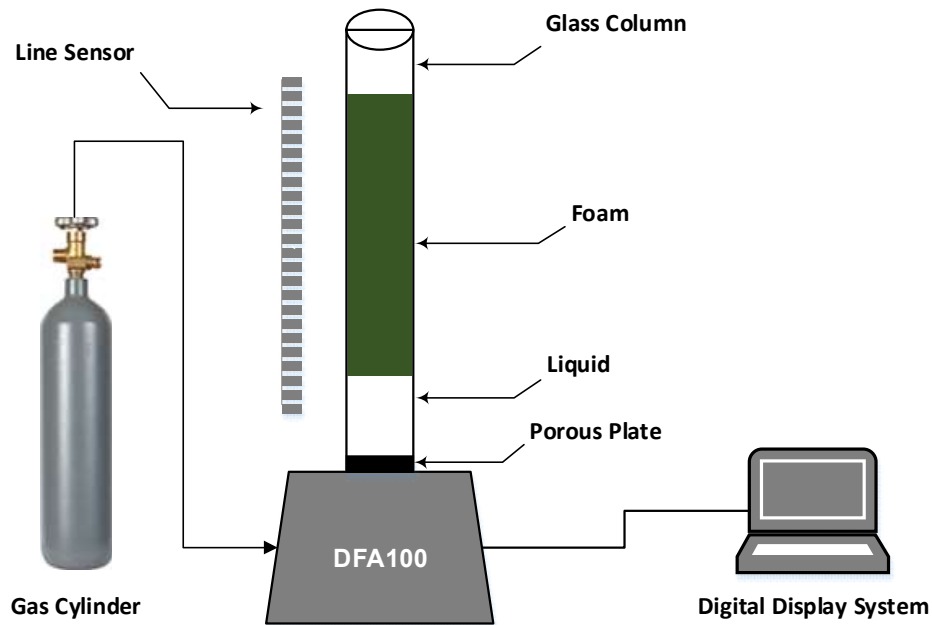


Figure 5 - A schematic illustration of the foam analyzer DFA 100 employed for assessing foam properties.

3.3.2 High-Pressure Foam Analyzer (HPFA)

A state-of-the-art High-pressure foam Analyzer (HPFA), shown in Figure 6, was utilized to assess the foam stability, structure, and bubble size of the foam at elevated pressure and temperature conditions. This sophisticated instrument comprises a high-pressure (HP) view cell for visualizing foam structure and decay, an electric heating jacket for precise temperature control, cameras, transmitted lights, and specialized prisms. It allows simultaneous measurement of foam height and structure over time through optical methods. Bubble shape and size were analyzed using high-resolution prisms. The experiment commenced with filling the HP view cell with a surfactant solution, followed by heating to the desired temperature. Once the desired temperature was achieved, the solution in the cell was partially drained to a specific level, and then the HP cell view was pressurized with N₂ to reach a pressure of 1000 psi. Foam generation occurred by pumping N₂ from the bottom through a porous plate at 50 mL/min. A back-pressure regulator was employed to manage increased pressure. Specially installed software facilitated video recording and analysis of the entire foaming and collapsing process, set with a duration of 350 minutes before automatic termination.

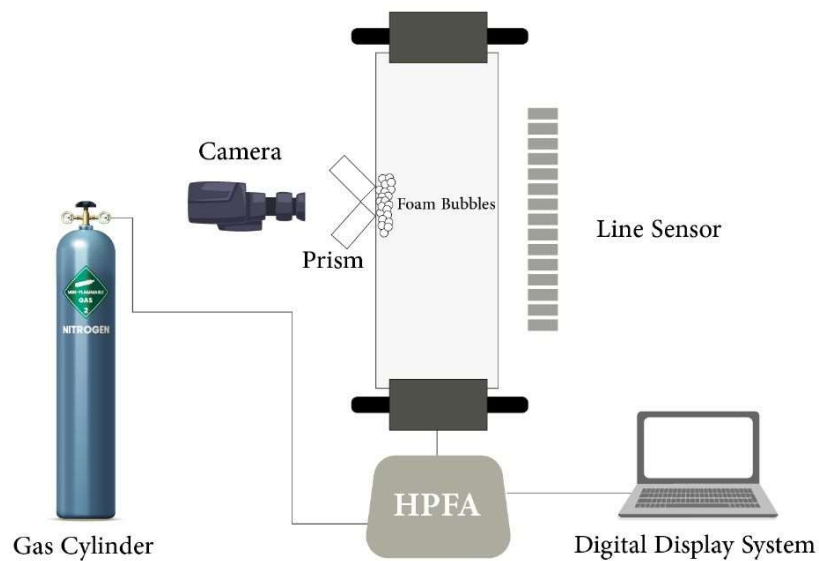


Figure 6 – A schematic illustration of the high-pressure foam analyzer HPFA employed for assessing foam properties.

3.3.3 High-Pressure, High-Temperature (HPHT) Foam Analyzer

The apparent viscosity of the foaming systems was determined utilizing an HPHT foam rheometer, depicted in Figure 7. Operating under a maximum pressure of 6,000 psi and temperatures up to 180°C, the apparatus includes a view cell with an imaging capture system for foam visualization. Gas injection is facilitated by a Quizix Q-6000-5K syringe pump with a variable flow rate of 0.001 to 400 mL/min. Foam generation takes place in a specialized foam generator filled with glass beads (120 and 200 mesh), while shear is imparted by a circulation pump adjustable from 0 to 1000 1/s. A coiled tube assesses apparent viscosity across different shear rates, with differential pressure measured by the GP:50 and Rosemount transducers. The circulation loop and foam generator components

are housed in an oven to maintain testing temperature, while manual adjustment of foam quality is achieved by separate gas or liquid injection. Experimental procedures involve loading 150 mL of surfactant solution, pressurizing the loop with N₂ gas, initiating shear for foam production, homogenizing, setting test parameters, and maintaining 75% foam quality. Automated logging records values during shear rate increments from 100 to 1,000 1/s at 15 to 40-minute intervals.

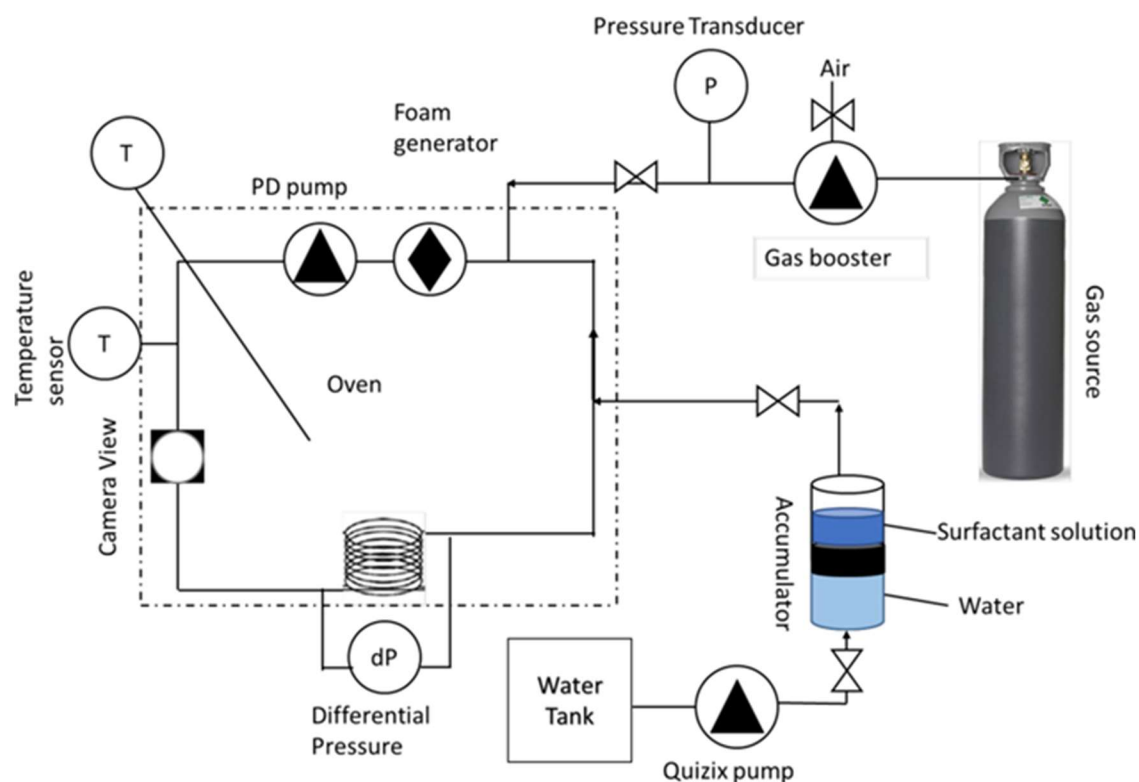


Figure 7 – A schematic of the high-pressure high-temperature (HPHT) foam rheometer used in this study.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results of the experimental work described in Chapter 3. It also presents a detailed discussion of the outcomes of the three outlined experimental phases described earlier. This chapter is divided into three main sections comprising the discussion of the results for each phase conducted.

4.1 Phase 01: Screening of Foaming Agents

A set of foaming agents has been tested at this phase to evaluate their compatibility with high-saline water, synthetic seawater, (SW) as well as mildly alkaline medium at ambient conditions. The aim was to have a completely clear solution without any suspensions or precipitates. AAES also has a privilege of being a highly degradable material and an eco-friendly additive that promotes its value for eco-friendly underbalanced drilling practices. Accordingly, only AAES foaming agent was decided to be subjected to further experimentation in this study. Figure 8 shows the foaming solutions that were prepared using the foaming agents listed in Table 4 in SW at pH of 9.5.

Table 6 summarize the status of compatibility if each foaming agent with SW and elevated pH contortions. The results showed that part of the tested foaming agents lead to a clear

solution when dissolved into SW and then turned into a non-clear solution when the pH of the solution was raised to the levels around 9.5. On another hand, another part was not compatible with neither SW nor mildly alkaline medium by resulting into a non-clear solution with either conditions. Lastly, only Ammonium Alcohol Ether Sulfate (AAES) resulted into clear solution with both SW and after adding the pH buffer featuring its potential candidacy for drilling fluid applications. AAES also has a privilege of being a highly degradable material and an eco-friendly additive that promotes its value for eco-friendly underbalanced drilling practices. Accordingly, only AAES foaming agent was decided to be subjected to further experimentation in this study.



Figure 8 – Different foaming solutions while dissolved in SW at a mildly alkaline medium.

Table 6 – Summary of the tested foaming agents and their compatibility status with SW at pH of 9.5.

Index	Surfactant Name	Type	Compatibility	
			SW	pH buffer
1	Ammonium Alcohol Ether Sulfate (AAES)	Anionic	clear	clear
2	C14-16 Alpha Olefin Sulfonate (AOS)	Anionic	clear	not clear
3	Petrostep S-13 C-HA (C13- 3PO Sulfates)	Anionic	not clear	not clear
4	Duomeen TTM	Cationic	not clear	not clear
5	Cocoamido Propyl dimethyl betaine	Zwitterionic	clear	not clear
6	Cocamido propyl Hydroxysultaine	Zwitterionic	clear	not clear
7	Armovis	Zwitterionic	not clear	not clear
8	(Petrostep LME 50) betaines	Zwitterionic	clear	not clear
9	Petrostep MME 50	Zwitterionic	clear	not clear
10	PETROSTEP CG-50	Zwitterionic	clear	not clear
11	Amorgel O	Nonionic at high pH	not clear	not clear
12	Ethomeen C/12	Hybrid	clear	not clear
13	Ethodumeen T/13	Hybrid	clear	not clear
SW it refers to the status of the foaming solution when get dissolved in synthetic seawater pH buffer it refers to the status of the foaming solutions in seawater after raising the pH to 9.5 by adding pH buffer (KOH) droplets				

4.2 Phase 02: Foaming Characterization

At this stage, the AAES foam was evaluated in terms of foam stability and rheology considering different parameters: surfactant concentration, pressure and temperature.

4.2.1 Surfactant Concentration Effect on Foaming

The tested solutions were prepared by dissolving different concentrations of AAES surfactant (0.1-2.0 wt.%) into DW and adding droplets of KOH to establish a mildly alkaline environment ($\text{pH} \sim 9.5$) at ambient conditions using DFA 100 setup. Figure 9 depicts the foam half-life for different AAES surfactant concentrations in the presence of N_2 . The study found that increasing the AAES concentration resulted in more stable foam. The foam was most stable at a concentration of 0.5 wt.%, and less stable foam was observed when the concentration exceeded this level. Obviously, surfactant molecules tend to cluster at the gas-liquid interface, forming a monolayer that stabilizes the foam bubbles and prevents them from coalescing and collapsing. Therefore, increasing the surfactant concentration in the liquid solution increases the number of surfactant molecules available to adsorb at the gas-liquid interface. This leads to a decrease in surface tension and an increase in foam stability because more surfactant molecules can form a denser and more cohesive monolayer at the liquid-air interface (plateau border) as shown in Figure 10. However, beyond a certain point, adding more surfactant to the solution may lead to a

decrease in foam stability. This can be explained as, at very high concentrations, surfactant molecules can start to aggregate and form micelles in the bulk liquid, reducing the availability of surfactant molecules at the gas-liquid interface and decreasing the ability of the surfactant to stabilize the foam bubbles. These results agree with the observations of several previous studies (Wang and Mulligan 2004; Wang 2014b; Jones et al. 2016; Majeed et al. 2020) who found that the stability of foam decreases at higher concentrations than a certain limit due to the excess molecules of surfactant within the foaming system. The excess of surfactant molecules increases the gravitation impact on foam drainage, which results in more liquid drainage from the film formed between adjacent bubbles. This eventually ruptures the foam film resulting in bubble coalescence.

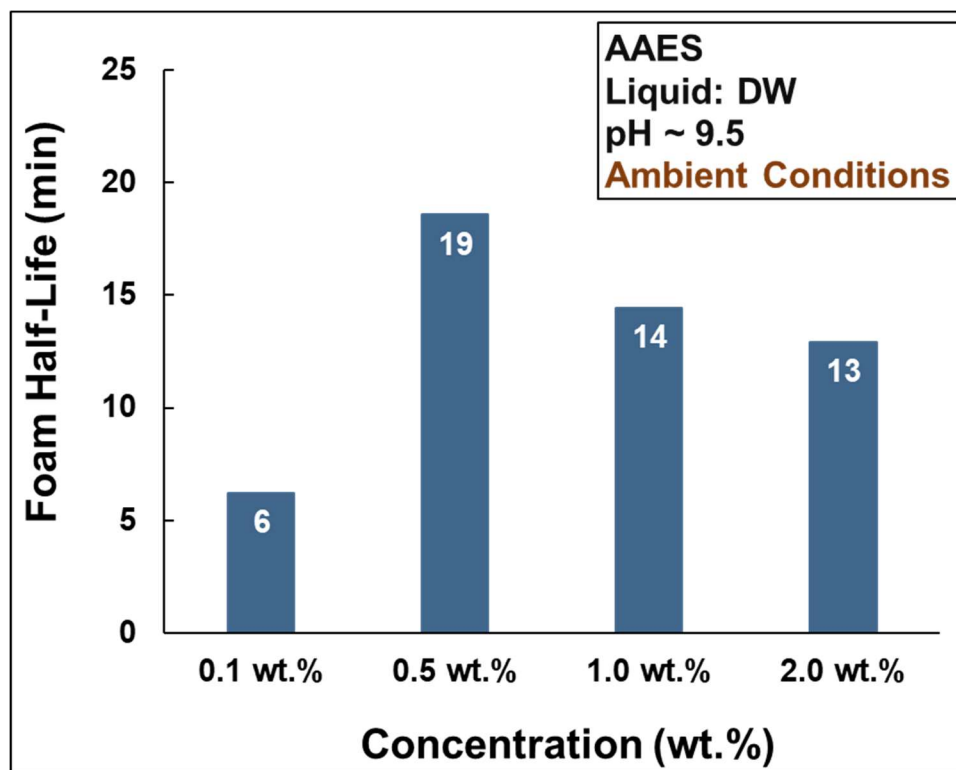


Figure 9 – Foam half-life for AAES foaming solutions with different surfactant concentrations in the presence of nitrogen and DW in a mildly alkaline environment (Using DFA 100).

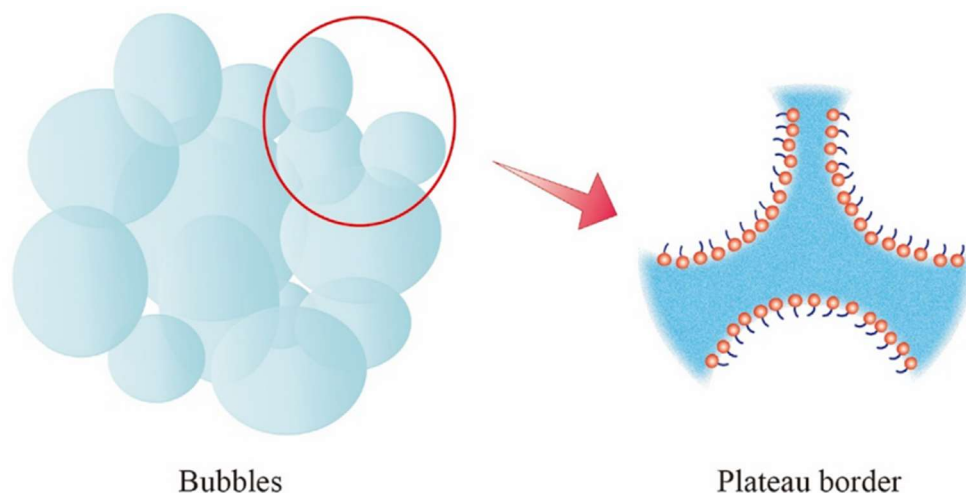


Figure 10 – Schematic diagram of morphology at air-liquid interface for the proposed AAES foam system.

Moreover, measuring the surface tension of the tested foaming solutions with air shows a steep reduction in the surface tension when the surfactant concentration increased from 0.1 wt.% to 0.5 wt.% as shown in Figure 11. However, beyond this limit, the reduction in the surface tension was not significant with increasing the surfactant concentration. Exceeding a concentration of 0.5 wt.% would likely yield minimal additional benefits in terms of surface tension reduction, potentially unjustifiably elevating the overall cost of the process. Based on the analysis of the data, 0.5 wt.% was selected to be the optimal concentration beyond which no significant change in in both the foam half-life and the surface tension was observed. The decision to adopt a 0.5% surfactant concentration as optimal was driven by the surface tension measurements in Figure 11. This concentration effectively reduces surface tension to values approaching the lowest limits while concurrently mitigating the formation of micelles in the lamella between bubbles. This precautionary measure prevents

potential destabilization of the foam structure due to an increased drainage rate, as micelles can disrupt the stability of the lamellar film.

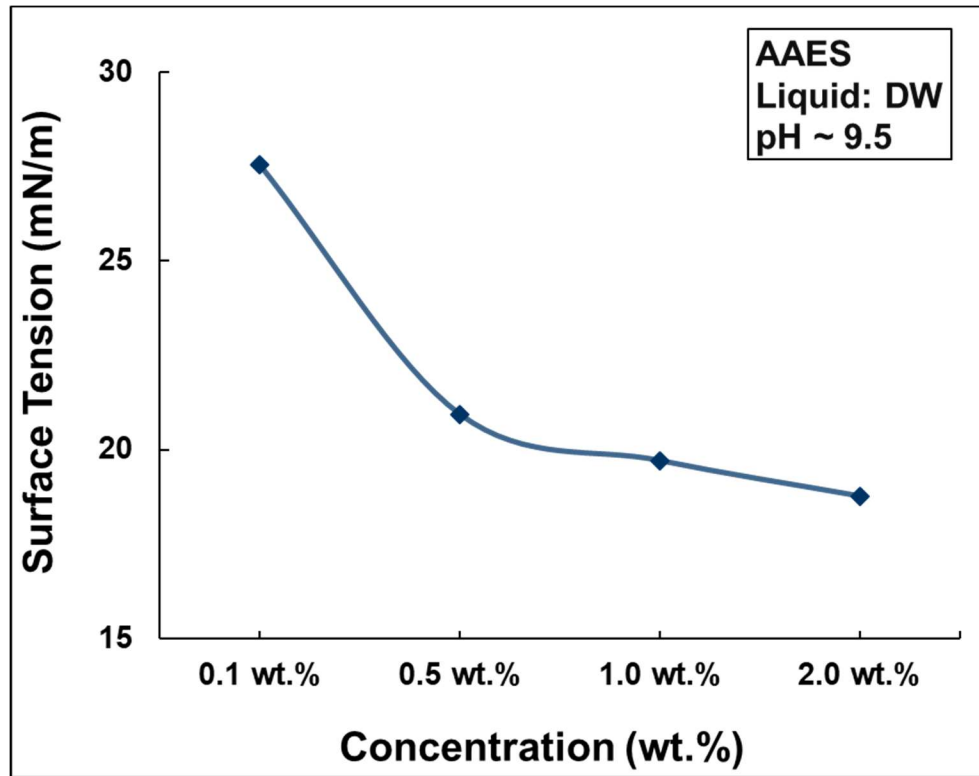


Figure 11 – Surface tension measurements of the tested foaming solutions at ambient conditions (Using Attension Theta Optical Tensiometer provided by Biolin Scientific Setup).

4.2.2 Pressure Effect on Foaming

Testing Conditions

In this section, AAES foam systems have been experimentally investigated under different pressures [14.7 psi, 500 psi, and 1000 psi] at the same temperature of 60 °C to assess the impact of varying pressures on AAES foam stability, foamability, and bubbles' structure.

Foam Stability

Figure 12 displays the relative volume of AAES foam at different pressures [14.7 psi, 500 psi, and 1000 psi] and a temperature of 60 °C in a mildly alkaline environment (pH ~ 9.5). The foam decay exhibited variations with pressure, with higher pressures showing reduced foam decay rates, indicating improved foam stability. Figure 13 illustrates the foam half-life, with the AAES foam having the shortest half-life at 14.7 psi (97 minutes), which more than doubled at 500 psi. Notably, at 1000 psi, the foam stability significantly improved, with only a 20% volume decrease over 350 minutes, demonstrating highly stable foams. These findings align with prior research, highlighting the positive impact of elevated pressure on foam bubble stability.(Pradhan and Khilar 1994; Szabries et al. 2019)

The observed changes in foam stability with varying pressures can be attributed to the effect of this parameter on the physical properties and behavior of foam. At higher pressures, the gas phase in the foam is compressed, leading to a reduction in the gas volume. This compression of the gas phase helps to stabilize the foam structure by reducing bubble coalescence and promoting stronger bubble films. Consequently, the foam exhibits slower decay over time, resulting in increased stability. On the other hand, at lower pressures, the gas phase expands, leading to increased bubble coalescence and weaker bubble films, which contributes to faster foam decay and reduced stability.

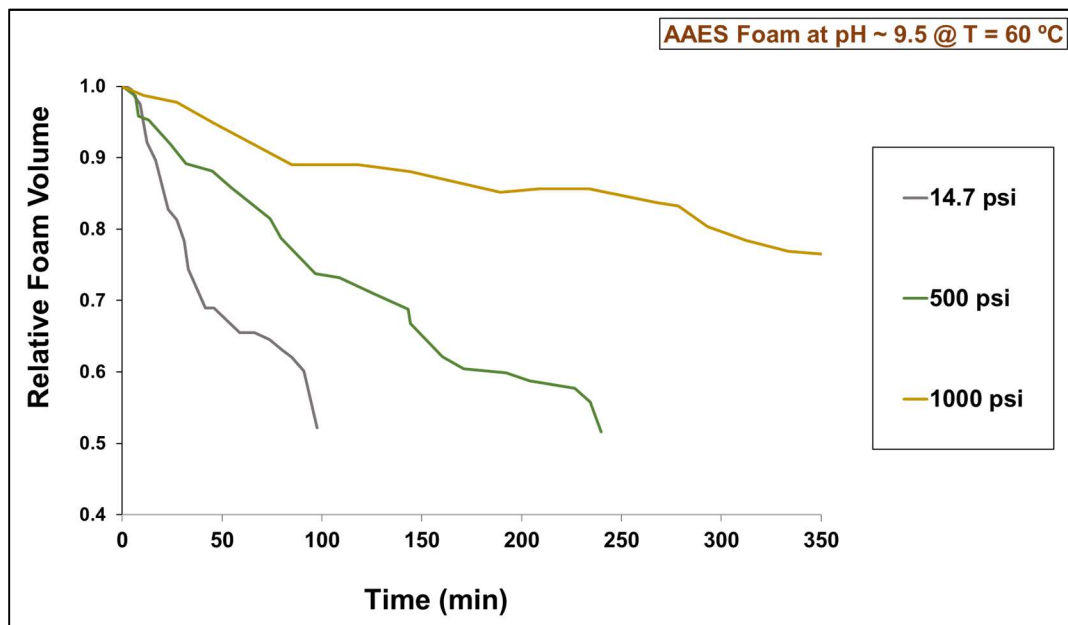


Figure 12 – Relative volume of AAES foam under different pressures and at temperature of 60 °C (Using HPFA).

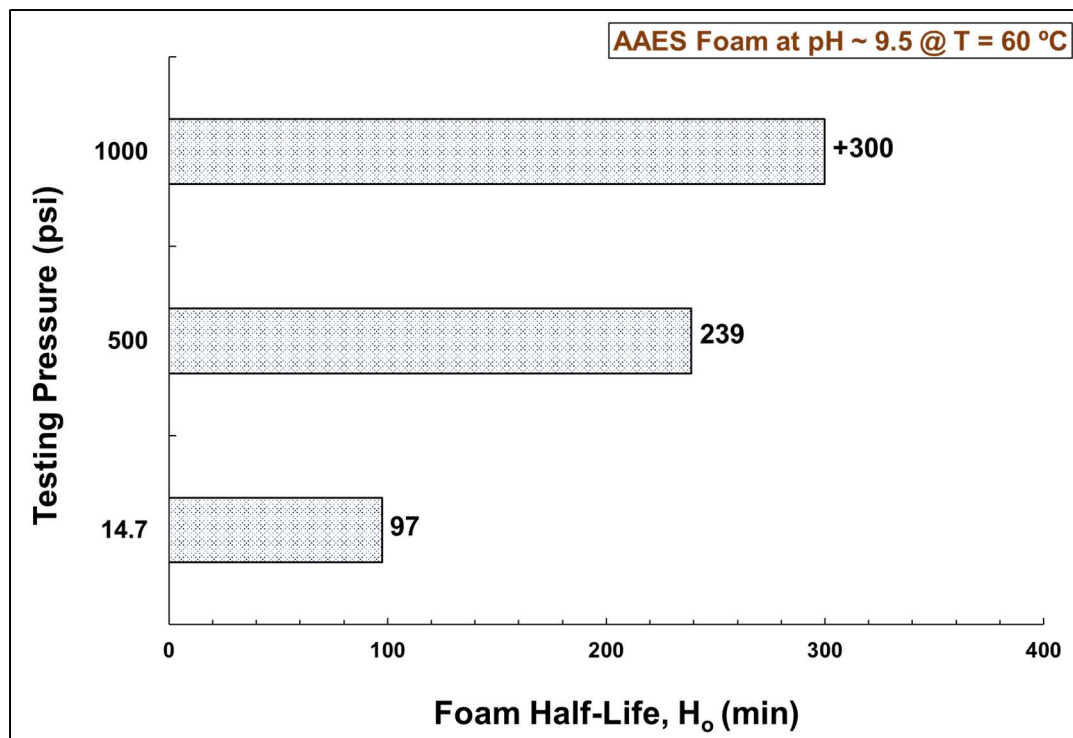


Figure 13 – Bubbles' half-life of AAES foam under different pressures and at temperature of 60 °C (Using HPFA).

Foamability

Foamability, which assesses a surfactant's inherent capacity to produce foam, is characterized by both the generated foam quantity and the count of gas bubbles (BC) entrapped within the liquid phase. In the foam generation process, Nitrogen (N_2) was introduced from the bottom through a porous plate at a consistent flow rate of 50 mL/min until the foam reached its maximum height in the high-pressure (HP) cell view. After ceasing gas injection, the resulting foam underwent evaluation to determine its initial foam volume and the bubble density expressed in bubble count per unit area (bubbles/mm²). Table 7 presents the average gas volume required to achieve the maximum foam height in each experiment, along with the corresponding initial bubble density of the AAES foam.

Increasing the pressure led to a decrease in the amount of gas necessary to attain the maximum foam height in the HP cell. Specifically, while 149 mL of N_2 gas was needed to generate a full foam column at 14.7 psi, this gas volume decreased by 15% at 500 psi and by 20% at 1000 psi. This phenomenon can be attributed to the rising pressure causing the density of the gas to increase and subsequently reducing surface tension.(Szabries et al. 2019; Al-Darweesh et al. 2023) Surface tension is responsible for holding the gas bubbles within the liquid phase and is a critical factor in foam stability. When surface tension is lowered, it becomes easier for the gas bubbles to form and stabilize in the liquid, resulting in improved foamability.

Furthermore, the results in Table 7 indicate that the initial bubble density is influenced by the system pressure. Elevating the pressure led to an increase in the initial bubble density observed after stopping the injection of N₂ gas. At 14.7 psi, the AAES foam exhibited the lowest foamability with 35 bubbles per mm². However, increasing the pressure to 500 psi resulted in smaller bubble sizes, leading to a 22% increase in the bubble count per unit area. Further raising the pressure to 1000 psi enhanced the bubble density further to 80 bubbles/mm². The reduction in gas volume needed to achieve the maximum foam height at higher pressures suggests that the gas is more efficiently trapped and distributed within the liquid phase.

Table 7 - Gas volume required to generate a full foam column under different pressures and at temperature of 60°C, expressed in milliliters (mL), as well as the initial bubble density.

Testing Conditions		Injected N ₂ Volume (mL)	Initial bubble density (bubbles/mm ²)
Pressure	Temperature (°C)		
14.7 psi	60	149	35
500psi		126	51
1000 psi		119	80

Foam Structure

Images of AAES foam were captured at various time intervals; 1, 30, and 60 minutes, under different pressures and at a temperature of 60 °C (Table 8). At a pressure of 14.7 psi, the analysis revealed the evolution of the foam structure over time. Initially, a non-uniform distribution of bubble sizes was observed, with larger bubbles positioned at the top of the

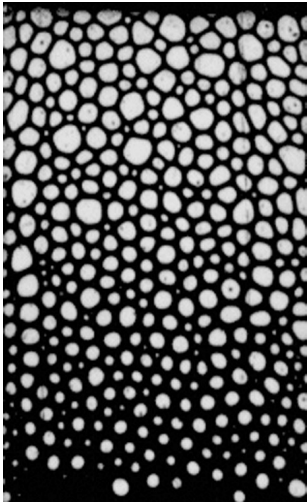
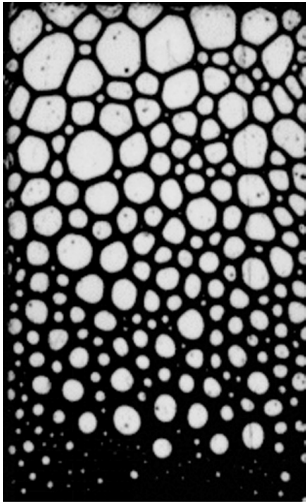
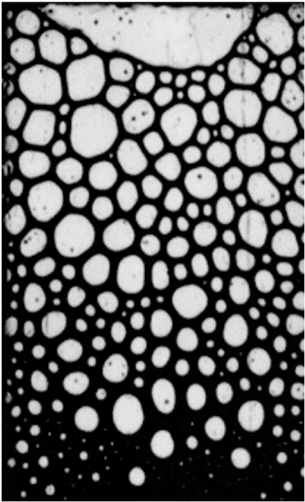
HP cell and smaller ones at the bottom, along with fine-textured bubbles just above the liquid solution. Over time, bubble coarsening occurred as a result of gas diffusion through liquid films due to pressure differences, leading to an increase in bubble size and a reduction in the bubble count per area. After approximately 60 minutes, a distinct bubble configuration featuring multiple border plateaus was observed at the top of the HP cell. However, when the pressure was increased to 500 psi and 1000 psi, the bubble size distributions displayed greater uniformity at the beginning of the test, with reduced dominance of bubble coarsening. As time elapsed, numerous small bubbles were observed, indicating the influence of higher pressure on bubble dynamics. The increase in pressure hindered bubble coarsening and enhanced the mechanical strength of the foam structure, preventing bubble merging and coalescence. Consequently, more small bubbles were retained, resulting in a more uniform bubble size distribution.

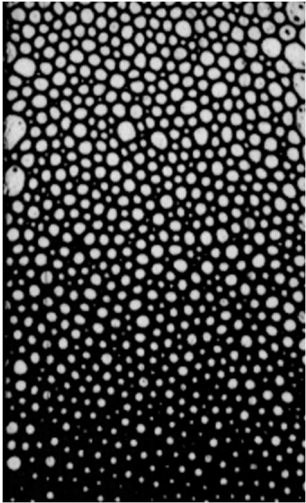
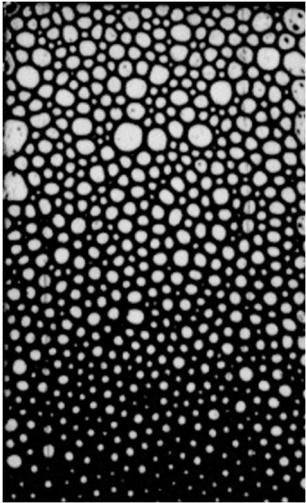
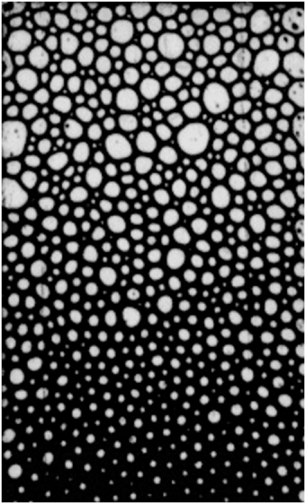
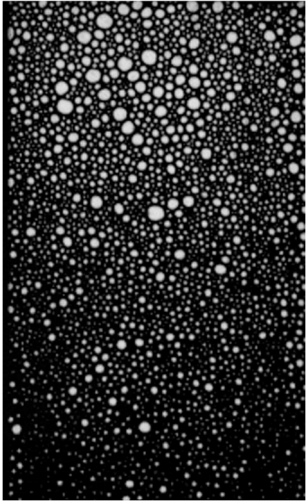
The recorded bubble density data in Figure 14 confirmed the observations from the captured images, demonstrating that as time progressed, the bubble density decreased with varying rates based on the system pressure. At 14.7 psi, a rapid reduction in bubble density to nearly one-third of its initial value was evident, while at 500 psi and 1000 psi, the rate of bubble count per unit area decrease was notably lower, sustaining a higher bubble count for an extended period. This behavior can be attributed to the pressure's effect on foam stability and bubble coalescence kinetics. At lower pressures, rapid coalescence of gas bubbles led to larger bubbles thus reducing bubble density. In contrast, at higher pressures, hindered gas diffusion through liquid films resulted in a more uniform distribution of

smaller bubbles, contributing to higher bubble density and improved foam stability over time.

Regarding the mean bubble size presented in Figure 15, notable differences are observed primarily at low pressures. Specifically, the initial mean bubble size at 14.7 psi significantly differs from that at higher pressures of 500 psi and 1000 psi. Over time, the mean bubble size increases at all pressures, with this effect diminishing as the pressure increases, particularly at elevated pressures of 500 psi and 1000 psi, where the bubble size remains relatively constant. This constancy of bubble size at higher pressures indicates a higher foam stability. The variations in mean bubble size can be attributed to the pressure-dependent bubble coarsening and coalescence kinetics.(Szabries et al. 2019).

Table 8 - Images of AAES foam bubble structures were captured at various time intervals under different pressures and temperature of 50 °C. The foam bubbles are displayed in grey, while the liquid film is represented in black.

System Pressure	1 min	30 min	60 min
14.7 psi			

500 ps			
1000 psi			

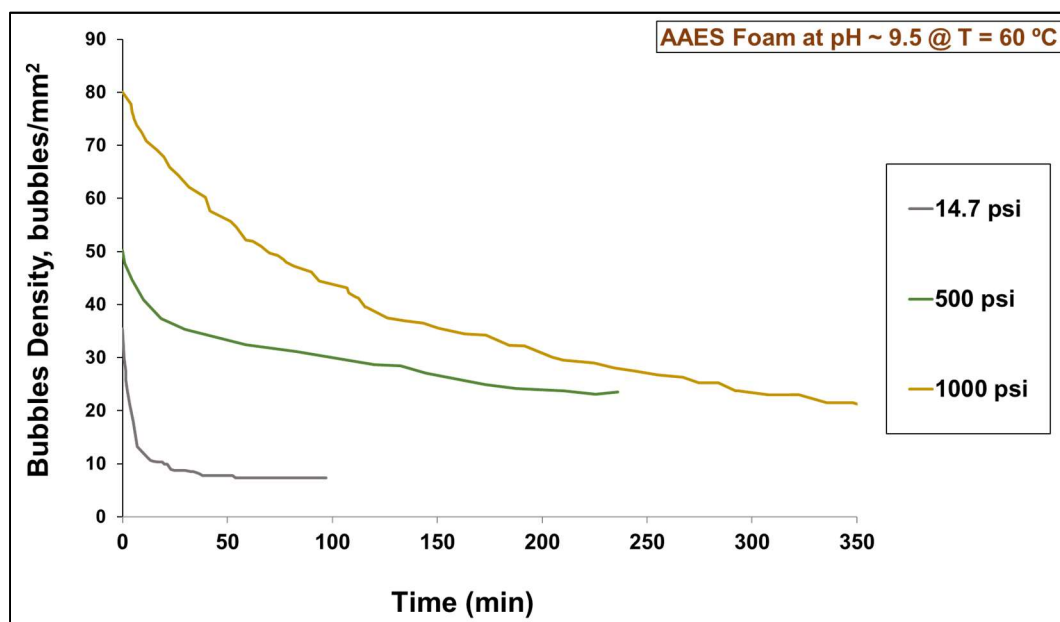


Figure 14 – Bubble density as a function of time under different pressures and a temperature of 60°C. The graphs display the bubble density up to the half-life of the foam for each experiment.

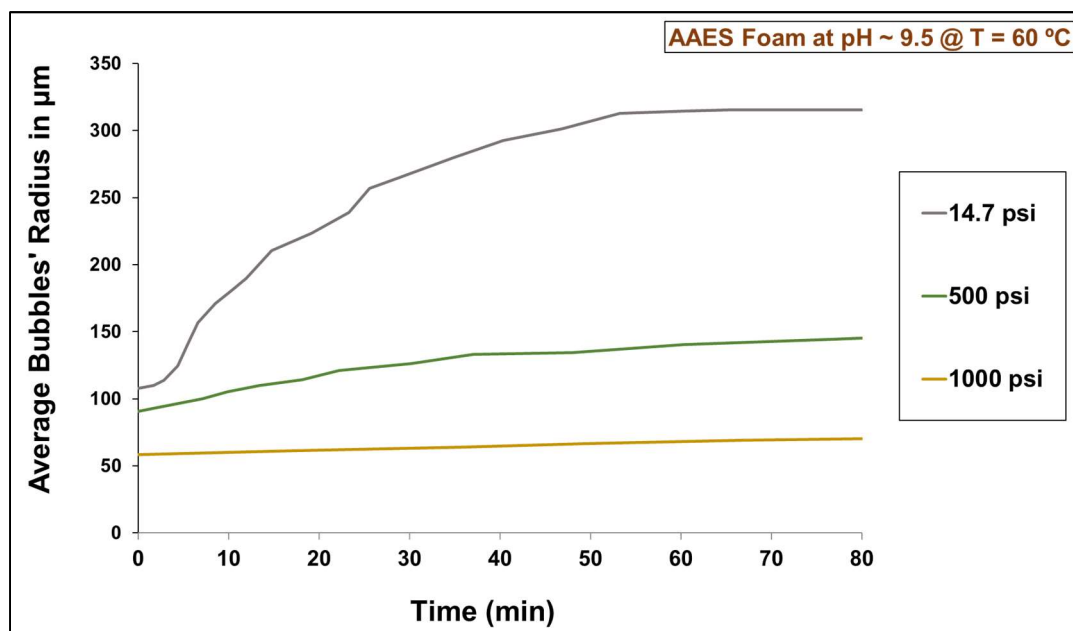


Figure 15 - Average bubbles' radius of AAES Foam over time under different pressures and at temperature of 60°C.

Foam Viscosity

In this subsection, the influence of gas pressure on foam viscosity has been investigated, as depicted in Figure 16. The apparent foam viscosity was assessed at three different pressures of N₂ gas: 14.7, 1000, and 3000 psi. Initially, a substantial increase of 66% in foam viscosity occurred at a low shear rate, rising from 8.01 cP to 13.29 cP when the N₂ pressure was elevated from 14.7 psi to 1000 psi. However, this increase decreased to nearly 47% at a shear rate of 500 1/s, where viscosity rose from 4.75 cP to 7.03 cP. Yet, only a slight improvement in foam viscosity was noted as the gas pressure was further raised from 1000 psi to 3000 psi. At 100 1/s, there was an approximate 10% increase (13.29 cP to 14.74 cP), and at 500 1/s, an increase from 7.03 cP to 7.94 cP. Remarkably, foam viscosity remained relatively constant at higher shear rates, ranging from nearly 500 1/s to 1000 1/s across all tested pressures.

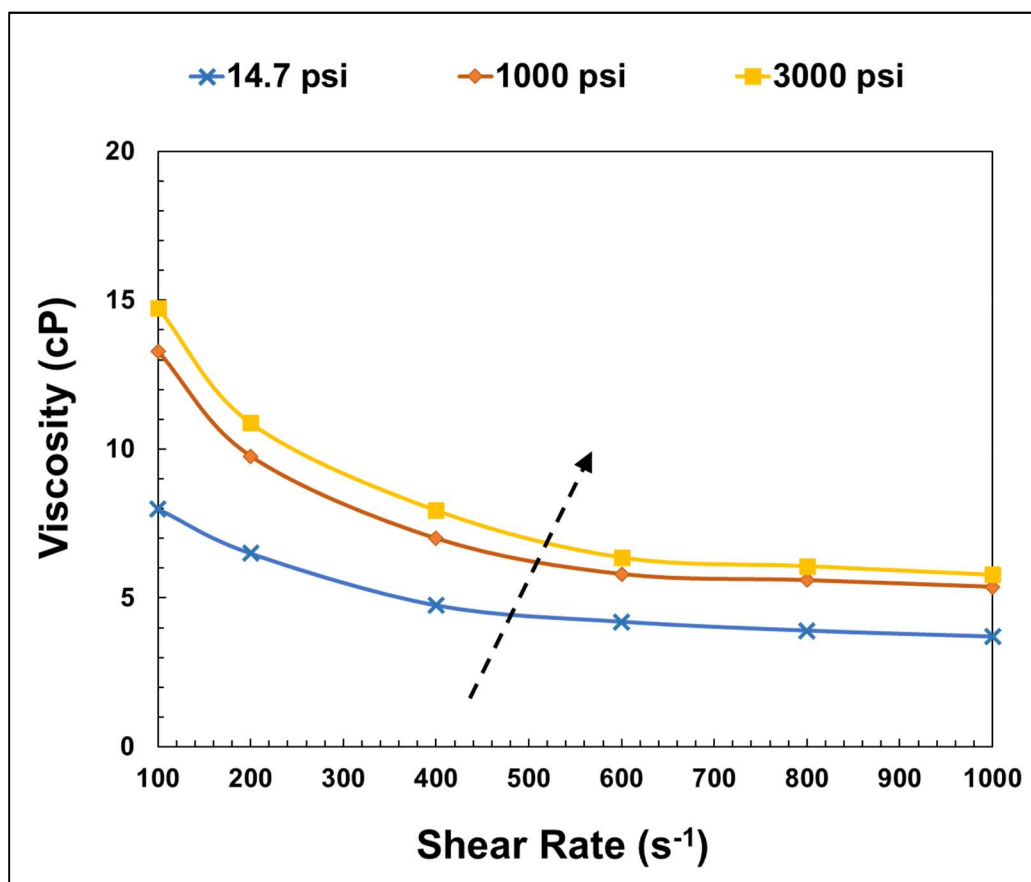


Figure 16 – Impact of pressure on the tested AAES-based foam over a wide range of shear rates at a temperature of 90°C and different pressure values.

4.2.3 Temperature Effect on Foaming

Testing Conditions

According to the previous section, the findings indicate that pressure positively influences both foam stability and foamability. In light of these results, the present section aims to explore AAES foam systems under an elevated pressure of 1000 psi and varying

temperatures (25, 50, 75, and 90°C) using HPFA setup to assess how temperature variations impact AAES foam stability, foamability, and bubble structure.

Foam Stability

Figure 17 illustrates the impact of varying temperatures, along with a pressure of 1000 psi, on the relative volume of AAES foam within a mildly alkaline environment (pH ~ 9.5). The findings indicate a significant influence of temperature on the rate of foam decay, with a notable effect observed at higher temperatures of 75 and 90°C. Conversely, lower temperatures of 25 and 50°C exhibited a limited impact on foam decay. These observations can be attributed to the influence of temperature on the kinetics of liquid drainage, coarsening, and bubble coalescence, occurring within the foam structure. At higher temperatures of 75 and 90°C, the increased thermal energy accelerates and enhances the diffusion of gas molecules through liquid films, leading to a more rapid decay of the foam. This results in a notable reduction in the foam's volume over time. Conversely, at lower temperatures of 25 and 60°C, the reduced thermal energy slows down coarsening and bubble coalescence, leading to a more gradual decay of the foam and thus preserving its volume to a greater extent. These disparities in foam decay rates have direct implications on AAES foam stability, quantified by the half-life of bubbles, as depicted in Figure 18. At temperatures of 60 °C and below, AAES foam demonstrated remarkable stability, with a half-life exceeding 300 minutes. However, at 75°C, the foam stability dramatically decreased, showing a half-life of only 60 minutes, and further reduced to 25 minutes at 90°C.

Moreover, an increase in temperature was associated with a clear decrease in the viscosity of the liquid phase, as demonstrated in Figure 18, showing viscosity measurements of AAES liquid phase under different temperatures and a pressure of 1000 psi. This decrease in liquid viscosity contributes to an accelerated liquid drainage rate from the foam structure, leading to faster foam decay (Kapetas et al. 2015; Kamal 2019b). Additionally, the higher temperature increases the surface tension of the foam, which reduces the surface energy of the surfactant molecules (Guo 2021). As a result, the surfactant molecules become less effective in maintaining the foam structure, further contributing to the decreased foam stability observed at higher temperatures. Conversely, at lower temperatures of 60°C and below, the reduced rate of liquid drainage, coupled with the higher surface energy of surfactant molecules, enhances foam stability, leading to an extended half-life of the foam bubbles. The results indicate that the influence of pressure on AAES foam stability is more pronounced up to 60°C, but its significance diminishes at higher temperatures (75 and 90°C). Conversely, the impact of temperature becomes more dominant in determining AAES foam stability at such elevated temperatures.

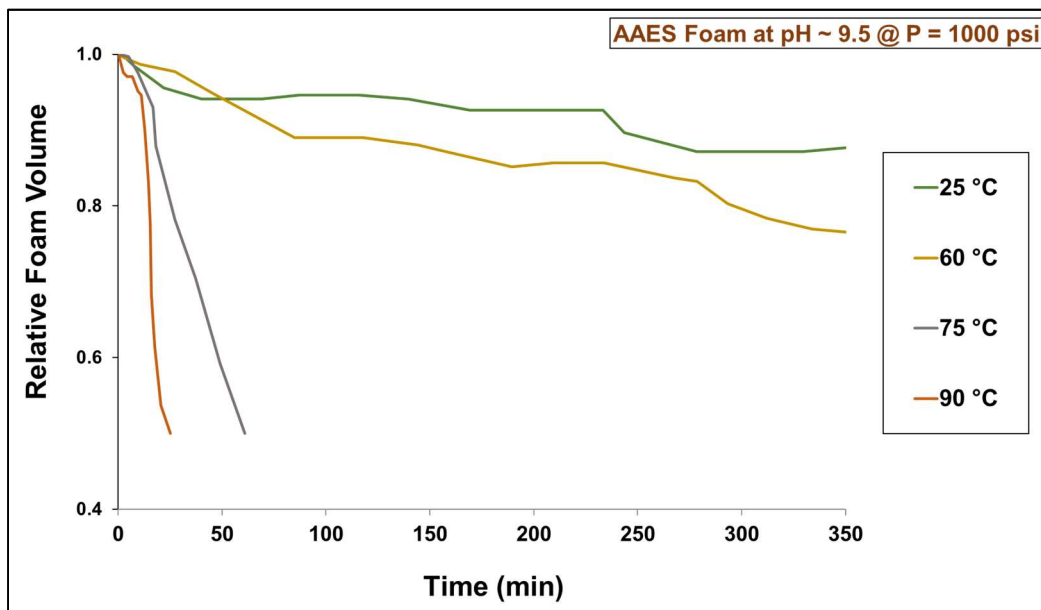


Figure 17 – Relative foam volume over time of AAES foam under different temperatures and at pressure of 1000 psi (Using HPFA).

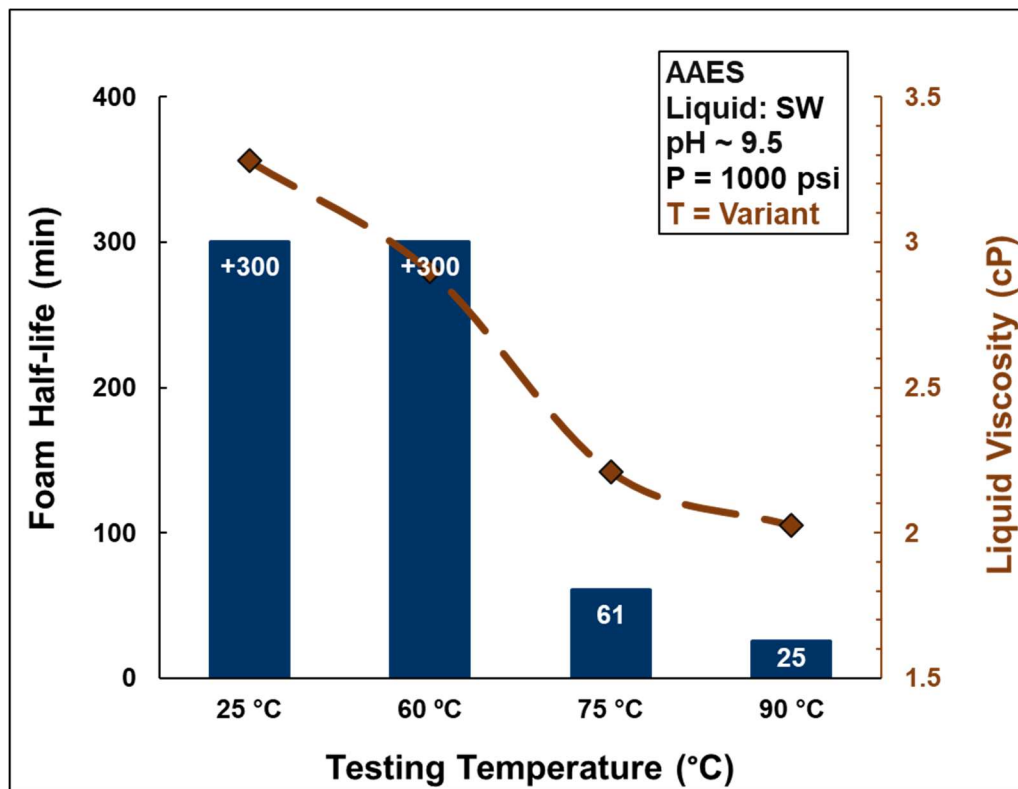


Figure 18 – Bubbles' half-life of AAES foam as well as the viscosity measurements of AAES Liquid- phase at shear rate of 600 s^{-1} under different temperatures and at pressure of 1000 psi (Using HPFA).

Foamability

In this subsection the impact of temperature on the AAES foamability was explored. Table 9 provides the gas volume utilized to attain the maximum foam height in each experimental run, along with the associated initial bubble density of the AAES foam. The findings indicate that, under a constant pressure, changes in temperature had a negligible effect on AAES foamability. The gas volume required to achieve the maximum foam height remained nearly consistent across different temperature conditions. Similarly, the initial bubble density was minimally impacted by temperature variations, with an average of approximately 80 bubbles/mm² observed regardless of the temperature. These results suggest that the initial foamability of AAES is relatively insensitive to temperature changes at such elevated pressure, unlike its foam stability.

Table 9 - Gas volume required to generate a full foam column under different temperatures and at pressure of 1000 psi, expressed in milliliters (mL), as well as the initial bubbles density measured in bubbles/mm⁻².

Testing Conditions		Injected N ₂ Volume (mL)	Initial bubble density (bubbles/ mm ²)
Pressure	Temperature (°C)		
1000 psi	25	130	76
	60	126	80
	75	122	82
	90	133	74

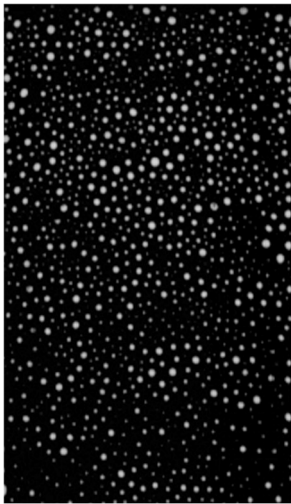
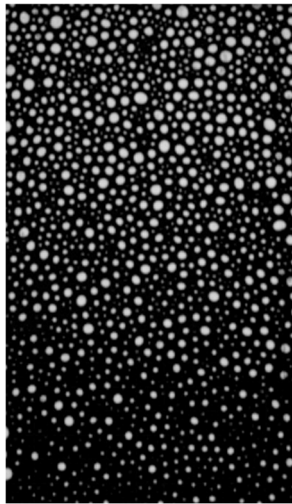
Foam Structure

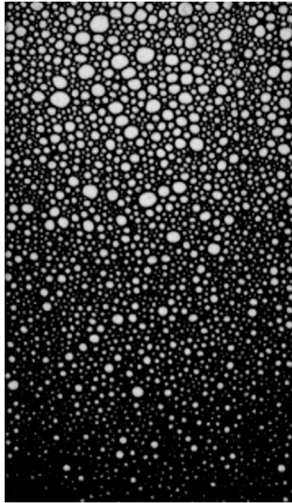
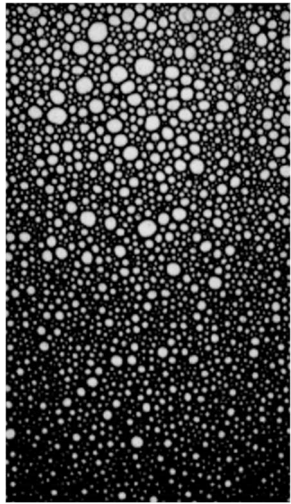
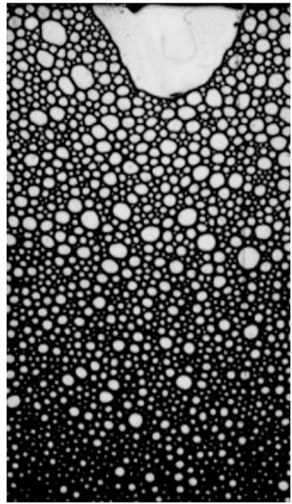
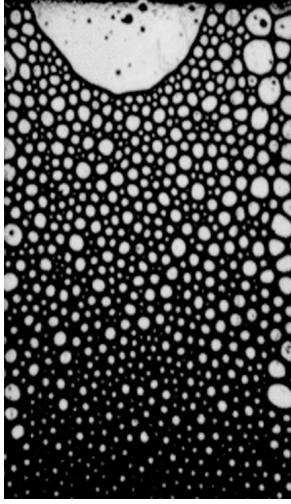
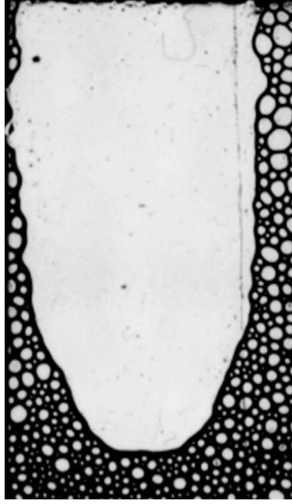
This subsection investigates the influence of temperature variations on the structure of AAES foam and its evolution over time. Table 10 displays images of AAES foam bubble structures captured at different time intervals under various temperatures (25, 50, 75, and 90 °C) and a pressure of 1000 psi. Notably, the foam structure at 25 and 50 °C remains relatively consistent over time, featuring fine-structured and stable foam bubbles. However, at 50°C, the images reveal a change in foam structure over time, with bubbles enlarging as time progresses. This change in foam structure becomes more significant at 90 °C, where bubbles grow considerably larger after 30 minutes and mostly diminish after 60 minutes.

Figure 19 illustrates the average bubbles' radius of AAES foam over time under different temperatures (25, 50, 75, and 90 °C) and at a pressure of 1000 psi. The bubbles' size remains relatively constant for extended periods at 25 and 50 °C, with an average bubble size of 60 μm . However, the behavior of AAES foam bubbles differs at higher temperatures. At 75°C, the gradient of the bubble size increase becomes more pronounced, with the mean bubble size increasing by approximately 72% over the foam half-life time of 61 minutes. The increasing rate of bubble size becomes even more significant at 90 °C, where the average bubble size increases by about 90% in just 25 minutes. Figure 20 depicts the bubble density over time under different temperatures and at a pressure of 1000 psi. The graphs illustrate the bubble density up to the foam's half-life for each experiment. The observations in Figure 20 align with the earlier findings and reveal that the number of bubbles per unit area decreases at higher rates with increasing temperature. These results

shed light on the intricate relationship between temperature and AAES foam structure and behavior. The remarkable stability and consistency of foam at lower temperatures suggests its promising potential applicability at surface and intermediate drilling sections. However, at higher temperatures, changes in foam structure and bubble size were evident, highlighting the need for a comprehensive understanding of these dynamics to optimize the performance of AAES foam at elevated temperatures and deeper sections. The efficiency of AAES foam can be further enhanced by incorporating additional additives that offer prolonged stability to the foam structure under such challenging conditions.

Table 10 - Images of AAES foam bubble structures were captured at various time intervals under different temperatures and pressure of 1000 psi. The foam bubbles are displayed in grey, while the liquid film is represented in black.

System Temp.	1 min	30 min	60 min
25 °C			

60 °C			
75 °C			
90 °C			

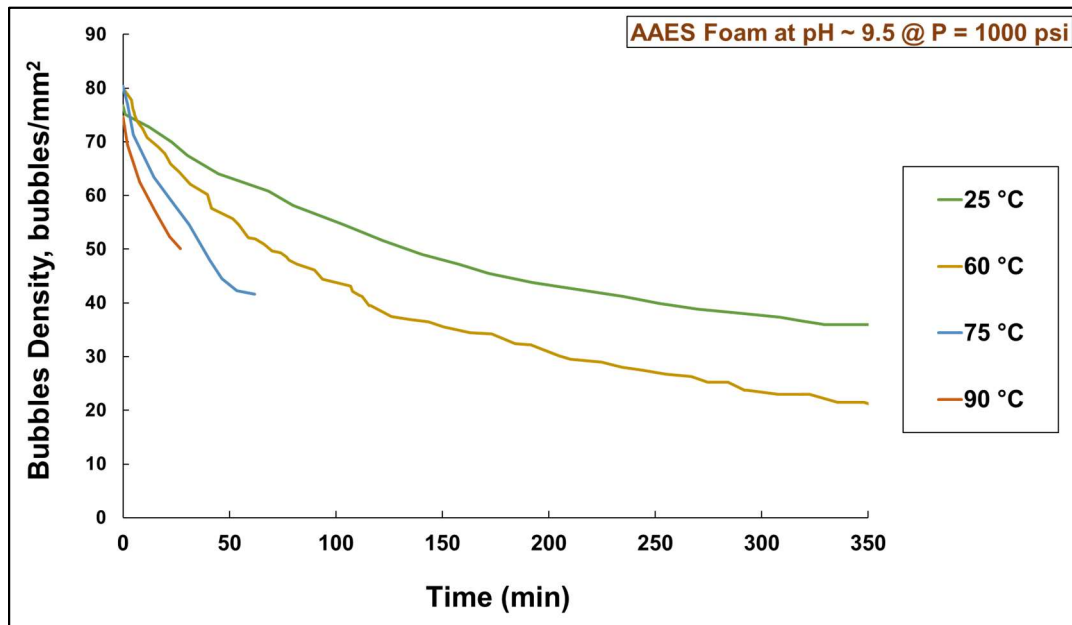


Figure 19 - Average bubbles' radius of AAES foam over time under different temperatures and at pressure of 1000 psi (Using HPFA).

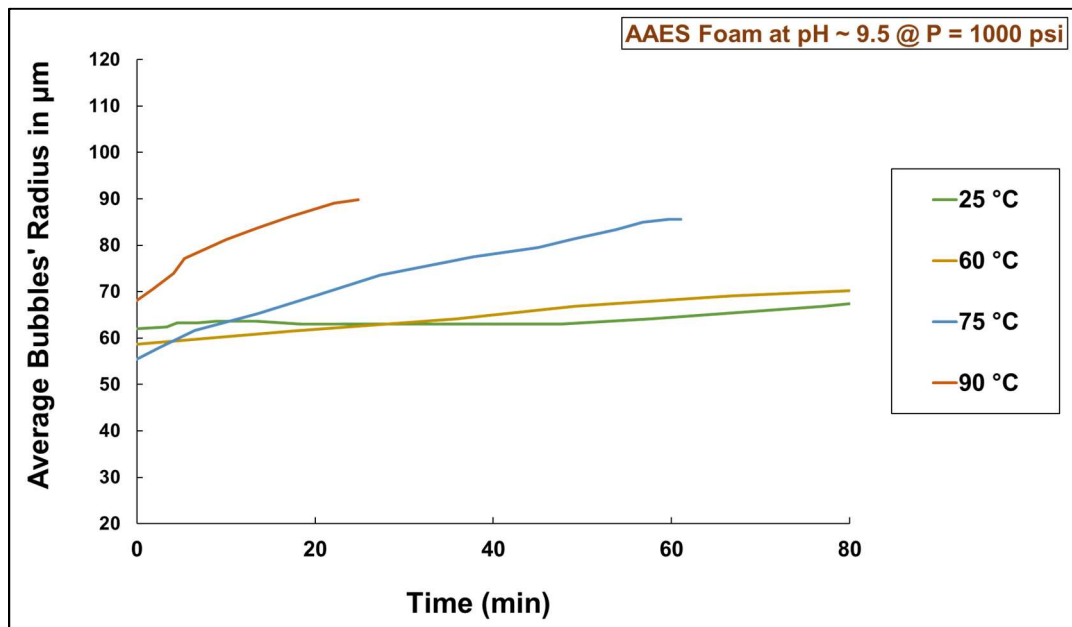
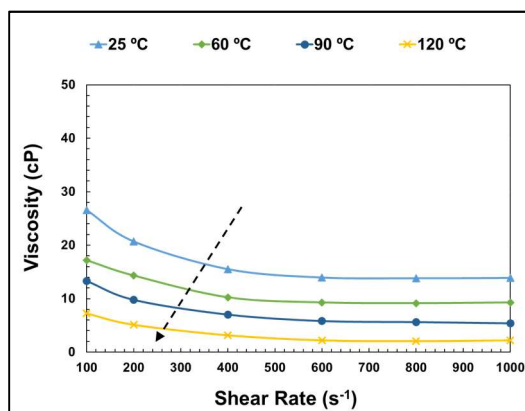


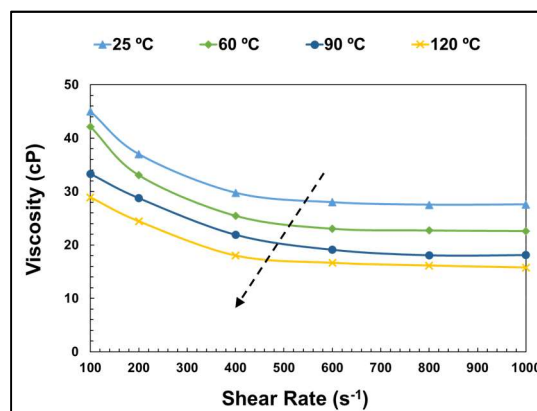
Figure 20 – Bubbles density as a function of time under different temperatures and a pressure of 1000 psi. The graphs display the bubble density up to the half-life of the foam for each experiment (Using HPFA).

Foam Viscosity

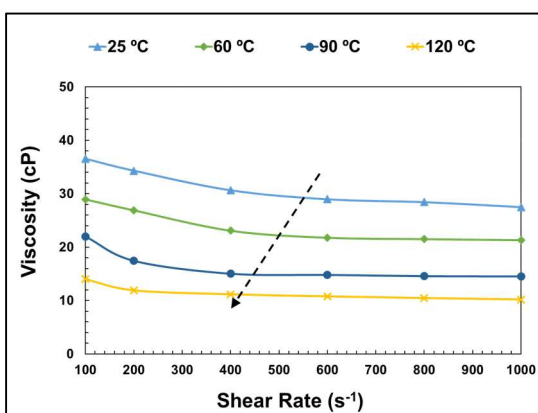
In this subsection, the influence of temperature on the viscosity of AAES-based foams was systematically investigated, as illustrated in Figure 21. The viscosity of tested AAES foams was evaluated under a constant pressure of 1000 psi at temperatures of 25, 60, 90, and 120°C. Under constant pressure conditions, it was observed that the viscosity of both AAES foam and AAES foam with additives increased as the temperature decreased, irrespective of the additive used. However, the rate of change in foam viscosity with increasing temperature varied among different additives, indicating distinct thermal stability profiles in response to temperature fluctuations. Figure 22 presents the alterations in foam apparent viscosity for the tested AAES-based foams at a pressure of 1000 psi and a shear rate of 500 1/s. The results highlight that the introduction of additives substantially improved the thermal stability of AAES foams, with PAC emerging as the most effective additive in enhancing foam resistance to viscosity changes due to temperature variations. Significantly, the viscosity of AAES foam (without additives) experienced a substantial 84% decrease, declining from 13.93 to 2.19 cP when the temperature rose from 25 to 120°C. In contrast, the viscosity reductions were relatively lower upon the addition of additives: 40% with a viscosity of 16.67 cP when PAC was introduced, 54% with a viscosity of 8.44 cP when X-gum was included, and 63% with a viscosity of 10.79 cP upon the addition of CMC, compared to the viscosity values of each respective system at 25°C. This notable enhancement in the thermal stability of the AAES foam system, facilitated by the addition of additives, underscores its potential for practical field applications, particularly in deeper depths where elevated temperatures are encountered.



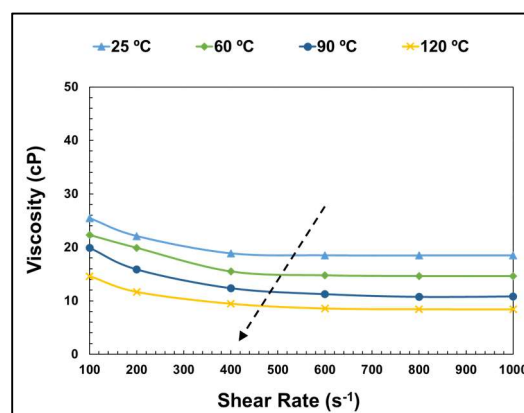
(a)



(b)



(c)



(d)

Figure 21 – Impact of temperature on the tested AAES-based foams: a) AAES, b) AAES + PAC, c) AAES + X-gum, d) AAES + CMC over a wide range of shear rates under a pressure of 1000 psi (Using HPFA).

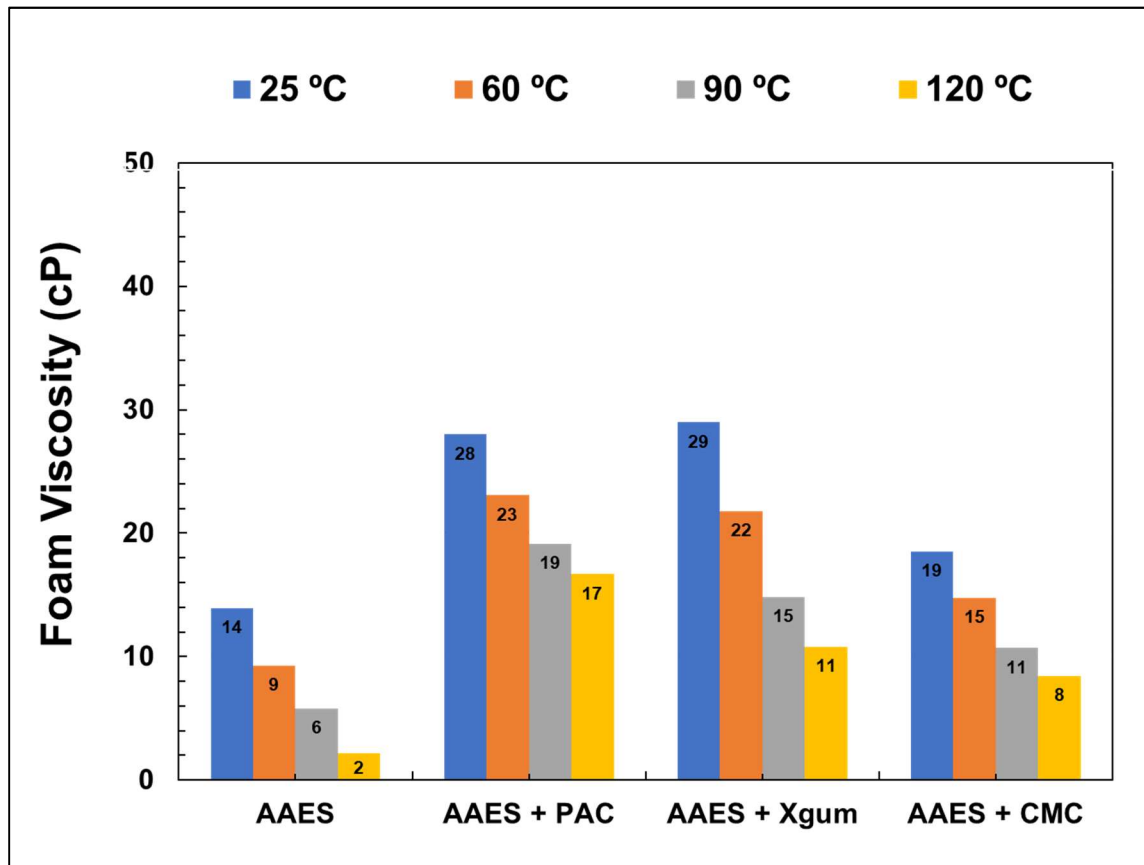


Figure 22 – Changes in foam apparent viscosity with temperature for the tested AAES-based foams at a pressure of 1000 psi and a shear rate of 500 1/s.

4.2.4 Foam Quality Effect on Foaming

This subsection investigates the impact of foam quality on the viscosity of AAES foam across shear rates ranging from 100 to 1000 1/s, as depicted in Figure 23. Results reveal a consistent increase in foam viscosity with elevated foam quality. Specifically, increasing foam quality from 65% to 75% induces a 17% rise in viscosity at low shear rates (from 11.39 cP to 13.29 cP), escalating to approximately 36% at shear rates surpassing 500 1/s (4.65 cP to 6.32 cP). Further elevation to 85% foam quality results in an 18% increase in apparent viscosity at low shear rates (from 13.29 cP to 15.71 cP), intensifying to around

30% at shear rates beyond 500 1/s (from 6.41 cP to 8.33 cP), relative to 65% foam quality. Afterward, the apparent viscosity maintains a relatively steady state up to 1000 1/s. The observed viscosity rise is attributed to enhanced gas-bubble interactions and structural changes in the foam system. Lower foam qualities exhibit dispersed gas bubbles and lower viscosity, while higher qualities demonstrate interconnected bubbles, increased resistance to flow, and heightened viscosity (Ramadan et al. 2003b). Diminished drainage and coarsening processes contribute to a more stable and viscous foam at higher qualities (Heller and Kuntamukkula 1987). The incremental viscosity increase at higher shear rates suggests that, despite shear-thinning behavior, the impact of gas volume fraction on the foam structure prevails within the investigated shear rate range (100 to 1000 1/s), highlighting the intricate interplay between gas and liquid phases in the foam.

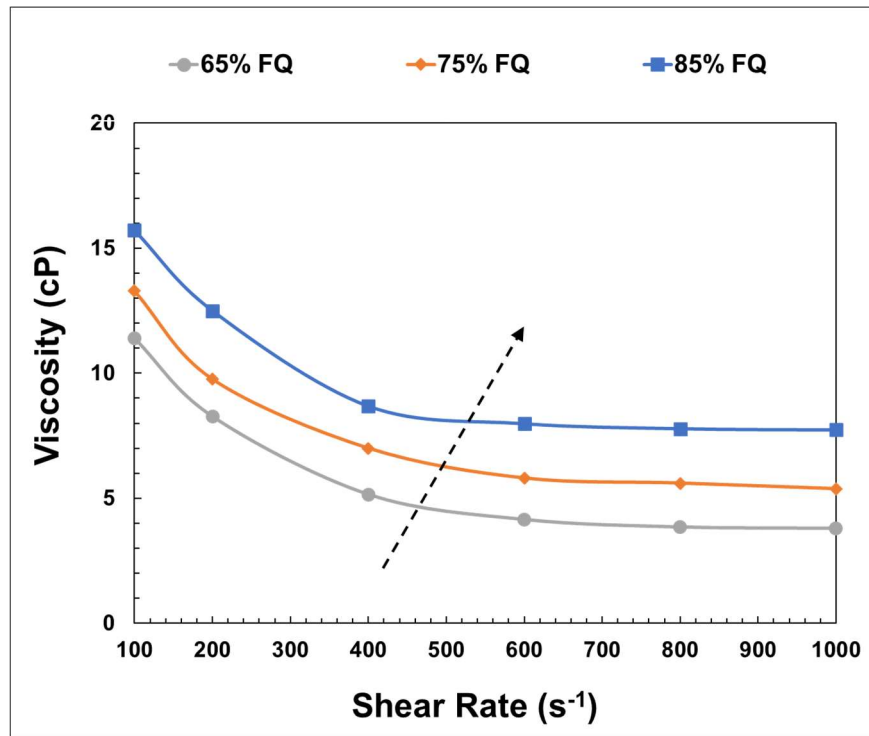


Figure 23 – Impact of foam quality on AAES-based foam at 1000 psi and 90°C.

4.3 Phase 03: Impact of Additives on Foaming Properties

In this section, the impact of additives, i.e., polymers and clay solids, have been investigated to evaluate their impact on the bulk properties of AAES foams.

4.3.1 Impact of Polymers on Foaming

Foam Stability

The influence of additives, namely PAC, X-gum, and CMC, on the stability of AAES foam at 1000 psi and 90°C is elucidated in Figure 24, where the foam relative volume is tracked over time. The findings reveal that the inclusion of additives significantly improves the stability of AAES foam, evidenced by the prolonged time required for the foam to reach its half value upon additive introduction. This increased duration translates into a higher bubbles' half-life for the AAES foam, as depicted in Figure 25. Specifically, X-gum and CMC exhibit a doubling effect on foam stability, while the addition of PAC results in a remarkable threefold increase in half-life. The observed enhancements in foam stability underscore the efficacy of these additives in fortifying the structural integrity of AAES foam, a crucial attribute for diverse applications where prolonged stability is imperative. The observed increase in foam stability with the inclusion of additives can be attributed to their respective influences on the rheological properties and structural integrity of the AAES foam system. The prolonged time for the foam to reach its half value signifies enhanced resistance to coalescence and drainage, key factors affecting foam stability. X-gum and CMC, known for their thickening and stabilizing properties (Derikvand and Riazi

2016; Sheng et al. 2016), contribute to a doubling of foam stability by reinforcing the film strength around gas bubbles. However, the substantial enhancement observed with PAC, resulting in a threefold increase in half-life, can be attributed to its superior film-forming and foam-stabilizing capabilities. PAC molecules form a more robust and cohesive film, effectively retarding coarsening and drainage processes. This improvement in foam stability, facilitated by the additives, holds promise for practical applications where prolonged foam performance is critical, such as in enhanced oil recovery processes or other foam-based technologies.

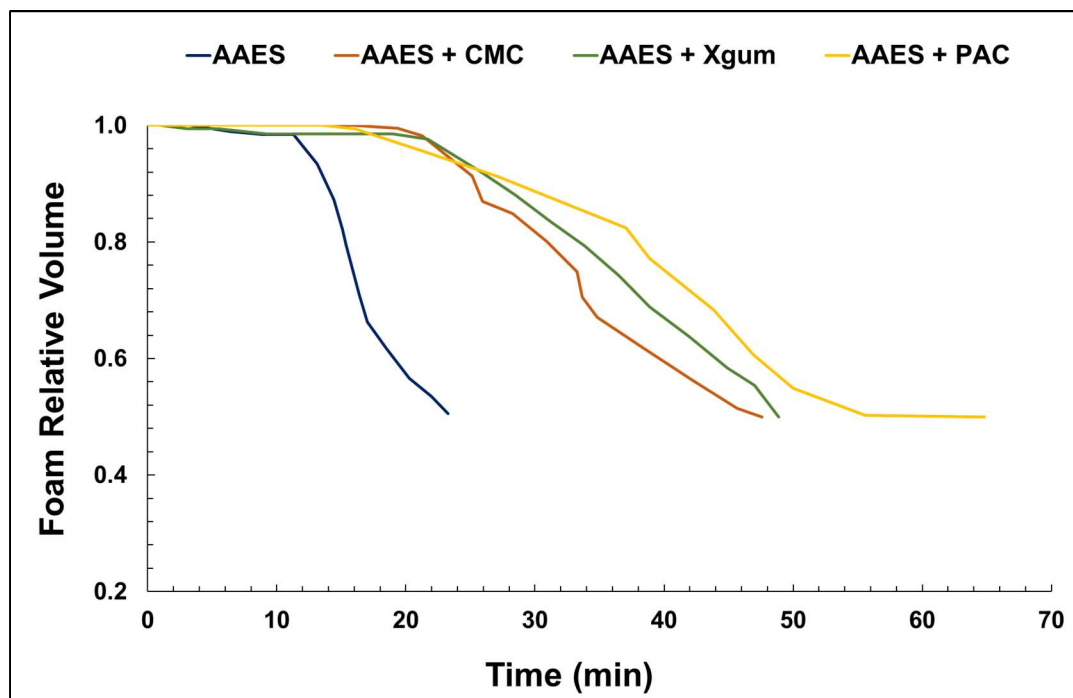


Figure 24 – Impact of additives on foam volume as a function of time at pressure of 1000 psi and temperature of 90°C (Using HPFA).

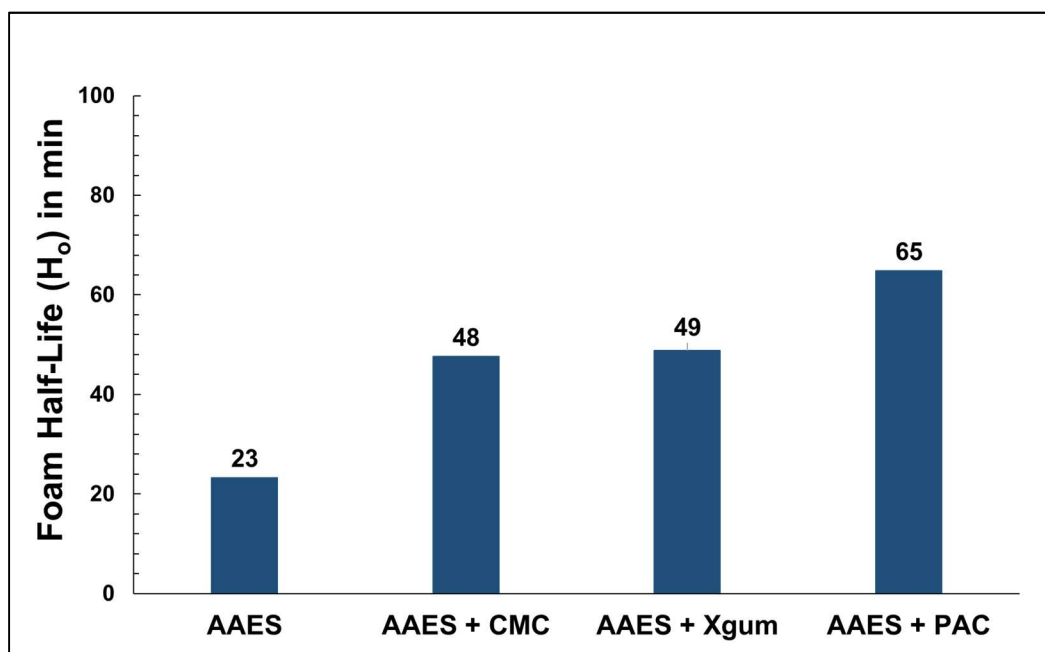


Figure 25 – Impact of additives on foam half-life at a pressure of 1000 psi and temperature of 90°C (Using HPFA).

Foam Viscosity

In this subsection, the effects of different additives, specifically PAC, CMC, and X-gum, on the viscosity of AAES-based foam have been explored. Figure 26 depicts how these additives influence foam viscosity at 90°C and 1000 psi. The apparent viscosity of the foam demonstrates a shear-thinning behavior at low shear rates, remaining consistent up to 500 1/s. Beyond this point, the apparent viscosity remains relatively stable up to 1000 1/s. Remarkably, all additives increase the apparent viscosity compared to the original AAES foam without additives. PAC emerges as the most effective additive, resulting in a significant 150% increase in viscosity at low shear rates, reaching 33.28 cP. This enhancement continues with an increasing shear rate, peaking at approximately 200% at 500 1/s, with a viscosity of 19.14 cP, and 238% at 1000 1/s, with a viscosity of 18.15 cP.

X-gum follows as the second most impactful additive, boosting foam viscosity by 66% at low shear rates (22 cP) and reaching 14.54 cP at 1000 1/s. CMC also contributes to improved foam viscosity, showing an increase of about 50% at low shear rates (19.89 cP) and peaking at 101% at 1000 1/s (10.87 cP). The observed shear-thinning behavior at low shear rates is typical of foam systems, where increased shear disrupts the foam structure, leading to decreased viscosity. The subsequent plateau in viscosity at higher shear rates indicates that the foam structure has stabilized under the applied shear forces. The additives, especially PAC, CMC, and X-gum, enhance foam viscosity by altering its rheological properties. PAC, with its high molecular weight, has the most significant impact, strengthening the foam structure and substantially increasing viscosity across different shear rates. These trends are supported by viscosity measurements of the liquid base fluid of the tested AAES foaming systems, as shown in Figure 27. The results suggest that the liquid viscosity of the tested foaming systems improves with the addition of additives in the order of $\text{PAC} > \text{X-gum} > \text{CMC}$. This corresponds with the apparent foam viscosity measurements, confirming that PAC offers the highest viscosity improvement in both the liquid phase and apparent foam viscosity. These findings establish a direct relationship between liquid viscosity and the apparent foam viscosity of AAES-based systems. In the light of these findings, PAC emerges as the most effective polymer to enhance the AAES foaming properties. Thus, only PAC was considered for further investigation in the later sections.

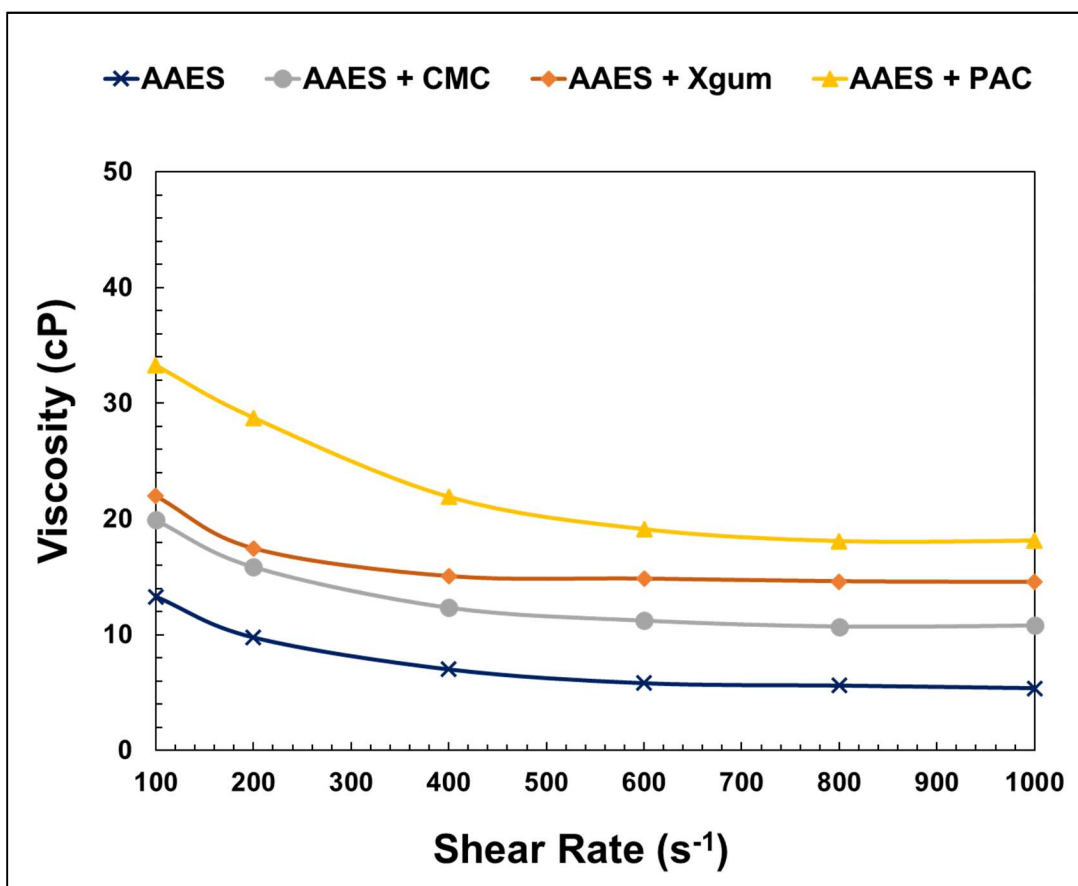


Figure 26 – Impact of additives on the tested AAES-Based foams over a wide range of shear rates under a temperature of 90°C and pressure of 1000 psi.

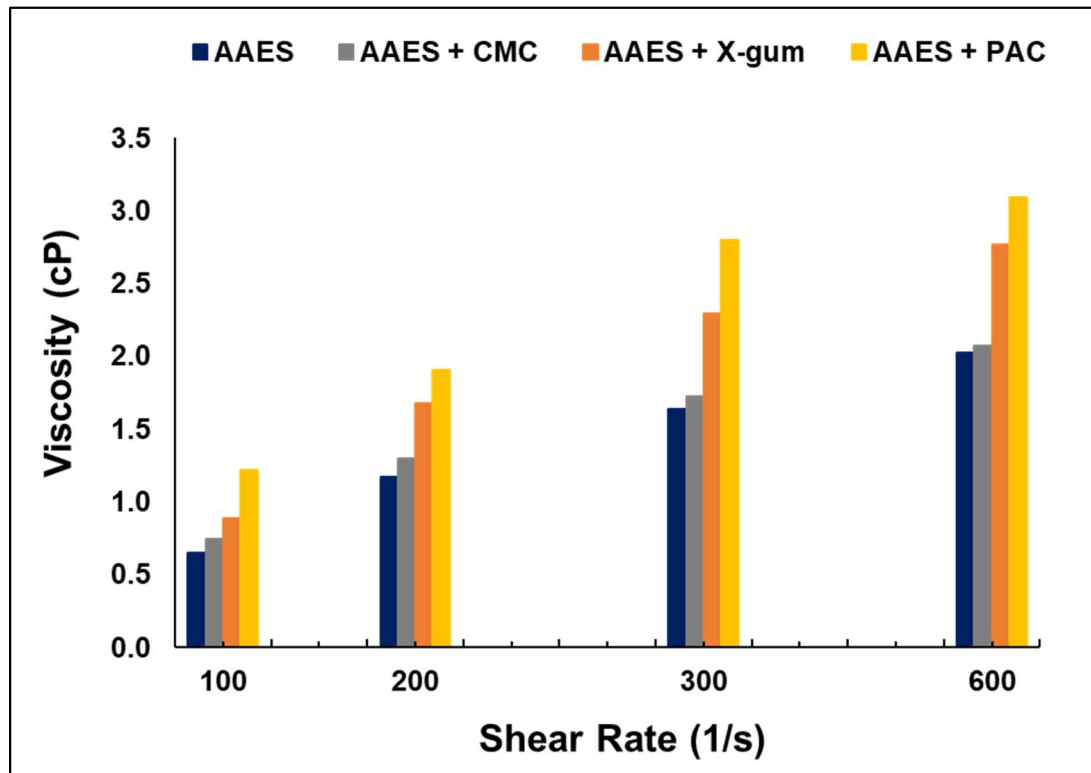


Figure 27 – Liquid viscosity measurements of the tested AAES foaming systems at 1000 psi and temperature of 90°C.

4.3.2 Impact of Clay Solids on Foaming

In this subsection, the impact of solid clays on the AAES foam stability was investigated. The results unveiled distinct behaviors among different additives concerning foam stability (Figure 28). Firstly, increasing bentonite concentration markedly enhanced foam stability, reaching its pinnacle at 4.0 g/L, where stability surged over 14 times compared to the base foam. The addition of Saudi bentonite to AAES foam significantly enhanced the stability of the foam up to a certain concentration, beyond which the stability started to decrease. This phenomenon can be attributed to the unique properties of bentonite clay and its interactions with the AAES surfactant and the foam structure. Bentonite clay is a type of montmorillonite, a naturally occurring clay mineral that is rich in smectite. It is known for its high surface area, high cation exchange capacity, and ability to absorb and retain large amounts of water. When added to the AAES foam, bentonite clay interacts with the surfactant molecules and the foam structure in several ways that contribute to enhanced stability. Initially, the addition of bentonite clay enhances the stability of the foam by (Obisesan 2021):

- Reducing Foam Drainage: Bentonite clay increases the viscosity of the foam by absorbing water and increasing the thickness of the foam film. This reduces the rate of foam drainage, allowing the foam to maintain its structure and stability for a longer period.
- Improving Foam Rheology: The addition of bentonite clay improves the rheological properties of the foam by increasing its apparent viscosity and

viscoelasticity. This makes the foam more resistant to deformation and collapse, leading to enhanced stability.

- **Enhancing Foam Morphology:** Bentonite clay can also influence the morphology of the foam by altering the size and distribution of the foam bubbles. This can lead to a more stable foam structure with improved resistance to coalescence and drainage.
- **Bentonite swelling:** This property also plays a crucial role in enhancing the stability of aqueous foams. Bentonite clay particles, when added to the foam, absorb and retain large amounts of water, leading to an increase in their volume and a change in their structural properties (Magzoub et al. 2019).

However, beyond a certain concentration of bentonite clay, the stability of the foam starts to decrease. This can be attributed to several factors (Seher et al. 2020):

- **Over-Viscosity:** Excessive addition of bentonite clay can lead to an over-viscosity of the foam, making it too thick and difficult to maintain its structure. This can cause the foam to collapse or break down more easily.
- **Interference with Surfactant Functionality:** High concentrations of bentonite clay can interfere with the functionality of the AAES surfactant, potentially disrupting the formation of the foam or altering its surface properties. This can lead to a decrease in foam stability.
- **Clay-Surfactant Interactions:** The interactions between bentonite clay and the AAES surfactant can also play a role in the observed decrease in foam stability.

High concentrations of bentonite clay may lead to the formation of complexes or aggregates that alter the surfactant's ability to stabilize the foam.

Conversely, vermiculite showed only a marginal improvement in foam stability with increasing concentration, implying a limited interaction between vermiculite particles and the foam matrix. While the most prolonged foam half-life was observed at 3.0 g/L, reaching 51 minutes, the overall impact on AAES foam stability remained modest compared to bentonite. The marginal improvement in foam stability observed with vermiculite can be attributed to its distinct structural and chemical properties compared to bentonite. Vermiculite has a lower surface area and cation exchange capacity than bentonite, which reduces its ability to interact with the foam matrix and enhance stability. The modest impact of vermiculite on AAES foam stability, despite its optimal concentration, suggests that the interactions between vermiculite particles and the foam matrix are limited, resulting in a less pronounced effect on foam stability compared to bentonite.

Lastly, perlite exhibited a counterintuitive pattern, with increasing concentration leading to a decline in foam stability. This can be explained by perlite's porous structure, which facilitates liquid drainage, accelerating bubble coalescence and collapse. This leads to a decline in foam stability with increasing perlite concentration, as the foam becomes more prone to collapse and drainage. These findings underscore the crucial role of additives' physicochemical properties in influencing foam stability, with bentonite enhancing, vermiculite marginally impacting, and perlite exacerbating foam instability. In the light of these findings, only bentonite was decided for further experimentation due to its proven positive impact of AAES foam stability.

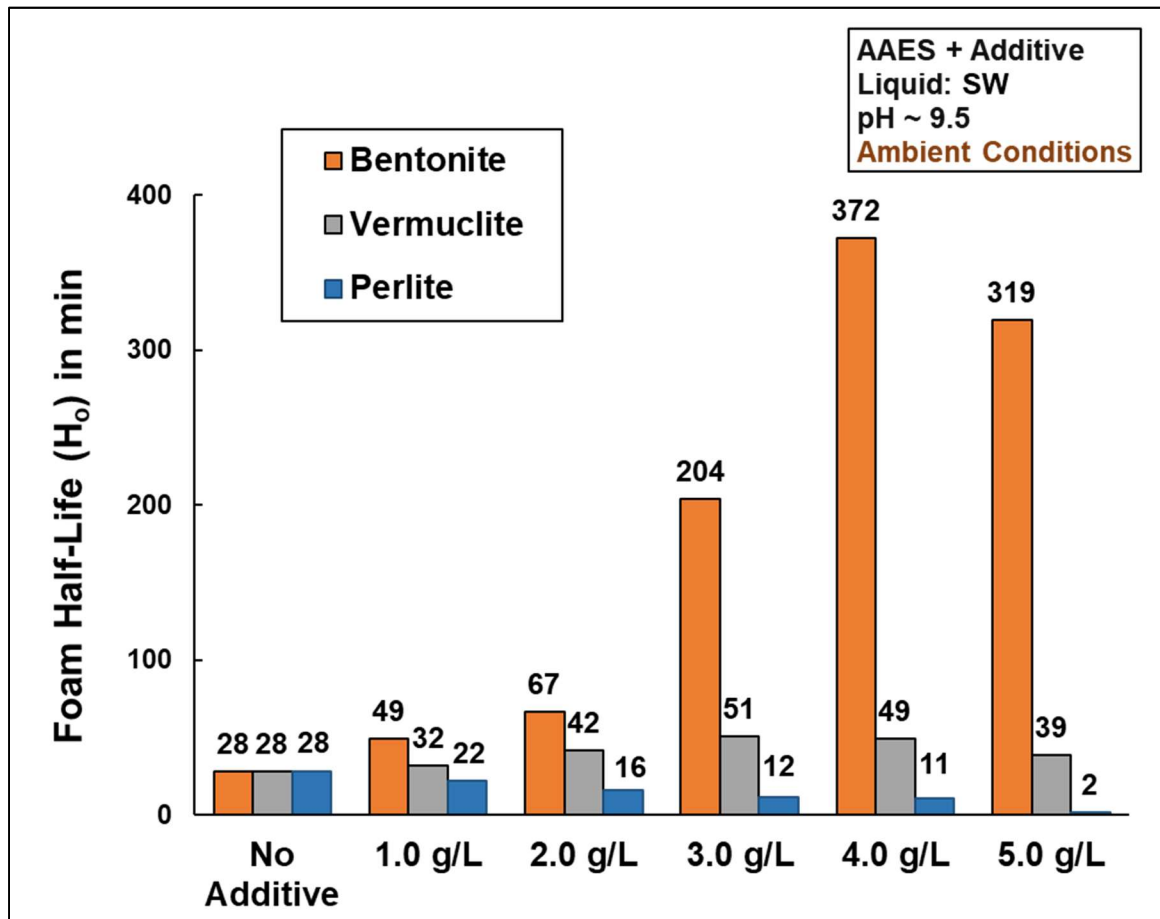


Figure 28 – Impact of adding clay solids on foam stability at ambient conditions (Using DFA 100 Setup).

4.3.3 Impact of Synergy of Polymers and Clay Solids on Foaming

In this subsection, the effect of the synergistic interaction between PAC and Saudi bentonite on AAES foam was examined. The resulting foaming systems were assessed in comparison to a commercial drilling blend to determine their performance viability for underbalanced drilling (UBD) applications.

Foam Stability

Upon testing under elevated pressure and temperature conditions, the incorporation of bentonite resulted in a noteworthy threefold increase in foam stability compared to the base fluid devoid of additives (Figure 29). Surprisingly, this enhancement surpassed the effect achieved by including PAC in the formulation. When PAC and bentonite are included together in the foam formulation, their combined effect boosts foam stability by fourfold compared to the base fluid without additives. This enhancement surpasses the effect achieved by including either PAC or bentonite alone in the formulation. The synergistic interaction between PAC and bentonite can be attributed to their complementary mechanisms in stabilizing the foam:

- **PAC Adsorption:** PAC molecules adsorb onto the bubble surfaces, forming a protective layer that hinders coalescence and drainage. This barrier effect prevents the formation of larger bubbles and promotes the retention of smaller, more stable bubbles within the foam structure.
- **Bentonite Swelling:** Bentonite clay particles absorb water and increase the viscosity of the foam, reducing liquid drainage and enhancing stability. Bentonite also improves the rheological properties of the foam, making it more resistant to deformation and collapse.
- **Foam Morphology:** The combination of PAC and bentonite likely creates a more robust and resilient foam structure that can withstand the challenges posed by elevated pressure and temperature conditions. Bentonite alters the size and

distribution of foam bubbles, leading to a more stable foam structure with improved resistance to coalescence and drainage.

- Interactions with Surfactant: Both PAC and bentonite interact with the surfactant molecules in the foam, potentially altering their surface properties and enhancing stability.

Apparently, formulations containing only PAC approached the foam stability range of the commercial blend, albeit marginally. However, the introduction of bentonite into the mix surpassed the foam stability achieved with the commercial blend.

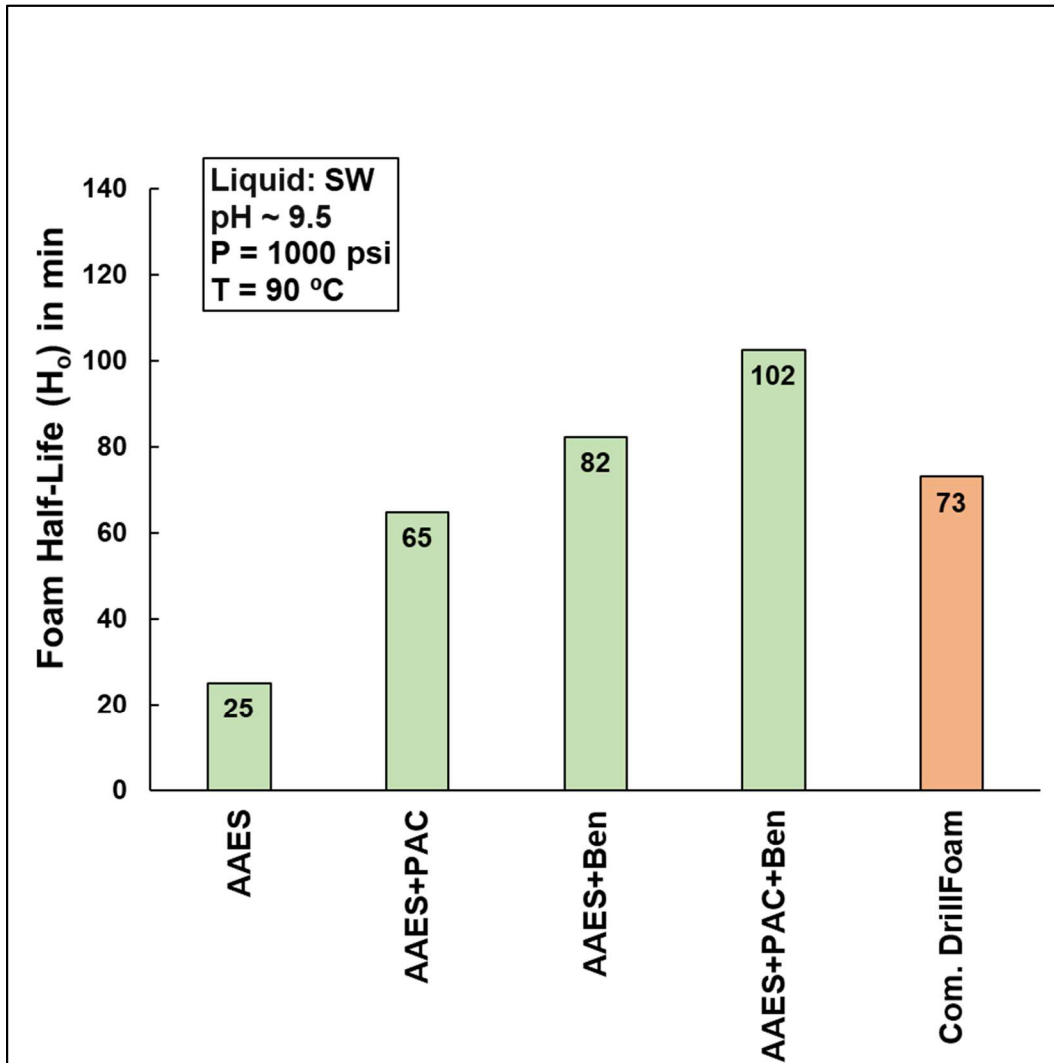


Figure 29 – Impact of including additives on foam stability at elevated pressure and temperature (Using HPFA).

Foam Viscosity

In a parallel trend to foam stability, the addition of bentonite to the formulation yielded a nuanced improvement in foam viscosity (Figure 30), slightly outperforming the impact of PAC inclusion. This enhancement can be attributed to bentonite's inherent swelling properties and its ability to modify the rheological behavior of the foam matrix. Bentonite

particles, upon hydration, form a gel-like network within the foam, increasing its viscosity and providing structural support against collapse. Remarkably, the combined inclusion of bentonite and PAC led to a substantial enhancement in the viscosity of the AAES foam, surpassing the base case by at least fivefold and surpassed the viscosity levels of the commercial blend. This synergistic effect can be rationalized by the complementary mechanisms of these additives: while bentonite primarily contributes to viscosity through its gelation properties, PAC acts as a flocculant, further enhancing the stability and viscosity of the foam structure. Even under the demanding conditions of 1000 psi pressure and 90°C temperature, the viscosity of the foam was markedly elevated by the synergistic action of bentonite and PAC. The heightened viscosity under such extreme conditions underscores the robustness of the foam formulation and its suitability for high-pressure, high-temperature applications, such as in oil and gas operations. These results illuminate the intricate interplay between additives and their collective impact on foam properties, highlighting the potential for tailored formulations to meet oil and gas industrial requirements.

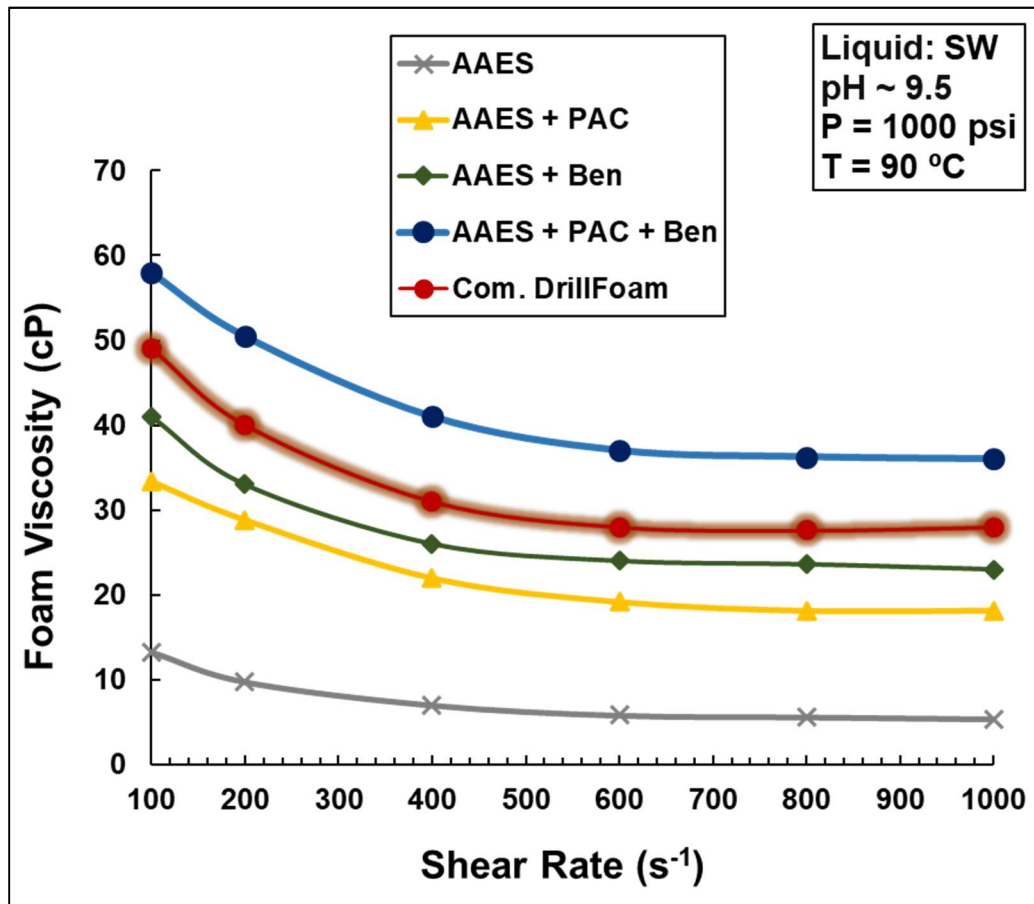


Figure 30 – Impact of including additives on foam viscosity at elevated pressure and temperature.

Yielding Behavior

In drilling applications, the yield point holds substantial importance, serving as a crucial indicator of the fluid's ability to suspend solids and maintain wellbore stability. The findings unveiled a notable trend: whenever bentonite was introduced into the system, either alone or in conjunction with PAC, the foam yield point surpassed that of the commercial blend (Figure 31). This observation underscores the pivotal role of bentonite

in augmenting the yield point of the foam formulation, thus enhancing its efficacy in drilling operations.

The heightened yield point can be attributed to bentonite's unique rheological properties, which promote the formation of a robust gel structure within the foam matrix. Bentonite, known for its colloidal nature and swelling capacity, interacts with the foam components to form a viscoelastic network that enhances suspension and prevents sagging or settling of solids. Additionally, the synergistic action of PAC and bentonite further reinforces the gel structure, leading to a pronounced increase in yield point compared to the commercial blend. These findings carry significant implications for drilling fluid design, highlighting the potential of bentonite-based formulations to improve wellbore stability and mitigate drilling challenges.

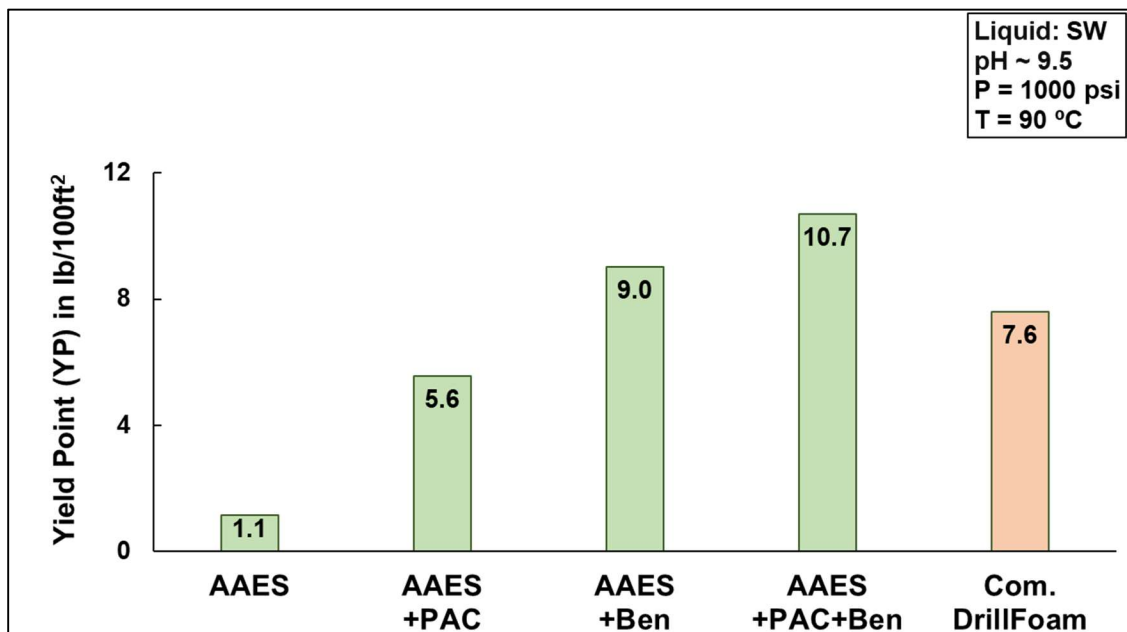


Figure 31 – Impact of adding clay solids on yield point at elevated pressure and temperature conditions.

4.3.4 Impact of Synergy of Polymers and Clay Solids on Oil Tolerance

Another critical aspect of underbalanced drilling application is the effect of anticipated oil influx from the formation into the wellbore under underbalanced conditions. The investigation into foam drainage rates provided notable insights: regardless of the formulation components, the foam drainage rate decreased with increasing oil volume in the system (Figure 32). However, the introduction of PAC and bentonite into the system significantly mitigated the drainage rates, lowering them considerably compared to the base foam without additives. This effect was especially pronounced when both PAC and bentonite were used together, resulting in foam performance comparable to, and in some cases exceeding, that of the commercial blend.

The roles of PAC and bentonite, both individually and in combination, are pivotal in enhancing the oil tolerance of foaming systems used in underbalanced drilling. When PAC is used alone, its polymeric structure helps stabilize the foam by increasing the viscosity of the liquid phase, thereby reducing the rate of liquid drainage and improving the foam's overall stability. This stabilization is beneficial in resisting the destabilizing effects of oil infiltration. Bentonite also contributes to foam stability when used alone by providing additional colloidal particles that enhance the foam's structure through physical reinforcement, further reducing drainage rates. When PAC and bentonite are combined, their synergistic interaction yields a significantly more stable foam. PAC enhances the viscosity while bentonite reinforces the foam matrix, resulting in a robust system that can tolerate higher volumes of oil. This combined effect is particularly effective, often surpassing the performance of commercial foaming agents, by maintaining foam integrity

and functionality in the presence of oil, making it an excellent candidate for underbalanced drilling applications.

The correlation between reduced drainage rates and increased foam stability underscores the intimate relationship between these two parameters. As drainage rates decrease, the foam structure becomes more resilient against collapse and coalescence, resulting in improved stability over time (Figure 33). These findings underscore the potential of additive formulations, particularly those incorporating PAC and bentonite, to optimize foam performance in UBD applications where oil influxes are anticipated.

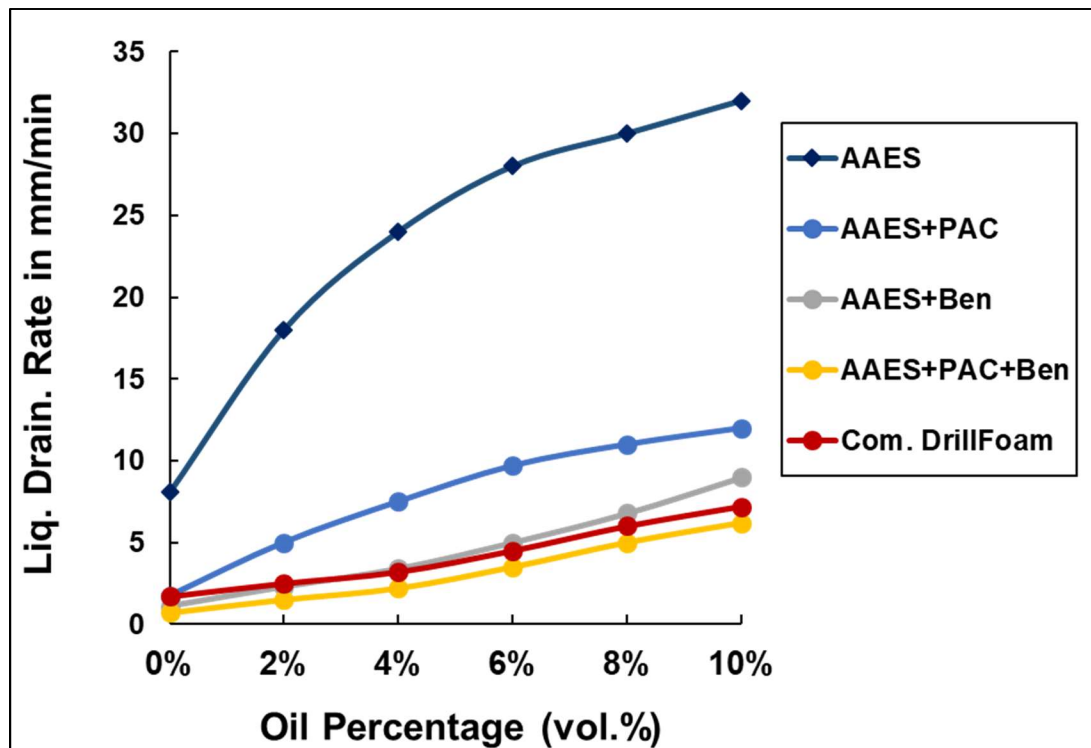


Figure 32 – Impact of additives on the hydrocarbon tolerance of the AAES foam in terms of foam drainage rate.

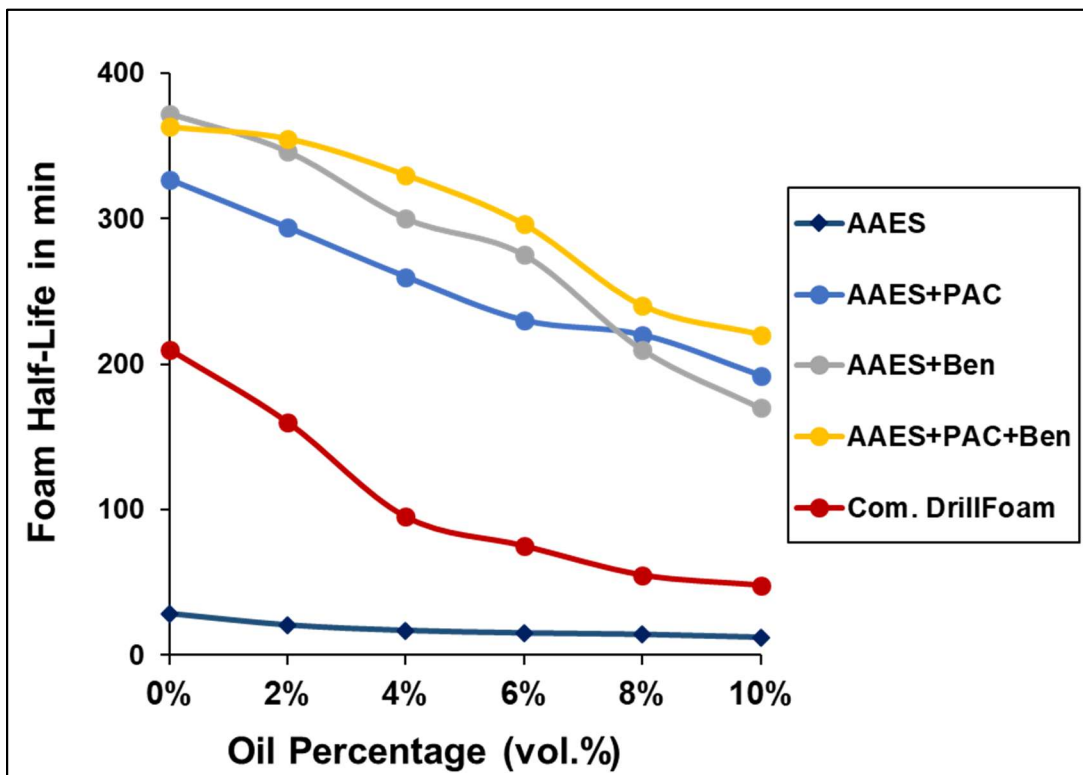


Figure 33 – Impact of additives on the hydrocarbon tolerance of the AAES foam in terms of foam stability.

CHAPTER 5

CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Conclusions

This study introduced a new eco-friendly foaming agent for underbalanced drilling applications. The impact of polymers and clay solids on both foam stability and viscosity was studied at elevated conditions of pressure and temperature. For a typical foam system using nitrogen gas, the key findings include:

- **New Drilling Foaming Agent** Ammonium Alcohol Ether Sulfate (AAES) is introduced as an eco-friendly foaming agent for underbalanced drilling applications with notable tolerance to high salinity levels & mildly alkaline environments.
- **Pressure & Temperature Impact** Gas pressure variations were observed to have a significant impact on both foam stability and viscosity up to temperatures of 60°C, with temperature emerging as the predominant factor beyond this threshold in controlling foam properties.
- **Polymer Impact** Using polymers such as PAC, CMC, and Xgum resulted in a substantial enhancement of both foam stability and viscosity, with PAC demonstrating the most pronounced improvement.

- **Solids (Clays) Impact** Introduction of clay solids exhibited diverse effects on foam characteristics depending on the clay type with bentonite notably enhanced both foam stability and viscosity.
- **Synergy of Solids & Polymers** A synergistic blend of PAC and bentonite outperformed commercial blend, yielding higher viscosity, stability, and yield point in foam formulations
- **Hydrocarbon Tolerance** Incorporating either PAC or bentonite increased foam resistance to hydrocarbon contamination.
- **Viable Drilling Foam Formulation** The results of this study highlight the effectiveness of an eco-friendly polymer combined with locally sourced Saudi bentonite clay in enhancing the performance of AAES foam. This formulation demonstrates significant potential as a candidate for underbalanced drilling (UBD) applications surpassing the performance of the commercial blend.

5.2 Future Directions for Enhanced Foam Drilling

For extending the investigation of foams for underbalanced drilling applications, some recommendations and future directions are suggested as follows:

- **Exploration of Weighted Foams**

Investigate the use of weighted foams to enable foam drilling across a broader range of pressures, enhancing drilling efficiency and performance.

- **Synergistic Surfactant Studies**

Study the combined effects of different surfactants to optimize foam bulk properties, aiming for improved stability and rheological characteristics for enhanced drilling operations.

- **Formation Type Impact Analysis**

Explore the influence of formation types, such as drilled cuttings, on foam stability and rheology to tailor foam formulations for specific drilling conditions and challenges.

- **Corrosion Inhibitor Assessment**

Investigate the effects of corrosion inhibitors on foaming properties to develop corrosion-resistant foam formulations for prolonged drilling operations.

- **Simulation-Based Evaluation**

Conduct simulation runs to assess the performance of developed drilling foam formulations under simulated drilling environments, providing insights into their effectiveness and suitability for real-world applications.

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Selected Publications :

1. **Gowida, A.**, Elkatatny, S. and Ibrahim, A.F., **2024**. Impact of Eco-Friendly Drilling Additives on Foaming Properties for Sustainable Underbalanced Foam Drilling Applications. *ACS omega*. DOI: 10.1021/acsomega.3c07882.
2. **Gowida, A.**, Elkatatny, S., Kamal, M.S. and Hussain, S.M.S., **2024**. Experimental study on an eco-friendly gemini foaming agent for enhancing foam drilling applications. *Journal of Petroleum Exploration and Production Technology*, pp.1-16. DOI:10.1007/s13202-024-01801-y.
3. **Gowida, A.**, Farid, A. and Elkatatny, S., **2024**. Foam Stability Analysis at High pH and Saline Environments for Underbalanced Drilling Operations. *Arabian Journal for Science and Engineering*, pp.1-15. DOI: 10.1007/s13369-024-08816-x
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