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

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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: SiO$_2$, Al$_2$O$_3$, TiO$_2$ and CuO. By measuring the half-life of bulk scale, results showed that SiO$_2$ produced the most stable foam, followed by Al$_2$O$_3$, TiO$_2$ 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 SiO$_2$.

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 CO$_2$-water interface (R), the surface tension of CO$_2$-water interface, $\gamma_{CO2-water}$ and the contact angle ($\theta$) 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.

$$E = \pi R^2 \gamma_{CO2-water} (1 \pm \cos \theta)^2$$

(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 SiO$_2$-CTAB (cationic surfactant) stabilized CO$_2$ 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 CO$_2$ phase.

In surfactant-stabilized foams, the disjoining pressure is equal to maximum capillary pressure ($p^*_{max}$) of the whole foam bubble, but it was proved that in the presence of nanoparticles, the $p^*_{max}$ 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 $p^*_{max}$, 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.

$$p^*_{max} = 2p\gamma_{gas-liquid} \cos \theta/R$$

(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 SiO$_2$ 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 SiO$_2$ 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.
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, CO$_2$ 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 SiO$_2$ with 67% SiOH in the presence of 3 mol/dm$^3$ 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 SiO$_2$ 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 SiO$_2$ in the absence or presence of surfactant is quite similar: within the range of 0.5-1 wt%.

| Reference         | Nanoparticles, surfactant, salinity, porous media, etc. | Range tested (optimum concentration) | Result and main finding |
|-------------------|----------------------------------------------------------|---------------------------------------|-------------------------|
| Espinosa et al., 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 et al., 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 |

Table 1. Optimum concentration of nanoparticles on foam stability.
| Author(s)                        | Surfactant, composition | CMC (wt%) | Foam characteristics |
|---------------------------------|-------------------------|-----------|----------------------|
| Karakashev et al., 2011 [13]    | Hydrophilic SiO$_2$, 0.01 mM SDS, DI 0.01-4 wt% | Maximum foam decay |
| Mo et al., 2012 [14]            | Hydrophilic SiO$_2$, 2% NaCl, sandstone (0.35 wt%) | Highest foam resistance |
| Yu et al., 2012b [15]           | Hydrophilic SiO$_2$, uninformed wt% NaCl, glass bead pack (0.5 wt%) | Less foam produced |
| Worthen et al., 2013b [16]      | Hydrophilic SiO$_2$, betaine, 0-3 wt% NaCl, beadpack and capillary tube 1-3 wt% | Highest foam apparent |
| AttarHamed et al., 2014 [17]    | Hydrophilic SiO$_2$, 15 nm, 0.1 wt% AOS, DI, static test 0.1 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%, MRF more pronounced |
| Sun et al., 2014 [19]           | Partially hydrophobic SiO$_2$, 0.5 wt% NaCl, sandpack flooding, with oil 0.1-2 wt% | At 2 wt%, only minor additional oil recovery (0.8%). Increased of IFT with SiO$_2$ present |
| Manan et al., 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% | Highest foam stability |
| Emrani and NasrEl-Din, 2017 [21] | Hydrophilic SiO$_2$, 0.5 wt% AOS, 1-10 wt% NaCl, static test 0.1-0.3 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% | Highest foam stability |
| Li et al., 2017 [5]             | Hydrophilic SiO$_2$, 0.3 wt% CTAB, static test 0.5-2 wt% | Based on half-life method |
| Vatanparast et al., 2017b [23]  | Hydrophilic SiO$_2$, 0.41 mM SDS (0.05 CMC), DI, static test 0.25-2.5 wt% | Optimum relative foam stability. Reduced of IFT with SiO$_2$ concentration. |
| Yekeen et al., 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% | Highest foam stability for CO$_2$-foam and air-foam, and air-foam produced more stable foam than CO$_2$-foam. |
| AlYousef et al., 2018 [25]      | Hydrophilic SiO$_2$, DI, nonionic surfactant. 0.25-1 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 SiO$_2$-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 SiO$_2$ size (1046 m$^2$/g) disappeared at 800°C but the peak of bigger particle size (660 m$^2$/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 SiO$_2$ 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 CO$_2$ (W/C) emulsion is more difficult to be stabilized than CO$_2$ in water (C/W) emulsion because of thermodynamic and transport limitation of CO$_2$ [9]. The hydrophilic SiO$_2$ 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 SiO$_2$ 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 hydrophobicity 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% CH$_3$, 50% SiOH + 50% CH$_3$ and 35% SiOH + 65% CH$_3$, and found that, at 90% foam quality, 50% SiOH + 50% CH$_3$ generated the most stable C/W emulsion with contact angle closer to 90°. Yeeken et al. (2017a) [24] also showed that SiO$_2$ with 50% SiOH and 50% methylsilyl capped have higher foam stability than hydrophilic SiO$_2$, 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].](image)

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].](image)

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 (> 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 SiO$_2$-SDS dispersion stability [35].

3. Challenges and opportunities of SiO$_2$ nanoparticles stabilized foam flooding

The application of SiO$_2$ 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 SiO$_2$ nanoparticles as foam stabilizer showed significant effect in improving the conventional surfactant foam. Synergistic SiO$_2$-surfactant increased foam stability, lamellae thickness, foam apparent viscosity, mobility reduction factor and bubble size. Therefore, to pave the way of utilizing SiO$_2$ 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 in 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\textsubscript{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\textsubscript{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\textsubscript{2}O\textsubscript{3} and TiO\textsubscript{2} while the mixture of SiO\textsubscript{2}:Al\textsubscript{2}O\textsubscript{3} nanofluid produced higher oil recovery compared to single SiO\textsubscript{2} or Al\textsubscript{2}O\textsubscript{3}[40].

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