

PAPER • OPEN ACCESS

Utilization of silicon dioxide nanoparticles in foam enhanced oil recovery – A comprehensive review

To cite this article: W M S M Latif *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **469** 012027

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the **collection** - download the first chapter of every title for free.

Utilization of silicon dioxide nanoparticles in foam enhanced oil recovery – A comprehensive review

W M S M Latif^{1*}, S N Sharbini¹, W R Wan Sulaiman¹ and A K Idris²

¹School of Chemical and Energy Engineering, Faculty of Engineering,
Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

²Faculty of Engineering, Universiti Teknologi Petronas, Perak, Malaysia.

*Corresponding author: mlshaharizuan@yahoo.com

Abstract. In recent years, the development of nanotechnology has paved the way of using nanoparticles as foam stabilizer. The applications of silicon dioxide (SiO₂) nanoparticles in improving foam stability received great attention among researchers over the past decade, either synergistic SiO₂ nanoparticles-surfactant foam or nanoparticles-gas supercritical foam. In fact, the significant difference between nanoparticles and surfactant as foam stabilizer is the adsorption energy of nanoparticles at gas-liquid interfaces, which are hundred or thousand times bigger than surfactant adsorption energy. Besides, the effectiveness of nanoparticles as foam stabilizer also influenced by the maximum capillary pressure, particle arrangement during film drainage, and the presence of aggregate and cork formation inside lamellae. Variety parameters of nanoparticles-fluid-rock properties have been studied in order to optimize foam flooding efficiency-e.g., type of nanoparticles, particle concentration, particle size, surface modification, salinity, permeability, wettability etc. However, to date, no attempt has been made to comprehensively review these existing literatures. Thus, to fill this identified gap, the results of previous studies are discussed, challenged and direction for further studies are suggested in this paper.

1. Introduction

It is well known that the amount of produced oil after primary and secondary recovery is only one-third of the total original oil in place (OOIP). To counter vast capital investment of exploration and developing new hydrocarbon reserves within era of highly fluctuating crude oil prices, major oil companies around the world are exploring all available options to extract more entrapped crude oil; namely by improved oil recovery (IOR) method and enhanced oil recovery (EOR) method from depleting brown oilfields. Likewise, the profound versatile physical and chemical properties of nanoparticles have lead to their application in almost all aspect of oil and gas sectors; and such as drilling, cementing and well stimulation, and its application in EOR and oil production are yet to be further discovered.

Foam flooding is widely recognized as an effective method to improve the limitation of gas flooding, especially on poor sweep efficiency and low incremental of oil recovery due to low density and viscosity of the injected gas, as well as reservoir heterogeneity effect. In fact, SiO₂ is the most utilized nanoparticles for foam EOR purposes. The abundance present of sand worldwide makes SiO₂ nanoparticles to be economically affordable and environmental friendly compared to other metal oxide nanoparticles. Besides, SiO₂ hydrophilic, hydrophobic or partially hydrophobic physicochemical nature can be easily altered by surface modification method to best suit various applications and nanoparticles purposes. For example, Bayat *et al.* (2016) [1] generated CO₂-foam in deionized water



(DI) by using four types of nanoparticles: SiO₂, Al₂O₃, TiO₂ and CuO. By measuring the half-life of bulk scale, results showed that SiO₂ produced the most stable foam, followed by Al₂O₃, TiO₂ and CuO respectively. Interestingly, 0.008 wt% was observed to be the optimum nanoparticles for all nanoparticles. Furthermore, the interaction energy by DLVO theory also showed that highest energy was obtained by SiO₂.

At gas-liquid interface of foam, surfactant adsorption is reversible but irreversible adsorption for the nanoparticles. As shown in Equation 1 below, the adsorption/deposition energy (E) of nanoparticles is influenced by the radius of particles adsorbed at CO₂-water interface (R), the surface tension of CO₂-water interface, $\gamma_{\text{CO}_2\text{-water}}$ and the contact angle (θ) of particle at the interface, which measured through the water phase. The positive sign before contact angle refers to hydrophilic particles ($\theta < 90^\circ$) while the negative sign refers to hydrophobic particles ($\theta > 90^\circ$). Besides, it should be noted that the presence of surfactant will reduce this “ E ” by reducing the surface tension.

$$E = \pi R^2 \gamma_{\text{CO}_2\text{-water}} (1 \pm \cos \theta)^2 \quad (1)$$

According to equation above, the maximum particle adsorption energy should occur at 90° . However, Denkov *et al.* [2] showed that, the stability of emulsion increased when the contact angle is less than 90° but nearly to 90° . Besides, emulsion stability also increased by larger hysteresis and smaller particles diameter, which demonstrates that the whole mechanism is not summarized in solely adsorption energy. Furthermore, Horozov (2008) [3] found that, the optimum contact angle for foam stabilization was 70° and 86° for monolayer and bilayer particles, respectively. Moreover, Hunter *et al.* (2008) [4] reported that most stable foam occurred at below 90° , particularly in between 60° - 70° . On the other hand, Li *et al.* (2017) [5] found that most stable SiO₂-CTAB (cationic surfactant) stabilized CO₂ foams occurred at contact angle between 60° - 90° . In addition, most hydrophilic (100% SiOH) and most hydrophobic nanosilica (14% SiOH), with contact angle between 0° - 30° and 150° - 180° respectively possess low adsorption energy and can be easily removed because they tend to remain dispersed either in aqueous or CO₂ phase.

In surfactant-stabilized foams, the disjoining pressure is equal to maximum capillary pressure (p_{max}^c) of the whole foam bubble, but it was proved that in the presence of nanoparticles, the p_{max}^c depends on the resistance of the dimple between two particles. Most importantly, Equation 1 above does not say anything about the stability of the thin layer liquid between bubbles, which stabilized by nanoparticles [6]. Hence, the stability of the thin liquid film between the droplet and the emulsion is consonance with the p_{mac}^c , given in Equation 2 below, which can be resisted by liquid menisci formed between the adsorbed particles, where p is packing diameter, and is different for each pack type.

$$p_{\text{max}}^c = 2p\gamma_{\text{gas-liquid}} \cos \theta/R \quad (2)$$

The lateral mobility of particles at the film surfaces plays a very important role in film stabilization by solid particles [3]. Particles in dilute monolayers cannot resist the hydrodynamic flow inside the thinning film, and are dragged away from the film centre, thus leaving the thinnest part of the film unprotected and vulnerable to rupture. In contrast, close packed particle monolayers at film surfaces can oppose the drag, thus slowing down the film thinning and preventing the film rupture by forming a stable bilayer or a bridging monolayer formed at the final stage of film thinning, as shown in Figure 1 below. On the other hand, Carn *et al.* (2009) [7] produced stable foam by using SiO₂ and TTAB cationic surfactant, and deduced that small scale flocculation in liquid bulk is one of the most important parameters in foam stabilization, although the used SiO₂ concentration is as low as 2 wt%. Besides, observations performed at the Plateau border scale brought to light the drainage kinetic slow-down process by evidencing that the presence of insoluble aggregates induces traffic jamming and even cork formation for silica concentrations above 2 wt %. Considering these observations, a simple mechanism of aggregate growth and core formation is proposed, as displayed in Figure 2 below.

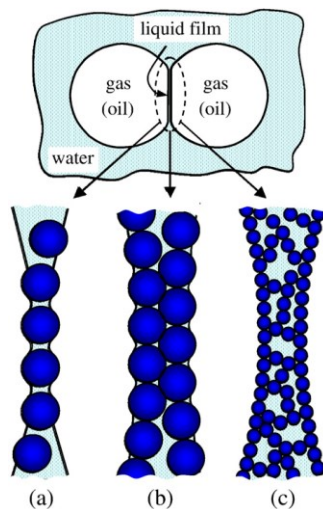


Figure 1. Particle arrangement in liquid film [3].

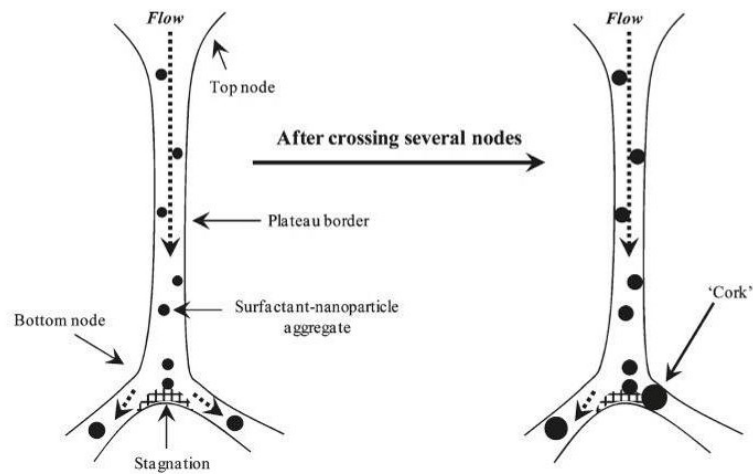


Figure 2. Traffic jamming and cork formation inside lamellae [7].

2. Parameters affecting foam stability

Considering all above mechanisms: adsorption/deposition energy, maximum capillary pressure, particle arrangement and traffic-jamming, the main parameters that induce nanoparticles assisted foam flooding are nanoparticles concentration, size of nanoparticles, surface modification and brine salinity, as review detail at below. Besides, other parameters that affect nanoparticles performance in generating stable foam are particle shape, CO₂ density, flow rate, shear rate, phase ratio, pH, particle-particle interaction at liquid-liquid interfaces and the presence of surfactant [8-11].

2.1 Effect of nanoparticles concentration

Generally, the stability of foam increase with increases of particles concentration, that higher concentration will generate fine and smaller bubbles, and well packing on lamellae and plateau borders. Hence, it will form more complete protective barrier around the dispersion droplets, which is capable in hindering foam film thinning and rupture. Conversely, low concentration or below the optimum concentration cause insufficient adsorption energy to attach completely at gas-liquid interfaces, resulted in poor foam stability. For example, Dickinson *et al.* (2004) [8] showed that, the bubble lifetime of hydrophobic SiO₂ with 67% SiOH in the presence of 3 mol/dm³ NaCl significantly increased foam stability duration from only 1-2 minutes to more than 24 hours, after increased the particles concentration from 0.01 wt% to 0.08 wt%.

However, too much particle concentration induces particle aggregation, which reduces the permeability of porous media and hinders oil recovery. Thus, the optimum particle concentration should be determined accurately during experimental. Several studies on the effect of SiO₂ concentration on foam performance are displayed in Table 1 below. It can be seen that optimum particles concentration in DI is lower than saline water, within the range of 0.01-0.05 wt% in DI while 0.5-1 wt% in saline water. Additionally, this table also indicated that optimum concentration of SiO₂ in the absence or presence of surfactant is quite similar: within the range of 0.5-1 wt%.

Table 1. Optimum concentration of nanoparticles on foam stability.

Reference	Nanoparticles, surfactant, salinity, porous media, etc.	Range tested (optimum concentration)	Result and main finding
Espinosa <i>et al.</i> , 2010 [10]	PEG coated SiO ₂ , DI	0.01-10 wt% (0.05 wt%)	0.01 wt% and 0.025 wt% were unable to form foam
Zhang <i>et al.</i> , 2010 [12]	Hydrophilic and hydrophobic SiO ₂ , salinity up to 10 wt% NaCl	0.05-5 wt% (0.5 wt% in DI and 5 wt% in	Highest foam apparent viscosity

		10 wt% NaCl)	
Karakashev <i>et al.</i> , 2011 [13]	Hydrophilic SiO ₂ , 0.01 mM SDS, DI	0.01-4 wt% (0.1 wt%)	Maximum foam decay
Mo <i>et al.</i> , 2012 [14]	Hydrophilic SiO ₂ , 2% NaCl, sandstone	0.01-0.5 wt% (0.35 wt%)	Highest foam resistance factor and lowest mobility.
Yu <i>et al.</i> , 2012b [15]	Hydrophilic SiO ₂ , uninformed wt% NaCl, glass bead pack	0.25-0.1 wt% (0.5 wt%)	< 0.3 wt% and > 1 wt%, less foam produced
Worthen <i>et al.</i> , 2013b [16]	Hydrophilic SiO ₂ , betaine, 0-3 wt% NaCl, beadpack and capillary tube	1-3 wt% (1 wt%)	Highest foam apparent viscosity
AttarHamed <i>et al.</i> , 2014 [17]	Hydrophilic SiO ₂ 15 nm, 0.1 wt% AOS, DI, static test	0-1 wt% (0.5 wt%)	Highest foam stability
Singh and Mohanty, 2014 [18]	PEG coated SiO ₂ , 0.5 wt% AOS, 1 wt% NaCl, with oil	0.1-0.5 wt% (0.3 wt%)	> 0.3 wt%, MRF more pronounced
Sun <i>et al.</i> , 2014 [19]	Partially hydrophobic SiO ₂ , 0.5 wt% SDS, 0.5 wt% NaCl, sandpack flooding, with oil	0.1-2 wt% (1.5 wt%)	At 2 wt%, only minor additional oil recovery (0.8%). Increased of IFT with SiO ₂ present
Manan <i>et al.</i> , 2015 [20]	Hydrophilic SiO ₂ , Al ₂ O ₃ , TiO ₂ and CuO, 0.5 wt% AOS, 1 wt% NaCl, static test	0.1-1 wt% (0.1 wt%)	Highest foam stability showed correlation with zeta potential value
Emrani and Nasr-El-Din, 2017 [21]	Hydrophilic SiO ₂ , 0.5 wt% AOS, 1-10 wt% NaCl, static test	0.1-0.3 wt% (0.1 wt%)	Highest foam stability and highest zeta potential
Kumar and Mandal, 2017 [22]	Hydrophilic SiO ₂ , CMC SDS, CMC CTAB, 0.5 wt% NaCl, static test	0.1-1 wt% (0.5 wt% for SiO ₂ and 0.25 wt% for CTAB)	Highest foam stability
Li <i>et al.</i> , 2017 [5]	Hydrophilic SiO ₂ , 0.3 wt% CTAB, static test	0.5-2 wt% (1.5 wt%)	Based on half-life method
Vatanparast <i>et al.</i> , 2017b [23]	Hydrophilic SiO ₂ , 0.41 mM SDS (0.05 CMC), DI, static test	0.25-2.5 wt% (1 wt%)	Optimum relative foam stability. Reduced of IFT with SiO ₂ concentration.
Yekeen <i>et al.</i> , 2017a [24]	SiO ₂ , Al ₂ O ₃ and partially hydrophobic (PH) SiO ₂ , 0.3 wt% SDS, 0.5 wt% NaCl, static test	0.05-5 wt% (1 wt% for SiO ₂ and Al ₂ O ₃ and 5 wt% for PH SiO ₂)	Highest foam stability for CO ₂ -foam and air-foam, and air-foam produced more stable foam than CO ₂ -foam.
AlYousef <i>et al.</i> , 2018 [25].	Hydrophilic SiO ₂ , DI, nonionic surfactant.	0.25-1 wt% (0.75 wt%).	Highest foam stability. NPs aggregated at 1 wt%.

After reviewing all the details, there is a similar trend within researchers, that most studies were using DI or just 5,000 ppm of NaCl in determined the CMC (critical micelle concentration) of surfactant, prior to foam flooding. However, it should be noted that the CMC is decreases after increasing the molecular mass of hydrophobic tail, reducing temperature and increasing salinity [26]. Therefore, by maintaining the CMC in DI at high salinity condition may reduce the effectiveness of nanoparticles as foam stabilizer, due to interaction of surface charge between nanoparticles-surfactant. Besides, most of researches were conducted using anionic surfactant, rather than cationic, non-ionic or amphoteric. It is well known that anionic surfactant has the highest foam stability and less aggregated

due to smaller carbon atom as hydrophobic tail, but it should be noted that anionic surfactant is less effective in high salinity, contrary with non-ionic surfactant.

On the other hand, it is well known that the oil recovery is less in oil wet (carbonate rock) compared to water wet or neutral wet, hence, more experimental of foam flooding should be conducted by using cationic surfactant due to cationic surfactant is less adsorbed in carbonate rock by repulsive force of same cationic charge. Moreover, the cationic surfactant as CTAB also capable in altering the wettability from oil wet to water wet or neutral wet. Thus, it is anticipated that conventional foam flooding could be improved with synergy effect: which is by utilizing the wettability alteration method.

2.2 Effect of nanoparticles size

Theoretically, smaller nanoparticles size has higher surface area per unit volume. Hence, the concentration of surface charge density is increases under same mass, which will generate smaller bubble size and more stable foam. Conversely, large nanoparticles are difficult to adhere at bubble's surface film due to higher adsorption energy. Besides, even it is adhered, its gravity may exceed the capacity of bubble's anti-deformation, cause it easier to burst. Azadgoleh *et al.* (2014) [27] studied the effect of salinity on particle size and the result showed that either high or low of electrolyte concentration, the nanoparticles tend to aggregate more as the bubble sizes increases.

Tang *et al.* (1989) [28] studied the effect of particles size on hydrophobic SiO₂-SDS-foam by ranging a series of particle size from 20 nm to 700 nm, and showed that, the finer the particle, the higher foam stability were obtained. Furthermore, the factor of gravity drainage becomes smaller with smaller size, until gas diffusion process turned out to be a dominating factor during foam destabilization. Besides, they also showed that particle size was the primary controlled parameter in improving foam stability, rather than particle concentration and hydrophobicity. Moreover, smaller size also has more resistant on bubble coalescence at elevated temperature. By using infrared (IR), Wang *et al.* (1999) [29] found that the peak of smaller SiO₂ size (1046 m²/g) disappeared at 800°C but the peak of bigger particle size (660 m²/g) disappeared at 700°C. Additionally, the smaller size also has larger diffusion coefficient (D) or Brownian motion, which confers them to have larger mobility during transportation. Moreover, Hu *et al.* (2018) [30] generated foam by using hydrophilic SiO₂ and cationic CTAB through “in situ surface activation process”, and found that smaller particle size has higher foam stability.

2.3 Effect of surface modification

Nanoparticles usually are very hydrophilic, hence, it prefers to be in liquid water rather than attach at gas-liquid interface. Also, water in CO₂ (W/C) emulsion is more difficult to be stabilized than CO₂ in water (C/W) emulsion because of thermodynamic and transport limitation of CO₂ [9]. The hydrophilic SiO₂ nanoparticles can be change to hydrophobic/partially hydrophobic by altering the wetting surface of nanoparticles by surface modification, Janus particle, “in situ surface activation” and appropriate coating as polyethylene glycol (PEG). In addition, foamability was primarily controlled by hydrophobicity (and hence by pH), followed by particle concentration, particle size and the degree of agglomeration.

The fundamental mechanism of altering the surface wettability of SiO₂ is by changing the percentage of silanol (SiOH) on its surface. The foam stability of C/W increased from 15 m to 12 hr as the hydrophilicity decreased from 100% SiOH to 76% SiOH. Besides, Binks and Lumsdon (2000) [31] found that partially hydrophobic nanosilica contained 42% SiOH for air in water (A/W) emulsion and 67% SiOH for oil in water (O/W) emulsion. Moreover, Horozov (2008) [3] reported that most stable silica nanofluid contains 32% SiOH for A/W foam. Furthermore, Worthen *et al.* (2013) [11] tested several SiOH percentage of nanosilica: 100% SiOH, 70% SiOH + 30% CH₃, 50% SiOH + 50% CH₃ and 35% SiOH + 65% CH₃, and found that, at 90% foam quality, 50% SiOH + 50% CH₃ generated the most stable C/W emulsion with contact angle closer to 90°. Yekeen *et al.* (2017a) [24] also showed that SiO₂ with 50% SiOH and 50% methylsilyl capped have higher foam stability than hydrophilic SiO₂, with the contact angle of 88.48° and 52.17° respectively.

The technique of increasing hydrophobicity of nanoparticles by reducing its abundant surface charge after adding hydrophobic surfactant tails by surfactant adsorption is known as “in situ surface activation” method. Therefore, the surface charge of hydrophilic SiO_2 can be altered to partially hydrophobic by using cationic, nonionic or zwitterionic surfactants, where primary control of this technique is surfactant concentration. The states of the hydrophilic SiO_2 -CTAB foam at different CTAB concentration are illustrated in Figure 3 below. At low CTAB concentrations (A), all SiO_2 nanoparticles were still in liquid phase due to hydrophilic charge have not been altered yet. When the CTAB concentration was moderate (B), the surface activation occurred, hence, SiO_2 nanoparticles started to attach at air-liquid interfaces, thus increasing the foam stability. At higher CTAB concentrations (C), the SiO_2 nanoparticles were attached with optimum surface on gas-liquid interfaces, and this condition was suggested as the most ideal concentration ratio of SiO_2 -CTAB, and the contact angle was probably between 60° - 90° . However, too much CTAB concentration (D) formed a surfactant bilayer on oppositely charged SiO_2 , which altered back to hydrophilic SiO_2 and inversed the emulsion. Consequently, the SiO_2 tend to stabilize air in water emulsion again.

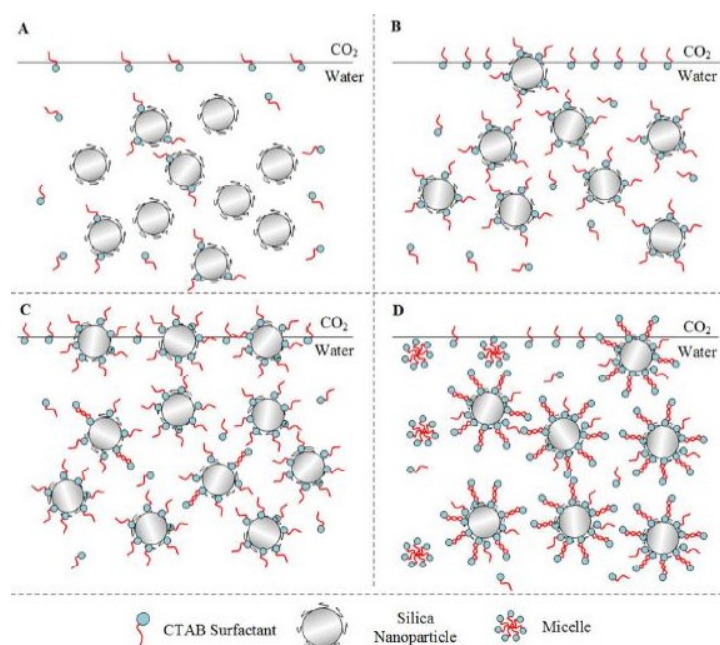


Figure 3. Effect of CTAB concentration interaction between hydrophilic SiO_2 -CTAB [5].

If surfactant does not adsorb onto nanoparticles, as they are having the same charge; both species will compete for the adsorption at oil-water interfaces, but only one will dominate (Binks and Rodrigues, 2007a). Therefore, contrary with attraction force of partially hydrophobic SiO_2 -SDS, the presence of negatively charge hydrophilic SiO_2 persuades the SDS to be more adsorbed at water-air interfaces by repulsion force, which further reduces the IFT. In other words, the nanoparticles still retain its non-surface active nature but the electrical repulsive increases the surface elasticity and surface activity of anionic surfactant, resulting in more surfactant will be adsorbed at the interface [23]. Additionally, it was reported that the foam generated by attraction force and hydrophobicity of partially hydrophobic SiO_2 -SDS was more stable than repulsive force of hydrophilic SiO_2 -SDS, measured by half-life of foam stability, film thickness and apparent viscosity [24].

2.4 Effect of salinity

The presence of electrolyte improves foam stability by increasing particle hydrophobicity, hence, improving the contact angle to nearly 90° . Simultaneously, the increase of nanoparticles adsorption at gas-liquid interfaces is akin to “salting out” an ionic surfactant, which causes the surfactant to behave

more hydrophobically. Binks and Horozov (2005) [32] showed that, in the absence of salt, no foam was produced by hydrophobic nanosilica (less than 14% SiOH), whereas the presence of small electrolyte concentration (8.5 mM) is enough to improve foamability and foam stability. Similar result was obtained by Kostakis *et al.* (2006) [33], that hydrophobic nanosilica showed little or no foamability at all in the absence of salt, whereas only small amount of NaCl (0.5 mol dm^{-3}) enabled to generate the stable foam. Moreover, Worthen *et al.* (2013) studied the effect of salinity on nanosilica with three different SiOH percentage: 35% SiOH, 50% SiOH and 70% SiOH and found that all three dispersions produced smaller bubble size and higher foam stability in the presence of 1% NaCl compared to DI.

Besides, Jiaqiang *et al.* (2010) [34] studied the effect of NaCl and CaCl_2 salts concentration on foam stability of surfactants mixture (SDS, ABS and CTAB), and found that foam stability decreased in higher salinity, and no foam was observed at 2 wt% of electrolyte concentration. Similar result was obtained for nanofluid, that high salinity increases the Van der Waals forces while decreases the repulsive electrostatic forces of nanoparticles, which decreases zeta potential, allows faster aggregation and reduces nanoparticles transport through porous media [35].

On the other hand, Metin *et al.* (2011) [36] found that, the dispersion of 0.5 wt% of SiO_2 nanofluid was stable in low salinity but it started to aggregate when the NaCl reached 1.5 wt%, known as Critical Salt Concentration (CSC). Moreover, divalent ions showed more induce effect where CSC of BaCl_2 , CaCl_2 and MgCl_2 were 100 times lower than NaCl. As displayed in Figure 4 below, the earliest CSC was obtained by MgCl_2 while the biggest particle diameter was obtained by CaCl_2 . Besides, it should be noted that CSC is independent of silica concentration and lowers at high temperature.

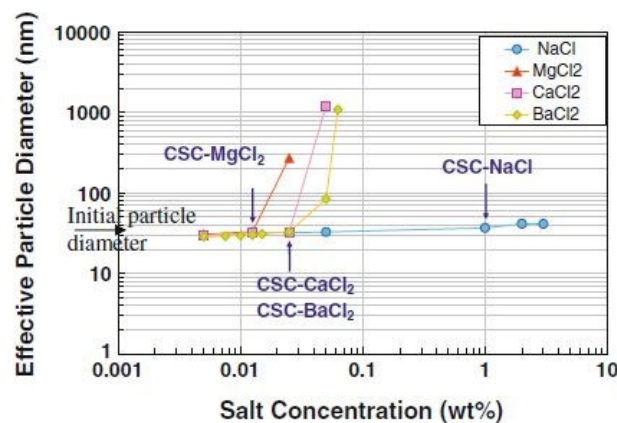


Figure 4: Effect of salinity on SiO_2 aggregation [36].

Additionally, to reduce the effect of salinity on particles aggregation, the hydrophilic SiO_2 can be supercharged by any anionic surfactant eg.: SDS. Mechanistically, the surfactant monomer adsorbed to nanoparticles by their tail, not the head group due to repulsive force by similar positive charge. Hence, it is possible to generate stable nanofluid in high salinity by adding the right amount of surfactant concentration, which is just below the CMC. Nevertheless, high concentration of surfactant ($> \text{CMC}$) is less efficient because more surfactant monomers will be crowded per unit area and thus joined up from their tails forming micelles rather than being adsorbed as a monomers on a similarly charged nanoparticle surface. As a result, the zeta potential of the dispersion reduces, as displayed in Figure 5 below. On the other hand, the threshold concentration of nanoparticles in generating stable foam also increases with salinity. For example, only 0.005 wt% of PEG-coated SiO_2 was required to produce stable C/W foam in DI, but it required 0.5 wt% of PEG-coated SiO_2 in 4 wt% of NaCl [10]. Besides, Zhang *et al.* (2010) [12] reported that the apparent viscosity of hydrophilic SiO_2 increased with salinity while apparent viscosity of hydrophobic SiO_2 decreased with salinity.

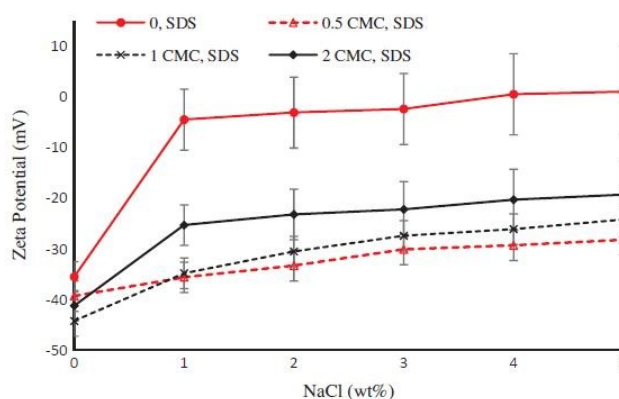


Figure 5. Effect of SDS concentration on SiO₂-SDS dispersion stability [35].

3. Challenges and opportunities of SiO₂ nanoparticles stabilized foam flooding

The application of SiO₂ nanoparticles greatly improved foam stability and mobility reduction, as well as wettability modifier [35]. On the other hand, previous studies on the effect of wettability showed that foam was more stable in water wet compared to oil wet, especially in the presence of oil, where the lamellae is easily detached and collapsed [37-38]. Since the wettability of oil wet can be altered to water wet or intermediate/neutral wet during synergy effects of foam flooding, either by nanoparticles or surfactant as wettability modifier, hence, the experimental of nanoparticles stabilized foam have a bright potential to be applied in carbonate reservoir. It is estimated that more than 60% of the world's oil reserve are held in oil wet carbonates, thus, the wettability alteration during synergy effect of EOR such as foam flooding etc. should be studied in-depth. Although synergy effect of surfactant foam flooding were tested in the absence of nanoparticles, the generated foam by solely surfactant has poor stability.

In fact, mixture of surfactants are more effective compared to single surfactant, especially in high salinity and high temperature conditions. Even though anionic surfactant is applied in sandstone reservoir, however, it is ineffective as wettability modifier [38-39]. Moreover, Li *et al.* (2012) [37] reported that foam generated by solely IOS was unstable compared to mixture of surfactants, that foam generated by a blended of anionic and amphoteric surfactants was more stable and recovered 93.1% of OOIP in oil wet sandpack after first stage alteration to water wet and later with foam flooding. Moreover, anionic surfactant has less tolerance against temperature (by having high cloud temperature) while nonionic surfactant has less tolerance against salinity. Although cationic surfactants have poor foam stability and easier to be aggregated, they are less to be adsorbed by carbonate rock thus have great potential to be applied in carbonate reservoir:- but only after its characteristics are improved by creating mixtures of surfactants.

4. Conclusion

From the existing literature, the application of SiO₂ nanoparticles as foam stabilizer showed significant effect in improving the conventional surfactant foam. Synergistic SiO₂-surfactant increased foam stability, lamellae thickness, foam apparent viscosity, mobility reduction factor and bubble size. Therefore, to pave the way of utilizing SiO₂ nanoparticles as foam stabilizer in future endeavor of oil and gas industries, several actions need to be taken:

- i. During low oil price, economic feasibility studies might not support nanoparticles to be implemented. Hence, effort in producing lower price of nanoparticles and combination of mechanisms during their usage, such as synergy effects of gas mobility reduction and wettability alteration is likely a better alternative compared to only one mechanism. Hence, technical and operational experiences acquired from traditional EOR methods should be exploited during R&D phases of nanoparticles-assisted EOR. To assist this condition, the collaborations between research institutions and oil

companies are strongly required, and more symposium and workshop should be conducted. Besides, national oil companies should play a vital role in piloting nanotechnology in the local pilot oilfields, presumably at much cheaper cost compared to international oil companies.

ii. Colloidal dispersion of SiO_2 should be stable against aggregation, especially in high salinity reservoir. On the other hand, since the adsorption of surfactant on nanoparticles is highly related with its CMC, hence, the CMC should be predicted accurately before adding nanofluid to ensure that inverse effect from excess surfactant concentration can be avoided.

iii. Understanding the fundamental theories and in-depth specific mechanism for various nano-assisted EOR methods requires performing accurate calculation and comprehensive modeling. However, it is still lack of suitable theoretical investigation and mathematical models to describe these processes because some of nano-assisted EOR methods involve complex and unclear mechanisms. Thus, theoretical investigation and mathematical models for various nano-assisted EOR methods should be conducted.

iv. Several type of nanofluids are theoretically better at certain mechanism while others are better in other mechanism, hence, the research on nanofluid mixture requires thorough investigation. For example, SiO_2 is better in gas mobility reduction, wettability alteration and IFT reduction but it was ineffective for oil viscosity reduction, which is effective by Al_2O_3 and TiO_2 ; while the mixture of $\text{SiO}_2\text{:Al}_2\text{O}_3$ nanofluid produced higher oil recovery compared to single SiO_2 or Al_2O_3 [40].

Acknowledgment

The authors are grateful to Malaysia Ministry of Education for funding this research.

References

- [1] Bayat A E, Rajaei K and Junin R 2016 *Colloids and Surfaces: A Physicochem. Eng. Aspects* **511**: 222-231
- [2] Denkov N D, Ivanov I B, Kralchevsky P A and Wasan D T 1992 *Journal of Colloid and Interface Science* **150** (2)
- [3] Horozov T S 2008 *Current Opinion in Colloid & Interface Science* **13**: 134-140
- [4] Hunter T N, Pugh R J, Franks G V and Jameson G J 2008 *Advances in Colloid and Interface Sciences* **137**: 57-81
- [5] Li S, Qiao C, Li Z and Wanambwa S 2017 *Energy and Fuels* **31**: 1478-1488
- [6] Kaptay G 2006 *Colloids and Surfaces A: Physicochem. Eng. Aspects* **282-283**: 387-401
- [7] Carn F, Colin A, Pitois O, Vignes-Alder M and Backov R 2009 *Langmuir* **25**: 7847-7856
- [8] Dickinson E, Ettelaie R, Kostakis T and Murray B S 2004 *Langmuir* **20**: 8517-8525
- [9] Adkins S S, Gohil D, Dickson J L, Webber S E and Johnston K P 2007 *Physical Chemistry Chemical Physics* **9**: 6333-6343
- [10] Espinosa D, Caldelas F, Johnston K, Bryant S L and Huh C 2010 *Paper SPE 129925 presented at the 2010 SPE Improved Oil Recovery Symposium*, Tulsa, Oklahoma, USA, April 24-28
- [11] Worthen A J, Bagaria H G, Chen Y, Byrant S L, Huh C and Johnston K P 2013 *Journal of Colloid and Interface Science* **391**: 142-151
- [12] Zhang T, Davidson A, Byrant S L and Huh C 2010 *Paper SPE 129885 presented at the SPE Improved Oil Recovery Symposium*, Tulsa, Oklahoma, USA, April 24-28
- [13] Karakashev S I, Ozdemir O, Hampton M A and Nguyen A V 2011 *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **382**: 132-138
- [14] Mo D, Yu J, Liu N and Lee R 2012 *Paper SPE 159282 presented at the SPE Technical Conference and Exhibition*, San Antonio, Texas, US, October 8-10
- [15] Yu J, Liu N, Li L and Lee R 2012b *Paper CMTC 150849 presented at the Carbon Management Technology Conference*, Orlando, Florida, USA, February 7-9
- [16] Worthen A J, Byrant S L, Huh C and Johnston K P 2013b *AIChE* **59**: 3490-3501
- [17] AttarHamed F, Zoveidavianpoor M and Jalilavi M 2014 *Petroleum Science and Technology* **32**: 2549-2558
- [18] Singh R and Mohanty K K 2014 *Paper SPE 169126 presented at the SPE Improved Oil Recovery Symposium*, Tulsa, Oklahoma, USA, April 12-16

- [19] Sun Q, Li Z, Li S, Jiang L, Wang J and Wang P 2014 *Energy Fuels* **28**: 2384-2394
- [20] Manan M A, Farad S, Piroozian A and Esmail M J A 2015 *Petroleum Science and Technology* **33**: 1286-1294
- [21] Emrani, A S and Nasr-El-Din H A 2017 *SPE Journal* **22** (02)
- [22] Kumar S and Mandal A 2017 *Applied Surface Science* **420**: 9-20
- [23] Vatanparast H, Samiee A, Bahramian A and Javadi A 2017 *Colloids and Surfaces A: Physicochem. Eng. Aspects* **513**: 430-441
- [24] Yekeen N, Idris A K, Manan M A, Samin A M, Risal A R and Kun T X 2017a *Chinese Journal of Chemical Engineering* **25**: 347-357
- [25] AlYousef Z A, AlMobarky M A and Scchchter D S 2018 *J. of Colloid and Interface Science* **511**: 365-373
- [26] Schramm L L and Wassmuth F 1994 *Foam Fundamentals and Applications in the Petroleum Industry* (Washington: The American Chemical Society)
- [27] Azadgoleh J E, Kharrat, R, Barati N and Sohbani A 2014 *Iranian Journal of Oil & Gas Science and Technology* **3**: 26-40
- [28] Tang F Q, Xiao Z, Tang J A and Jiang L 1989 *J. Colloid and Interface Science* **131**: 498-502
- [29] Wang L, Wang Z, Yang H and Yang G 1999 *Materials Chemistry and Physics* **57**: 260-263
- [30] Hu, N., Li, Y., Wu, Z., Lu, K., Huang, D. and Liu, W. (2018). *Journal of the Taiwan Institute of Chemical Engineers* **88**: 1-8
- [31] Binks B P and Lumsdon S O 2000 *Langmuir* **16**: 8622-8631
- [32] Binks B P and Horozov T S 2005 *Angew. Chemie-Int. Ed.* **44**: 3722-3725
- [33] Kostakis T, Ettelaie R and Murray B S 2006 *Langmuir* **22**: 1273-1280
- [34] Jiaqiang J, Yanfang L, Xue Y, Zhihong Z, Jianhua Y and Hongjun Z 2010 *Paper SPE 131449 presented at the CPE/SPE International Oil & Gas Conference and Exhibition, Beijing, China, June 8-10*
- [35] Al-Anssari S, Arif M, Wang S, Barifcani A, Levedev M and Iglauer S 2018 *Fuel* **211**: 405-414
- [36] Metin C O, Lake L W, Miranda C R and Nguyen Q P 2011 *J Nanoparticles Res* **13**: 839-850
- [37] Li R F, Hirasaki G J, Miller C A and Masalmeh S K 2012 *SPE Journal* December: 1207-1220
- [38] Singh R and Mohanty K K 2016 *SPE Journal* August: 1-14
- [39] Mohammed B and Babadagli T 2015 *Advances in Colloid and Interface Science* **220**: 54-77
- [40] Alomair O A, Matar M M and Alsaeed Y H 2014 *Paper SPE-171539 presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition, Adelaide, Australia, October 14-16*