Effects of surface tension on the dynamics of a single micro bubble near a rigid wall in an ultrasonic field

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ABSTRACT

Acoustic cavitation is a very important hydrodynamic phenomenon, and is often implicated in a myriad of industrial, medical, and daily living applications. In these applications, the effect mechanism of liquid surface tension on improving the efficiency of acoustic cavitation is a crucial concern for researchers. In this study, the effects of liquid surface tension on the dynamics of an ultrasonic driven bubble near a rigid wall, which could be the main mechanism of efficiency improvement in the applications of acoustic cavitation, were investigated at the microscale level. A synchronous high-speed microscopic imaging method was used to clearly record the temporary evolution of single acoustic cavitation bubble in the liquids with different surface tension. Meanwhile, the bubble dynamic characteristics, such as the position and time of bubble collapse, the size and stability of the bubbles, the speed of bubble boundaries and the micro-jets, were analyzed and compared. In the case of the single bubbles near a rigid wall, it was found that low surface tension reduces the stability of the bubbles in the liquid medium. Meanwhile, the bubbles collapse earlier and farther from the rigid wall in the liquids with lower surface tension. In addition, the surface tension has no significant influence on the speed of the first micro-jet, but it can substantially increase the speed of second and the third micro-jets after the first collapse of the bubble. These effects of liquid surface tension on the bubble dynamics can explain the mechanism of surfactants in numerous fields of acoustic cavitation for facilitating its optimization and application.

1. Introduction

Acoustic cavitation, a process which essentially refers to formation, growth, and implosive transient collapse of a tiny gas–vapor bubble driven by ultrasonic pressure wave in liquid medium [1], is an amazing phenomenon that has attracted much attention since it is in the heart of many applications in industry [2,3], biological science [4,5] and daily life [6].

In many of these applications, the presence of surfactants reduces the surface tension of the liquid and lowers the cavitation threshold which could save energy and improve efficiency [7-10]. For example, it was found that a clear increase in particle removal efficiency 78 nm SiO2 particles is obtained when Triton X-100 (a kind of surfactants) is employed at the optimized process conditions [7]; ultrasound assisted extraction efficiency of natural products (such as chlorophyll, olive oil) from plants could also be significantly improved by adding surfactants in the solvent [10]. In many of these processes, the dynamic characteristics of each cavitation bubble, including bubble growth, stability, dissolution and coalescence, is crucial. Therefore, a sound understanding of influence of surfactants on a single bubble in an acoustic field is essential not only from a fundamental view, but also from an economical perspective.

To date, the bubble dynamics near a boundary have attracted much attention and have been proved to be associated with various applications through experiments [6,11-22] and simulations [11,15,17,23-26]. However, except for the simulations, only a limited number of experimental studies have addressed the effect of surfactants on single bubble cavitation [13,16,27-30]. Crum [30] investigated the influence of surfactants in water on the bubble generation by rectified diffusion during cavitation and found that the adsorption of surfactants at bubble/
solution interface increased the rate of rectified growth of acoustic bubbles. Lee et al. [31,32] extended this work and observed the same results that the rate of bubble growth is significantly higher in surfactant solutions compared with that in water, they attribute this phenomenon to the resistance to gas transfer across the interface provided by the surfactant molecules.

Besides the above mentioned studies which are exploring the effect of surfactants on the bubbles’ growth process, Ashokkumar et al. [13] focused on the influence of surfactants on the radial dynamics of an acoustically driven bubble in free field and found that the bubble dynamics was not significantly affected by the adsorption of both volatile and non-volatile surface active solutes, however the intensity of single bubble sonoluminescence (SBSL) changed. As a typical property of acoustic cavitation, SBSL has been a useful probe to monitor the inertial cavitation activity of single bubble [33,34]. A plenty of studies have paid much attention on the effect of surfactants on sonoluminescence and its related mechanism [27,28,35-37]. The other important characteristic, that usually be used to identify the type or intensity of acoustic cavitation, is acoustic emission [38,39]. Stottlemyer et al. [9], Lee et al. [27] and Ashokkumar et al. [40] have carried out an extensive investigation on the effect of surfactants on the characteristics of acoustic emission, and draw a conclusion that the surface active properties of surfactants can be expected to affect the bubble–bubble interactions within an acoustic cavitation field. Other studies of the effect of surfactants on acoustic cavitation were mainly focus on sonochemistry reactions, such as the works of Ashokkumar and Islam et al. [41,42].

As the complexity of acoustic cavitation field, it’s hard to experimentally investigate the dynamics of a single cavitation bubble in surfactants solution. A plenty of researchers have studied this issue using simulation calculations [28,43-46], and the results show that surface tension plays an important role in acoustic cavitation bubbles. Only a limit number of experimental studies have been reported as discussed above, and they were mainly focused on the amount and size of the cavitation bubbles, but the detailed dynamics of the single bubble in an ultrasonic field which can be directly associated with the main mechanism of most applications were missing.

In this work, the temporary evolutions of single bubble near a rigid wall in liquids with different surface tension were observed and the dynamic characteristics of the single bubble were analyzed and compared to reveal the influence mechanisms of surface tension on the acoustic cavitation. The conclusions in present work could be important for identifying or correcting the mechanisms of acoustic cavitation and for facilitating its optimization and application.

2. Materials and methods

2.1. Materials

All chemicals were used as received unless otherwise noted. SDS special purity grade was used as purchased from Biofroxx. The deionized water used to prepare all solutions was obtained from a three-stage Milli-Q purification system and has a surface tension of 72.59 mN/m at 21 °C. In the experiment, four different concentrations of SDS aqueous solutions were prepared, and their detailed properties including density, surface tension and kinematic viscosity were measured at 21 °C, as shown in Table 1. The kinematic viscosity (μ) and surface tension (σ) measurements were performed respectively on a viscometer (HAAKE™ Viscotester™ E, Thermo Scientific™, USA) and an auto interface tension meter (K100, KRÜSS GmbH, Germany). As shown in Table 1, only the surface tension changes with the SDS concentration. In the experiments, these SDS aqueous solutions were used to investigate the influence of liquid surface tension on bubble dynamics near a rigid wall. It is well known that the accumulation of surfactant molecules at interfaces lowers the interfacial energy because the surfactant molecules have both hydrophilic and hydrophobic sections which are attracted to the water (polar) and air (non-polar) phases respectively. As a result, the addition of surfactants would also lead to series of environmental water pollution, such as the foaming in the solution, the decreasing of the entrained air content, and the increasing of environmental toxicity. In present work, we mainly focus on the influence of the physical parameter (surface tension) on the dynamics of a generated air bubble. To avoid other influences of surfactants on the bubble dynamics, the solutions with different concentrations of surfactants were degassed for at least 2

![Diagram](https://example.com/diagram.png)
h to remove foams and the solutions were used only once for no more than 1 min. In the experiments, bubbles were generated by the air out of the solution and studied for no more than 300 μs in an ultrasonic field, so their dynamics would not be affected by the air content of the solutions.

2.2. Experimental set-up

The experimental arrangement, which has been introduced in detail in our previous work [20], is shown in Fig. 1. In present work, the high-speed camera was operated at 480,000 frames per second (fps), and the transducer was driven by an ultrasonic generator at around 20.45 kHz, and the temperature of the liquid in the acrylic tank was maintained at approximately 21 °C. Single air bubbles were generated in a regulated co-flow micropipette injector, and their sizes were controlled by keeping the size of the micropipette and the flow speed at a proper combined value, which has been detailed introduced in our previous work [20]. To verify the repeatability of our experiments, the micropipette used in present work was tested to generate bubbles at an initial radius of 20 μm (See Fig. S1 and Table S1 in the Supplementary material). As the small size of the bubble and the slow speed of bubble rising, the influence of gravity and buoyancy on the changes of bubbles’ shape was negligible in the short period of time for acoustic cavitation. Thus, the influence of gravity and buoyancy on the bubble is not under consideration in present work.

A hydrophone (TC4013, RESON, Denmark) was used to measure the acoustic pressure in the tank where the single bubble was captured from Fig. 3. Temporal evolution of the individual micro bubble near a rigid wall in the deionized water ($R_0 = 20 \mu \text{m, } \gamma_d = 2.00, \sigma = 72.59 \text{ mN/m}$).
the beginning that the transducer was triggered to work, as shown in Fig. 2(a). As the transducer worked in longitudinal vibration mode, the generated acoustic wave near the bubble could be considered as planar wave and its stable pressure amplitude was about 0.29 MPa in 20.45 kHz. After processing the pressure data via Fourier transform, the corresponding frequency spectrum was obtained, as shown in Fig. 2(b). The highest peak occurs at approximately 20 kHz, which accords with the resonant frequency of the transducer. In present experiment, it takes a period time for the transducer to reach a stable output, and the harmonic waves were obvious at the moment the ultrasonic generator begins to work.

3. Results and discussion

As an important effect mechanism in many applications of ultrasonic cavitation, impacting of single cavitation bubble on the rigid wall has been attracted much attention of researchers. As the foundation, the dynamic characteristics of single cavitation bubble near a rigid wall is vital to help to reveal the mechanism. In present work, the behaviors and typical characteristics of single cavitation bubble near a rigid wall in the liquid with different surface tension are analyzed to study the influence of liquid surface tension on the acoustic cavitation.

3.1. Time evolution of bubble shape in the liquid with different surface tension

The single bubble was generated near a rigid wall with the initial radius \( R_0 = 20 \mu m \) and its dynamic behaviors in an ultrasonic field were investigated in the deionized water and different concentrations of SDS aqueous solutions (The detailed information is shown in Table 1). The initial relative distance between the bubble and the rigid wall \( \gamma_d \), which is defined as the ratio of the distance between the bubble center and the rigid wall to the bubble’s initial radius \( R_0 \), was controlled at 2.00. Fig. 3 shows the typical temporary evolution of individual micro bubble driven by ultrasound near a rigid wall in the deionized water. The corresponding time information is marked below each frame, and the time
zero \((t = 0)\) in this work is defined as the moment the bubbles begin to oscillate under the driving of ultrasonic field.

The ultrasonic driven single bubble near a rigid wall in deionized water goes through four phases, oscillation, movement, collapse and rebound, which have been reported by Wu et al. \([20]\) As shown in frames 1–3 in Fig. 3, a single bubble \((R_0 = 20 \, \mu m)\) is generated near the rigid wall with \(\gamma_d = 2.00\) in deionized water and then significantly oscillates because of the time varying pressure in the ultrasonic field which is called the primary Bjerknes force caused by the primary sound field, while the bubble also has tiny transverse movement because of the secondary Bjerknes force caused by the rigid wall which can be considered as a mirror of the single bubble on the rigid wall. Then the bubble begins to move toward the rigid wall because of the combination of acoustic wave and the secondary Bjerknes force, meanwhile, the shape of individual bubbles becomes non-spherical after several microseconds as shown in frames 4–5 in Fig. 3. Next, one side of the individual bubble boundary near the wall which is defined as the near side in present work touches the rigid wall and its shape becomes ellipsoid (frames 6 and 7). Under ultrasound excitation, the bubble boundary far away from the rigid wall which is defined as the far side in present work moves rapidly toward the rigid wall (frame 8). The bubble tip continues moving and eventually turns into a high-speed jet to strike on the rigid wall (frame 9), and then rebound (frame 10). After several cycles of oscillation on the rigid wall, the single bubble begins the second collapse and rebound phase (frames 11–15). The same situation occurs on the third collapse phase of the single bubble (frames 16–20).

The single bubbles in liquid with lower surface tension have similar behaviors to that in deionized water, they go through the same four phases and collapse more than one times except for a few minor differences. Figs. 4–7 re the comparison of a single bubble’s typical temporal evolution in solutions with different surface tension and in the deionized water under the same experimental conditions \((R_0 = 20 \, \mu m, \gamma_d = 2.00)\) for different periods (respectively corresponding to the four rows of Fig. 3).

As shown in Fig. 4, the single bubbles in the liquid with different surface tension all oscillate first and then move to the rigid wall. As the
As the existence of the rigid wall, the single bubbles become elliptical while moving to the rigid wall. In the early stage of the bubbles’ first collapse, the collapse time of the bubble is significantly advanced due to the decrease of the liquid’s surface tension, and the relative distance between the bubble and the rigid wall increases before the appearance of the first high-speed jets (frame 1 of Fig. 5(a-e)). And then the boundary of the bubbles near the rigid wall, which is defined as “the near side”, is restricted by the rigid wall because of the boundary layer flow and the reflected acoustic wave near the wall. At the same time, the far side of the bubbles’ boundary collapse inward generating a liquid jet when the bubble begins to shrink in the ultrasonic field (frame 2 of Fig. 5(a-e)). The liquid jet shown in frame 2 of Fig. 5(a-e) indicated the first occurrence of the bubble collapse, so the previous frame (frame 1 of Fig. 5(a-e)) was defined as the beginning of the collapse phase, and the corresponding time of frame 1 was defined as the time of bubble collapse in present work. During the late stage, the generated liquid jets impale the bubble, strike the rigid wall, rebound to fuse on the rigid wall and behave much different because of the different jets’ speeds in the liquid with various surface tension (frames 4-5 of Fig. 5(a-e)).

During the second collapse phase, there are a few differences on bubble’s dynamics in liquid with different surface tension. As the surface tension decreases (from Fig. 4 (a) to (e)), the bubbles have an obvious trend to move to the rigid wall and appear to be non-spherical earlier (frame 4 of Fig. 4 (a-e)). Compared with bubbles in deionized water, the bubbles in SDS aqueous solutions are more likely to exhibit irregular surface morphology during the movement phase to the rigid wall, such as surface depression or obvious asymmetry (frames 4 and 5 of Fig. 4(b-e)).

As the existence of the rigid wall, the single bubbles become elliptical while moving to the rigid wall. In the early stage of the bubbles’ first collapse, the collapse time of the bubble is significantly advanced due to the decrease of the liquid’s surface tension, and the relative distance between the bubble and the rigid wall increases before the appearance of the first high-speed jets (frame 1 of Fig. 5(a-e)). And then the boundary of the bubbles near the rigid wall, which is defined as “the near side”, is restricted by the rigid wall because of the boundary layer flow and the reflected acoustic wave near the wall. At the same time, the far side of the bubbles’ boundary collapse inward generating a liquid jet when the bubble begins to shrink in the ultrasonic field (frame 2 of Fig. 5(a-e)). The liquid jet shown in frame 2 of Fig. 5(a-e) indicated the first occurrence of the bubble collapse, so the previous frame (frame 1 of Fig. 5(a-e)) was defined as the beginning of the collapse phase, and the corresponding time of frame 1 was defined as the time of bubble collapse in present work. During the late stage, the generated liquid jets impale the bubble, strike the rigid wall, rebound to fuse on the rigid wall and behave much different because of the different jets’ speeds in the liquid with various surface tension (frames 4-5 of Fig. 5(a-e)).

During the second collapse phase, there are a few differences on bubble’s dynamics in liquid with different surface tension. As the surface tension decreases, the bubble’s temporary evolutions become more violent (frames 2-4 of Fig. 6(a-e)). And compared with that in the deionized water, the bubble bursts into numerous small bubbles after collapse in the liquid with lower surface tension (frames 5 of Fig. 6(a-e)). In addition, in the SDS aqueous solutions, the interval between the bubble’s first and second collapse is shorter (frames 1 of Fig. 5(a-e) and Fig. 5(a-e)) than that in deionized water (frames 6 and 11 of Fig. 3)

After the bubble’s second collapse, these small bubbles fuse into one bubble after a period of time and begin the third collapse and rebound process (frames 1-5 of Fig. 7(a-d)) except that in the liquid with the minimum surface tension (frames 1-5 of Fig. 7(e)). As shown in Fig. 6 (e), the bubble is separated into two parts during the second collapse
phase (frames 1–3 of Fig. 6(e)), and the distance of the two bubble groups gradually increases because of the shearing force after the micro-jet impacting on the rigid wall (frames 4 and 5 of Fig. 6(e)); then the bigger bubbles in these two parts separately collapse with a micro-jet directing towards the position on the rigid wall between the two bubble groups (frames 1–5 of Fig. 7(e)).

Due to the addition of surfactants (SDS), the surface tension of the liquid medium is reduced, which reduces the ability of the bubbles to maintain continuous spherical arc under the action of external forces. Therefore, the bubbles in the surfactant solutions appear slightly irregular shape during the oscillation and movement phases. Meanwhile, the reduction in surface tension makes it easier for bubbles to collapse under the effect of asymmetric pressure near the rigid wall, which leads to the changes of the time and position of bubble collapse. In addition, as the pressure threshold of collapse in surfactant aqueous solutions is lower than that in deionized water, so the interval between the bubble’s first and second collapse is shorter when adding surfactants in deionized water. But during the collapse phase, the bubble burst into many small bubbles; the interval between the bubble’s second and third collapse is longer compared with that in pure deionized water, since the reduction in liquid surface tension will obviously increase the time of the bubbles’ fusion process.

3.2. Bubble oscillating near a rigid wall

During oscillation phase, we can find the bubble’s oscillation frequency is much higher than the transducer’s driving frequency which might be the reason of the high-frequency noise reduced by the ultrasonic generator at its starting point, in addition, the bubble’s dynamic behaviors do not have obvious difference, as shown in Fig. 4. To further analyze the bubble’s dynamics in liquids with different surface tension, oscillation characteristics of the single bubble near a rigid wall were analyzed based on the experimental results and simulated by simulation method.

3.2.1. Simulation model

As the rigid wall didn’t move or vibrate during the irradiation of the ultrasound, the rigid wall can be similarly modeled as the mirror of the single bubble on the rigid wall. Thus, the primary and the second Bjerknes force can be respectively regarded as the reasons of the
oscillation and movement of the single bubble.

Here a coupled bubble oscillation model and the Keller-Miksis model are used based on previous work [47] to calculate the bubble’s oscillation in the ultrasonic field.

Newton’s 2nd equation is used to describe the motion of bubbles in a sound field.

\[
\frac{d}{dt}(M_i U_i) = \frac{d}{dt}\left( \frac{1}{2} \rho V_i U_i \right) = F_{B,i} + F_{D,i}
\]

(1)

where \( V_i = \frac{4}{3} \pi \rho R^3_i \) is the volume of the bubble, \( M \) is the virtual mass, and \( F_{B,i} \) and \( F_{D,i} \) is the secondary Bjerknes force and drag force respectively.

Equation (1) can be solved for \( \ddot{X}_i = \dot{U}_i \)

\[
\ddot{X}_i = \frac{1}{R^3_i} \left[ \frac{3}{2} \dot{R}_i \sum_{j \neq i} \dot{R}_j \frac{d_{ij}}{d_{ij}} \right]
\]

(2)

The secondary Bjerknes force for bubble is given by

\[
F_{B,i} = \frac{\rho}{4\pi} \sum_{j \neq i} \dot{V}_i \cdot \dot{V}_j \frac{d_{ij}}{d_{ij}}
\]

(3)

where \( d_{ij} \) is the distance between bubble \( i \) and \( j \).

The Bjerknes force becomes then

\[
F_{B,i} = \frac{\rho}{4\pi} \sum_{j \neq i} R_i^2 \dot{R}_j \dot{R}_j \frac{d_{ij}}{d_{ij}}
\]

(4)

The drag force is given by

\[
F_{D,i} = -12 \pi \mu R_i U
\]

(5)

Thus, the coupled bubble oscillation equation is as follows,

\[
R_i \ddot{R}_i + \frac{3}{2} R_i^2 = \frac{p(R_i) - p(t)}{\rho} - \frac{1}{4} U_i \dot{U}_i - \sum_{j \neq i} \frac{1}{d_{ij}^3} (R_j^2 \dot{R}_j + 2R_j \dot{R}_j^2)
\]

(6)

where \( p(R_i) \) is the pressure just outside the bubble which is given by

\[
p(R_i) = \left( p_{\infty} + \frac{2 \sigma}{R_i} \right) \left( \frac{R_0}{R_i} \right)^{\gamma} - 2 \frac{\sigma}{R_i} - 4 \frac{\mu R_i}{\rho}
\]

(7)

and \( p(t) \) is the pressure outside the bubble which contains the static pressure \( p_{\infty} \) and the time dependent acoustic pressure \( p(t) \):

\[
p(t) = p_{\infty} + p(t)
\]

(8)

where \( p(t) \) has been measured by a hydrophone in present work. Here we use water as a liquid with \( \mu = 0.001 \text{ Pa}s, \rho = 998 \text{ kg m}^{-3} \), \( \gamma = 1.4 \).

According to the experimental results, single bubbles’ oscillating in spherical shape are mostly during the first 50 \( \mu s \) in the solutions with different surface tension, so the pressure data was measured for 50 \( \mu s \) after the ultrasonic transducer was turned on (Fig. S2 in the Supplementary material).

3.2.2. Comparisons of experimental and simulation results about bubble’s dynamics of oscillation near a rigid wall

The comparisons of the experimental and simulation results on the bubble’s oscillation in the deionized water are shown in Fig. 8. The red...
dotted cycle represents the simulation result of the bubble’s boundary at each time point, and the red filled circle represents the centre of the bubble. As shown in Fig. 8, we can find a great agreement between the simulation and experimental results in deionized water, and also find tiny horizontal displacement of the bubble during its oscillation phase. The reason for the bubble’s radial oscillation is the periodic change of acoustic pressure in the liquid, and the transverse movement of the bubble should be attributed to the combination of acoustic motion and the secondary Bjerknes force.

Fig. 9 (a) and (b) give the comparisons of the bubble’s temporary evolution of radius and position in liquids with different surface tension. Tiny increase trends of the oscillation amplitude and horizontal movement distance are found at the end of the oscillation phase as the decrease of the surface tension. These differences are not obvious during bubble’s oscillation and movement, but they become more obvious over time. It is well known that surface tension can keep the bubble stable and the difference of surface tension would affect the inner and outer pressure difference at the same situation. As shown in equation (7), the surface tension $\sigma$ only has little influence on the solution of the simulation model, as the value of $\sigma$ is very small compared to the liquid’s pressure. Other than the acoustic motion and the secondary Bjerknes force, the influence of surface tension on the bubble’s motion is not obvious in a short time, but this influence would keep increasing slowly as time goes on, which is similar to the “compound interest” in finance.

In addition, the radius and the position of the bubble at the first 52 $\mu$s were compared between the experimental and simulation results, which reveal a great agreement in deionized water, as shown in Fig. 10(a) and (b). In other liquids with lower surface tension, the comparisons of the experimental and simulation results are also in the same case of that in the deionized water (see Fig. S3 and Fig. S4 in the Supplementary material). But the radius and the position of the bubble in liquids with different surface tension do not show any obvious differences during oscillation phase in experiments, which could be caused by the restriction of the frame rate and the resolution of the camera in the experiment system.

3.3. Position of bubble collapse

Position of bubble collapse near a rigid wall would greatly influence the flow at the rigid wall which is vital for many applications of acoustic cavitation, such as the cleaning activities. As mentioned in section 3.1, position of bubble’s first collapse in the SDS aqueous solutions is much different from that in deionized water. To detailed analyze the position characteristics of bubble collapse in different concentrations of SDS aqueous solutions, the position of bubble collapse $\gamma_c$ is investigated according to the bubble’s temporary evolution, as shown in Fig. 3 and Fig. 5. To investigate the position of bubble collapse, the typical frame at the beginning of the collapse phase is determined. In Section 3.1, the time of bubble collapse has been defined according to the bubble’s typical characteristics of shape which is based on the generation of the first liquid jet.

The position of bubble collapse $\gamma_c$ is defined as

$$\gamma_c = \frac{L_c}{R_0}$$

where $L_c$ is the distance between the bubble’s mass center and the

![Fig. 10. The comparisons of the simulation and experimental results in deionized water: (a) the single bubble’s radius and (b) the single bubble’s position as a function of time.](image)

![Fig. 11. (a) The typical frame of the beginning of the collapse phase; (b) the relationship between the position of bubble collapse $\gamma_c$ and the surface tension of the liquid.](image)
rigid wall, and \( R_0 \) is the bubble’s initial radius.

Fig. 11(a) is the corresponding frame at the beginning of the collapse phase (time of bubble collapse). To find the bubble’s mass center \( O \), a series of code based on the boundary identification is used in present work. In the code, to get the accurate localization of the bubble’s center in irregular shape, we used the Image recognition and analysis techniques based on centroid algorithm in which the content of the bubble is considered as uniform distribution all the time. The algorithm framework is shown as Fig S5 in the Supplementary material. When the position of point \( O \) is confirmed, the value of \( L_c \) can be easily calculated, as shown in Fig. 11(a).

To present the effect of surface tension on the position of bubble collapse, the relationship between \( \gamma_c \) and surface tension \( (\sigma) \) is shown in Fig. 11(b). As the decrease of the liquid surface tension, the value of \( \gamma_c \) increases substantially, and the increasing rate slows down. In a word, the bubble collapses more easily and the position of the bubble collapse gets farther to the rigid wall as the decrease of the liquid surface tension.

### 3.4. Properties of the micro-jets

As mentioned in section 3.1, the bubble in liquid with lower surface tension collapses more violently. In order to further investigate the effect of liquid surface tension on the dynamic characteristics of bubble collapse under ultrasound excitation, the velocities of the micro-jet during bubble’s collapse were calculated and analyzed in the liquid medium with different values of surface tension. The velocities of the micro-jets directing towards the rigid wall are determined from the photographic series with 480,000 fps, i.e. the average speed of the jet is shown in Fig. 12.

As shown in Fig. 12, the first micro-jet has the maximum speed, and the speed of the prior jet is always bigger than the later one \( v_1 > v_2 > v_3 \). And the speed of the first micro-jet fluctuates between 21.52 m/s and 23.39 m/s, but it is not obviously related to the value of \( \sigma \). The fluctuation of the speeds may be the reason of the systematic error which is due to the limitation of the shooting rate of the high-speed camera. Therefore, it can be judged that the speed of the micro-jet during the first collapse phase is not significantly affected by the liquid surface tension. The situation of the second and the third micro-jets seem to be much different, the values of their velocities significantly increase with the increase of the surface tension. Because the bubble collapses on the rigid wall during its second and third collapse phase, but the decrease in the surface tension makes the bubble expanding bigger, which leads a greater pressure difference between inside and outside of the bubble during the collapse phase.

### 3.5. Time of bubble collapse

In addition to the properties of the micro-jets, the time of bubble collapse also changes significantly as the surface tension decreases. Time of bubble collapse \( t_c \) is defined as the beginning of the first collapse phase in section 3.1, which is an important characteristic of acoustic bubble that could reflect the intensity of the acoustic cavitation. Through analyzing the temporary evolution of the bubble in the liquid medium with different surface tension characteristics, the related conclusions of time of bubble collapse corresponding to the surface tension of the liquid are drawn.

As shown in Fig. 13, the time of bubble collapse \( t_c \) decreases significantly from 79.2 to 54.2 \( \mu s \) as the reduction of the liquid surface tension. That’s mainly the reason of the influence of surfactants on the stability of the single bubble. As discussed in section 3.2 about the bubble’s oscillation, it is found that the bubble’s oscillation amplitude has begun to show a tiny increasing trend as the decrease of the surface tension (Fig. 10(a)). Thus, the bubble in liquid with lower surface tension would have a higher energy of motion at the same time. In addition, the cavitation threshold in the liquid with smaller surface tension would be lower. Thus, the bubble collapses earlier in the liquid with lower surface tension in the ultrasonic field.

The bubble would collapse several times in the ultrasonic field, and the first two or three times were clearly recorded in present work, the information of their occurrence time is listed in Table 2. It is found that the interval between the bubble’s collapses in the deionized water and the SDS aqueous solutions are much different, as discussed in section 3.1.1. In addition, the intervals between two collapses are always the integer multiple of 50 \( \mu s \) (approximately 50 \( \mu s \) or 100 \( \mu s \)), which is exactly one cycle of the main frequency of the ultrasonic field (20 kHz), as shown in Fig. 2. These results show that the ultrasound with main
frequency plays the most important role during the collapse phase of the bubble, and the ultrasonic harmonics only affect the small amplitude vibration of the bubble and have less effect on the bubble collapse process.

3.6. Bubble volume

As the content of the bubble in present work is air, the volume of the bubble can reflect the energy of the bubble partly for qualitative analysis. Based on the method to analyze the position of bubble collapse, the bubble is regarded as rotational symmetric of the horizontal central line, and the number of pixels inside the bubble’s boundary in the 2-D image which is defined as $S$ can be used to qualitatively calculate the volume of the bubble by the numerical transform. Then, the volume parameter $V_b$ is calculated and normalized by:

$$V_b = \left(\frac{S}{S_0}\right)^{3/2}$$  \hspace{1cm} (10)

where $S_0$ is the number of pixels inside the boundary of the initial bubble.

Fig. 14(a) and (b) give the description of the bubble’s boundary for a whole bubble and separated small bubbles, and Fig. 14(c) quantifies the volume profile of the bubble ($V_b$) versus time in liquid with different surface tension.

It is found that the variation amplitude of the bubble’s volume increases obviously as the decrease of the surface tension, as shown in Fig. 14(c), which indicates that the bubble’s volume oscillation in the liquid with lower surface tension would be more intense as described in Section 3.1. In addition, it is also found that the variation amplitude of bubble’s volume would not keep increasing in the ultrasonic field. That is because the energy exchange between the bubble and the environment through high-speed liquid jet and striking, so the variation amplitude of bubble’s volume decreases obviously after each bubble collapse.

4. Conclusions

The effects of the liquid medium’s surface tension on the dynamics of a single bubble in an ultrasonic field are investigated in present work. Synchronous high-speed microscopic imaging is proposed to record the bubble evolution for investigating the bubble dynamic characteristics and the formation of micro-jets. Statistics on the bubble collapse time, position of bubble collapse, the properties of the micro-jets and the volume of the bubble are also presented to quantify the dynamic behaviors of the bubble near a rigid wall. The main conclusions and new findings are summarized as follows:

1. The surface tension obviously affects the dynamic behaviors of the bubble, especially for the bubble collapse.
2. The decrease of surface tension reduces the ability of keeping the bubble surface smooth, which is specifically manifested as the irregular sunken of the bubble boundary under the driving of the asymmetric force near the rigid wall.
3. In liquid with lower surface tension, the bubble’s motion is more intense and would collapse earlier and farther away from the rigid wall.
4. It can be concluded that the influence of the surface tension on the bubble’s dynamics increases as the ultrasonic amplitude and the motion speed of the bubble increase, for example, the influence on the bubble’s shape from oscillation to rebound and the three liquid jets.

In summary, the adding of the surfactant into the deionized water significantly changes the bubble dynamics near a rigid wall in an ultrasonic field. Lower surface tension would lead to the more intense dynamics of the bubble, such as the shorter bubble collapse time, the higher speed of the micro-jets and the instability of the bubble. These results give an insight in the influence mechanism of the surface tension on single acoustic cavitation bubbles, and would provide more information for the use of the surfactant in the applications of acoustic cavitation to facilitate their optimizations.

CRediT authorship contribution statement

Hao Wu: Conceptualization, Methodology, Data curation, Writing-Original draft preparation, Investigation. Hao Zheng: Visualization, Formal analysis, Software. Yuanyuan Li: Data curation, Validation. Claus-Dieter Ohlc: Visualization and simulation. Haixia Yu: Supervision, Writing- Reviewing and Editing. Dachao Li: Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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