Analysis of stability of silica nano-particle-laden microbubble dispersion

Rashi Gupta1 · Roshan Saini1 · Rajeev Parmar1

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Abstract
Microbubbles are small gas-filled bubbles which have wide application in various industries. The stability of microbubble is of primary concern for the application of microbubble. In this research, the stability of microbubble dispersion generated using CTAB surfactant is analyzed by drainage mechanism. The stability of microbubble dispersion is studied on the basis of the half-life of microbubble dispersion. Microbubble dispersion gas fraction and apparent rise velocity of interface of microbubble dispersion are also calculated. The size of microbubble is estimated from the apparent rise velocity of interface of microbubble dispersion. Further, silica nano-particles are added to the surfactants to study their effect on the stability of microbubble dispersion. The observed results clearly indicate that the stability of microbubble dispersion is significantly affected by the surfactant concentration and the weight of silica nano-particle in the liquid. Similar results were observed for the apparent rise velocity of interface and bubble size of dispersion. The present work may be beneficial for the application of microbubble in various chemical and biochemical industries and scientific community.

Keywords Microbubble dispersion · Stability · Half-life · Apparent rise velocity · Bubble size · Gas fraction

Introduction
Microbubbles are gas bubbles having size in the range 1 to 100 μm. The term colloidal gas apheres is also used in literature for gas microbubbles having the size range 10–100 μm (Amiri and Sadeghialabadi 2014; Jauregi and Varley 1998; Jauregi et al. 2000). They are used in various processes like removal of fine metal oxide particle, separation of fine suspended carbon, oxidation of benzene, synthesis gas fermentation, sludge solubilization, treatment of industrial waste water, and various environmental process (Parmar and Majumder 2013). Microbubbles give a large interfacial area per unit volume compared to the conventional coarse bubbles (Bredwell and Worden 1998). The surface of microbubble also carries charge, which helps microbubble for higher degree of separation (Parmar and Majumder 2016). Another significant characteristic of microbubble is their high dissolution rate, which helps in the intensification of mass transfer (Zeng et al. 2020). The stability of microbubble is a vital property for the application of microbubble dispersion. Conventionally the stability of microbubble dispersion is determined by the liquid drainage rate, though electrical method is also used in literature (Moshkelani and Amiri 2008; Parmar and Majumder 2015). Amiri and Woodburn (1990) were the first to predict an analytical model for drainage rate for microbubble dispersion. Jauregi et al. (2000) applied the drainage rate of microbubble dispersion to prediction the stability and bubble diameter. Yan et al. (2005) further studied the kinetics of liquid drainage for microbubble dispersion. Feng et al. (2009) investigated the various factors affecting the drainage mechanism of microbubble dispersion. They concluded that surfactant and electrolyte concentrations and pH are the three main process parameters that significantly affect the stability. Parmar and Majumder (2015) also concluded that increasing surfactant concentration can significantly enhance the dispersion stability. In addition to that, some researcher concluded that addition of small amount of particle can alter the surface morphology of dispersion. This was demonstrated by Binks and
Horozov (2005). Kostakis et al. (2006) reported that bubbles can be stabilized by addition of silica particles. Amiri and Sadeghialiabadi (2014) further evaluate the stability of microbubble in the presence of montmorillonite nanoparticles. Recently Ruby and Majumder (2018) examined the stability of micro and nano-particle loaded microbubbles. Unfortunately, there is a cognition gap on various properties of microbubble dispersion which are important for the implication of microbubbles to large scale. The hydrodynamic and physicochemical properties of microbubble dispersion like gas holdup, microbubble size, rise velocity, surfactant concentration, particle concentration, etc. can significantly affect the drainage mechanism, which in turn affect the stability of microbubble dispersion. The interaction of surfactant and nano-particle is a complex phenomenon. Efforts are required to examine the complex drainage mechanism of microbubble dispersion, in order to enlarge this technology at large scale. The objective of the present article is to analyze the effects of nano-particle and surfactant concentration on the stability of microbubble dispersion. The present article also aimed to examine the effects of silica nano-particle on hydrodynamic properties of microbubble dispersion.

### Experimental procedure

#### Materials

In the present study, aqueous solutions of cetyltrimethyl ammonium bromide (CTAB) was employed as liquid phase, whereas air was used as gas phase. The concentration of CTAB varied from 50 to 3000 mg/l. Experiments were also carried out with silica nano-particles to alter the stability of the microbubbles. The nano-particles of weight 0.5 g, 1 g, 1.5 g, 2 g, 2.5 g, and 3 g are mixed in 250 mg/l aqueous concentration of surfactants. The densities of the solution were measured with a specific gravity bottle. The various physicochemical properties of liquid are presented in Table 1.

#### Methods

**Generation of microbubbles**

Microbubble can be generated by several methods (Parmar and Majumder 2013). In the present work microbubble dispersion was generated by the method similar to Sebba (1985). Sebba (1985) generated gas aphrons by using a high speed spinning device. This method is also used for microbubble generation in literature (Amiri and Sadeghialiabadi 2014; Jauregi et al 2000; Ruby and Majumder 2018). In the present study surfactant is mixed in 250 ml of water. Microbubble is generated in the surfactant solutions with and without adding the nano-particles with help of high-speed stirrer (approx. 18,000 rpm; Model-Jaipan JX 4). The blade within the stirrer rotate at about 18,000 rpm producing a high sheared within the gas–liquid/gas–liquid–solid mixture, for about 60 s, which creates microbubble dispersion. The schematic of experimental setup is shown in Fig. 1. All the experiments were carried out at room temperature.

### Table 1 Density and viscosity for different concentrations of CTAB

| Concentration of CTAB (mg/l) | Density (kg/m³) | Viscosity (mpas) |
|-----------------------------|-----------------|-----------------|
| 50                          | 999.73          | 1.291           |
| 100                         | 999.78          | 1.293           |
| 200                         | 999.88          | 1.310           |
| 250                         | 999.91          | 1.311           |
| 500                         | 1000.18         | 1.313           |
| 750                         | 1000.43         | 1.315           |
| 1000                        | 1000.68         | 1.318           |
| 3000                        | 1002.68         | 1.338           |

![Fig. 1 Schematic representation of experimental setup](image-url)
Estimation of microbubble gas fraction

The efficiency of any gas–liquid reaction is highly governed by interfacial area (Kantarci et al. 2005). The interfacial area in turn depends on the gas fraction of the microbubble suspension. Gas fraction is affected by various parameters like phase velocities, bubble diameter, physical and chemical properties of liquid, operating temperature, and pressure. Microbubble dispersion gives a high gas fraction, which is significant for many process industries. An increase in gas holdup will increase gas–liquid interfacial area. After generation of microbubble, it is passed to the measuring cylinder. With the passage of time, the microbubbles disengage, and the level of clear liquid increases in the cylinder. The final gas fraction of the microbubble dispersion ($\varepsilon_{md}$) is calculated as:

$$\varepsilon_{md} = \frac{H - d}{H}$$  \hspace{1cm} (1)

where $H$ represents total height of microbubble dispersion initially in the cylinder and $h$ denotes final height of clear liquid in the cylinder.

Determination of stability of microbubble dispersion

The half-life of the microbubble dispersion is widely used as an indicator for analyzing the stability (Amiri and Sadeghialabadi 2014; Parmar and Majumder 2015; Ruby and Majumder 2018). The half-life of microbubble dispersion is the time taken to drain half of initial liquid volume of microbubble dispersion. In conventional colloidal gas aphrons, the stability is generally determined by the rate at which liquid drains from the dispersion and the rate of aphrons breakdown, though in microbubble dispersions, the breakdown and coalescence of microbubbles is very less. So dispersion liquid drainage rate or the drainage time is the rationale factor in specifying the stability. A longer drainage time for the dispersion represents more stable microbubble dispersion. A longer drainage time also signifies a higher half-life. Therefore, the stability of microbubble is related to the half-life of microbubble (Feng et al. 2009). In the present study, freshly prepared microbubble dispersion from the mixer is poured into the measuring cylinder, and the volume of the drained liquid below the dispersion is recorded and measured as function of time. The variation of liquid drainage volume with time for 500 mg/l of CTAB is shown in Fig. 2. From the plot of liquid drainage volume and drainage time, the half-life of dispersion can be calculated. Figure 3 shows a typical demonstration for the estimation of half-life from the liquid drainage in 500 mg/l of CTAB without containing nano-particles.

Estimation of the apparent rise velocity of interface

The microbubble due to its small size possesses low rise velocity. In the present work, the apparent rise velocity of interface is determined by tracking the level of clear liquid interface in the cylinder. It was assumed that microbubble dispersion contains equal sized and spherical bubbles and there is no coalescence and breakup of microbubbles. As microbubble dispersion is poured in measuring cylinder, the liquid flows downward, and bubbles rise due to buoyancy, leaving the clear liquid interface. This rise in interface with respect to the time is recorded. The apparent rise velocity

Fig. 2 Variation of liquid drainage volume with time for 500 mg/l of CTAB
of interface \( V_{\text{md}} \) of microbubble dispersion can be calculated as:

\[
V_{\text{md}} = \frac{H_i - H_j}{t_i - t_j}
\]  

(2)

where \( H_i \) is interface height at \( t_i \) and \( H_j \) is the interface height corresponding \( t_j \).

**Determination of the average microbubble size**

The size of microbubble dispersion is vital parameter to govern the interfacial area and mass transfer characteristic of bubbles. So, determination of microbubble size becomes very crucial for its implication in process intensification unit, since the value of rise velocity of interface of microbubble dispersion is very less. If we assume that microbubbles do not coalesce at the gas liquid interface and the interface of microbubble dispersion rises with a velocity equal to the terminal velocity of bubble, then, under such conditions, an approximate microbubble size \( (d_{mb}) \) in the dispersion can be calculated based on the relation:

\[
d_{mb} = \sqrt{\frac{18V_{\text{md}}H_i}{\mu_l(\rho_l - \rho_g)}}
\]  

(3)

where \( \mu_l \) denotes the viscosity of the liquid or slurry, \( \rho_l \) represents the density of microbubble-liquid mixture, \( \rho_g \) is the density of air, and \( g \) is the gravitational acceleration. Similar methods have been adopted in previous studies to calculate the microbubble size. This method does not require sophisticated and costly equipment. The bubble size predicted by apparent rise velocity of interface is quite comparable than those predicted by particle size analyzer and image analysis method (Parmar and Majumder 2015; Ruby and Majumder 2018).

**Result and discussion**

**Gas fraction of microbubble dispersion**

The effect of surfactant concentration on the microbubble dispersion gas fraction is shown in Fig. 4. The results show that the gas fraction increases linearly up to the concentration of 250 mg/l. From 250 mg/l, the gas fraction changes to a lesser extent. The increase in gas fraction of microbubble dispersion with CTAB concentration is mainly due to the enhancement of bubble population in the dispersion. The microbubble density increases with the addition of CTAB in water. Thus, a densely populated dispersion of microbubble will result in high gas fraction. Initially the bubble population increases with concentration of CTAB; however, as soon the critical micelle concentration of CTAB is attained (328 mg/l), the microbubble population increases to a lesser extent, causing a lower growth rate of gas fraction with the concentration.

**Stability of microbubble dispersion without and with nano-particles**

The presence of surfactant can substantially influence the interfacial surface property. The effect of surfactant CTAB concentrations on the liquid drainage is shown in Fig. 5. It is seen from the figure that the volume of drained liquid increases with time. The similar type of curve is also reported in previous studies for microbubble dispersion.
It is seen from Fig. 5 that volume of drained liquid and the drainage time is influenced by the CTAB concentration. At higher concentration of CTAB, the volume of drained liquid is lower, and the drainage time is higher. The higher drainage time corresponds to higher life time which in turn reflects the higher stability of microbubble dispersion. Therefore, at higher concentration of CTAB, the microbubble dispersion shows higher lifetime and higher stability. Addition of surfactant in liquid lowers the interfacial surface tension that causes the production of smaller bubbles in the dispersion; the smaller bubbles moves with relative slower speed causing a higher drainage time. The other significant cause for the enhancement of stability is that the degassing of gas from the bubbles also reduces as the surfactant concentration increases. The presence of the surfactant in liquid also imparts a significant barrier to escape the gas from the microbubble into the liquid medium (Borden and Longo 2002). The bubble elasticity and the mechanical strength also increase with addition of surfactant (Fendler 1991; Feng et al. 2009). Table 2 gives the value of half-life time for microbubble dispersion for different CTAB surfactant without silica particles.

Parmar and Majumder (2015) generated microbubble dispersion by pressurized dissolution method and reported the half-life of microbubble dispersion of about 434 s at 500 mg/l of CTAB. Ruby and Majumder (2018) used mixture assembled with a high-speed stirrer to generate dispersion and reported the half-life of microbubble dispersion of about 185 s at 500 mg/l which is very close to the value obtained in the present work. This can lead to one important conclusion that the method of generation of microbubble also affects the half-life of dispersion. The effect of silica nano-particle on the stability of microbubble dispersion is shown in Fig. 6. It is seen that at fixed surfactant concentration of 250 mg/l, the stability of dispersion is affected by the silica nano-particle. The half-life of microbubbles dispersion increases with increasing the silica concentration in the liquid. The silica particles adsorb on the surface of microbubbles and promote the stability. The other possible cause for the enhancement of the stability of microbubble dispersion is the increment in average viscosity of liquid. Due to which the drag on the bubble increases. The adsorbed nano-particle also reduces the degassing of the gas from the core of bubbles. Another important conclusion that can be made from the present work is that the final drained liquid volume at concentrations 2.5 g and 3.0 g of silica nano-particle in CTAB solution is higher than that of concentration of 2.0 g. This clearly indicates that above the concentration of 2.0 g of silica nano-particle in the surfactant, the solution gets saturated with the nano-particles, the gas–liquid

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**Table 2 Half-life and final drainage volume for different concentrations of CTAB**

| Concentration of CTAB (mg/l) | Half-life (sec) | Liquid drainage volume (ml) |
|-----------------------------|----------------|-----------------------------|
| 50                          | 140            | 265.02                      |
| 100                         | 145            | 238.64                      |
| 200                         | 155            | 188.40                      |
| 250                         | 170            | 171.44                      |
| 500                         | 180            | 154.48                      |
| 750                         | 185            | 149.46                      |
| 1000                        | 190            | 139.42                      |
| 3000                        | 205            | 135.65                      |

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**Fig. 5** Variation of drained liquid volume with drainage time in different concentration of CTAB without nano-particles

**Fig. 6** Variation of drained liquid volume with drainage time in CTAB with silica nano-particles
interfacial tension starts depleting, that causes reduction in gas holdup, and thus the liquid holdup increases. The variation of half-life of microbubble dispersion with silica nano-particle in surfactant solution is shown in Fig. 7. It is clear from the figure that microbubble dispersion half-life increases with increasing silica concentration within the present experimental range.

**Apparent rise velocity of interface and size of the microbubble dispersion**

The hydrodynamic of bubble moving in a pool of liquid is affected by the property of liquid. The effect of CTAB concentration on the apparent rise velocity of interface of microbubble dispersion is shown in Fig. 8. It is seen that the apparent rise velocity of interface decreases with increasing the CTAB concentration. Addition of surfactant increases the viscosity of liquid, although the magnitude of this increment in viscosity is negligible. On increasing the CTAB concentration, the gas liquid interfacial tension decreases. This causes a reduction in surface energy at interface. Due to which the bubble size of the generated microbubble reduces. The effect of CTAB concentration on microbubble size without silica particle is shown in Fig. 9. It is observed that the microbubble dispersion size decreases with the addition of CTAB. The reduction of microbubble size in the presence of surface active agent is also reported by several studies.

Parmar and Majumder (2014) reported the reduction of microbubble size with SDS surfactant. The addition of glycerol also reduces the size of microbubble by reducing the interfacial surface tension (Parmar and Majumder 2015). Ruby and Majumder (2018) also reported the reduction in size of microbubble with SDS and Saponin. The addition of surfactant also imparts an additional shear on trailing pole of the bubble due to concentration gradient. That also tends to retard the bubbles. However, above 500 mg/l, the rise velocity shows a little reduction with increases in surfactant concentration. CTAB has critical micelle concentration at 328 mg/l. So, the addition above 328 mg/l contributes more in viscosity increase rather than the lowering the interfacial tension. The effect of silica nano-particle addition on the apparent rise velocity of interface of dispersion is shown in Fig. 10. It is seen that the rise velocity of interface of microbubble dispersion decreases with increase in silica concentration in surfactant. It is also observed that the apparent rise velocity of interface in presence of silica particle decreases.
Conclusion

The effect of concentration of cetyltrimethyl ammonium bromide (CTAB) on gas holdup, size, rise velocity, and microbubble stability of microbubble dispersion is investigated. The stability of microbubble dispersion is analyzed by using drainage mechanism. It was observed that the half-life of microbubble increased from 140 to 205 s as the CTAB concentration increase from 50 to 3000 ppm. The half-life of microbubble dispersion at 500 ppm came to be 180 s which is very close to the value reported by Ruby and Majumder (2018) and lesser than the value reported by Parmar and Majumder (2015). The gas fraction of microbubble dispersion is found to be affected by physiochemical properties of the liquid. It was observed that the value of gas fraction of the microbubble dispersion increases from 0.158 to 0.56, as the CTAB concentration increases from 50 to 3000 ppm. An increase in concentration of surfactant in liquid causes an increase in gas fraction and stability of microbubble. The apparent rise velocity of interface and bubble size is found to be decreased with increase in concentration of surfactant in liquid. The effect of silica nano-particle on stability and apparent rise velocity of interface is also examined. The results clearly showed that the adsorption of nano-particle on microbubble surface can significantly enhance the stability of microbubble dispersion. The apparent rise velocity interface of microbubble dispersion is found to be decreased by addition silica particle. The present work may be useful for the application of microbubble-aided process in various chemical and biochemical industries and scientific community.

Author contribution Rashi Gupta contributed in generation of experimental data and analysis of the results. She also participated in the investigation and methodology of processes. Roshan Saini contributed in generation of experimental data and analysis of the results. Dr Rajeev Parmar contributed in the supervision and validation of the experiments. He also participated in the writing of the original draft.

Data availability All data generated or analyzed in the present research article are included in article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors have given their consent to publish this research article.

Competing interests The authors declare no competing interests.

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