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Original Research Article

Experimental Investigations on Enzyme Foam Stability

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ABSTRACT

Foams are produced and stabilized in the presence of surface-active compounds such as surfactants and enzymes. The unavailability of significant research on enzyme foam generation and stability in industrial processes motivated this study whose objective is to investigate the potential of an enzyme to generate and stabilise foam under different conditions of temperature, salinity, pH and enzyme concentration. The residual foam height ratio (R5) method was used to analyse the foam stability under these conditions. The result of the study showed that the enzyme used in this study has the capacity to generate and stabilise foam, but the condition under which the foam is generated however influences its stability. Also, the foam stability depends on enzyme concentration, and it increases with increase in enzyme concentration. Increase in temperature however had an inverse effect on foam stability as it reduced its stability. Furthermore, a decrease in foam stability was observed with increase in brine salinity at all temperatures and enzyme concentrations. Finally, at high enzyme concentrations, increase in the pH of the solutions resulted in the production of very stable foams with R5 values greater than 70% for all temperatures investigated but at low enzyme concentration, the neutral solution (pH of 7) favoured the foam stability. This study presents the novel insight on enzymatic foam stability in salinity and temperature relevant to hydrocarbon reservoir.

1. INTRODUCTION

Foams are special kind of colloidal dispersion systems in which gases are dispersed in liquids. The dispersed phase is sometimes referred to as the internal (disperse) phase, and the continuous phase as the external

phase (Stevenson, 2012). Studies on foams have reached the zenith over the years because of their vast applicability in domestic products and industrial processes such as personal care products, detergency, food manufacturing processes as well as enhanced oil recovery and drilling operations etc.

The success of foam applications largely depends on its foamability and stability which are influenced by different environmental factors such as type and concentration of foaming agent, temperature, salinity, solution pH, presence of oil etc. (El-Mahdy, 2019; Obisesan et al., 2021). Foams are generally formed in the presence of surface-active compounds that enhance the dispersion of gaseous phase in liquid phase due to their adsorption at the gas-liquid interface. This interfacial adsorption of surface-active compounds usually result in surface tension reduction that enhances foam stability (Laurier, 1994; Stevenson, 2012; Udoh and Vinogradov, 2019a).

Extensive studies have been carried out on the stability of foams generated by chemical surface-active compounds such as surfactants. For example, El-Mahdy, (2019) investigated the effects of salinity and oil on foamability and foam stability of surfactant solutions and their results showed that increase in the concentration of surfactants enhanced foam stability. They also observed reduction in foam stability with increase in solution salinity with one of the surfactants used while no effect was observed with another surfactant. This suggests the possibility of ionic interactions between the electrolytes and the surfactants used for the foam generation. Negar et al. (2019) investigated the effect of salinity variation on foam stability using 0.5, 2.0 and 3.5 wt.% salinity and surfactant concentrations of 0.5, 2.0 and 3.5 wt.% concentrations. Their results also showed that foam stability decreased with increase in solution salinity, and this was attributed to increased repulsive forces in the solution that weakens foam lamellae due to increased negatively charged ions in the solution. Their salinity test was however conducted with NaCl solution which is not a true replicate of reservoir brines because the formation brines commonly found in the reservoir are multi-components in nature and not just single component. The use of combined nanoparticles and surfactant for foam stability and flooding in high temperature and high salinity conditions relevant to oil reservoirs have been explored by Singh and Mohanty, (2017). Their results showed that the foam strength increases with increase in surfactant concentration but the foam decay with increase in temperature. Other study by Wang et al. (2017) investigated the effect of temperature on foaming ability and stability of surfactant generated foam and they observed increase in foam ability but decrease in its stability with increase in temperature. The recent work by Obisesan et al. (2021) also investigated the impact of salt on the drainage behaviour of aqueous foams and their results showed that the presence of salts in the aqueous phase affects the adsorption of surfactant.

Although a good number of research on surfactant foam generation and stability have been conducted with positive results, the cumulative effect of continual surfactant application can however constitute an environmental threat due to their toxic and non-degradable nature (Hamme et al., 2006). Furthermore, enzymes have been identified as a possible alternative to surfactants because of their surface activity and environmental-friendly attributes, but sadly, they have received little or no consideration (Udoh 2019). Hence, the aim of this study is to investigate the potential of enzyme to generate and stabilise foam under different conditions of temperature, salinity, pH and enzyme concentration. Enzymes can modify the interfacial and surface tensions of fluids hence, they are classified as surface-active compounds which can be used for foam generation (Udoh and Vinogradov, 2019a,b). Consequently, enzymatic foam may be generated during enzyme application process and the stabilisation of the foam is fundamental to its application in enhanced oil recovery process.

2. MATERIALS AND METHODS

2.1. Material Collection and Preparation of Samples

The synthetic formation brine used in this study was prepared based on the composition of the referenced reservoir formation brine with compositional breakdown of 98.2% sodium chloride (NaCl), 0.6% calcium chloride ($CaCl_2$), 0.8% magnesium carbonate ($MgCO_3$), 0.2% potassium chloride (KCl) and 0.2% sodium

sulphate (Na_2SO_4) and the total salinity of 32 g/L. These salts were dissolved in a litre of distilled water based on the measured detailed in Table 1. Three brines were used for salinity tests namely, hundred percent formation brine (100%), fifty percent formation brine (50%) and ten percent formation brine (10%). These brines represent brine in the reservoir and injection brine salinities that are used for enhanced oil recovery process. The enzyme used in this study is a commercial 100% enzyme solution named greenzyme and supplied by Biotech Processing Supply, Dallas, Texas, USA. The choice of this enzyme is based on its surface activity and enhanced oil recovery potential detailed in previous studies such as (Udoh and Vinogradov, 2019a,b; Udoh and Evangelista, 2020). Different concentrations of enzyme solutions were prepared by diluting the 100% stock solution with distilled water to attained 1, 3, 5, and 10 wt.% concentrations that were used for the experiment. For the pH variation investigation, three commercial buffer solutions of pH 4, pH 7 and pH 10 were used.

Table 1: Compositional breakdown of brines with varied salinities

Salts	Compositions of salts (%)	100% salinity Conc. (g/L)	50% salinity Conc. (g/L)	10% salinity Conc. (g/L)
NaCl	98.20	31.424	15.712	3.1424
$MgCO_3$	0.80	0.256	0.128	0.0256
$CaCl_2$	0.60	0.192	0.096	0.0192
Na_2S0_4	0.20	0.064	0.032	0.0064
KCl	0.20	0.064	0.032	0.0064
Total	100.00	32.000	16.000	3.2000

2.2. Methods

The apparatus used for the experiments is a long glass column with a fritted glass at the bottom of the column for gas dispersion. For each of the test, 20 mL of enzyme solutions was carefully fed into the column in such manner that foam generation was prevented. Thereafter, 40 mL of air was injected into the column through the sintered glass as the base and the air inlet valve connecting the column to the injection syringe was immediately closed. The air was supplied manually at 20 second interval and the dispersion of air through the column of varied enzyme solutions resulted in generation of foam in the medium. The initial heights of the foams and solutions in column were measured and changes in foams and solutions heights were determined as a function of time using a high-resolution camera for accuracy. The experiment was repeated 3 times for each of the solution. The experimental variables considered in study are (i) enzyme concentration (0, 1, 3, 5 and 10 wt.%), (ii) brine salinity (10, 50, and 100 wt.%), (iii) solution pH (4, 7 and 10) and (iv) temperature (25, 45, 65 and 85 ^oC). The foam stability was determined based on R5 parameter (Equation 1) that relates the ratio of the foam height at five minutes after foaming (h_5) to the initial foam height (h_0) as proposed by Lunkenheimer and Malysa, (2003). The higher the R5, the better the stability of the foam and lower values of R5 indicate low foam stability, while foams with R5 of 50% is metastable.

$$R5 = \frac{h_5}{h_0} \times 100 \quad (1)$$

3. RESULTS AND DISCUSSION

3.1. Effect of Enzyme Concentration on Foam Stability

Figure 1 presents the results of the effect of enzyme concentration variation on foam stability at different temperatures. For 0% concentration (enzyme-free) solution, random foam breakage that started immediately after the formation of foam was observed, and all the foams collapsed quickly. This phenomenon validates the theory which states that pure liquids do not foam because of the absence of surface-active-agent that can retard lamellae drainage or enhance interfacial stabilisation (Azira et al., 2008). The use of enzyme was however able to generate foams that exhibited better stability than the foam generated without enzyme. Generally, increase in foam stability was observed with increase in enzyme concentration irrespective of the system temperature. The use of 1 wt.% enzyme concentration does not seem to be a good foam stabiliser

especially at high system temperature. This means that for better and efficient foam stabilisation, higher enzyme concentrations (3 wt.% and above) would be required. The observed increase in foam stability with increase in enzyme concentrations is consistent with the previous studies that also observed increase in foam stability with increase in surfactant concentrations (El-Mahdy, 2019; Negar et al., 2019; Obisesan et al., 2021). The better foam stability achieved with increase in enzyme concentration is attributable to increase in its interfacial adsorption at high concentration.

3.2. Effect of Temperature on Foam Stability

The results of the effect of temperature on foam stability are presented in Figure 2. Generally, reduction in foam stabilities was observed with increase in temperature irrespective of the enzyme concentration used for the foam stabilisation. This shows that increase in temperature has an adverse effect on foam stability at different enzyme concentrations. This observed decrease in foam stabilities at high temperatures can be related to the lower surface viscosity at higher temperatures, thus, resulting in a more rapid liquid drainage and therefore lower foam stability (Wang et al., 2017). On the contrary, at low temperatures, higher viscosity of the continuous liquid phase will result in low drainage rate thereby enhancing the foam stability (Delahaije et al., 2019). For 0% enzyme concentration solution, the effect of temperature on foam stability was relatively negligible, hence, remains constant with unstable foams.

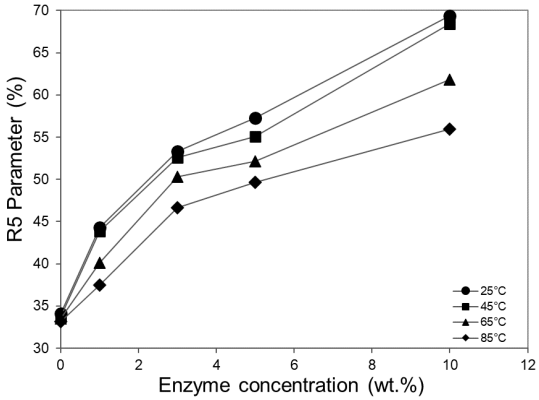

Figure 1: The effect of enzyme concentration on foam stability at different temperatures

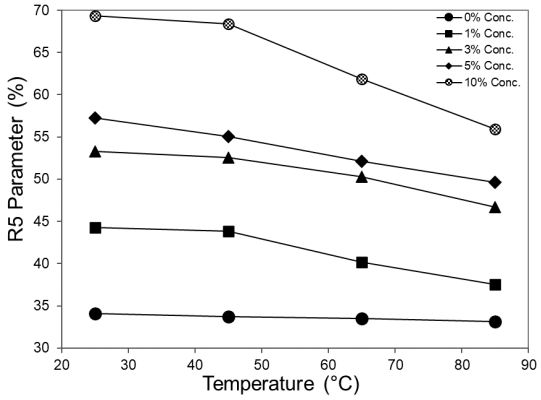

Figure 2: The effect of temperature on foam stability in different enzyme concentration solutions

The low concentration (1%) enzyme solution was however characterised by low foam stability that was further compounded by increase in the system temperatures. This is due to low interfacial enzyme adsorption and low viscosity that enhances fast liquid drainage. For higher enzyme concentrations (3%, 5% and 10 wt.%) solutions, stabile foams with R5 greater than 50% were still produced despite the temperature rise, although the foam stability still followed the same trend and more stable foams were best formed at lower temperatures. Increase in enzyme concentrations means more enzyme adsorption at the interfacial thereby enhancing foam stability. High enzyme concentrations also increase the solution viscosity thereby reducing the rate at which the liquid drainage occurs and hence, higher stability was till attained at high temperature. Even though the foam stabilities reduced with increase in temperature relative to lower temperature stability, higher enzyme concentrations still enhanced foam stability. The observed decrease in foam stability as the system temperature increases is consistent with previous studies that also observed reduction in foam stability with increase in temperatures (Singh and Mohanty, 2017; Wang et al., 2017; Delahaije et al., 2019).

3.3. Effect of Salinity on Foam Stability

Figure 3 shows the results of the experimental investigation of the effect of brine salinity on foam stability at different enzyme concentrations and temperatures. Decrease in foam stabilities was generally observed as the brine salinity increases at all temperatures and enzyme concentrations except that of 0% (enzyme-free saline solution). All the enzyme-free saline solutions were seen going against the trend of enzyme solutions

(that is, the foam stability increased with increasing salt concentration) although their stabilisation levels were very low. This anomaly is attributable to increase in the solution viscosity due to increase in salt concentration in the solution at high salinity. This increased solution viscosity will reduce the drainage rate (Delahaije et al., 2019). For varied enzyme concentrations at fixed temperature, better foam stability was achieved in low salinity brine (10 wt.%) and the least in high salinity 100% formation brine. This shows the significant effect of solution salinity on foam stability. When salts are dissolved in water, they dissociate into ions and in the presence of surface-active agent such as enzyme, they can form ionic surface-active molecules in solutions and at high salinity these ions can screen the enzyme thereby reducing its interfacial activity (Oh and Shah, 1993). This screening effect will reduce the electric double layer thickness and the effectiveness of the enzyme interfacial adsorption (Eslahian et al., 2014). This effect is more prominent at low enzyme concentrations because of the dominant effect of brine salinity, but as its concentration increases, the effect of enzyme surface activity becomes more dominant than that of the salinity as evident by the observed higher foam stabilities at high concentrations.

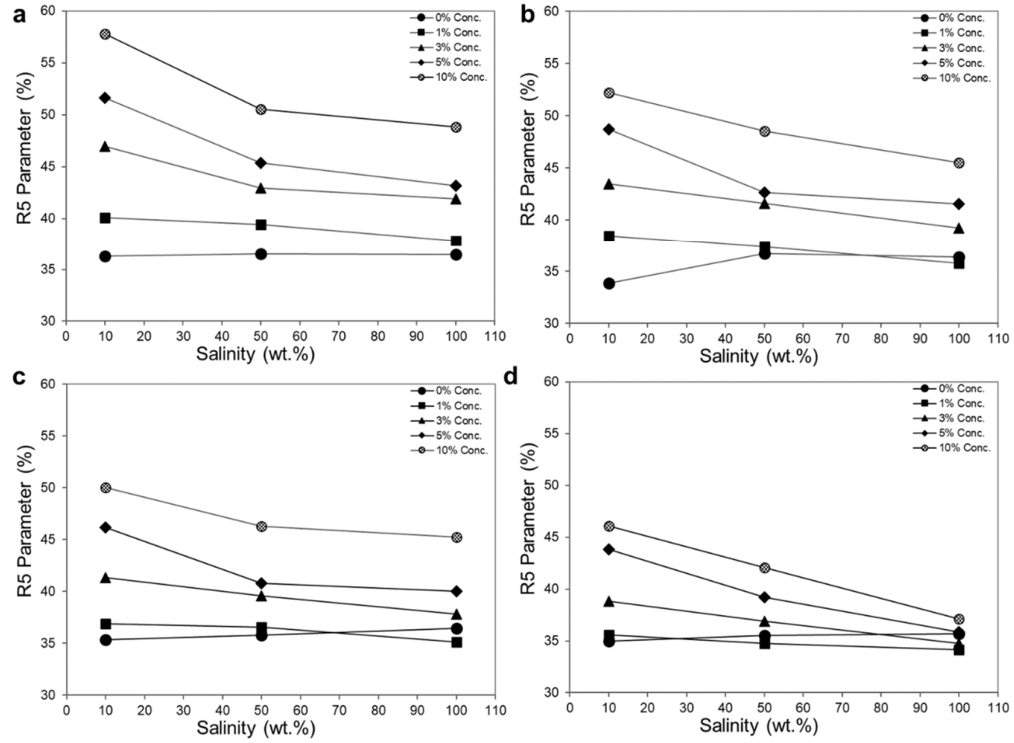

Figure 3: The effect of salinity on foam stability at varied enzyme concentrations and temperatures: (a) 25 °C (b) 45 °C (c) 65 °C (d) 85 °C

A similar effect was observed by Obisesan et al. (2021) from their investigation on the impact of salt on the drainage behaviour of aqueous foams in which their results showed that the presence of salts in the aqueous phase affects the adsorption of surfactant. El-Mahdy (2019) also observed reduction in foam stability with increase in solution salinity with one of the surfactants used while no effect was observed with another surfactant. This shows the effect of ionic interactions between the salts and the foaming agents used for foam generation. Negar et al. (2019) also observed decrease in foam stability with increase in solution salinity. The results of the effect of temperature on foam stability enzyme solutions alone (Figure 2) showed that increase in temperature reduces enzyme foam stability, but in the above results (Figure 3), the combined effects of temperature and salinity on enzyme solutions were presented. From these results, a continuous decrease in foam stabilities with increase in temperature was observed irrespective of the salinity and enzyme

concentrations. This further shows the adverse effect of temperature on enzymatic foam stability. A comparison between the results of the enzyme solutions (Figure 2) and saline enzyme solution (Figure 3) shows the significant effect of salinity. In the former, the highest foam stability of 69.35% was attained in 10 wt.% enzyme solution at 25 ^{o}C which reduced to 55.92% at 85 ^{o}C. In the saline enzyme solution however, the highest foam stability of 57.80% was attained in 10 wt.% enzyme solution at 25 ^{o}C which reduced to 48.81% at 85 ^{o}C. This shows that the foam generated by this enzyme may not be suitable for enhanced oil recovery application under the conditions investigated in this study because higher concentration of enzyme will be required for an efficient application of the foam in reservoirs that are characterised by high salinity and high temperature.

3.4. Effect of pH on Foam Stability

Figure 4 shows how the variation of pH affected the stability of enzymatic foam at different enzyme concentrations and temperatures. Generally, high foam stability was observed for all the solutions. For enzyme solutions, two trends were observed in the results: (1) at high enzyme concentrations (3, 5 and 10 wt.%), increase in the pH of the solutions resulted in the production of outstandingly very stable foams with R5 values greater than 70% for all temperatures investigated and (2) at low enzyme concentration (1 wt.%), increase in the pH to 7 resulted in a slight increase in the foam stability for all temperatures investigated but further increase in pH to 10, reduced the foam stability at all temperatures.

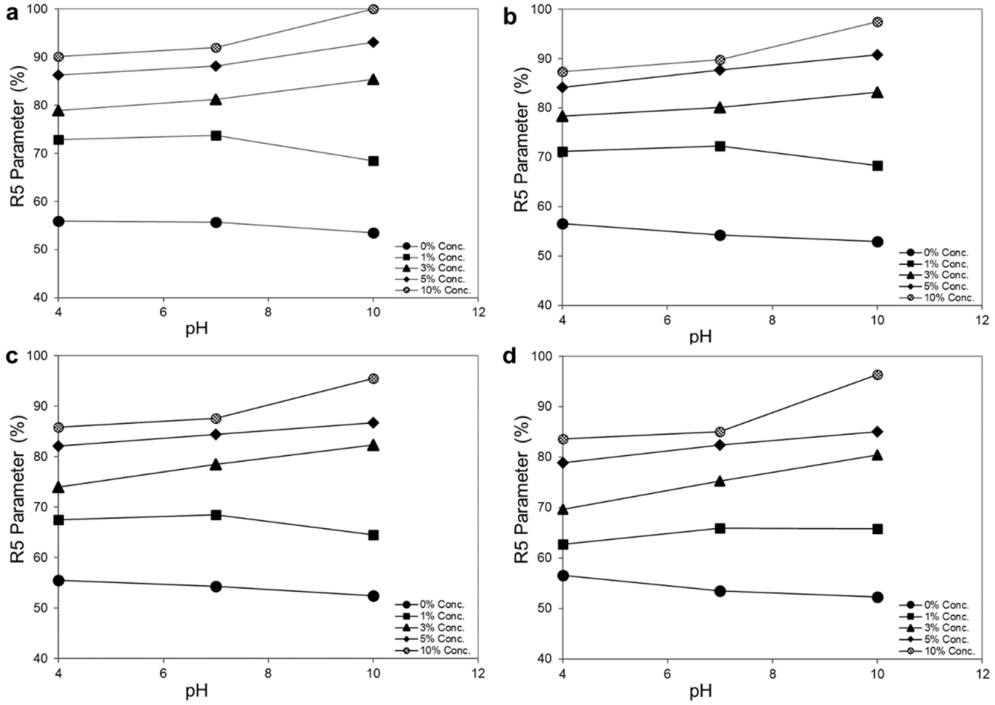

Figure 4: The effect of pH on foam stability at different enzyme and temperatures: (a) 25 °C (b) 45 °C (c) 65 °C (d) 85 °C

Hence, at low enzyme concentration a neutral solution (pH of 7) favors the stability of foam while at high concentration, a basic solution (pH 10) is more favorable. For enzyme-free solutions (0% enzyme concentration), increase in the pH of the solution reduced the stability of foam at all temperatures investigated. The observed enhanced foam stability attained with high solution pH is consistent with the results of the study by Du et al. (2003) that observed smaller ovalbumin foam size at pH 6.5 and pH 9.5 and best foam fractionation at pH 9.5. Smaller foam bubbles are known to be more stable than large bubbles

because they are slow in forming bubble coalescence that can cause destabilisation of the foam (Govindu et al., 2019). This is due to the fact that smaller bubbles tend to drain more slowly under gravity and also exhibit stronger capillary suction resisting drainage than large bubbles. It is a known fact that all enzymes are proteins, but all proteins are not enzymes, and the major components of enzyme molecule are amino acids and the carboxyl groups (Udoh and Evangelista, 2020). The solution pH affects the ionization of these components, and it makes enzyme to have positive charge at low pH and negative charge at high pH due to the dominant dissolution of NH^{3+} and carboxyl groups, respectively (Udoh, 2019; Udoh and Vinogradov, 2019b). These two ionizable groups makes enzymes to have hydrophilic property while the hydrocarbon group gives it hydrophobic nature thereby making it possible for enzyme to adsorb at the air-solution interface with its hydrophilic ends toward the solution and the hydrophilic end toward air. The intensity of this adsorption determines the effectiveness of their interfacial activities (Hammershøj et al., 1999). Finally, the result of this test further shows that the increase in temperature reduces foam stability although the effect is less significant in pH solutions due to their high foam stability.

4. CONCLUSION

The potential of enzyme to generate and stabilise foam under varied conditions was investigated in this study. The experimental variables considered were enzyme concentration, temperature, salinity and solution pH. The results of the study showed that the enzyme has the capacity to generate and stabilise foam under the aforementioned conditions. Also, increase in enzyme concentration enhances enzymatic foam stabilities under all conditions investigated but increase in temperature and salinity have adverse effect on foam stabilities while solution pH significantly enhanced foam stability.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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