Investigation on the Effect of Types of Nanoparticles and Temperature on Nanoparticles-Foam Stability

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Abstract

Foam has been proposed as a mobility control agent in gas-based enhanced oil recovery. However, surfactant-based foam stability deteriorates at higher temperature. Currently, nanoparticles have been widely tested in foamability and foam stability. Hence, this paper is aimed to investigate the stability of nanoparticles-foam at different temperatures using 5,000 ppm anionic alpha olefin sulfonate surfactant in 3.0 wt% sodium chloride, and 1.0 wt% of sodium hydroxide to control the system pH. Silicon dioxide and aluminium oxide nanoparticles were used to examine the effect of nanoparticles in stabilizing foam. Foam stability was measured based on foam half-life in static condition. The performance of the nanoparticles were analysed at 25°C, 40°C, 60°C and 90°C. It was found that aluminium oxide nanoparticles enhanced foam better compared to silicon dioxide nanoparticles. These results were supported with the microscopic observation of foam structure and lamellae inside the glass tube. These findings contributed to the understanding of the effects of nanoparticles in enhancing foam stability.

Keywords
Nanoparticles, Temperature, Foam Stability, Microscopic

1. Introduction

Gas flooding is widely applied in the field due to its efficient oil viscosity reduction but poor sweeping effect is notable as gas fingering occurred in the porous media. This is due to the significant viscosity difference between gas and residual oil as well as high gas mobility. Therefore, foam is one of the methods proposed to minimize gas mobility and viscous channelling, thus improving sweeping effect. Foam is a two-phase medium that gas is trapped in liquid lamellae where lamellae serve as a barrier to control gas movement. The low surface tension favours the foamability of a solution. Talebian *et al.* (2013) mentioned that foam can improve recovery efficiency by reducing viscous instability and mobility depending on reservoir condition with proper injection strategies. Nevertheless, foam is sensitive to the presence of oil, water salinity, pressure and temperature. Foam lamella breaks or coalesces easily at higher temperature and thus higher amount of surfactant would be required to yield stronger lamellae.

However, one of the considerations is the cost implied on excessive surfactant usage to generate stable foam at high temperature condition (Emrani & Nasr-El-Din, 2015). Hence, adding nanoparticles in the foam is an option to foam additive which believed offer better stability. For instance, a study by Singh & Mohanty (2014) showed that the presence of 0.1 wt% of silicon dioxide (SiO_2) in 0.5 wt% alpha olefin sulfonate surfactant (AOS) could increase the static foam half-life from 48 hours to 68 hours in a confined system, also, further increase in concentration of SiO_2 could stabilize foam with durable foam half-life for more than 4 days. Besides that, Eftekhari *et al.* (2015) found that adding nano-ash (which consists of mostly SiO_2) in the foam could reduce surfactant usage to achieve the same foam viscosity. Furthermore, Guo *et al.* (2017) showed that nano-ash and iron (III) oxide (Fe_3O_4) nanoparticles promotes better foamability and stability in the combination of AOS and lauramidopropyl betaine (LAPB) surfactants as the foam half-life increased from 83 minutes to 238 minutes and 118 minutes respectively. Therefore, the main purpose of this study is to investigate nanoparticles-foam stability at different temperatures with respective concentrations of nanoparticles, brine, and surfactant. Two types of nanoparticles were used to determine its effect

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towards foamability and foam stability. The operating conditions for this study is limit at atmosphere pressure and the temperatures studied were 25°C, 40°C, 60°C and 90°C.

2. The Presence of Nanoparticles in Foam

As observed from the earlier research work by Espinosa (2011), Worthen *et al.* (2012), Aroonsri *et al.* (2013) and Liu (2015), the usage of SiO_2 nanoparticles in CO_2-in-water foam generation seems to serve an alternative to surfactant usage. Later, Singh *et al.* (2015) and Lee *et al.* (2015) revealed that nanoparticles unable to create foam in water without surfactant because particle unable to stabilize gas-water interface alone. Among all the surfactants added with nano-ash, anionic surfactant yielded the most stable static foam with half-life of greater than 50 hours, stable fine foam and smaller bubble size were also observed when injected with CO_2 (Singh *et al.*, 2015). On the other hand, Lee *et al.* (2015) discovered that cationic surfactant modified the surface properties of nano-ash and thus generate stable foam. However, Singh *et al.* (2015) has screened out this mixture because cationic surfactant formed relatively huge agglomeration with nano-ash due to neutralization of surface-charge.

Previous researches also show that increasing water salinity inhibits foamability and foam stability. Farajzadeh *et al.* (2008) the thickness of foam film decreasing with increasing salt concentration in AOS surfactant. Besides that, Eftekhari *et al.* (2015) found that stability of nano-ash-stabilized foam degraded when water salinity increased from zero to 5 wt% and smaller bubble size was observed in dense at higher water salinity. On top of that, the presence of Ca^{2+} ions in water had more adverse effect on nano-ash-stabilized foam foamability and stability probably because surfactant and Ca^{2+} formed precipitation which resulting nano-ash formed coagulation among itself (Eftekhari *et al.*, 2015).

The pressure and temperature underneath are greater than surface condition. Several researches have been done on foamability and foam stability with the effect of pressure and temperature. Tyrode *et al.* (2003) discovered that the foamability of cationic fluorosurfactant solution declined with increasing temperature from 20°C to 80°C. Zhang *et al.* (2011) further added that very stable CO_2-in-water foam can be generated at 95°C when surface-treated SiO_2 was added into the solution. On the other hand, Singh and Mohanty (2014) found that foam half-life decreased with increasing temperature up to 95°C at atmospheric pressure. Although the same foam degrading trend was observed, adding SiO_2 in the foam did enhanced foam half-life at that temperature. The foam half-life has increased for 14 minutes at 95°C when 0.3 wt% of SiO_2 was added and this indicates that particles could strength foam structure and make foam less sensitive to temperature increment (Singh & Mohanty, 2014). Even at higher pressure of 290 psi, Emrani and Nasr-El-Din (2015) showed that adding SiO_2 and Fe_3O_4 in AOS promotes longer foam half-life at room temperature. However, the comparison of the foam stability at higher temperature with and without nanoparticles is lacking in the study.

3. Methodology

3.1 Materials and Equipment

Two nanoparticles were used as foam stabilizer, namely silicon dioxide (SiO_2, US Research Nanomaterials, Inc.) and aluminium oxide (Al_2O_3, Sigma-Aldrich, USA). The basic properties of these nanoparticles are summarized in Table 1. Sodium chloride (NaCl, Merck Millipore, Germany) was dissolved in distilled water to make brine of 30,000 ppm salinity. An anionic surfactant solution, alpha olefin sulfonate (AOS C14-16, Bio-Terge® AS-40, 39% active, Stepan Company, USA) at 5,000 ppm was mixed with the brine. Sodium hydroxide (NaOH, Sigma-Aldrich, USA) was added in the solution to increase the pH of base fluids. Carbon dioxide gas (CO_2) is used as received. A foam analyser, FoamScan® (Teclis, France) was used to study static foam stability and foamability with and without nanoparticles at temperature 25°C, 40°C, 60°C and 90°C, respectively. An integrated camera was used to capture image of foam microscopically throughout the experiment. An ultrasonic cleaner (model TPC-120, TELSONIC AG, Switzerland) was used to stabilize nanoparticles in brine at room condition. A pH/mV Bench Meter (model S20 SevenEasy™, METTLER TOLEDO) was used to measure the pH of solutions (the pH of base fluids is shown in Table 2).

Table 1. Basic Properties of Nanoparticles

Material	Average Particle Size* (nm)	Density* (g/cm³)	Specific Surface Area* (m^2/g)	Average pH in brine	Wettability
Silicon dioxide	30	2.4	180 – 600	5.14	Hydrophilic
Aluminium oxide	13	4.0	85 – 115	8.06	Hydrophilic

* Product specifications provided by supplier

Table 2. Composition of base fluids and its respective pH

Base Fluid	Mixture	Concentration (ppm)	Average Solution pH
Base	Sodium chloride Alpha olefin sulfonate	30,000 5,000	7.67
Alkaline base	Sodium chloride Alpha olefin sulfonate Sodium hydroxide	30,000 5,000 10,000	12.79

3.2 Method

Prior experiment being conduct, SiO_2 and Al_2O_3 nanoparticles were added into brine respectively and undergone sonication for 30 minutes to achieve optimum nanofluid stability and thermal conductivity. Static foam stability was studied using FoamScan®, a glass tube with inner diameter of 35 mm and a double wall coupled with a circulating bath controlling the temperature in the tube. Foaming mixtures were prepared accordingly and measured its pH before injecting in to the glass tube. Foam was generated by sparging CO_2 gas at constant rate of 100 ml/min though a porous glass frit of 3 mm thickness with 160-micron pores size into 50 ml of foaming mixture. The foam was generated at constant room temperature and atmospheric pressure and stopped automatically when the foam volume has reached 150 ml. Foamability of sample was obtained at that foam volume and the foam start decaying until half of its original volume has reached which indicating its half-life and stability. The experiment was repeated by adding SiO_2 and Al_2O_3, respectively at 40°C, 60°C and 90°C accordingly. Microscopic images of foam were captured every 10 seconds throughout the experiment.

4. Results and Discussion

4.1 Effect of Nanoparticles in Foamability

The effect of nanoparticles in foamability is generally insignificant at all temperatures in both base fluids – neutral and alkaline, as shown in Figure 1 and Figure 2 respectively. These results show similar trend with previous study by Guo *et al.* (2017) whereby the foamability of solution in the presence of nano-ash and Fe_3O_4 of nanoparticles was insignificant at room temperature. In the context of foamability with temperature effect, the experimental results show minimal upward trend in foamability. This finding is also slightly different from another earlier study by Tyrode *et al.* (2003) where it claimed the foamability of solution decreased with increasing temperature from 20°C to 80°C. One of the possible reasons because N_2 gas was used in the study rather than CO_2 gas. Lv *et al.* (2016) further supports these results by mentioning that foam generated with CO_2 gas sparging possessed shorter half-life than of N_2 gas due to solubility of CO_2 gas at room condition. Although nanoparticles does not effectively enhance foamability, it seems the foaming behaviour with CO_2 gas sparging could categorize into lower temperature (below 90°C) and higher temperature (90°C and above) conditions which higher solution foamability is observed at temperature 90°C and vice versa.

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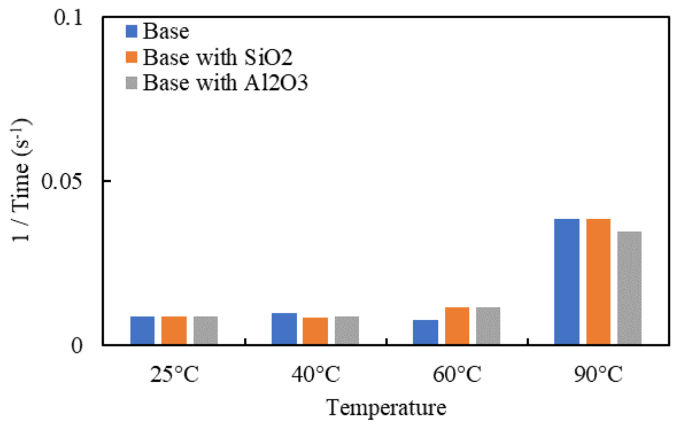

Figure 1. Foamability of base fluid without nanoparticles (blue), base fluid with SiO_2 (orange) and base fluid with Al_2O_3 (grey) at temperatures 25°C, 40°C, 60°C and 90°C respectively. Overall, it has shown that the effect of nanoparticles in foamability is insignificant.

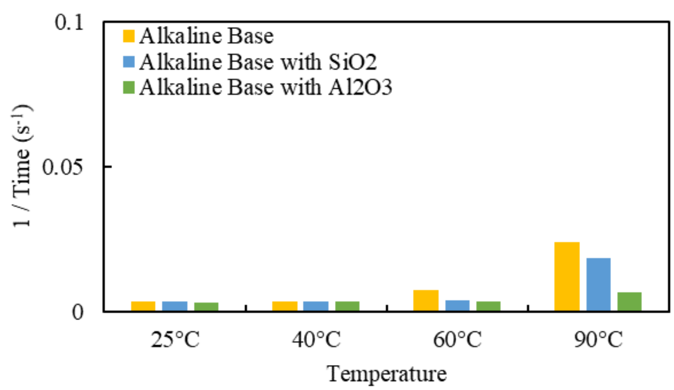

Figure 2. Foamability of alkaline base fluid without nanoparticles (yellow), alkaline base fluid with SiO_2 (light blue) and alkaline base fluid with Al_2O_3 (green) at temperatures 25°C, 40°C, 60°C and 90°C respectively. Generally, it has shown insignificant effect on foamability with the presence of nanoparticles.

4.2 Effect of Nanoparticles in Foam Stability

The presence of nanoparticles in foam has slightly increased the foam stability at all temperature in both neutral and alkaline base fluids as shown in Figure 3 and Figure 4 accordingly. Surprisingly, Al_2O_3 nanoparticles stabilized foam better than typical SiO_2 in this experiment. The results obtained are moderately in line with several previous literatures but the slight difference may attribute to the different in material used. For instance, Guo *et al.* (2017) tested foam stability enhancement using nano-ash and Fe_3O_4 while in this experiment, SiO_2 and Al_2O_3 were used instead. Besides that, these experimental results also show similar foam stability degrading trend based on previous study done by Singh and Mohanty (2014) which foam half-life decreased with increasing temperature at atmospheric pressure even with the presence of nanoparticles. Hence, it has shown that the presence of nanoparticles could improve foam half-life at that different temperatures and Al_2O_3 nanoparticles possessed better stabilizing effect than SiO_2.

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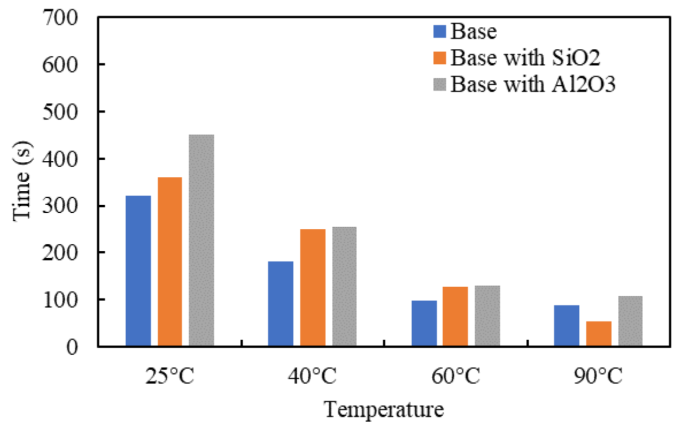

Figure 3. Foam half-life of base fluid without nanoparticles (blue), base fluid with SiO_2 (orange) and base fluid with Al_2O_3 (grey) at temperatures 25°C, 40°C, 60°C and 90°C respectively. It generally shows the presence of nanoparticles has slightly increased foam half-life.

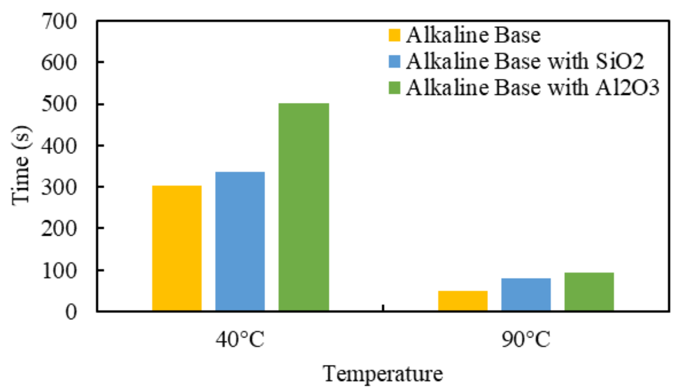

Figure 4. Foam half-life of alkaline base fluid without nanoparticles (yellow), alkaline base fluid with SiO_2 (light blue) and alkaline base fluid with Al_2O_3 (green) at temperatures 40°C and 90°C to represent low temperature and high temperature conditions, respectively. This figure shows nanoparticles do increase foam half-life.

4.3 Microscopic Study

The shape of bubble does not change with the presence of nanoparticles in both neutral and alkaline base fluids and at all temperatures. For example, Figure 5 shows the shape of bubbles with and without nanoparticles at times during foam generation and half-life. Nevertheless, the presence of nanoparticles could delay the rate of liquid drainage in foam as mentioned by Singh and Mohanty (2014) that slower liquid drainage rate could slow down the coalescence of bubbles and thus enhance foam half-life and stability. For instance, Figure 6 illustrates the rate of liquid drainage in foam by observing its lamellae thickness with and without nanoparticles at respective time. At time t = 150 s, the base-fluid foam is relatively more angular in shape; the base-fluid-with-SiO_2 foam is somewhat in between the angular and spherical shapes; while base-fluid-with-Al_2O_3 foam is more spherical in shape. Compared to the bubble shape at its previous time t = 110 s, it shows the liquid drainage in base-fluid-with-Al_2O_3 foam is the slowest among all because the bubble shape is well-retained after certain time.

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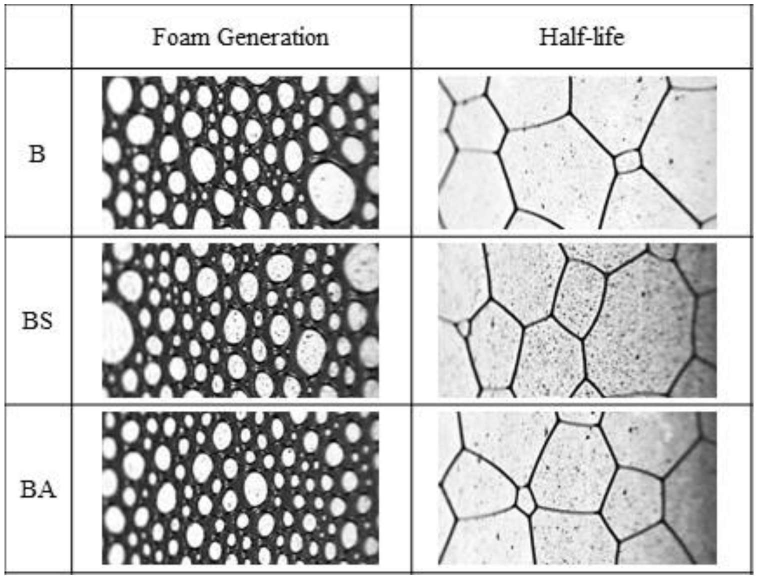

Figure 5. Microscopic foam images at 25°C with and without nanoparticles. The alphabetic codes represent base fluid (B), base fluid with SiO_2 (BS), and base fluid with Al_2O_3 (BA). It shows the presence of nanoparticles does not alter the shape of bubbles during foam generation and half-life.

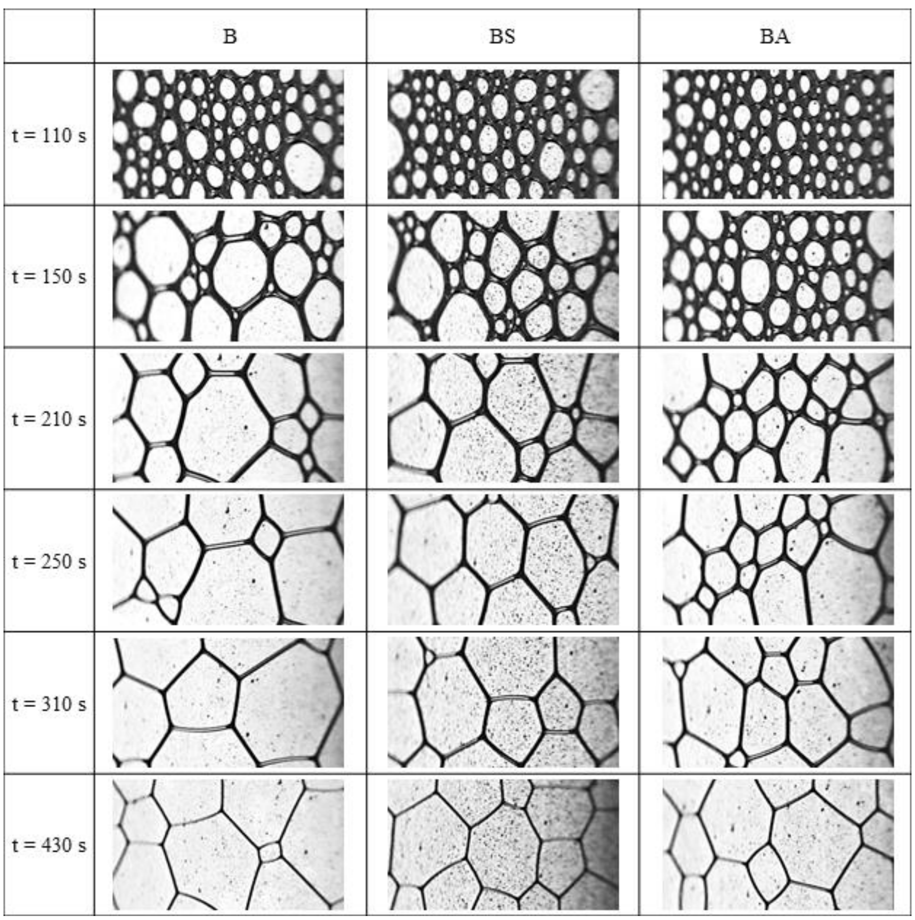

Figure 6. Microscopic foam images at respective time at temperature 25°C. The alphabetic codes represent base fluid (B), base fluid with SiO_2 (BS), and base fluid with Al_2O_3 (BA). The delay in liquid drainage rate is relatively most observable at time t = 150 s.

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5. Conclusion

Generally, the presence of nanoparticles does not significantly enhance the foamability in both neutral and alkaline base fluids with increasing temperature. However, the foamability by CO_2 gas sparging seems behaves differently at temperature below and at 90°C. In agreement with most of the previous literatures, while foam half-life degraded with increasing temperature, the presence of nanoparticles did enhance its half-life at that temperature. Based on results obtained from this experiment, aluminium oxide possessed better stabilizing effect than silicon dioxide at all temperature regardless the system pH. From the microscopic foam images, adding nanoparticles in foam do not change the shape of bubble at any time and any condition. Nevertheless, the presence of nanoparticles in foam could retard its liquid drainage rate and thus slowing down the bubble coalescence process that will eventually increase foam half-life and stability at any temperature.

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