

Analysis of Stability of Silica Nano-Particle-Laden Microbubble Dispersion

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Research Article

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Abstract

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

1. Introduction

Microbubbles are gas bubbles having size in the range 1 to 100 μm . 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 gives 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). The other important characteristic of microbubbles are its high dissolution rate, which helps in intensification of mass transfer (Zeng et al., 2020). The stability of microbubble is a vital property with implications for the preceding discussed applications. 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 present 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 effects 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 stabilize 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

implication of microbubbles to large scale. The hydrodynamic and physicochemical properties of microbubble dispersion like gas holdup, microbubble size, rise velocity, surfactant concentration and particle concentration etc. can significantly affects the drainage mechanism, which in terns affect the stability of microbubble dispersion. The interaction of surfactant and nanoparticle 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 analyse the effects of nanoparticle and surfactant concentration on the stability of microbubble dispersion. The present article also aimed to examine the effects of silica nanoparticle on hydrodynamic properties of microbubble dispersion.

2. Experimental Procedure

2.1. Materials

In the present study, aqueous solutions of cetyltrimethyl ammonium bromide (CTAB) was employed as liquid phase, whereas air were used as gas phase. The concentration of CTAB varied from 50 mg/l to 3000 mg/l. Experiments were also carried out with silica nanoparticles to alter the stability of the microbubbles. The nanoparticles of weight 0.5 gm, 1 gm, 1.5 gm, 2gm, 2.5 gm and 3 gm 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.

Table 1
Density and viscosity for different concentration of CTAB

Concentration of CTAB (mg/l)	Density (kg/m ³)	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

2.2. Methods

2.2.1. Generation of microbubbles

Microbubble can be generation by several methods (Parmar and Majumder, 2013). In the present work microbubble dispersion was generated by the method similar to Seeba (1985). The surfactant is mixed in 250 ml of water. The solution of surfactant and water with and without nano-particles were mixed in high

speed stirrer (approx. 18000 rpm; Model- Jaipan JX 4) to generate microbubble. The blade within the stirrer rotate at about 18000 rpm producing a high sheared within the gas-liquid/gas-liquid-solid mixture, for about 60 seconds, which creates microbubble dispersion. The schematic of experimental set up is shown in figure 1. All the experiments were carried out at room temperature.

2.2.2. Estimation of microbubble gas fraction

The efficiency of any gas-liquid reaction is highly governed 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. Microbubbles 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 (ϵ_{md}) is calculated as

$$\epsilon_{md} = \frac{H - h}{H} \quad (1)$$

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

2.2.3. Determination of stability of microbubble dispersion

The half-life of the microbubble dispersion is widely used as an indicator for analysing the stability (Amiri and Sadeghialiabadi, 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. Freshly prepared microbubble dispersion from the mixer are poured into the measuring cylinder and the volume of the drained liquid below the dispersion are recorded and measured as function of time. The variation of liquid drainage volume with time for 500 mg/l of CTAB is shown in Figure 2. From the plot of liquid drainage volume and drainage time the half-life of dispersion can be calculated. Figure 3 shown a typical demonstration for the estimation of half-life from the liquid drainage in 500 mg/l of CTAB without containing nanoparticles.

2.2.4. Estimation of the microbubble rise velocity

The microbubble due to its small size possess low rise velocity. Though the value of rise velocity is very important for determination the bubble residence time and Reynolds number of bubbles. In the present work, the rise velocity 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 rises due to buoyancy, leaving the clear liquid interface. This rise

in interface with respect to the time is recorded. The rise velocity (V_{md}) of microbubble dispersion can be calculated as

$$V_{md} = \frac{H_i - H_j}{t_i - t_j} \quad (2)$$

Where H_i is interface height at t_i and H_j is the interface height corresponding t_j .

2.2.5. Determination of the average microbubble size.

The size microbubble dispersion is vital parameter to govern the interfacial area and mass transfer characteristic of bubbles. So, determination of microbubble size become very crucial for its implication in process intensification unit. If it is assumed that the all bubbles moves with same velocity equal to the velocity of clear liquid interface. Since, the value of rise velocity of microbubble dispersion is very less and it can be assumed that the microbubbles rises with a velocity equal to the terminal velocity of bubble. Then the microbubble size (d_{mb}) in the dispersion can be calculated as per the relation:

$$d_{mb} = \sqrt{\frac{18V_{md}\mu_l}{\rho_l - \rho_g}} \quad (3)$$

where μ_l denotes the viscosity of the liquid or slurry, ρ_l represents the density of microbubble-liquid mixture, ρ_g is the density of air and g is the gravitational acceleration.

3. Result And Discussion

3.1.1. Gas fraction of microbubble dispersion

The effect of surfactant concentration on the microbubble dispersion gas fraction is shown in Fig. 4. The results shows 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 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 holdup. 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.

3.1.2. Stability of microbubble dispersion without and with nanoparticles

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 microbubble dispersion shows a S-shaped curve. The S-shaped curve is also reported in previous studies for microbubble dispersion (Feng et al., 2009; Ruby and Majumder, 2018; Yan et al., 2005). It is seen from the 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 impart 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 increases 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.

Table 2
Half-life and final drainage volume 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

Parmar and Majumder (2015) generated microbubble dispersion by pressurized dissolution method and reported the half-life of microbubble dispersion of about 434 seconds 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 seconds 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 effects the half-life of dispersion. The effect of silica nanoparticle 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 nanoparticle. 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 promotes the stability. The other possible cause for the enhancement the stability of microbubble dispersion is the increment in average viscosity of liquid. Due to which the drag on the bubble increases. The adsorbed nanoparticle 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 at 2.5 gm and 3.0 gm of silica nanoparticle in CTAB the final drained liquid volume came to be higher than at 2.0 gm of silica nanoparticles. As the surfactant solution gets saturated with the nanoparticles, the gas-liquid 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 nanoparticle 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.

3.1.3. Rise velocity 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 rise velocity of microbubble dispersion is shown in Fig. 8. It is seen that the rise velocity of microbubble dispersion decreases with increasing the CTAB concentration. Addition of surfactant increases the viscosity of liquid. Although, the magnitude of this increment in viscosity is small. On increasing the CTAB concentration the gas liquid interfacial tension decreases. This cause 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 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 microbubble dispersion (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 tend to retard the bubbles. However, above 500 mg/l the rise velocity shows a little reduction with increases in surfactant concentration. CTAB again critical micelle concentration at 328 mg/l. So, the addition above 328 mg/l contribute more in viscosity increase rather than the lowering the interfacial tension. The effect of silica nanoparticle addition on the rise velocity of dispersion is shown in Fig. 10. It is seen that the rise velocity of microbubble dispersion decreases with increase in silica concentration in surfactant. It is also observed that the rise velocity in presence of silica particle decreases till concentration of surfactant reaches 2 gm. Beyond this concentration the rise velocity does not change significantly. This is due to two reasons; the viscosity of surfactant solution increases as the

silica concentration increases the other cause is the interfacial surface tension change as the silica particle increases.

4. Conclusion

The effect of concentration of CTAB on gas holdup, size, rise velocity and microbubble stability of microbubble dispersion is investigated. The stability of microbubble dispersion is analysed by using drainage mechanism. The gas holdup of microbubble dispersion is found to be affected by physiochemical properties of the liquid. An increase in concentration of surfactant in liquid cause an increase in gas holdup and stability of microbubble and decrease the rise velocity and bubble size. The effect of silica nanoparticle on stability and rise velocity is also examined. The results clearly showed that the adsorption of nanoparticle on microbubble surface can significantly enhance the stability of microbubble dispersion. The rise velocity of microbubble 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.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors have given their consent to publish this research article

Availability of data and materials

All data generated or analysed in the present research article are included in article

Competing interests

The authors declare no competing interests.

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Authors' contributions

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.

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Figures

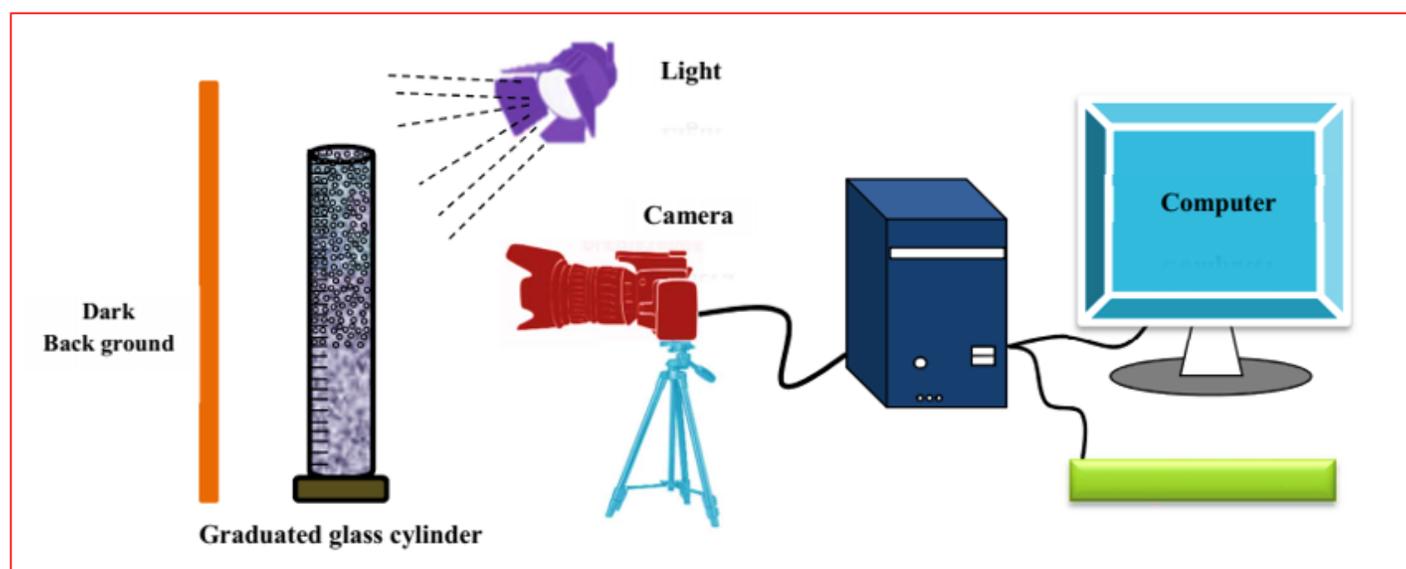


Figure 1

Schematic representation of experimental setup.

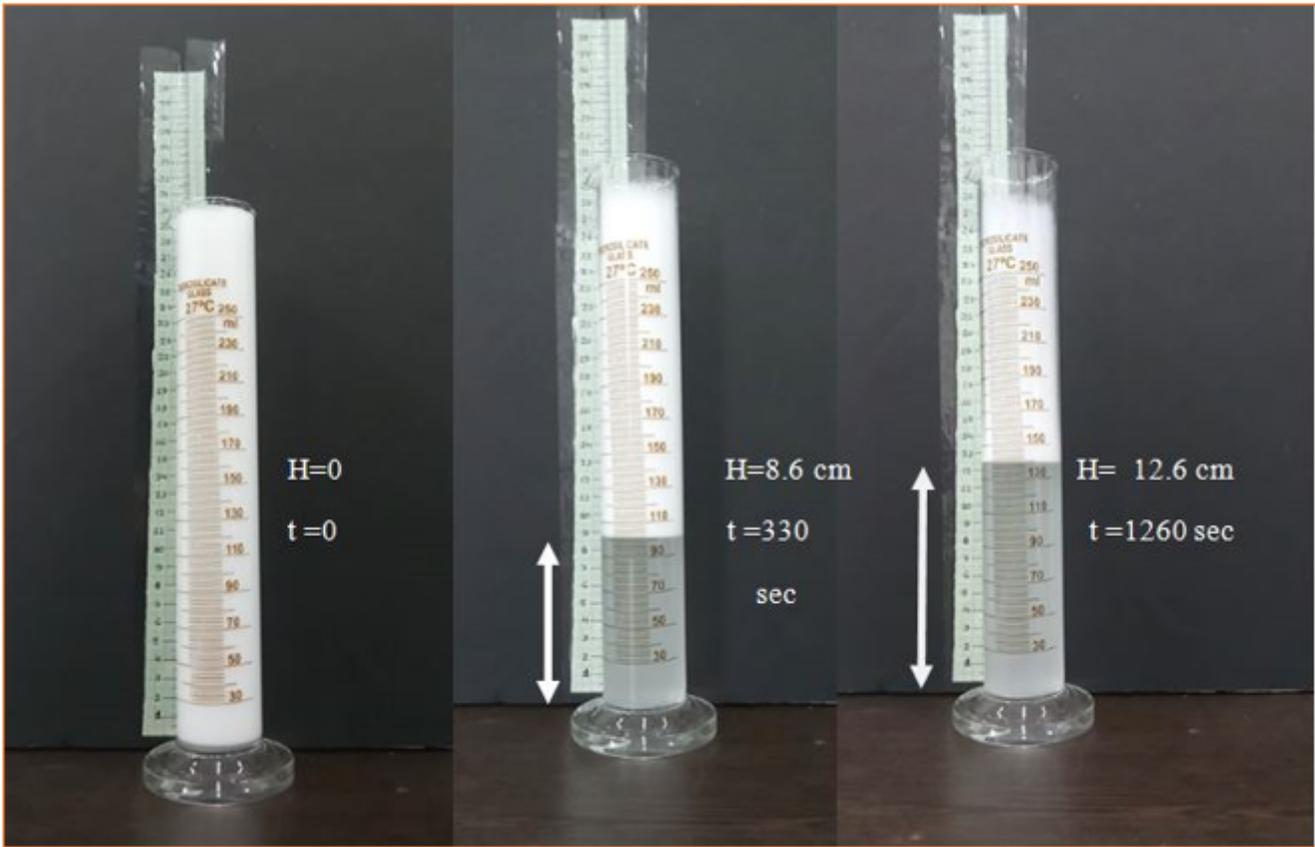


Figure 2

Variation of liquid drainage volume with time for 500 mg/l of CTAB.

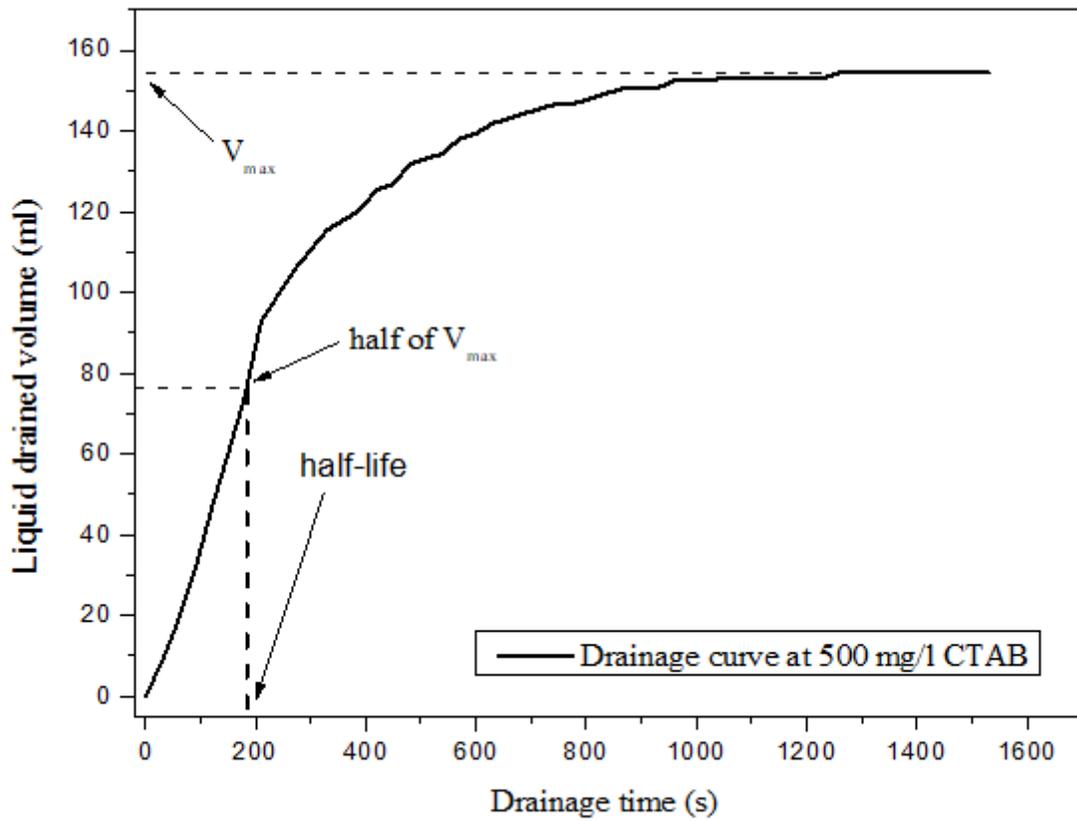


Figure 3

Typical framework to calculate the half-life of microbubble dispersion.

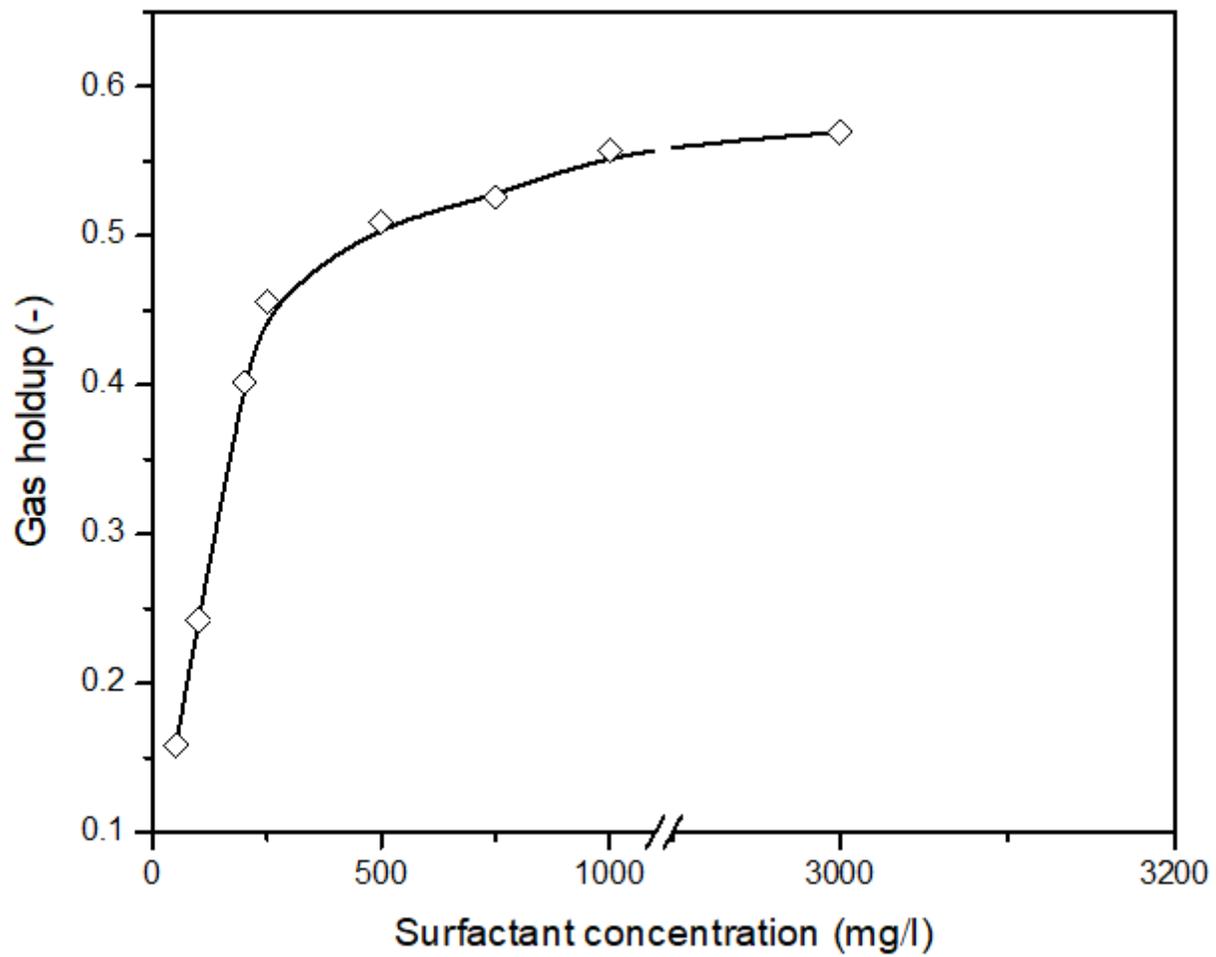


Figure 4

Variation of gas fraction of microbubble dispersion in different concentration of CTAB without nanoparticles.

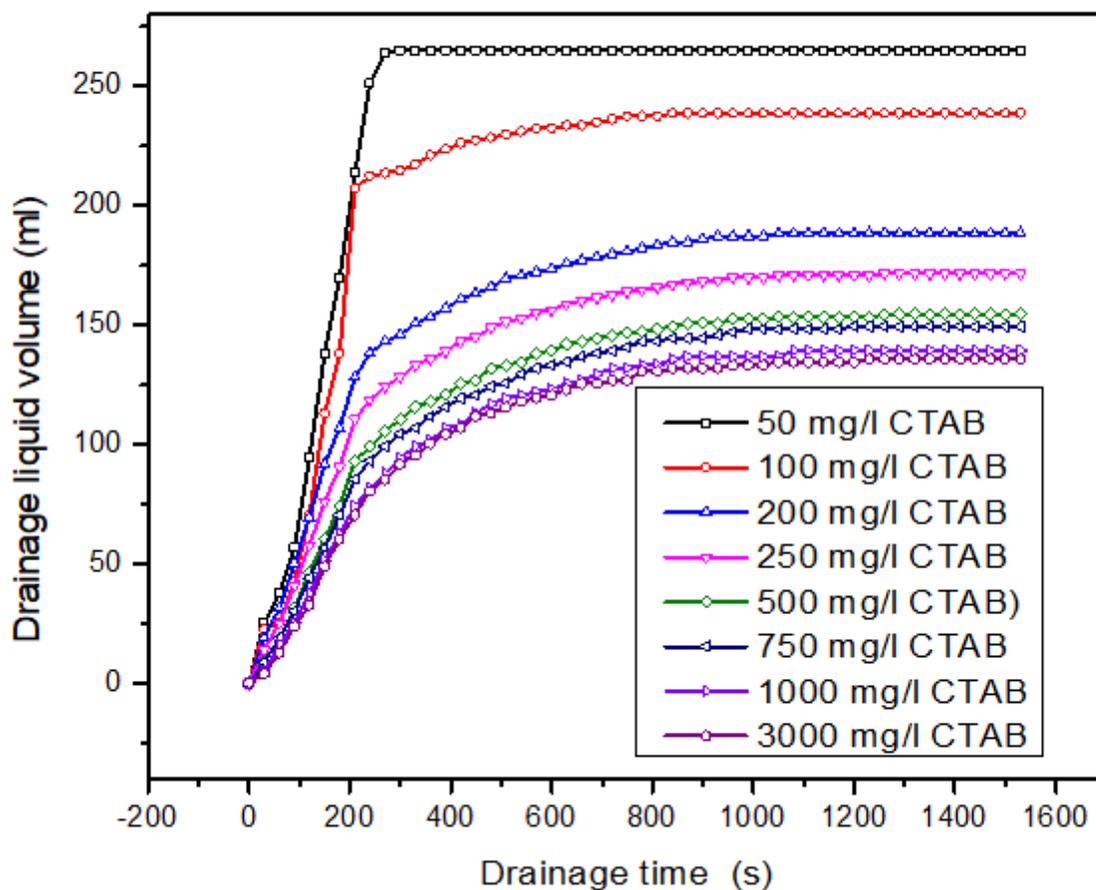


Figure 5

Variation of drained liquid volume with drainage time in different concentration of CTAB without nanoparticles.

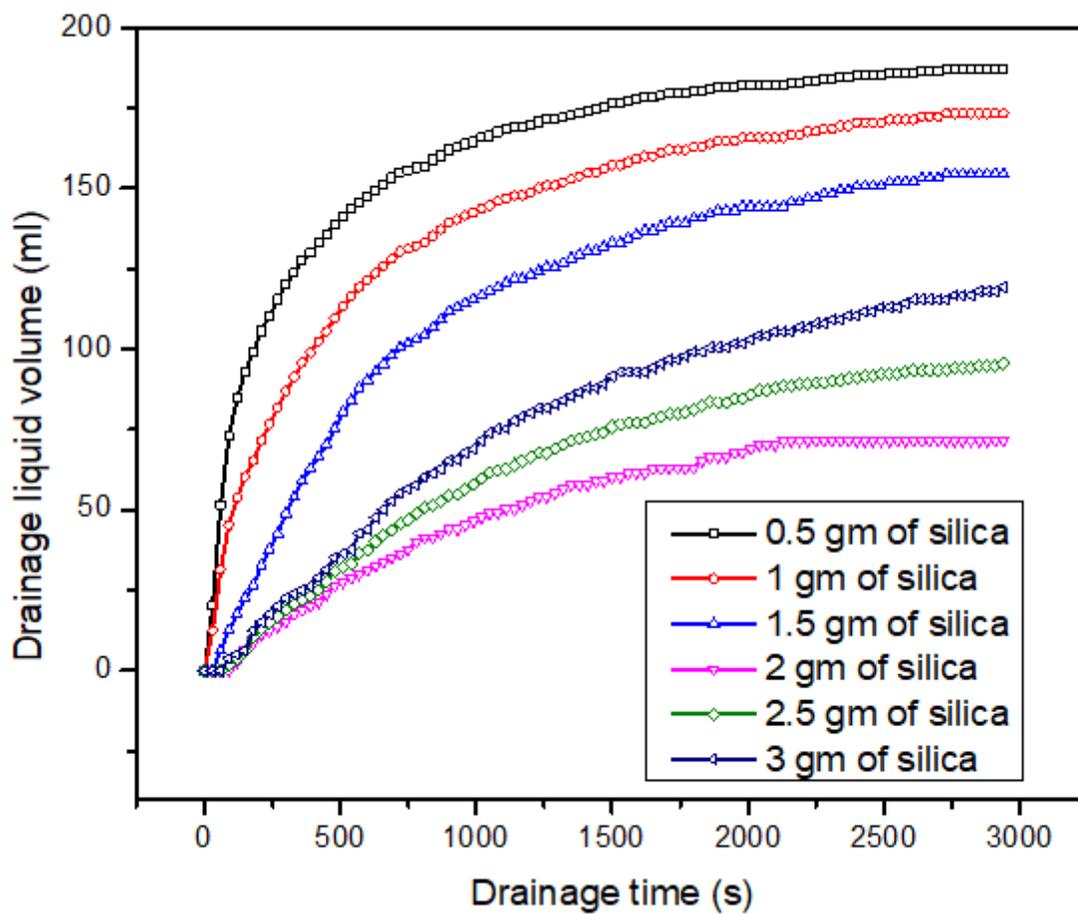


Figure 6

Variation of drained liquid volume with drainage time in CTAB with silica nanoparticles.

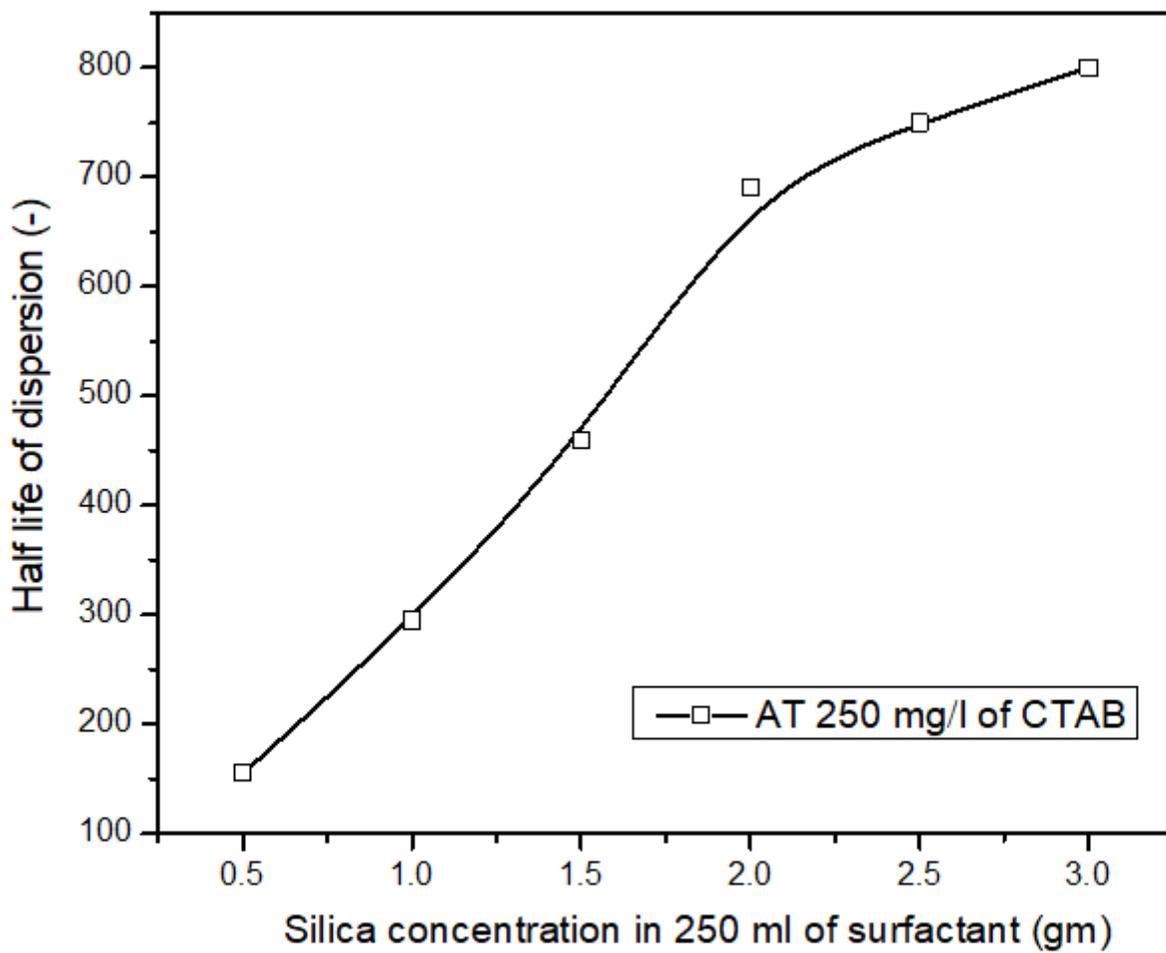


Figure 7

Variation half-life with different silica nanoparticles concentration in CTAB.

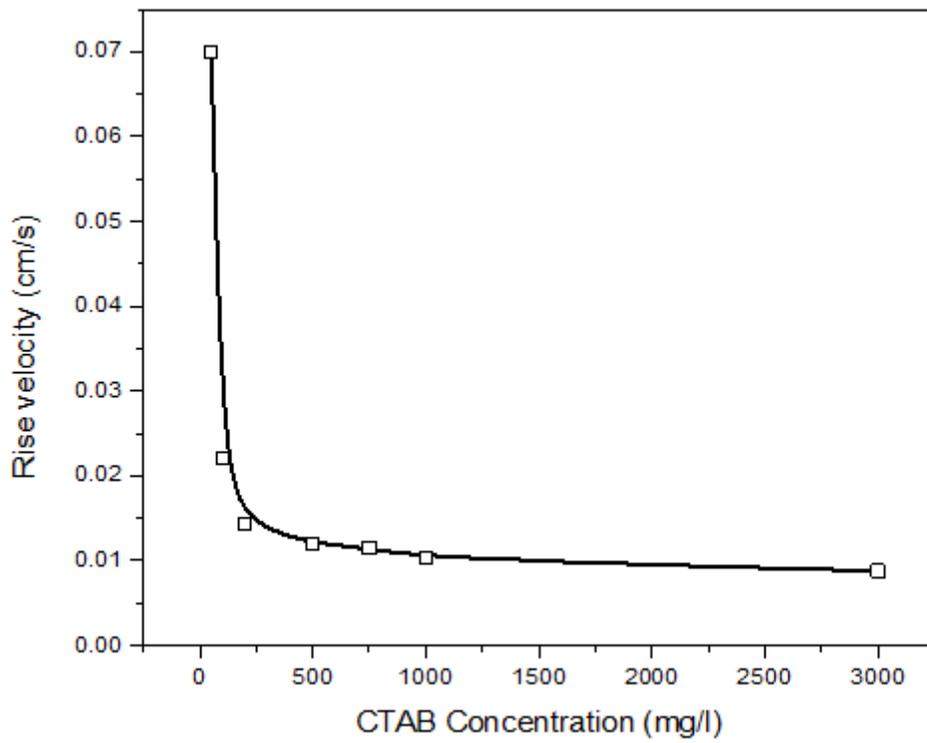


Figure 8

Effect of CTAB concentration on rise velocity of microbubble dispersion.

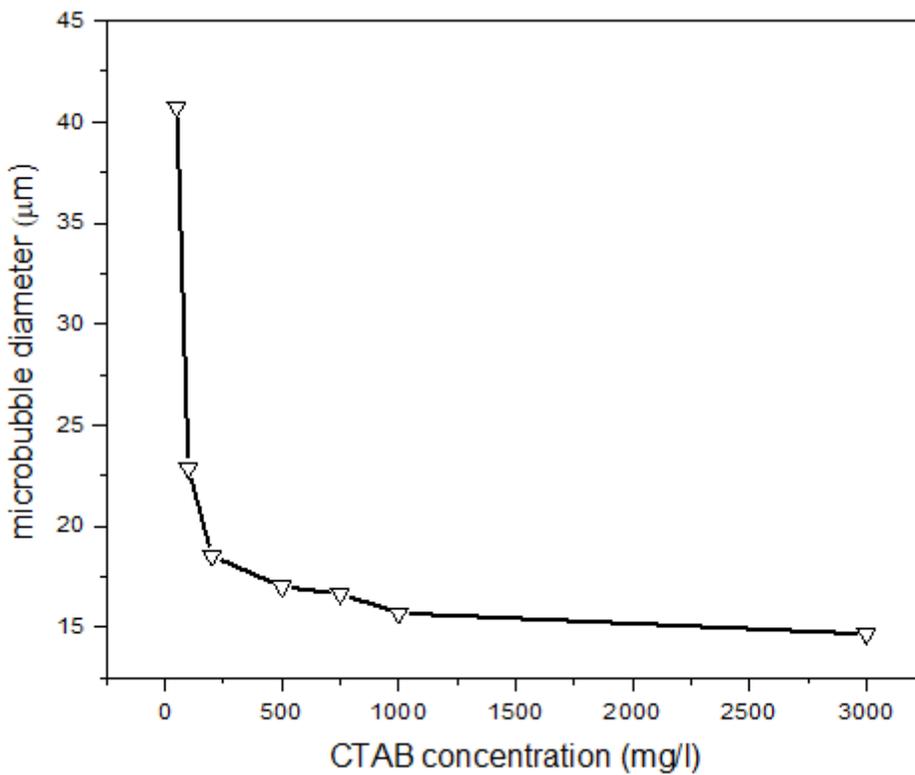


Figure 9

Effect of CTAB concentration on size of microbubble dispersion.

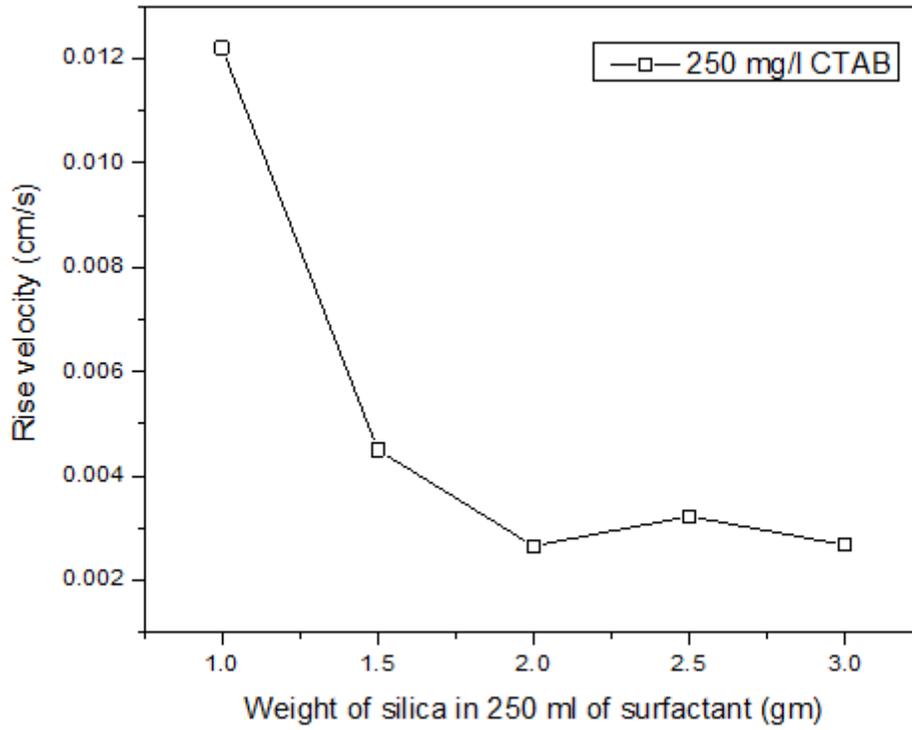


Figure 10

Effect of silica concentration on rise velocity of microbubble dispersion.