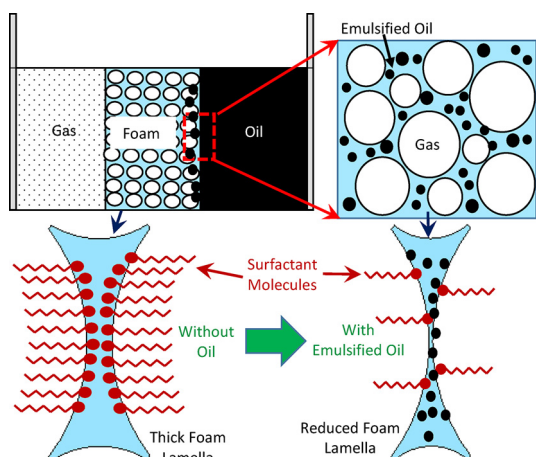# Experimental investigation of emulsified oil dispersion on bulk foam stability

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GRAPHICAL ABSTRACT

ABSTRACT

Recently aqueous foams have shown promising results to overcome viscous fingering and gravity segregation problems during gas injection process. However, one of the main challenges is the stability of the foams in the presence of oil bank at the front of injected foam. Oil can penetrate into the foam structure in the form of continuous phase or emulsions which might deteriorate lamellae and plateau borders that can result in bubble coalescence and foam rupture. The combination of the surfactant solution, responsible for stabilizing foams, with oil increases the potential for the formation of oil emulsions. In this condition emulsions stability and phase behaviour have the main influence on the bulk foam stability. The objective of this research is to conduct a comprehensive study on the effect of emulsified oil, at different concentrations and salinities on the stability of bulk foams used during oil displacement processes. This was achieved using a foam column test, in which foam is generated and its decay monitored with time. The half-life for each sample was noted and a comparison was made for different cases. Furthermore, changes in the foam bubble sizes and distribution were observed and analysed using an image processing software. A gradual reduction in the half-life of foam was observed with increasing concentration of emulsified oil. The degree to which a foam structure is destabilized by the emulsified oil droplets is dependent on the type and concentration of surfactant employed in generating the foam. At 2 wt% concentration of emulsion, the half-life recorded for foam generated by AOS surfactant, was 107 min, while for the foam generated by SDBS was only 39 min. Further analysis of the results showed a reduction in the

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number of dispersed oil droplets with increasing the salinity. In addition, the effect of increased salinity of the emulsion on foam stability was again found to be a function of the type of the surfactant is present in the foam system.

## 1. Introduction

Natural energy responsible for displacing hydrocarbons diminishes gradually with time. To increase the recovery factor, certain enhanced oil recovery techniques are being employed in the oil industry. One of such methods involves the injection of immiscible gases to reduce oil viscosity and interfacial tension between displacing and displaced fluids, thus improving the mobility of hydrocarbons [1–3]. Due to extreme differences in the density and viscosity of gas and oil, there is a continuous penetration of gas into the oil phase. This results in viscous fingering effects which ultimately reduce the sweep efficiency in the reservoir [1,4]. A successful technique commonly employed to curb the problem of gravity override is the injection of foamed gas into the reservoir. The foamed gas is generated by introducing gas into a solution of surfactant. When the foam is generated, the gas phase is discontinuous and separated by thin liquid films of Lamella [4,5]. Therefore, the movement of gas within the system is highly restricted and dependent on the breaking and reforming of the lamellas [6]. This process reduces gas mobility and improves the sweep efficiency in reservoirs significantly. Foam gas also applied in the gas lifting and liquid loading process and shown successful results in improving oil unloading and reducing gas mobility in the vertical wells [7–9]

Boud and Holbrook in 1958 pioneered the use of foams for gas mobility reduction [10]. In their pursuit of enhancing the effectiveness of secondary gas injection, they injected a specific volume of foaming solution before gas injection. They observed an increase in oil recovery and a reduction in gas mobility with the generation of the foamed gas. A number of research studies have been conducted on the application of foams in reducing the gas mobility [6,11–17]. Bernard and Holm conducted experiments to study the effect of foam on the permeability of a system to gas [9,11]. Their observations showed that the effectiveness of foams in gas permeability reduction increased with the permeability of the system. They later concluded that foams could be used for selective blocking of higher permeable regions. Therefore, the integrity of foams, used in recovery processes is of utmost importance, which depends on several factors such as the properties of foaming agent, presence of additional liquid or solid phase in the foam structure, rock petrophysical properties and the reservoir condition. [18–20]. A foam that maintains its integrity for the most part of a flood project, is the one in which the rate of coalescence of bubbles is low due to the presence of sufficient stabilising agents. Bulk foam is a term used in describing foams collectively at large scale. It is imperative that a prolonged separation between the gas and liquid is maintained for foams used in enhanced oil recovery processes. Thus, many studies have been conducted to test the behaviour and stability of foams under various conditions [18,20–24].

The type and concentration of surfactants used in foam generation have a large influence on foam stability [23,25–28]. The foamability, obtained by measuring the time taken to generate a certain volume of foam [12,28], is a function of the chemical structure of the surfactant. Jones and Laskaris, conducted bulk and core flood experiments to study the effect of different concentrations of surfactant on the foam behaviour [25]. Results from bulk test showed the foam stability is enhanced as the concentration is increased beyond the critical micelle concentration. In the core-flood tests, a decrease in concentration of surfactant caused a reduction in the foam quality as well as the apparent viscosity of gas which are signs of an early gas breakthrough. Simjoo et al. investigated the foaming capacity and foam maximum density of alpha-olefin-sulfonate (AOS) surfactant at different concentrations [28]. Analysis of the results showed an increase in the foaming capacity

and maximum density at higher concentrations of surfactants in foam films. Wang and Li also conducted experiments to study the effect of increasing the concentration of surfactant on the foam stability [29]. Triton X-100 and propane ($C_3H_8$) was used as surfactant and gas respectively. The results from their experiments showed that the stability of foam is insensitive to changes in concentration beyond the critical micelle concentration. This observation was not consistent with that of Jones and Laskaris, who conducted experiments on ionic surfactants [25]. Their experiments showed that foam stability increases with concentration even beyond the critical micelle concentration. Wang and Li conducted the experiment using non-ionic Triton X-100 surfactant as opposed to Jones and Laskaris who conducted experiments using two formulations of anionic Alpha Olefin Sulfonate (AOS). Based on the experiments outlined above, it is evident that surfactants behave differently depending on their ionic properties. Thus, sufficient screening tests should be conducted to determine the behaviour and characteristics of each surfactant under different conditions.

The stability of foams is also influenced by the presence of continuous hydrocarbons due to interactions between the oil phase and lamella. In oil recovery processes where oil is present within a foam system, a secondary film is developed between the gas and oil phases which is called a pseudo-emulsion film [4]. Lower chain hydrocarbons are known to have an adverse effect on the stability of foams [18, 30 and 31]. This is purely a function of the entering and bridging coefficients of the liquid film separating the gas phase from the liquid phase. For a short chain hydrocarbon molecules with lower viscosity, the magnitude of these coefficients is high, ensuring easier penetration. Once, penetration occurs, a non-symmetrical unstable pseudo-emulsion film separating the oil from the gas phase is created. Longer chain hydrocarbon molecules are less detrimental due to their increased viscosity. The oil droplet may not penetrate but accumulates at the plateau borders slowing down the thinning rate of the films. [18,28,32–39].

Schramm and Novosad, observed the interactions between foam and oil using an etched glass micromodel [30,31]. They pointed out that three types of foams could be formed in the presence of oil. Type A foam shows little or no interaction with oil, and the stability of this foam is credited to the formation of a very large droplet of oil, making it difficult to pass through plateau junctions to destabilize the lamellas. Type A foams are formed in the presence of long chain hydrocarbon molecules within the foam structure. Type B foams, on the other hand, are less stable. This is because smaller oil droplets are formed upon contact with the foam that can be transported up the plateau borders into the lamella. Type C foams proved to be more detrimental to the stability of foams as even smaller oil droplets are formed. These droplets can enter even the thinnest lamella causing a rapid coalescence of the lamella. Type C foams are formed as a result of the presence of shorter chain hydrocarbon molecues in the foam structure. These results are consistent with Robinson and Woods' theory which explains that an oil droplet will cause destabilization if it penetrates the gas-liquid interface on contact and in turn spread strongly along the interface [40]. Schramm and Novosad also described different criteria that must be met for the destabilization of foams by oils; the entering (E), spreading (S) and bridging (B) coefficients [31]. For an oil phase to enter, spread or bridge a foam lamella, the individual coefficients must be positive. These coefficients are calculated with the following equations:

$$E = \sigma_{w/g} + \sigma_{w/o} - \sigma_{o/g} , \qquad (1)$$