Chapter 3

Mesoscale Analysis of Aeration for Cavitation Erosion Protection

3.1 Background

Cavitation often occurs in high-velocity water flows. Cavitation-induced erosion is a major threat facing many engineering projects. For hydraulic and hydropower engineering projects, the major methods for alleviating and preventing cavitation erosion can be classified as follows. The first method is to optimize the geometric design of water passages to minimize intense water flow separation, which leads to the formation of negative pressure, the necessary condition for cavitation to occur. However, water flow separation cannot be completely prevented in real-world projects due to the performance, cost-efficiency, and construction efficiency required of water passages. The second method is to improve the surface roughness of water passages when water flow separation is difficult to avoid, thereby reducing the source of cavitation. However, even with the best control of the surface roughness, the surface of water passages cannot be absolutely smooth. Thus, cavitation may occur when the cavitation number of the water flow is lower than a certain value. The third method is to use erosion- and wear-resistant materials. However, no materials have been found that can sufficiently and effectively resist cavitation erosion. In addition, the bonding between an erosion-resistant surface material and the substrate has remained a challenge. The fourth method is to aerate the water flow to reduce and prevent cavitation erosion. Because the first three methods cannot sufficiently prevent cavitation erosion, the fourth method is actually the major means used in real-world engineering to reduce and prevent cavitation erosion (Peterka 1953; Vischer and Hager 1998).

The engineering practice of aeration for cavitation erosion protection was introduced as early as the 1960s. The Grand Coulee Dam in the United States was modified by adding chute aerators after frequent cavitation erosion was observed downstream of the tapered exits of the flood discharge outlets. No cavitation erosion has occurred since the modification, demonstrating that aeration is an effective means for preventing cavitation erosion. Aeration measures have also been successfully implemented in later engineering projects, such as the Glen Canyon Dam and the

Yellowtail Dam in the United States and the Mica Dam in Canada. Currently, aeration has been incorporated as a mandatory requirement in design specifications for high-velocity discharge structures and, as a result, has been widely adopted for cavitation erosion protection. However, there has been a lack of a clear understanding of the mechanism of aeration for cavitation erosion protection, and there are inconsistent explanations for why aeration can prevent cavitation erosion (Ivany and Hammitt 1965; Hammitt 1980; Auret et al. 1993; Xu et al. 2010; Brennen 2014). The lack of experimental research into the mechanism of aeration for cavitation erosion protection is the main reason for this gap. Almost all the existing explanations lack the support of experimental data.

Due to inadequate research into the mechanism, the effectiveness of aeration-based cavitation erosion protection technology in engineering applications has been compromised to different degrees (Rasmussen 1956; Pfister et al. 2011). As a typical example, aeration-based cavitation erosion protection technology was adopted for the spillway tunnel of an engineering project, but the structure still suffered severe cavitation erosion. The upstream section of the spillway tunnel was constructed with a relatively high elevation to facilitate the configuration of the inlet gate, while the downstream section was constructed with a relatively low elevation to facilitate the connection with the outlet. The upstream and downstream sections were connected with a steep-slope section. The connection between the steep-slope and downstream sections had a concave-curve streamwise section. The flow velocity inside the tunnel was higher than 35 m/s. To prevent cavitation erosion, two bottom aerators were constructed, one in the steep-slope section and one at the end of the concave-curve section. However, after the project was commissioned, severe cavitation erosion occurred in an approximately 400-m long section downstream of the end of the concave-curve section. After repeated investigations were conducted on the root cause of the erosion, the sidewalls at the end of the concave-curve section—a dead corner that cannot be protected by the two aerators nor free-surface aeration—became the focus. An effective solution for the problem was to add an aeration structure on the sidewalls. However, only a very small flip bucket could be constructed on the sidewalls, because an excessive lateral contraction might cause the water flow to jump up and impact the tunnel roof. Because a very small flip bucket was expected to entrain air to a very low concentration, a question arises: Can such a low air concentration effectively prevent cavitation erosion? Only with a clear understanding of the inherent mechanism of aeration for cavitation erosion protection can this question be answered scientifically.

In fact, similar to cavitation and cavitation erosion, aeration for cavitation erosion protection is essentially a mesoscale phenomenon. Its effectiveness depends on the interaction between three factors: cavitation bubbles, air bubbles, and solid walls. Only with an in-depth understanding of the inherent mesoscale mechanism of aeration for cavitation erosion protection can reliable theoretical input be provided for the research and development of aeration-based cavitation erosion protection technology and the design of aeration structures for cavitation erosion protection of engineering projects.

3.2 Attenuation Effect of Air Bubbles on the Collapse Intensity of Cavitation Bubbles

The collapse of a cavitation bubble is accompanied by a strong acoustic effect (Vogel et al. 1989). Therefore, the collapse intensity of cavitation bubbles can be comprehensively evaluated using underwater noise monitoring techniques. In the following, the effects of the following factors on the collapse intensity of cavitation bubbles are analyzed: the relative position, relative size, and quantity of air bubbles interacting with the cavitation bubbles.

3.2.1 Intensity of the Collapse Noise of a Cavitation Bubble Interacting But Not Connected with Air Bubbles

First, the attenuation of the intensity of the collapse noise of a cavitation bubble interacting with a single air bubble is examined.

The effect of an air bubble on the attenuation of the collapse intensity of cavitation bubbles varies with the distance between the air bubble and cavitation bubble. Here, the sound pressures on the air bubble side and the other side of a cavitation bubble measured using a hydrophone are designated SP_1 and SP_2 , respectively. $SP_{\max,1}$ and $SP_{\max,2}$ are the maximum noise measurements obtained by a hydrophone at the corresponding sides. Figure 3.1 shows high-speed images of the evolution of a

Fig. 3.1 High-speed images of the collapse of a cavitation bubble interacting with an air bubble at different air bubble-cavitation bubble distances (frame rate: 180,000 fps; frame width: 48.31 mm; exposure time: 3.95 μs)

cavitation bubble interacting with an air bubble obtained from a series of experiments, in which the air bubble-cavitation bubble distance was gradually decreased but not to the extent that the two bubbles merged. In experiment a (Fig. 3.1a), the initial equivalent radius of the air bubble $R_a = 3.54$ mm, the cavitation bubble expanded to a maximum radius of $R_{\max} = 8.23$ mm at $t = 1222$ μs , and the dimensionless distance between the centroids of the air bubble and cavitation bubble $\omega = 2.93$. The peak sound pressures on the air bubble side and the other side of the cavitation bubble measured using a hydrophone, $SP_{\max,1}$ and $SP_{\max,2}$, were 55.49 and 57.89 kPa, respectively.

Similarly, in experiment b (Fig. 3.1b), $R_a = 3.08$ mm, $R_{\max} = 7.77$ mm, $\omega = 1.58$, $SP_{\max,1} = 59.22$ kPa, and $SP_{\max,2} = 59.76$ kPa. In experiment c (Fig. 3.1c), $R_a = 3.079$ mm, $R_{\max} = 7.51$ mm, $\omega = 1.18$, $SP_{\max,1} = 26.00$ kPa, and $SP_{\max,2} = 28.45$ kPa.

The dimensionless distance between the air bubble and cavitation bubble gradually decreased from experiment a to c. In the development phase of the cavitation bubble, the air bubble underwent extremely complex morphological changes and certain degrees of size oscillations. These size oscillations of the air bubble under the effect of the cavitation bubble served to effectively absorb part of the cavitation bubble's energy and decrease the collapse intensity of the cavitation bubble. The peak sound pressures measured using a hydrophone illustrate this effect well.

In an experiment in which a cavitation bubble interacted with an air bubble in the absence of a boundary effect, the peak collapse sound pressure of the cavitation bubble measured using a hydrophone was $SP = 60.0$ kPa. We first examine the first phase of a cavitation bubble, or the scenario in which a cavitation bubble does not merge an air bubble to form a gas-containing cavitation bubble.

Figure 3.2 shows the sound pressures (measured using a hydrophone) produced by the collapse of a cavitation bubble interacting with a large air bubble under the

Fig. 3.2 Collapse noise of a cavitation bubble interacting with an air bubble at different air bubble-cavitation bubble distances (with the size of the air bubble held constant)

following conditions: position of cavitation bubble $\omega = 0$, position of air bubble $\omega < 0$, and positions of the two hydrophones $\omega > 11$. As the dimensionless air bubble-cavitation bubble distance ω increased, the collapse sound pressure of the cavitation bubble gradually increased to 60 kPa. At $\omega > 4$, the sound pressure decreased slightly. This occurs because when an air bubble is close to a hydrophone probe, the air bubble has a shielding effect on the probe.

The effect of an air bubble on the attenuation of the collapse intensity of cavitation bubbles varies with the air bubble-to-cavitation bubble size ratio. Figure 3.3 shows the high-speed images of the collapse of a cavitation bubble interacting with an air bubble obtained from a series of experiments, in which the air bubble-to-cavitation bubble size ratio gradually increased. In experiment a (Fig. 3.3a), $R_{\max} = 7.77$ mm, $\varepsilon = 0.35$, $\omega = 1.58$, $SP_{\max,1} = 58.58$ kPa, and $SP_{\max,2} = 60.56$ kPa. In experiment b (Fig. 3.3b), $R_a = 3.08$ mm, $R_{\max} = 7.51$ mm, $\omega = 1.58$, $SP_{\max,1} = 26.00$ kPa, and $SP_{\max,2} = 28.45$ kPa. In experiment c (Fig. 3.3c), $R_a = 4.62$ mm, $R_{\max} = 7.34$ mm, $\omega = 1.74$, $SP_{\max,1} = 12.95$ kPa, and $SP_{\max,2} = 21.43$ kPa. The results of the above series of experiments showed that as the air bubble-to-cavitation bubble size ratio gradually increased, the effect of the air bubble on the attenuation of the collapse noise of the cavitation bubble became more pronounced. In addition, the peak sound pressure on the air bubble side (measured with a hydrophone) was considerably lower than that on the other side. This result indicates that the air bubble not only attenuated the collapse noise of the cavitation bubble but also partially shielded the transmission of the cavitation bubble's collapse noise toward the air bubble side.

A comparison of the collapse sound pressures of the cavitation bubble interacting with an air bubble of three different sizes (small, medium, and large) showed that as ω increased, the effect of the air bubble on the attenuation of the collapse noise

Fig. 3.3 High-speed images of the collapse of a cavitation bubble interacting with an air bubble of different relative sizes and distances

of the cavitation bubble gradually decreased. In addition, as the volume of the air bubble increased, the range of influence of the air bubble on ω increased (Fig. 3.4).

Next, we investigate the effect of two air bubbles on the attenuation of the intensity of the collapse noise of a cavitation bubble.

The first scenario is that two air bubbles are located on the same side of a cavitation bubble. Figure 3.5 shows the collapse sound pressure (measured with a hydrophone) of a cavitation bubble interacting with two large air bubbles on the same side. The ratio between the distances from the two air bubbles to the cavitation bubble was 1:2. The horizontal axis shows the values of the smaller ω . As ω increased, the sound pressure on the SP_1 side first gradually increased to 40 kPa and then gradually decreased. Our explanation for this result is as follows: When an air bubble is close to a cavitation bubble, the air bubble has a shielding effect on the collapse sound pressure of the cavitation bubble, whereas when an air bubble is relatively far from a cavitation bubble, the air bubble has a shielding effect on the hydrophone probe. Because of the absence of the shielding effect of an air bubble on this side, the collapse sound pressure on the SP_2 side was approximately equal to that produced by the cavitation bubble in the absence of a boundary effect.

A comparison of the collapse sound pressures of cavitation bubbles interacting with two air bubbles of three different sizes (small, medium, and large) located on the same side showed that as ω increased, the effect of the air bubbles on the attenuation of the collapse noise of the cavitation bubble gradually weakened. In addition, as the volume of the air bubbles increased, the range of influence of the air bubbles on ω increased (Figs. 3.6 and 3.7).

Another scenario is that a cavitation bubble interacts with two air bubbles located on opposite sides. Figure 3.8 shows the collapse sound pressures (measured with a

Fig. 3.4 Collapse noises of a cavitation bubble interacting with an air bubble of different relative sizes at the same air bubble-cavitation bubble distance

Fig. 3.5 High-speed images of the collapse of a cavitation bubble interacting with two air bubbles located on the same side (frame rate: 180,000 fps; frame width: 48.31 mm; exposure time: 3.95 μs ; $R_{max} = 7.97 \text{ mm}$; $\varepsilon_1 = 0.37$; $\varepsilon_2 = 0.35$; $\omega_1 = 3.78$; $\omega_2 = 2.01$)

Fig. 3.6 Collapse noise of a cavitation bubble interacting with two air bubbles on the same side at different air bubble-cavitation bubble distances

hydrophone) of a cavitation bubble interacting with two large air bubbles located symmetrically on opposite sides at different air bubble-cavitation bubble distances. As the dimensionless distance from the air bubbles to the cavitation bubble increased, the collapse sound pressure first gradually increased to 40 kPa and then gradually decreased. Our explanation of this result is as follows: When close to a cavitation bubble, the two air bubbles have a shielding effect on the collapse sound pressure of

Fig. 3.7 Variation in the collapse noise of a cavitation bubble interacting with two air bubbles located on the same side with the radii of the air bubbles

Fig. 3.8 High-speed images of the collapse of a cavitation bubble interacting with two air bubbles located on opposite sides (frequency of images: 180,000 fps; frame width: 48.31 mm; exposure time: 3.95 μ s; $R_{\max} = 7.97$ mm; $\varepsilon_1 = 0.36$; $\varepsilon_2 = 0.35$; $\omega_1 = 1.61$; $\omega_2 = 1.46$)

the cavitation bubble, whereas when far from a cavitation bubble, the two air bubbles have a shielding effect on the hydrophone probe.

A comparison of the collapse sound pressures of a cavitation bubble interacting with two air bubbles of three different sizes (small, medium, and large) located on opposite sides showed that as ω was increased, the effect of the air bubbles on the attenuation of the collapse noise of the cavitation bubble gradually weakened. In

addition, as the volume of the air bubbles increased, the range of influence of the air bubbles on ω increased (Figs. 3.9 and 3.10).

Finally, we investigate the intensity of the collapse noise of a cavitation bubble interacting with four air bubbles.

A comparison of the collapse sound pressures of a cavitation bubble interacting with four air bubbles of two different sizes (small and medium) showed that as

Fig. 3.9 Collapse noise of a cavitation bubble interacting with two air bubbles located symmetrically on opposite sides at different air bubble-cavitation bubble distances

Fig. 3.10 Collapse noise of a cavitation bubble interacting with two air bubbles of three different sizes located symmetrically on opposite sides

ω increased, the effect of the air bubbles on attenuating the collapse noise of the cavitation bubble gradually decreased (Fig. 3.11).

The collapse sound pressure of a cavitation bubble interacting with four air bubbles was experimentally investigated by varying the size of the air bubbles from small to medium only due to the difficulty of conducting experiments at three different sizes with desirable experimental accuracy (Figs. 3.12 and 3.13). The collapse sound pressure of a cavitation bubble interacting with four air bubbles gradually increased as the dimensionless distance from the air bubbles to the cavitation bubble increased.

$$R_{max} = 8.22 \text{ mm}, e_a = 0.36, \varepsilon_1 = 1.82, \varepsilon_2 = 2.23, \varepsilon_3 = 1.89, \varepsilon_4 = 1.93$$

Fig. 3.11 High-speed images of the collapse of a cavitation bubble interacting with four air bubbles (frequency of images: 180,000 fps; frame width: 48.31 mm; exposure time: 3.95 μs ; $R_{max} = 8.22$ mm; $\varepsilon_a = 0.36$; $\omega_1 = 1.82$; $\omega_2 = 2.23$; $\omega_3 = 1.89$; $\omega_4 = 1.93$)

Fig. 3.12 Collapse noises of a cavitation bubble interacting with four air bubbles

Fig. 3.13 Variation in the collapse noise of a cavitation bubble interacting with four air bubbles as the air bubble size increases from small to medium

The collapse sound pressure of a cavitation bubble interacting with a single air bubble was compared with that of the cavitation bubble interacting with two air bubbles located on the same side to investigate the effect of the quantity of air bubbles on the collapse noise of a cavitation bubble (Fig. 3.14). The sound pressure of a cavitation bubble interacting with two air bubbles located on the same side was generally lower than that of the cavitation bubble interacting with a single air bubble. However, the difference was small, indicating that an increase in the quantity of air bubbles did not result in a considerable decrease in the sound pressure.

Fig. 3.14 Collapse noise of a cavitation bubble interacting with different quantities of air bubbles

Fig. 3.15 Collapse noise of a cavitation bubble interacting with air bubbles in different air bubble-cavitation bubble configurations

The sound pressure of a cavitation bubble interacting with air bubbles symmetrically located on opposite sides was compared that of a cavitation bubble interacting with air bubbles located on the same side to investigate the effect of the position of air bubbles on the collapse noise of a cavitation bubble (Fig. 3.15). The sound pressure in the first air bubble-cavitation bubble configuration was larger or smaller than that in the second configuration, but the difference was not large. Changing the position of air bubbles did not result in a significant change in the sound pressure.

When the distance between an air bubble and a cavitation bubble is small enough, they will thread together and air goes into the cavitation bubble, therefore the collapse noise decreases further as shown in Fig. 3.16.

3.2.2 Intensity of the Collapse Noise of a Cavitation Bubble Interacting and Connected with an Air Bubble

Figure 3.17 shows high-speed image of a cavitation bubble interacting with, absorbing, and merging an air bubble obtained a series of experiments conducted under the same conditions. In the experiments, the dimensionless radius of the air bubble (the ratio between the radii of the air bubble and cavitation bubble) ε was varied in the range of 0.213–0.217; the maximum radius of the cavitation bubble $R_{\max}$ was varied in the range of 3.575–4.063 mm; the dimensionless distance from the cavitation bubble center to the nearest air bubble surface ω was varied in the range of 0.721–1.012. The images in column 1 show the position of the center of the electrode pair before the inception of the cavitation bubble relative to the position of an air bubble. A cavitation bubble emerged at the moment shown by the images in column 4. The cavitation bubble kept expanding up to the moment shown in column 6, when the air bubble was penetrated by the principal shock wave of the cavitation

Fig. 3.16 Collapse noise of a cavitation bubble interacting with air bubbles in different air bubble-cavitation bubble distances

bubble. In experiment b, in which the dimensionless radius of the air bubble was the smallest among the four experiments, not only was the air bubble penetrated, but it also split to form new, small bubbles, as shown near the bottom edge of image b6. As the cavitation bubble expanded further, the intensity of the principal shock wave decreased, and the outer size of the air bubble increased due to the high compressibility of the noncondensed gas inside the air bubble, as shown by the images in columns 7–9. From columns 10–17, the cavitation bubble kept shrinking. During the course, the rapid shrinking of the cavitation bubble was accompanied by the emptied space rapidly refilling with the surrounding water. Under the effect of the refilling flow, the air bubble elongated, with the shape of the main body of the air bubble changing from flat in the buffering phase to thin and long. As the cavitation bubble further shrank, the liquid in the original path of the jet that penetrated the air bubble moved toward the cavitation bubble center more quickly than the liquid surrounding the cavitation bubble. At this moment, the air bubble exhibited a stepped morphology at the original position of the penetrating jet. This phenomenon can be

Fig. 3.17 High-speed images of a cavitation bubble interacting and merging with an air bubble (frame rate: 19,700 fps; exposure time: 48 μ s; image size: 17.333 * 7.367 mm; **a** $R_{\max} = 4.008$ mm; $\omega = 1.012$; $\varepsilon = 0.218$; **b** $R_{\max} = 4.063$ mm; $\omega = 0.721$; $\varepsilon = 0.213$; **c** $R_{\max} = 3.575$ mm; $\omega = 0.864$; $\varepsilon = 0.227$; **d** $R_{\max} = 3.958$ mm; $\omega = 0.734$; $\varepsilon = 0.219$)

mainly explained by the following mechanism: A volume of liquid without an air bubble in the vicinity cannot be easily placed under tension, whereas the air bubble can be easily pulled toward the cavitation bubble center due to the high compressibility of the noncondensed gas inside the air bubble, thereby developing stepped morphology. In addition, as shown in Fig. 3.17, the refilling flow-induced stepped air bubble surface developed markedly slower in experiment a (in which the ω value was the largest among the four experiments) than in the other three experiments. In experiments b–d, the air bubble was connected with the cavitation bubble in the later collapse phase of the cavitation bubble.

As shown by the above analyses of the morphological evolution of the cavitation bubble and air bubble throughout the expansion-collapse life cycle of the cavitation bubble, in the expansion phase of the cavitation bubble, the air bubble surface was concave on the cavitation bubble side due to the effect of the principal shock wave. The concave region developed gradually and ultimately developed into a jet penetrating the air bubble, which underwent a shrinkage-expansion mode of morphological evolution. As the cavitation bubble collapsed, the air bubble was elongated by the refilling flow and exhibited a stepped surface on the side near the cavitation bubble center. The morphological evolution of an air bubble has the following effects: First, as the air bubble is tensioned to a stepped shape, it greatly buffers the shrinkage and collapse of the cavitation bubble. Second, the cavitation bubble and air bubble merge to form a gas-containing cavitation bubble.

Figure 3.18 compares the life cycles of a gas-containing cavitation bubble and its nongas-containing counterpart. In Fig. 3.18a, b, the solid lines show the life cycle (phases 1–5) of a gas-containing cavitation bubble; the dashed lines show the life cycle of its nongas-containing counterpart. The radius of the air bubble in Fig. 3.18a,

Fig. 3.18 Comparison of the life cycles of a gas-containing cavitation bubble and its nongas-containing counterpart

b is $Ra = 0.96$ and 1.49 mm, respectively. As shown clearly in the figure, the durations of all the five life-cycle phases of a gas-containing cavitation bubble are longer than those of its nongas-containing counterpart. This result indicates that the presence of an air bubble serves to extend the life cycle and reduce the velocity and collapse intensity of cavitation bubbles. A comparison of Fig. 3.18a, b shows that an increase in the radius of the air bubble, or an increase in the gas content of the gas-containing cavitation bubble, leads to a marked increase in the life cycle of the cavitation bubble. Therefore, a larger air bubble has a greater effect on the buffering of the expansion and collapse of a cavitation bubble.

Figure 3.18c shows the relationship between the duration of the first life-cycle phase of a gas-containing cavitation bubble over that of its nongas-containing counterpart and the bubble radius ratio (the ratio of the radius of the air bubble to that of the cavitation bubble). In the figure, the horizontal axis is the bubble radius ratio, and the vertical axis is the duration of the first life-cycle phase. As the bubble radius ratio ϵ , or the gas content of the gas-containing cavitation bubble, increased, the ratio of the life cycle of the gas-containing cavitation bubble to that of its nongas-containing counterpart increased. This result indicates that a higher gas content leads to a greater effect on the buffering of the expansion and collapse of a cavitation bubble.

Figure 3.19 compares the volumetric evolution of a gas-containing cavitation bubble and its nongas-containing counterpart. Figure 3.19a, b show the temporal volumetric evolution of a gas-containing cavitation bubble formed by a small air bubble and its nongas-containing counterpart. Figure 3.19c, d show the temporal volumetric evolution of a gas-containing cavitation bubble formed by a large air bubble and its nongas-containing counterpart.

In Fig. 3.19a, the nongas-containing cavitation bubble (a') starts rapidly expanding upon its inception, with its radius increasing to the maximum value in a very short period of time, then rapidly shrinks and collapses, with its volume decreased sharply to 3.51 mm^3 . This is followed by two or three rounds of rebound of the cavitation bubble, as shown by the smaller peaks after the major peak in the figure. The

Fig. 3.19 Comparison of the temporal volumetric evolution of a gas-containing cavitation bubble and its nongas-containing counterpart

maximum volumes of the cavitation bubble at the expansion and the first and second rebounds are 182.45, 22.06, and 8.22 mm^3 , respectively. The gas-containing cavitation bubble (a), which has the same volume as the air bubble (3.68 mm^3) upon its inception, emerges and rapidly expands to the maximum volume, which is much larger than that of its nongas-containing counterpart. Then, it rapidly shrinks and collapses, with the volume decreased to 13.02 mm^3 . Similarly, the gas-containing

cavitation bubble undergoes two or three rounds of rebound. The maximum volumes at the expansion and the first and second rounds of rebound are 275.40, 64.53, and 45.29 mm³, respectively. The gas-containing cavitation bubble has a much larger volume than that of its nongas-containing counterpart at all the corresponding rebounds. This result indicates that the presence of an air bubble leads to a larger volume of a cavitation bubble in the expansion (to the maximum volume) and the following rebounds. The nongas-containing cavitation has an extremely small volume of 3.51 mm³ at the first collapse, which has a high intensity and a strong damaging effect. The gas-containing cavitation bubble has a volume of 13.02 mm³ at the first collapse, indicating that the volume of the cavitation bubble does not shrink as much as that in the case of the nongas containing cavitation bubble due to the presence of the air bubble. Thus, the collapse of the gas-containing cavitation bubble has a markedly lower intensity and a markedly weaker damaging effect. Figure 3.19b shows the similar temporal volumetric evolution processes of a gas-containing cavitation bubble (b) formed by a smaller air bubble and its nongas-containing counterpart (b').

In Fig. 3.19c, the nongas-containing cavitation bubble (f') rapidly expands to the maximum volume then rapidly shrinks and collapses. It has an extremely small volume at the first collapse, which is followed by several rounds of rebound and recollapse. After $t = 1500 \mu\text{s}$, its volume gradually approaches 0. Compared with its nongas-containing counterpart, the gas-containing cavitation bubble (f) rapidly expands to a much larger maximum volume after a slightly longer time and has a larger volume at the first collapse. Similarly, this is followed by several rounds of rebound and recollapse. However, as shown in the figure, during the rounds of rebound and recollapse, the volume of the gas-containing cavitation bubble (which varies in the range of 40–100 mm³) is much larger than that of its nongas-containing counterpart and does not show a decreasing trend. Figure 3.19d shows the similar collapse characteristics of a smaller gas-containing cavitation bubble and its nongas-containing counterpart. A larger air bubble leads to a significant increase in both the maximum volume and the volume at the rebounds of the cavitation bubble. In addition, the volume at the rebounds does not show a decreasing trend. A comparison of the behaviors of a cavitation bubble interacting with large and small air bubbles indicates that a larger air bubble has a more significant effect on the buffering of the expansion and collapse of a cavitation bubble.

In Fig. 3.19e, f, the horizontal axis is the bubble radius ratio; the vertical axis is the volumetric increase, which is defined as the ratio of the difference between the volume of a gas-containing cavitation bubble and that of its nongas-containing counterpart at the same life-cycle phase to the volume of the nongas-containing cavitation bubble. Figure 3.19e shows the increase in the maximum volume, δV_{max} . Figure 3.19f shows the increase in the volume at the first collapse, δV_{min} . A higher gas content has a more significant effect on the buffering of the expansion and collapse of a cavitation bubble. The increase in the maximum volume of a cavitation bubble is larger than 0.4. This result is due to the following mechanism: A cavitation bubble has a negative pressure when expanded to the maximum volume. A gas-containing cavitation bubble has a much larger pressure than its nongas-containing counterpart expanded to the same

volume. In addition, a cavitation bubble with a higher gas content can be expanded to a larger maximum volume. In other words, when the contained gas changes from a gas nucleus to a large air bubble, the volume of the cavitation bubble increases sharply. However, a further increase in the gas content does not lead to a large increase in the volumetric increase of the cavitation bubble. In summary, a higher gas content leads to a significantly longer life cycle, a larger maximum volume, and a larger volume at the collapse of a cavitation bubble. However, the relationship between the increases and the bubble radius ratio is subject to further investigation.

Figure 3.20 shows the maximum collapse sound pressures $SP_{\max}$ of a cavitation bubble in two different scenarios: (1) interacting with an air bubble at different dimensionless air bubble-cavitation bubble distances and (2) evolving in the absence of an air bubble.

As shown in Fig. 3.20, in the absence of an air bubble, the maximum collapse sound pressure $SP_{\max}$ of a cavitation bubble stays at approximately 60 kPa. The collapse sound pressure of a cavitation bubble interacting with but not merged with an air bubble is completely different from that of a cavitation bubble evolving in the absence of an air bubble. Specifically, as the dimensionless cavitation bubble-air bubble distance is decreased, the collapse sound pressure of the cavitation bubble decreases continuously from approximately 60 to approximately 10 kPa. As the cavitation bubble-air bubble distance further decreases, the cavitation bubble evolves and finally absorbs the air bubble, forming a gas-containing cavitation bubble. The gas-containing cavitation bubble has a larger minimum volume at collapse and a longer life cycle, thus radiating a markedly smaller energy at collapse. The collapse sound pressure decreases to below 10 kPa.

Fig. 3.20 Collapse noise of a gas-containing cavitation bubble

As shown clearly in Fig. 3.20, the presence of an air bubble contributes to an effective decrease in the collapse intensity of cavitation bubbles. In addition, the effect of an air bubble on a cavitation bubble is much stronger when they are merged than when they are not merged. An air bubble's effect on the attenuation of the intensity of the collapse noise of a cavitation bubble is closely related to the air bubble's mechanism of influence.

3.3 Direction-Changing Effect of an Air Bubble on the Collapse of a Cavitation Bubble

An air bubble not only can attenuate the collapse intensity of cavitation bubbles but also can influence the direction of collapse of a cavitation bubble. The latter effect is referred to as the direction-changing effect.

3.3.1 *Direction-Changing Effect of an Air Bubble on the Collapse of a Cavitation Bubble*

First, we examine the direction of collapse a cavitation bubble near a free surface. A free surface can be a normal water surface, an air bubble with an infinite radius, or an elastic boundary. The collapse of a cavitation bubble near a free surface produces a microjet moving away the free surface. This characteristic has been experimentally investigated and demonstrated by Gibson and Blake (1982).

A cavitation bubble collapses away from a free surface when the distance between the cavitation bubble and the free surface is small. The collapse is not affected by the free surface at large cavitation bubble-free surface distances. To determine the critical condition for a cavitation bubble to collapse away from a free surface, a large amount of data on the direction of collapse of a cavitation bubble collapsing near a free surface has been collected, as shown in Fig. 3.21, where the horizontal axis is the maximum radius of air bubble $R_{\max}$ and the vertical axis is the dimensionless air bubble-free surface distance ω_s .

As shown in the figure, the critical condition for a cavitation bubble to collapse away from a free surface is $\omega_s \approx 5$; i.e., the distance from the cavitation bubble center to the free surface is approximately 5 times that of the maximum radius of the cavitation bubble. When the ratio of the distance between the cavitation bubble center and free surface to the maximum radius of the cavitation bubble is larger than 5, the direction of collapse of the cavitation bubble is not affected by the free surface, and the cavitation bubble collapses in the original place. When the ratio of the distance between the cavitation bubble center and free surface to the maximum radius of the cavitation bubble is smaller than 5, the direction of collapse of the cavitation bubble

Fig. 3.21 Critical condition for a cavitation bubble to collapse away from a free surface

is affected by the free surface, and the cavitation bubble collapses away from the free surface.

First, we investigate the mesoscale mechanism behind an air bubble's effect on the alleviation of cavitation erosion by examining the air bubble-cavitation bubble interaction, particularly the effect of an air bubble on the collapse characteristics of a cavitation bubble.

The dimensional distance between a cavitation bubble and an air bubble is defined as follows:

$$\omega = S/R_{\max} \quad (3.1)$$

the ratio of the radius of an air bubble to that of a cavitation bubble is defined as follows:

$$\varepsilon = R_a/R_{\max} \quad (3.2)$$

where S is the distance between the centers of the air bubble and cavitation bubble (mm), R_a is the radius of the air bubble (mm), and $R_{\max}$ is the maximum radius of the cavitation bubble (mm).

In the following, we discuss the effect of these two parameters on the air bubble-cavitation bubble interaction and analyze the collapse characteristics of a gas-containing cavitation bubble.

To investigate the effect of the air bubble-cavitation bubble distance on the direction of collapse of a cavitation bubble, a series of four experiments were conducted by varying the distance between the centers of the cavitation bubble and air bubble S , the maximum radius of the cavitation bubble $R_{\max}$, and the radius of the air bubble R_a .

The same electric voltage and resistance were used to generate the cavitation bubbles in the four experiments (Fig. 3.22), but the cavitation bubbles had different maximum radii. The difference between the maximum radii of cavitation bubbles a and b was only 0.001 mm, but the differences between the radii of cavitation bubbles

Fig. 3.22 Interaction between a cavitation bubble and an air bubble at different distances (frame rate: 19,700 fps; exposure time: 48 us; image size: 17.333 * 7.367 mm; **a** $R_{\max} = 2.926$ mm; $\delta = 1.810$; $\varepsilon = 0.333$; **b** $R_{\max} = 2.925$ mm; $\delta = 1.204$; $\varepsilon = 0.389$; **c** $R_{\max} = 2.004$ mm; $\delta = 0.996$; $\varepsilon = 0.405$; **d** $R_{\max} = 3.146$ mm; $\delta = 0.194$; $\varepsilon = 0.362$)

c and d and those of cavitation bubbles a and b were large. This is due to the following mechanism: When a cavitation bubble is close to an air bubble, the cavitation bubble is connected with the air bubble in the expansion phase, as shown in images c5 and d3. At this moment, the cavitation bubble contains a large amount of noncondensed gas and is a gas-containing cavitation bubble.

In Fig. 3.22, column 1 shows the distance between the air bubble and the center of the electrode pair at the moment just before the inception of the cavitation bubble. Column 2 shows the dazzling light produced by the electric discharge between the electrodes. The distance between the air bubble and the center of the electrode pair in experiment a was larger than that in experiment d. As shown in the figure, the intensity of the light produced by the electric discharge was high near the center of the electrode pair but gradually decreased with the distance from the center. Cavitation bubbles a and b expanded to the maximum volume before the moment shown in column 6, whereas cavitation bubbles c and d expanded to the maximum volume in the moments shown in columns 7 and 8, respectively. In this phase, in experiments a and b (in which the distance between the air bubble and the center of the electrodes pair was large), the air bubble was penetrated by the principal shock wave produced by the expansion of the cavitation bubble. Comparing experiments a and b, the air bubble was penetrated at a later moment in experiment a than in experiment b (as shown in images a4 and b3, respectively). In experiments c and d (in which the distance between the air bubble and the center of the electrode pair was small), the air bubble was penetrated in the early expansion phase of the cavitation bubble in experiment c, whereas the air bubble completely merged the cavitation bubble and formed a gas-containing cavitation bubble in experiment d. In experiment c, not only was the

air bubble penetrated by the principal shock wave but also a part of the air bubble separated from the parent air bubble to form a small separate bubble, as highlighted in the figure.

After the cavitation bubble entered the collapse phase, while the space occupied by the cavitation bubble was freed by the collapse, the freed space was quickly refilled by the surrounding water, and the air bubble was driven by the centralizing flow to move toward the cavitation bubble center by a very small distance, as shown by the images from experiment b. Compared with experiment a, the air bubble moved toward the cavitation bubble center more noticeably in experiment b than in experiment a. Because of the combined effect of the shock wave and the centralizing flow produced by the collapse of the cavitation bubble, the air bubble surface was concave on the side far from the cavitation bubble and on the side near the cavitation bubble, exhibiting an overall dumbbell shape. In addition, the air bubble had a more typical dumbbell shape in experiment a (in which the air bubble-cavitation bubble distance was larger than that in experiment b) than in experiment b. In experiments a and b, the cavitation bubble did not move toward the air bubble in the collapse phase. In addition, rebound bubbles emerged after the complete collapse of the cavitation bubble in both experiments. These rebound bubbles moved away from the air bubble, and the movement was more noticeable at a larger distance between the air bubble and the center of the electrode pair. Compared with experiments a and b, the cavitation bubble exhibited a longer expansion-collapse life cycle in experiments c and d, although the same needle-plate electric voltage was used for both experiments. This phenomenon is due to the following mechanism: At a small distance between an air bubble and the center of an electrode pair, part or even all of the noncondensed gas inside the air bubble enters the cavitation bubble in its expansion or collapse phase, thereby forming a gas-containing cavitation bubble. In addition, the cavitation bubble has a longer expansion-collapse life cycle if a larger amount of noncondensed gas entered the cavitation bubble in its expansion phase. As analyzed above, the direction of collapse of a cavitation bubble does not change in the final collapse phase regardless of whether the cavitation bubble has absorbed noncondensed gas or has interacted with an air bubble in the expansion or collapse phase.

As revealed by the investigation of a cavitation bubble interacting with an air bubble at different distances, as the distance between the centers of the cavitation bubble and air bubble gradually decreased, in the expansion phase of the cavitation bubble, the intensity and length of the jet penetrating the air bubble gradually increased, and the air bubble and cavitation bubble merged when the distance between the centers of the cavitation bubble and air bubble was very small; in the collapse phase of the cavitation bubble, the penetrating jet was pulled toward the air bubble center at a higher rate, and the air bubble underwent more drastic morphological changes.

As the air bubble-to-cavitation bubble size ratio was varied, the effect of the air bubble on the direction of collapse of the cavitation bubble varied markedly. Figure 3.23 shows the entire process of the air bubble-cavitation bubble interaction. Figure 3.23a shows the interaction between a cavitation bubble and a small air bubble. Figure 3.23b shows the interaction between a cavitation bubble and a large air bubble.

Fig. 3.23 Cavitation bubble-air bubble interaction (frame rate: 3000 fps; exposure time: 42 μ s; image size: 9 $\times$ 9 mm; $\delta = 0.91$; $R = 3.4$ mm; **a** $\varepsilon = 0.31$; **b**: $\varepsilon = 0.89$)

The dimensionless radius of an air bubble is defined as $\varepsilon = r/R$, where r is the radius of the air bubble and R is the maximum radius of the cavitation bubble. When the air bubble is small (Fig. 3.23a), the cavitation bubble and air bubble attract each other, the cavitation bubble collapses toward the air bubble, and the two bubbles are merged into one in the rebound phase. When the air bubble is large (Fig. 3.23b), the cavitation bubble and air bubble repel each other, and the cavitation bubble collapses away from the air bubble.

As shown in Fig. 3.23, ε is a critical parameter influencing the direction of collapse of a cavitation bubble. Figure 3.24 shows the relationship between the direction of collapse of a cavitation bubble β and ε (40 experimental observations). The midpoint of the line connecting a cavitation bubble and an air bubble is designated as the pole, and the line passing through the centers of the cavitation bubble and air bubble is designated as the polar axis; then, the direction of the cavitation bubble is defined as the positive direction of angle β . As shown in the figure, the cavitation bubble always collapses at a position on the line connecting the centers of the cavitation bubble and air bubble. In the figure, a positive value of β indicates that the cavitation

Fig. 3.24 Relationship between the direction of collapse of a cavitation bubble and ε ($\delta = 0.91$, $R = 3.4$ mm)

bubble collapses away from the air bubble, whereas a negative value indicates that the cavitation bubble collapses toward the air bubble. At $\delta = 0.91$ and $R = 3.4$ mm, the critical value of ε , $\varepsilon_{cr} \approx 0.42$. When $\varepsilon < \varepsilon_{cr}$, the cavitation bubble and air bubble attract each other, and the cavitation bubble collapses toward the air bubble. When $\varepsilon > \varepsilon_{cr}$, the cavitation bubble and air bubble repel each other, and the cavitation bubble collapses away from the air bubble. This phenomenon can be explained by momentum conservation and the effect of a cavitation bubble's shock wave on the deformation of an air bubble. Because the density of air is lower than that of water, the momentum of the cavitation bubble on the air bubble side is smaller than that on the opposite side. However, under the effect of the cavitation bubble's shock wave, the air bubble shrinks, rebounds, and reshinks, and the reshrinkage of the air bubble occurs simultaneously with the collapse of the cavitation bubble, resulting in the momentum of the cavitation bubble on the air bubble side being higher than that on the opposite side. These are two opposing effects. To maintain momentum conservation, the cavitation bubble collapses toward the side with the higher momentum. Therefore, there exists an ε_{cr} , where when $\varepsilon < \varepsilon_{cr}$, the momentum of the cavitation bubble on the air bubble side is higher than that on the opposite side. The extreme condition of this scenario is that the air bubble is a very small gas nucleus and is similar to a cavitation bubble (two interacting cavitation bubbles attract each other). When $\varepsilon > \varepsilon_{cr}$, the momentum of the cavitation bubble on the air bubble side is lower than that on the opposite side. The extreme condition of this scenario is that the air bubble has an infinite volume and is similar to a free surface (a cavitation bubble evolving near a free surface collapses away from the free surface). The direction of the collapse of a cavitation bubble can also be explained directly from the perspective of the pressure gradient.

Generally, the direction of collapse of a cavitation bubble near an air bubble is shown in Fig. 3.25 (Xu et al. 2020), where ε is the relative size of the air bubble (the radius of the air bubble/the maximum radius of the cavitation bubble), γ is the relative distance between the cavitation bubble and the air bubble (the distance between two sphere centers/the maximum radius of the cavitation bubble). The figure can be divided into four areas: no direction, away from the air bubble, towards the air bubble, and merged air bubble.

3.3.2 *Direction-Changing Effect of an Air Bubble on a Cavitation Bubble Evolving Near a Wall*

The position of a cavitation bubble relative to a wall is measured using the dimensionless parameter $\gamma_{bw} = D/R_{\max}$, where D is the smallest distance from the cavitation bubble center to the wall and $R_{\max}$ is the maximum radius of the cavitation bubble during its evolution. The size of an air bubble relative to that of a cavitation bubble is measured using a dimensionless parameter, $\varepsilon = R_a/R_{\max}$, where R_a is the radius of the air bubble and $R_{\max}$ is the maximum radius of the cavitation bubble during

Fig. 3.25 The direction of collapse of a cavitation bubble near an air bubble

its evolution. In addition, the position of an air bubble relative to that of a cavitation bubble is measured using the dimensionless parameter $\omega = S/R_{\max}$. The S is the distance from the center of cavitation bubble to the center of air bubble and $R_{\max}$ is the maximum radius of the cavitation bubble during its evolution. The positional relationship between the air bubble, cavitation bubble, and wall is measured with the angle θ between the line connecting the centers of the air bubble and cavitation bubble and the normal line from the cavitation bubble center to the wall, with the cavitation bubble center as the apex. The spatial relationship between the cavitation bubble, air bubble, and wall can be determined using the four parameters γ , ε , ω , and θ , defined above, as shown in Fig. 3.26.

Fig. 3.26 Definition of parameters for describing the spatial relationship between an air bubble, a cavitation bubble, and a wall

We first investigate the effect of the air bubble-cavitation bubble distance on the collapse characteristics of a cavitation bubble near a wall.

Figure 3.27 shows high-speed images of a cavitation bubble interacting with an air bubble obtained from a series of five experiments, in which the cavitation bubble-air bubble distance was varied and the cavitation bubble-wall distance was held constant. In the five experiments, the maximum radius of the cavitation bubble $R_{\max}$ was varied in the range of 2.275–2.817 mm, and the dimensionless radius of the air bubble was varied in the range of 0.300–0.548. Table 3.1 shows the parametric settings for the experiments.

As shown in Fig. 3.27, in experiment a (in which the air bubble-cavitation bubble distance was small, with the dimensionless distance from the cavitation bubble center

Fig. 3.27 Air bubble-cavitation bubble-wall interaction at different ω values (frame rate: 19,700 fps; exposure time: 48 μ s; image size: 17.333 * 7.367 mm; spatial relationship between the air bubble, cavitation bubble, and wall is shown in Table 3.1)

Table 3.1 Parametric settings for experiments of air bubble-cavitation bubble-wall interaction at different ω values

	$R_{\max}$ (mm)	γ	ε	ω	θ
Experiment a	2.600	2.729	0.500	0.088	22.932
Experiment b	2.275	3.976	0.548	0.882	1.909
Experiment c	2.817	2.558	0.327	0.924	1.762
Experiment d	2.383	3.773	0.477	1.420	6.189
Experiment e	2.708	3.760	0.300	3.020	0

to the air bubble surface set at 0.088), after its inception, the cavitation bubble rapidly merged with the air bubble and further evolved into a gas-containing cavitation bubble. In experiment b (in which the dimensionless distance from the cavitation bubble center to the nearest air bubble surface was set at 0.882), a cavitation bubble was generated by an electric discharge between the electrodes, and the air bubble was penetrated under the effect of the principal shock wave of the cavitation bubble, forming a penetrating jet. In addition, the air bubble had a volume smaller than its volume before the inception of the cavitation bubble. This result is mainly due to the effect of the principal shock wave. As the cavitation bubble developed further through the expansion-collapse life cycle, the penetrating jet continued to develop into a long jet. Prior to the moment shown in Row 7, the jet penetrating the air bubble continued to grow and gradually developed toward the wall. When the cavitation bubble developed to the moments shown in Rows 8 and 9, the jet penetrating the air bubble reached the wall, and the cavitation bubble entered its later collapse phase, when the cavitation bubble radiated a strong collapse shock wave. Under the effect of the collapse shock wave, the overall outer size of the penetrated air bubble decreased. At this moment, part of the penetrating jet detached from the air bubble and adhered to the wall, and the nondetached part of the penetrating jet began to move toward the cavitation bubble center, as shown in images b10 and b11 (Fig. 3.27). When the cavitation bubble completed the first collapse, the air bubble shrank to the minimum volume and exhibited an irregular spatial morphology. In experiment c (Fig. 3.27), in which the dimensionless distance from the center of the air bubble to the nearest air bubble surface was 0.924, the bubbles underwent evolution similar to that in experiment b. Under the effect of the principal shock wave radiated by the cavitation bubble, a jet emerged and penetrated the air bubble. The penetrating jet reached the wall at the moment shown in image c5, earlier than in experiment b. This result is mainly because of the smaller γ and larger ω . In the later collapse phase of the cavitation bubble, under the effect of the collapse shock wave of the cavitation bubble, the overall outer size of the air bubble decreased. Similarly, part of the penetrating jet detached from the air bubble and adhered to the wall, but the nondetached part of the penetrating jet did not move toward the cavitation bubble center along with the parent air bubble. The difference between the results of experiments c and b was that the penetrating jet developed at a much slower rate in experiment c than in experiment b.

In experiment d (Fig. 3.27), in which the air bubble-cavitation bubble distance was further increased, a jet also developed to penetrate the air bubble. However, different from experiments b and c, the penetrating jet did not reach the wall and did not detach from the air bubble. Before the moment shown in row 7, the jet penetrating the air bubble continued to grow. After the cavitation bubble entered the collapse phase, the space freed by the collapse of the cavitation bubble was quickly refilled by the surrounding water. Under the effect of the refilling flow, the outer size of the air bubble quickly increased, as shown in image d9. In the later collapse phase, the cavitation bubble radiated a strong collapse shock wave into the surrounding water. Under the effect of the shock wave, the outer size of the air bubble decreased, indicating that the air bubble was being compressed. The penetrating jet gradually

disappeared. Being surrounded by a complex flow field, the air bubble exhibited an irregular spatial morphology. In experiment e (Fig. 3.27), in which the dimensionless distance from the cavitation bubble center to the nearest air bubble surface was further increased to 3.020, no jet developed to penetrate the air bubble. The outer size of the air bubble throughout the expansion-collapse life cycle of the cavitation bubble was the smallest among the five experiments, indicating that the air bubble played a considerable role in the buffering of the principal and collapse shock waves but did not experience severe deformation.

In summary, for an air bubble located between a wall and a cavitation bubble, as the cavitation bubble evolves through the expansion-collapse life cycle, the air bubble is subjected to three motions, namely, merging with the cavitation bubble, forming a penetrating jet, and experiencing overall deformation, if the air bubble-cavitation bubble distance is small. For a ω value in the range of 1–1.5, a jet develops to penetrate the air bubble; a decrease in ω leads to a stronger penetrating jet, and vice versa. At $\omega > 1.5$, no jet develops to penetrate the air bubble; the air bubble undergoes a shrinkage-expansion-reshrinkage mode of morphological evolution but does not experience severe surface deformation.

Figure 3.28 shows high-speed images of the interaction between an air bubble, a cavitation bubble of similar size, and a wall obtained from a series of experiments in which the cavitation bubble-wall distance was held constant and the distance between the cavitation bubble center and the air bubble surface was varied. In the series of experiments, the maximum radius of the cavitation bubble $R_{\max}$ was varied in the range of 1.679–2.004 mm; the radius of the air bubble was varied in the range of 0.974–0.975 mm, and the distance between the cavitation bubble center and the wall was kept constant at 3.684 mm. In experiment a (in which the distance from the cavitation bubble center to the nearest air bubble surface was 1.661 mm and the radius of the air bubble was 0.975 mm), the cavitation bubble radiated a principal shock wave in the expansion phase. Under the effect of the principal shock wave, the air bubble experienced shrinkage deformation and its surface near the cavitation bubble center was compressed and concave. When the principal shock wave was strong, the air bubble was penetrated, and a penetrating jet formed, as shown in image a4. As the cavitation bubble further developed, the principal shock wave radiated by the cavitation bubble into the surrounding water weakened, and the jet penetrating the air bubble continued to develop outward. A comparison of images a4–a7 shows that the penetrating jet gradually developed, resulting in an increasing part of the air bubble being penetrated. After the cavitation bubble entered the shrinkage phase (image a7), the length of the penetrating jet continued to increase, but the penetrating jet thinned. Because of the long penetrating jet, the cavitation bubble gradually radiated a collapse shock wave into the surrounding water after entering the collapse phase. Under the effect of the collapse shock wave, the parent air bubble began to undergo shrinkage deformation, as shown by a comparison of images a7 and a8. As the cavitation bubble continued to radiate a collapse shock wave into the surrounding water, the slender penetrating jet gradually detached from the parent air bubble, as shown by the black mass shown in the left part of image a9 (Table 3.2).

Fig. 3.28 Air bubble-cavitation bubble-wall interaction at the same value of γ and different values of ω (frame rate: 19,700 fps; exposure time: 48 us; image size: **a** 12.133 * 7.367 mm; **b–f** 13.867 * 7.367 mm; the spatial relationship between the air bubble, cavitation bubble, and wall is shown in Table 3.2)

In experiment b (in which the smallest distance from the cavitation bubble center to the air bubble surface was increased to 1.901 mm), the air bubble also underwent a shrinkage-expansion-reshrinkage mode of deformation and was penetrated by a jet. However, the penetrating jet had a different morphology in experiment b than in experiment a. More specifically, the penetrating jet in experiment b was wider and had a sharper frontal end and larger overall length than those in experiment a, as shown by a comparison of images b6 and a7. After the cavitation bubble entered the collapse phase, the principal shock wave attenuated drastically to a very weak level.

Table 3.2 Parametric settings for experiments of air bubble-cavitation bubble-wall interaction at the same value of γ and different values of ω

	$R_{\max}$ (mm)	γ	ε	ω	θ
<i>Experiment a</i>	1.679	2.194	0.581	0.989	189.462
Experiment b	1.842	1.824	0.500	1.032	176.698
Experiment c	2.004	1.784	0.378	1.569	166.349
Experiment d	2.058	1.632	0.447	2.124	193.610
Experiment e	1.950	1.667	0.444	2.543	185.870
Experiment f	2.004	1.703	0.486	2.645	205.016

At that moment, the frontal section of the jet penetrating the air bubble detached from the parent air bubble, as shown in image b7. As the cavitation bubble further collapsed, the intensity of the collapse shock wave increased. At this moment, the air bubble experienced more drastic deformation, as shown in image b8.

In experiment c (in which the smallest distance from the cavitation bubble center to the air bubble surface was further increased to 3.144 mm), the air bubble shrank, expanded, and reshrank under the effect of the principal shock wave of the cavitation bubble, and a penetrating jet developed. However, compared with experiments a and b, the penetrating jet in experiment c was much shorter and thinner, as shown by a comparison of images c4 and c5 with the images for the corresponding moments in the previous two experiments. In addition, the penetrating jet was slenderer. When the cavitation bubble developed to the maximum volume (c6), the penetrating jet detached from the parent air bubble to form separate small bubbles. In the later collapse phase of the cavitation bubble, the air bubble experienced larger deformation in experiment c. However, the color of the severely deformed air bubble in experiment c was darker than those in experiments a and b at the corresponding moment. For an air bubble that has experienced severe deformation and energetic motion, a dark color indicates that minimal liquid is present inside the air bubble, whereas a light color indicates that there is a large amount of liquid inside the air bubble. Based on this criterion, in experiment c, the air bubble experienced severe deformation, but its surface was not severely concave, and there was not a large amount of liquid inside it.

In experiments d, e, and f, the smallest distances from the cavitation bubble center to the bubble surface were further increased to 4.371, 4.959, and 5.301 mm, respectively. At these smallest distances from the cavitation bubble center to the air bubble surface, the air bubble experienced a shrinkage-expansion-reshrinkage mode of deformation throughout the expansion-collapse life cycle of the cavitation bubble, but no penetrating jet developed. In the expansion phase of the cavitation bubble, the air bubble surface was concave on the cavitation bubble side, which was mainly due to the expansion shock wave. In the final collapse phase of the cavitation bubble, the air bubble surface was concave to different degrees on the side away from the cavitation bubble, and the volume of the air bubble shrank. As analyzed in the previous chapters, this result is due to the strong collapse shock wave radiated by the cavitation

bubble into the surrounding water in the final phase of collapse. The concave surface of the air bubble on the side near the cavitation bubble in the early phase and on the side away from the cavitation bubble in the later phase served to greatly buffer the principal and collapse shock waves of the cavitation bubble.

To summarize the above analyses, in the series of experiments on the interaction between a cavitation bubble and an air bubble of similar sizes near a wall with the distance from the cavitation bubble center to the wall held constant and the smallest distance from the cavitation bubble center to the air bubble surface varied, at smaller cavitation bubble-air bubble distances, the air bubble experienced larger deformation, a more energetic jet developed to penetrate the air bubble, and the penetrating jet ultimately detached from the parent air bubble. As the distance between the cavitation bubble center and air bubble surface increased, the penetrating jet gradually weakened, or no penetrating jet developed; the air bubble surface was concave on the side near the cavitation bubble in the expansion phase of the cavitation bubble and was concave on the side away from the cavitation bubble in the collapse phase of the cavitation bubble.

In the following, we investigate the effect of the size of an air bubble relative to that of a cavitation bubble on the collapse characteristics of a cavitation bubble near a wall. Figure 3.29 shows high-speed images of air bubble-cavitation bubble-wall interactions obtained from a series of experiments, in which the distance between the cavitation bubble center and the wall and the same size of the cavitation bubble were held constant and the size of the air bubble was varied. In the series of experiments, the maximum radius of the air bubble $R_{\max}$ was varied in the range of 1.950–2.600 mm, the dimensionless distance from the cavitation bubble center to the wall was varied in the range of 2.068–2.792, and the dimensionless radius of the air bubble was varied in the range of 0–0.545. In experiment a, a cavitation bubble was allowed to interact with a wall in the absence of an air bubble. This experimental setting simulated the extreme scenario of a cavitation bubble interacting with an air bubble of a very small radius near a wall. The radius of the air bubble was gradually increased from experiment b and f. In experiment b (in which the dimensionless radius of the air bubble was 0.295), the cavitation bubble after its inception radiated a principal shock wave into the surrounding water. Under the effect of the principal shock wave, the air bubble was compressed and deformed, as shown in image b3. While the air bubble was being further subjected to the effect of the principal shock wave, a jet developed to penetrate the air bubble. As shown in image b4, as the effect of the principal shock wave weakened, the penetrating jet developed further and finally reached the wall, at which time the air bubble exhibited a spherical outer profile, as shown in images b1–b6. After the cavitation bubble entered the later collapse phase, the air bubble was elongated under the effect of the refilling flow. However, owing to the collapse shock wave radiated by the cavitation bubble into the surrounding water, the air bubble exhibited a slenderer overall morphology in this final phase than in the previous phases. As discussed in the previous section, the wall has an adsorbing effect on the jet penetrating the air bubble. Thus, in the later collapse phase of the cavitation bubble, the air bubble was elongated, while the penetrating jet was

Fig. 3.29 Air bubble-cavitation bubble-wall interaction at different air bubble sizes ($-90^\circ < \theta < 90^\circ$; frame rate: 19,700 fps; exposure time: 48 μ s; image size: 13.867 * 7.367 mm; the parametric settings for the experiments are shown in Table 3.3)

being adsorbed on the wall, thereby detaching the penetrating jet from the parent air bubble, as shown in image b9.

In experiment c, the volume of the air bubble was further increased, with its dimensionless radius increased to 0.400. After its inception, the cavitation bubble radiated a shock wave into the surrounding water. The air bubble was compressed and shrank because of the principal shock wave, as shown in image c3. As the principal shock wave weakened, the volume of the air bubble increased. Owing to the small air bubble-wall distance, the air bubble was compressed flat by the principal shock wave. After the cavitation bubble entered the collapse phase, the space freed by the volumetric shrinkage of the cavitation bubble was quickly refilled by the surrounding water. The air bubble was elongated by the effect of the rapid refilling flow while being adsorbed on the wall, resulting in a conical morphology of the air bubble, as shown in images c8 and c9. In experiment d (in which the radius of the air bubble was further increased), owing to the small air bubble-cavitation bubble distance, not only was the air bubble compressed under the effect of the principal shock wave

of the cavitation bubble, but a penetrating jet also developed and reached the wall. As the cavitation bubble expanded further, the penetrating jet developed further. However, the development of the penetration was blocked by the wall, resulting in the frontal part of the penetrating jet spread onto the wall, while the parent air bubble still maintained a spherical morphology. As the cavitation bubble collapsed, the air bubble was elongated, and the penetrating jet was adsorbed to the wall, resulting in the air bubble elongating into a cylindrical structure.

In experiments e and f (in which the radius of the air bubble was further increased), the air bubble was compressed under the effect of the principal shock wave of the cavitation bubble, a penetrating jet developed, and the penetrating jet spread onto the wall after being blocked by the wall. Compared with the previous experiments, the air bubble was elongated in the later collapse phase of the cavitation bubble in experiments e and f but to markedly lower degrees. After the cavitation bubble collapsed, rebound bubbles emerged under the effect of the surrounding high-turbulence water flow, and the development of the rebound bubbles was affected by the continuously deformed air bubble. In experiments a–d, the residual of the collapsed cavitation bubble moved toward the wall, whereas in experiments e and f, the residual moved into the surrounding water. This is mainly due to the following mechanism: With the distance from the center of a cavitation bubble center to a wall held constant (that is, with the effect of the wall on the cavitation bubble held constant), a smaller air bubble has a weaker effect on the cavitation bubble, resulting in the cavitation bubble moving toward the wall. A larger air bubble has a larger buffering effect on a cavitation bubble, resulting in the cavitation bubble moving into the surrounding water. Therefore, with the size of the cavitation bubble and the distance from the cavitation bubble enter to the wall held constant, there exists a critical value of the radius of the air bubble. An air bubble with a radius larger than the critical value not only can buffer the shock wave radiated by the cavitation bubble toward the wall but can also change the direction of collapse of the cavitation bubble, thereby having two effects that protect the wall. An air bubble with a radius smaller than the critical value only has the effect of buffering the shock wave of the cavitation bubble.

In summary, with the size of the cavitation bubble and the cavitation bubble-wall distance held constant, the air bubble was compressed, and a penetrating jet developed and was elongated under the effect of the principal shock wave of the cavitation bubble. When the penetrating jet reached the wall, the wall had a strong adsorbing effect on the penetrating jet. In the later collapse phase of the cavitation bubble, not only did the part of the air bubble adsorbed on the wall buffer the refilling flow between the wall and cavitation bubble but the air bubble also had a strong buffering effect on the collapse shock wave radiated by the cavitation bubble. A larger air bubble not only had a buffering effect on the shock wave radiated by the cavitation bubble but also caused the cavitation bubble to ultimately collapse away from the wall into the surrounding water, thereby preventing the microjet from impacting the wall and protecting the wall (Table 3.3).

Figure 3.30 shows high-speed images of air bubble-cavitation bubble-wall interactions obtained from a series of five experiments, in which the cavitation bubble center-wall distance and the size of the cavitation bubble were held constant and the

Table 3.3 Parametric settings for the experiments on the air bubble-cavitation bubble-wall interaction at the same values of $R_{\max}$ and γ and different values of ε

	$R_{\max}$ (mm)	γ	ε	δ	θ
Experiment a	2.600	2.792	0	—	—
Experiment b	2.383	2.227	0.295	1.252	2.526
Experiment c	2.167	2.225	0.400	1.377	2.420
Experiment d	1.950	2.667	0.500	1.087	4.014
Experiment e	2.275	2.452	0.525	1.214	0.796
Experiment f	2.383	2.068	0.545	0.885	17.571

Fig. 3.30 Air bubble-cavitation bubble-wall interaction at different air bubble sizes ($90^\circ < \theta < 270^\circ$; frame rate: 19,700 fps; exposure time: 48 μ s; image size: **a** 12.133 * 7.367 mm; **b–e** 13.867 * 7.367 mm; air bubble-cavitation bubble-wall spatial relationship is shown in Table 3.4)

size of the air bubble was varied. In experiment a, the cavitation bubble was allowed to interact with the wall in the absence of an air bubble. This experiment setting simulated the extreme scenario of a cavitation bubble interacting with an air bubble with a radius of 0 near a wall. In the experiments, the radius of the cavitation bubble was varied in the range of 1.786–2.004 mm; the radius of the air bubble was varied in the range of 0–1.246 mm; the distance from the cavitation bubble center to the wall was kept constant at approximately 3.5 mm. In experiment a, the dimensionless vertical distance from the cavitation bubble center to the wall γ_{bw} was 1.972. As discussed above, the cavitation bubble collapses toward the wall under this condition. In the experiment, the cavitation bubble did collapse toward the wall, as shown in image a9.

In experiment b, the cavitation bubble interacted with an air bubble with a radius of 0.650 mm on the left side. In the expansion phase of the cavitation bubble, not only did the overall volume of the air bubble shrink under the effect of the principal shock wave of the cavitation bubble, but the air bubble surface was also penetrated, compressed, and forced into a concave shape by the principal shock wave on the side near the cavitation bubble. Under the continuous effect of the principal shock wave, the concave surface gradually developed into a jet to penetrate the surface on the opposite side, as shown in image b4. As the cavitation bubble expanded further, the penetrating jet developed further, and the left part of the jet became slender, as shown in image b5. As the cavitation bubble expanded to the maximum volume and entered the collapse phase, the space freed by the volumetric shrinkage of the cavitation bubble was quickly refilled by the surrounding water, generating an energetic refilling flow. Under the effect of the refilling flow, the frontal section of the penetrating jet gradually detached from the parent air bubble, forming a separate small bubble, as shown in image b6. The part of the air bubble near the cavitation bubble was elongated and deformed by the refilling flow between the cavitation bubble and air bubble, and the air bubble as a whole was elongated and deformed. As the cavitation bubble rapidly collapsed, it radiated a collapse shock wave into the surrounding water. The volume of the elongated air bubble further shrank because of the effect of the collapse shock wave. During this course, the air bubble had an active effect of buffering the collapse shock wave. In the later collapse phase, the cavitation bubble also collapsed toward the wall.

In experiment c, the radius of the air bubble was 0.866 mm, larger than that in experiment b. Compared with experiment b, the air bubble also experienced a shrinkage-expansion-reshrinkage mode of evolution, and a penetrating jet developed. However, the penetrating jet was wider and emerged later in experiment c than in experiment b, as shown in image c7. In the later collapse phase, the cavitation bubble also collapsed toward the wall.

In experiment d, the radius of the air bubble increased to 1.191 mm, larger than those in experiments b and c. Compared with experiments b and c, the air bubble also experienced a shrinkage-expansion-reshrinkage mode of evolution, and a penetrating jet developed. However, the penetrating jet was wider than that in experiments b and c and emerged later than in experiment c. In the later collapse phase, the cavitation bubble also collapsed toward the wall. In experiment e, the radius of the air

Table 3.4 Parametric settings for experiments on air bubble-cavitation bubble-wall interaction at the same value of γ but different values of ε

	$R_{\max}$ (mm)	γ	ε	δ	θ
Experiment a	1.950	1.972	0		
Experiment b	2.058	1.816	0.316	0.819	176.009
Experiment c	1.896	1.742	0.457	1.000	178.877
Experiment d	1.786	1.939	0.667	0.992	170.538
Experiment e	2.004	1.838	0.622	1.066	215.218

bubble was increased to 1.246 mm, larger than that in experiments b–d. Compared with experiments b–d, the air bubble in experiment e also experienced a shrinkage-expansion-reshrinkage mode of evolution, and a penetrating jet developed. However, the penetrating jet was slenderer in experiment e than in experiment d. This is mainly due to the following mechanism: The distance from the cavitation bubble center to the air bubble surface was 2.136 mm in experiment e and 1.771 mm in experiment d. Because the shock wave rapidly attenuates in the direction of radiation, an air bubble farther from a cavitation bubble receives less energy. Thus, the penetrating jet was weaker in experiment e than in experiment d. In addition, the penetrating jet emerged later in experiment e than in experiment d. In the later collapse phase, the cavitation bubble collapsed toward the wall, but the motion of the residual of the collapse toward the wall weakened (Table 3.4).

In the following, we investigate the effect of the cavitation bubble-wall distance on the collapse characteristics of a cavitation bubble near a wall.

Figure 3.31 shows high-speed images of the cavitation bubble-air bubble-wall interaction obtained from a series of experiments, in which the cavitation bubble-wall distance was varied. In the five experiments, the maximum radius of the cavitation bubble $R_{\max}$ was varied in the range of 1.842–2.383 mm, ε was varied in a small range, and the value of γ_{bw} was gradually increased from experiments a to d. In experiment a, a cavitation bubble emerged immediately after the electric discharge between the electrodes. At this moment, the cavitation bubble radiated a principal shock wave into the surrounding water. Because of the small cavitation bubble-wall distance, the wall had a large effect on the cavitation bubble. Meanwhile, the air bubble (which was located between the cavitation bubble and wall) underwent shrinkage deformation under the effect of the principal shock wave of the cavitation bubble, as shown in images a2–a4. At the moment shown in image a4, the cavitation bubble expanded to the maximum volume, and a jet emerged to penetrate the air bubble. While being penetrated by the principal shock wave of the cavitation bubble, the air bubble reached the wall and, under the effect of the cavitation bubble, spread over the wall, as shown in images a5 and a6. For the morphological evolution of the cavitation bubble in experiment a (in which the air bubble was located between the cavitation bubble and wall), when the cavitation bubble radiated a principal shock wave into the surrounding water, the air bubble was compressed, and the volume of water between the wall and cavitation bubble moved toward the wall, and the

air bubble continued to expand in the later collapse phase of the cavitation bubble up to the moment when the cavitation bubble had evolved through the complete expansion-collapse life cycle.

In experiment b, in which the dimensionless cavitation bubble-wall distance was increased to 2.771 (from 2.256 in experiment a), the air bubble also shrank and a penetrating jet developed under the effect of the principal shock wave of the cavitation bubble. When the air bubble was completely penetrated, the penetrating jet quickly reached the wall, as shown in image b3. In the expansion phase of the cavitation bubble, subjected to the blocking effect of the wall after reaching the wall, the penetrating jet immediately spread over the wall and evolved into a conical morphology, as shown in images b4–b6. As the cavitation bubble developed further and entered the collapse phase, as shown in image b5, the main body of the air bubble was elongated continuously by the refilling flow and evolved into a morphology where the width of the main body of the air bubble was smaller than that of the penetrating jet, as shown in images b7 and b8. In experiment c (in which the distance from the cavitation bubble center to the wall was further increased), when the cavitation bubble expanded to the maximum volume, a jet developed to penetrate the air bubble, but the penetrating jet had a much lower intensity than that in experiments a and b. In the collapse phase of the cavitation bubble, the air bubble was elongated by the effect of the refilling flow, and its outer size gradually increased, as shown in images c3–c8. In the final collapse phase, the cavitation bubble radiated a strong shock wave into the surrounding water. Under the effect of the collapse shock wave, the air bubble began to undergo shrinkage deformation. Meanwhile, the penetrating jet reached the wall and, under the adsorbing effect of the wall, was elongated but did not completely detach from the wall. In experiment e (in which the distance from the cavitation bubble center to the wall was increased to 3.773), the cavitation bubble was subjected to a weak effect of the wall, and the interaction between the air bubble, cavitation bubble, and wall was similar to the interaction between an air bubble and cavitation bubble in the absence of a wall. In the experiment, a jet developed to penetrate the air bubble, but the penetrating jet did not reach the wall. The air bubble also experienced a shrinkage-expansion-reshrinkage mode of evolution. However, owing to the large dimensionless distance from the cavitation bubble center to the nearest air bubble surface, the air bubble had a regular profile in the final collapse phase of the cavitation bubble. When the cavitation bubble-wall distance was increased to four times that of the maximum radius of the cavitation bubble $R_{\max}$, the air bubble adhered to the wall and, under the effect of the principal shock wave and collapse shock wave of the cavitation bubble, only experienced shrinkage-expansion-reshrinkage deformation. In addition, the air bubble shrank to the minimum volume in the final collapse phase of the cavitation bubble.

In summary, as the dimensionless distance from the cavitation bubble center to the wall γ_{bw} decreased, the effect of the wall on the expansion-shrinkage life cycle of the cavitation bubble increased. Under the combined effect of the wall and air bubble, the cavitation bubble surface on the air bubble side was blocked by the unbalanced pressure gradient around the wall, and the air bubble gradually exhibited nonspherical expansion. Under the effect of the principal and collapse shock waves

Table 3.5 Parametric settings for experiments of air bubble-cavitation bubble-wall interaction at different values of γ

	$R_{\max}$ (mm)	γ	ε	ω	θ
Experiment a	1.842	2.256	0.676	1.118	0
Experiment b	2.004	2.771	0.622	1.080	8.820
Experiment c	2.383	3.5	0.614	1.318	8.797
Experiment d	2.275	3.773	0.452	1.794	4.865

of the cavitation bubble, the air bubble exhibited a shrinkage-expansion-reshrinkage mode of morphological evolution. In addition, at a small air bubble-cavitation bubble distance, a jet developed to penetrate the air bubble under the effect of the principal shock wave, and the wall had an adsorbing effect on the penetrating jet (Table 3.5).

Figure 3.32 shows high-speed images of the air bubble-cavitation bubble-wall interactions obtained from a series of experiments with different distances between the cavitation bubble center and wall. In experiment d, a cavitation bubble was allowed to interact with an air bubble in the absence of a wall. This parametric setting simulated the air bubble-cavitation bubble-wall interactions at a very large cavitation bubble-wall distance. As the cavitation bubble-wall distance increases, the effect of a wall on the expansion-collapse characteristics and direction of collapse of a cavitation bubble gradually weakens. At $\gamma > 3$, the effect of the wall on the cavitation bubble basically disappears. In the series of experiments, the maximum radius of the cavitation bubble $R_{\max}$ was varied in the range of 1.896–2.438 mm; the distances from the cavitation bubble center to the wall for experiments a–c were

Fig. 3.32 Cavitation bubble-air bubble-wall interaction at different cavitation bubble-wall distances ($90^\circ < \theta < 270^\circ$; frame rate: 19,700 fps; exposure time: 48 us; image size: **a** 13.867 * 7.367 mm; **b** 13.867 * 7.367 mm; **c** 17.333 * 7.367 mm; **d** 17.333 * 7.367 mm; the air bubble-cavitation bubble-wall spatial relationship is shown in Table 3.6)

3.305, 3.521, and 5.418 mm, respectively. Experiment d can be considered to use a cavitation bubble-wall distance of ∞ .

In experiments a and b, the distance between the cavitation bubble center and wall was set at two small values with a small difference between them. During the whole expansion-collapse life cycle of the cavitation bubble and the evolution of the rebound bubbles, the air bubble exhibited a shrinkage-expansion-reshrinkage mode of deformation. The cavitation bubble radiated a principal shock wave into the surrounding water in its expansion phase. Under the effect of the principal shock wave, a jet developed to penetrate the air bubble, and a part of the penetrating jet detached from the air bubble, as shown by the images for experiment a. In addition, the penetrating jet developed to a greater length and width in experiment a than in experiment b. The different penetrating jets were mainly caused by the different cavitation bubble-air bubble distances. However, the air bubble exhibited similar modes of morphological evolution. In the two experiments, after the cavitation bubble entered the collapse phase, the space freed by the volumetric shrinkage of the cavitation bubble was quickly refilled by the surrounding water. Under the effect of the refilling flow, the air bubble with the penetrating jet experienced volumetric shrinkage, while the penetrating jet moved toward the cavitation bubble center, as shown in images a7, a8, b7, and b8. In experiments a and b, because distance between the cavitation bubble center and the wall in experiment a was smaller than that in experiment b, the rebound bubbles emerged in the rebound phase of the cavitation bubble and moved toward the wall more quickly in experiment a than in experiment b, as shown in images a10–a16 and b10–b16.

In experiment c, the air bubble experienced morphological evolution similar to that in experiments a and b. More specifically, the air bubble also underwent a shrinkage-expansion-reshrinkage mode of evolution and was also penetrated by a jet to form separate bubbles. In experiment c, in which the dimensionless distance from the cavitation bubble center to the wall γ_{bw} was 2.500, the cavitation bubble was still in the range of influence of the wall. However, owing to the presence of the air bubble, the evolution of the cavitation bubble was mainly influenced by the air bubble. The residual of the collapsed cavitation bubble showed the potential to move toward the wall in the later collapse phase. However, owing to the very small distance and weak energy of the motion, the residual of the collapsed cavitation bubble did not move toward the wall in the later collapse phase. As shown by the above experiments, as the distance from the cavitation bubble center to the wall was gradually increased, the effect of the wall on the cavitation bubble gradually weakened, and the velocity at which the residual of the collapsed cavitation bubble moved toward the wall gradually decreased (Table 3.6).

Table 3.6 Parametric settings for experiments of air bubble-cavitation bubble-wall interaction at different values of γ

	$R_{\max}$ (mm)	γ	ε	ω	θ
Experiment a	1.896	1.743	0.486	1.000	178.898
Experiment b	2.004	1.757	0.351	1.569	166.159
Experiment c	2.167	2.500	0.375	0.906	197.021
Experiment d	2.438	∞	0.378	0.621	159.146

3.3.3 Combined Direction-Changing Effects of a Wall and an Air Bubble on the Collapse of a Cavitation Bubble

A cavitation bubble interacting with an air bubble and a wall is subjected simultaneously to two effects: (1) the effect of the wall on attracting the collapse of the cavitation bubble and (2) the effect of the air bubble on repelling or attracting the collapse of the cavitation bubble. In this section, we will analyze the interaction between a cavitation bubble, an air bubble, and a wall in two different scenarios of their spatial relationship: (1) the air bubble is located between the cavitation bubble and wall; and (2) the cavitation bubble is located between the air bubble and wall.

Figure 3.33 shows the direction of collapse of a cavitation bubble interacting with an air bubble and a wall obtained from a series of experiments, in which the cavitation bubble was located between the air bubble and wall (image a1 and a2) or the air bubble

Fig. 3.33 Repelling and attracting effects of an air bubble on a cavitation bubble

was located between the cavitation bubble and wall (a3 and a4). As shown by the experimental results presented in the figure, the cavitation bubble moved away from the air bubble due to the repelling effect of the air bubble, while the wall had an attracting effect on the evolving cavitation bubble. Under the combined effect of these two different forces, the cavitation bubble finally collapsed in the direction of the combined vector of the two forces. Images b1 and b2 show the results of the experiment in which the cavitation bubble was located between the air bubble and wall. Images b3 and b4 show the results of the experiment in which the air bubble was located between the cavitation bubble and wall. Similar to experiment a (in which the air bubble exerted a repelling force on the cavitation bubble), in experiment b (in which the air bubble exerted an attracting force on the cavitation bubble and the cavitation bubble collapsed near a rigid wall), the final direction of collapse of the cavitation bubble depended on the direction of the combined vector of the two forces.

As shown by significant experimental observations of cavitation bubble-air bubble-wall interaction in which a cavitation bubble was located between an air bubble and a wall or an air bubble was located between a cavitation bubble and a wall, the final direction of collapse of a cavitation bubble depends on the direction of the combined effect of the repelling or attracting force exerted by the air bubble on the cavitation bubble and the attracting force exerted by the wall exerted on the cavitation bubble. In addition, an air bubble more often has a repelling effect on a cavitation bubble than an attracting effect on a cavitation bubble. Understanding the combined effect of an air bubble and wall on a cavitation bubble has important implications for cavitation erosion protection-purposed aeration of high-velocity water flows (Fig. 3.34).

3.4 Retarding Effect of an Air Bubble on the Collapse Shock Wave of a Cavitation Bubble

In this section, we analyze another effect an air bubble has on a cavitation bubble—the retardation of the collapse shock wave of a cavitation bubble.

3.4.1 *Retarding Effect of an Air Bubble on the Collapse Shock Wave of a Cavitation Bubble*

Before analyzing an air bubble's effect of retarding the collapse shock wave of a cavitation bubble, we investigated the effect of a free surface on the collapse shock wave of a cavitation bubble through a series of experiments (Fig. 3.35).

In experiment a (Fig. 3.35), in which the dimensionless distance from the cavitation bubble to the free surface $\varphi_s = 0.95$, the cavitation bubble completed the first round of oscillations at $0 \text{ ms} < t < 2.056 \text{ ms}$. During the first round of oscillations,

Fig. 3.34 Combined effect of an air bubble and wall on the collapse of a cavitation bubble

Fig. 3.35 Reflection of a cavitation bubble's shock wave by a free surface

because of the small cavitation bubble-wall distance, the cavitation bubble expanded to occupy part of the free surface's space, causing the free surface to become convex. At this moment, the cavitation bubble no longer had the original regular spherical morphology, as shown in image a1 (Fig. 3.35). When the cavitation bubble shrank to the minimum volume, the free surface remained convex, as shown in image a2 (Fig. 3.35). During the course of collapse, the cavitation bubble radiated a shock wave into the surrounding water. At such a small free surface-cavitation bubble distance, the cavitation bubble's collapse shock wave exhibited a clear multilevel structure, as shown in image a3 (Fig. 3.35). As this dispersed multilevel shock wave propagated outward, it was reflected by the free surface, generating a reflecting wave that propagated into the water, as shown in image a5 (Fig. 3.35). The reflecting wave passed through the cavitation bubble and caused secondary cavitation around the cavitation bubble, as shown in image a6 (Fig. 3.35). In experiment b (Fig. 3.35), the dimensionless distance from the cavitation bubble to the free surface φ_s increased to 1.70. Compared with that of experiment a (Fig. 3.35), the shock wave radiated by the collapse of the cavitation bubble in experiment b also exhibited a clear multilevel structure, as shown in image b2 (Fig. 3.35). However, the degree of dispersion of the shock wave was smaller in experiment b than in experiment a (Fig. 3.35), as shown by a comparison of images a3 and b3 (Fig. 3.35). The dispersed shock wave propagated to the free surface to generate a reflecting wave, which also had a multilevel structure. In experiment c (Fig. 3.35), the dimensionless distance from the cavitation bubble to the free surface φ_s further increased to 2.78. The collapse shock wave of the cavitation bubble in experiment c did not have a multilevel structure and did not have a multilevel structure after being reflected by the free surface.

In the following, we investigate the effect of the air bubble-cavitation bubble distance on a cavitation bubble's collapse shock wave.

Figure 3.36 shows high-speed images of the collapse shock wave of a cavitation bubble obtained from a series of experiments, in which a cavitation bubble was allowed to interact with an air bubble at different air bubble-cavitation bubble dimensionless distances ω in a free field. In experiment a (Fig. 3.36a), a cavitation bubble was allowed to evolve in a free field without an air bubble, thereby enabling a comparison of the shock wave morphological evolution of a cavitation bubble interacting with an air bubble and that of a cavitation bubble not interacting with an air bubble. In Fig. 3.36b–g (for experiments b–g), the black mass shown in the left part of the images is an air bubble.

In experiment a, the cavitation bubble had a maximum radius $R_{\max}$ of 9.83 mm when expanded to the maximum volume and shrank to the minimum volume at $t = 2.344$ ms. Because the cavitation bubble evolved in a free field, the cavitation bubble did not show a clear direction of collapse during the course of shrinkage, as shown in image a4 (Fig. 3.36). During the course of collapse, the cavitation bubble radiated into the surrounding water a strong shock wave, which rapidly propagated outward. Because the cavitation bubble evolved in a free field (that is, in the absence of any external interferences), the collapse shock wave exhibited a regular spherical spatial morphology.

Fig. 3.36 Effect of the air bubble-cavitation bubble distance on the collapse shock wave of a cavitation bubble

In experiment b (Fig. 3.36b), the air bubble-cavitation bubble distance increased to a relatively large value of 1.59. The cavitation bubble completed the first collapse at approximately 2.305 ms and radiated a shock wave at collapse. As shown by the high-speed images, the collapse shock wave had a regular morphology similar to that of the shock wave produced by the collapse of the cavitation bubble in the free field without an air bubble. In experiment b (Fig. 3.36b), when the cavitation bubble's shock wave propagated to the air bubble, a dark-colored wave radiated from the air bubble surface in the reverse direction, as shown in image b6 (Fig. 3.36). After passing through the air bubble, the cavitation bubble's collapse shock wave was lighter in color on the left side of the air bubble than in other areas.

In experiments c–e (Fig. 3.36c–e), the air bubble-cavitation bubble distances were gradually reduced to 1.43, 1.33, and 1.06, respectively. In all three experiments, the cavitation bubble radiated a shock wave into the surrounding water during the course of collapse. Because of the small air bubble-cavitation bubble distances, the shock waves produced by the collapse of the cavitation bubble in these three experiments had different morphologies than that in experiment a (Fig. 3.36). First, the shock wave radiated by the cavitation bubble exhibited a very clear multilevel structure in experiments c–e. As the dispersed waves propagated outward, the interwave distance increased with decreasing dimensionless cavitation bubble-air bubble distance ω , as shown in Fig. 3.36c–e. Second, when the shock waves propagated to the air bubble surface, a clear wave was reflected from the air bubble surface and propagated in the reverse direction, as shown in Fig. 3.36c, d. Finally, when the collapse shock wave of the cavitation bubble passed through the air bubble and continued to propagate, the shock wave considerably deformed in the area shielded by the air bubble, as shown in image c6 (Fig. 3.36), and the degree of deformation gradually decreased with decreasing cavitation bubble-air bubble dimensionless distance (Fig. 3.36d) and finally became unidentifiable (Fig. 3.36e).

In experiment f (Fig. 3.36), in which the cavitation bubble-air bubble distance was further decreased, the cavitation bubble absorbed the air bubble during its course of development, forming a gas-containing cavitation bubble, as shown in image f2 (Fig. 3.36). When the cavitation bubble shrank to the minimum volume, it completely merged with the air bubble, as shown in image f4 (Fig. 3.36). In addition, compared with the results of other experiments (Fig. 3.36), the cavitation bubble shrank to a markedly larger minimum volume in experiment f. Another important phenomenon observed in experiment f was that the cavitation bubble did not radiate a clear shock wave into the surrounding water during its course of collapse.

In the following, we investigate the effect of the air bubble-to-cavitation bubble size ratio on the collapse shock wave of the cavitation bubble.

Figure 3.37 shows high-speed images of the collapse shock wave of a cavitation bubble obtained from a series of experiments in which cavitation bubbles were allowed to interact with air bubbles of different dimensionless sizes ε in a free field. In the experiments, the radius of the air bubble R_a was varied in the range of 1.30–2.71 mm, and the air bubble-cavitation bubble dimensionless distance was kept constant at approximately 1.30. The black mass shown in the left part of images a1–e1 (Fig. 3.37) is an air bubble.

In experiment a (Fig. 3.37a), in which the air bubble had a very small volume, the air bubble did not have a considerable effect on the morphology of the cavitation bubble throughout its expansion-shrinkage life cycle, as shown in images a2 and a3 (Fig. 3.37). During the course of the cavitation bubble's evolution, the air bubble was compressed, elongated, and split. During the course of collapse, the cavitation bubble radiated a shock wave into the surrounding water that had a spherical morphology similar to that in experiment a. However, compared that in with experiment a, a markedly different phenomenon was observed in experiment b: The shock wave produced by the collapse of the cavitation bubble propagated to the back side of the air bubble and experienced considerable deformation there, as shown in

Fig. 3.37 Effect of the air bubble size on the collapse shock wave of a cavitation bubble

image b6 (Fig. 3.37). In both experiments a and b (Fig. 3.37), the evolution of the cavitation bubble was influenced by the air bubble, but the shock wave produced by the cavitation bubble did not have a clear multilevel structure.

In experiment c (Fig. 3.37), the relative size of the air bubble ε was further increased to 0.21. Similar to experiments a and b, the cavitation bubble did not experience considerable deformation throughout its expansion-shrinkage life cycle and did not show considerable movement toward the air bubble in the collapse phase. However, the cavitation bubble in experiment c produced a markedly different collapse shock wave than those in experiments a and b. In experiment c (Fig. 3.37), the shock wave radiated by the cavitation bubble during the course of collapse exhibited a degree of dispersion, as shown in image c4 (Fig. 3.37), and experienced deformation in the spatial morphology in the area shielded by the air bubble, as shown in image c5 (Fig. 3.37).

Finally, in experiment d (Fig. 3.37), the radius of the air bubble R_a was increased to approximately 2.72 mm. Throughout its expansion-shrinkage life cycle, the cavitation bubble did not experience deformation under the effect of the air bubble, as shown in images d2 and d3 (Fig. 3.37). In experiment d, the shock wave radiated by the collapse of the cavitation bubble exhibited a considerable degree of dispersion; in addition, the shock wave was reflected by the air bubble surface to generate a wave that propagated in the reverse direction toward the cavitation bubble center.

3.4.2 Impact Intensity of the Collapse Shock Wave of a Cavitation Bubble Interacting with an Air Bubble Near a Wall

First, we investigate the effect of the air bubble-cavitation bubble distance on the collapse shock wave of a cavitation bubble interacting with an air bubble near a wall.

Figure 3.38 shows high-speed images of the collapse shock waves of cavitation bubbles obtained from a series of experiments, in which a cavitation bubble was allowed to interact with an air bubble at different air bubble-cavitation bubble distances ω near a wall. In experiment a (Fig. 3.38a), a cavitation bubble was allowed to evolve near a wall without interacting with an air bubble, thereby enabling a

Fig. 3.38 Shock wave of a cavitation bubble interacting with an air bubble at different air bubble-cavitation bubble distances near a wall

comparison of the shock wave of a cavitation bubble interacting with an air bubble near a wall and that of a cavitation bubble evolving near a wall without interacting with an air bubble. In Fig. 3.38b–f, the black mass shown in the middle part of the images is an air bubble (after the inception of a cavitation bubble, the black mass shown in the left part of the images is a cavitation bubble); the boundary on the right side of the images is a rigid wall.

In experiment a (Fig. 3.38), in which the cavitation bubble-wall dimensionless distance γ_{bw} was 2.850, the wall did not interfere with the evolution of the cavitation bubble, and the cavitation bubble did not show any signs of moving toward the wall during the first collapse. The collapse of the cavitation bubble radiated a shock wave with a regular spherical morphology into the surrounding water. The shock wave rapidly propagated outward and reached the wall, exerting a large transient impact on the wall.

In experiment b (Fig. 3.38), in which there was an air bubble between the cavitation bubble and wall and the air bubble-cavitation bubble distance was small, the cavitation bubble was connected with the air bubble in the expansion phase of the cavitation bubble, forming a gas-containing cavitation bubble, as shown in image b4 (Fig. 3.38). The gas-containing cavitation bubble shrank to a minimum volume that was markedly larger than that in experiment a (Fig. 3.38). In addition, the gas-containing cavitation bubble did not radiate a shock wave into the surrounding water, as shown in images b4–b6 (Fig. 3.38).

From experiments c–e (Fig. 3.38), the air bubble-cavitation bubble distance gradually increased. In experiment c (Fig. 3.38), when the cavitation bubble shrank to the minimum volume, the air bubble-cavitation bubble distance became very small, the air bubble experienced considerable deformation, and the part of the bubble near the cavitation bubble center exhibited a conical morphology, as shown in image c3 (Fig. 3.38). At this moment, the cavitation bubble and air bubble were not merged. As the cavitation bubble further evolved, it radiated a shock wave into the surrounding water that exhibited a very clear multilevel structure, as shown in image c5 (Fig. 3.38). The multilevel shock wave propagated outward and ultimately reached the wall. The cavitation bubble exhibited evolution in experiment d (Fig. 3.38) similar to that in experiment c (Fig. 3.38) and radiated a shock wave of a multilevel structure during the course of collapse. In experiment e (Fig. 3.38), the cavitation bubble exhibited morphological evolution basically similar to that in experiment d (Fig. 3.38) and radiated a shock wave with a multilevel structure. What was different among experiments c–e was that as the air bubble-cavitation bubble distance ω increased, the degree of dispersion of the shock wave varied. In experiment c (Fig. 3.38), the shock wave dispersed into three levels, as shown in image c5 (Fig. 3.38); in experiment d, the shock wave dispersed into two levels, as shown in image d5 (Fig. 3.38), and the distance between the two levels was large; in experiment e, the shock wave was dispersed into two levels, but the distance between the two levels was very small, as shown in image e5 (Fig. 3.38).

In experiment f (Fig. 3.38), the air bubble-cavitation bubble distance was large. When the cavitation bubble shrank to the minimum volume, it radiated a shock wave that did not exhibit considerable deformation in the area between the air bubble

and wall and maintained a regular spherical morphology, similar to experiment a (Fig. 3.38).

As shown by the collapse shock waves of cavitation bubbles interacting with air bubbles at different air bubble-cavitation bubble distances, an air bubble has an effect on the dispersion of the collapse shock wave of a cavitation bubble. However, the high-speed images in Fig. 3.38 only show that the shock wave is dispersed but do not show the intensity of the dispersed shock wave. In the experiments, the pressure caused by the shock wave on the wall was measured using a pressure gage buried inside the wall. Figure 3.39 shows the measurements of the shock wave-induced pressure on the wall obtained from the experiments shown in Fig. 3.38.

Fig. 3.39 Impact of a cavitation bubble collapse shock wave on a wall at different air bubble-cavitation bubble distances

In experiment a (Fig. 3.39), the temporal variations in the impact of the regular spherical shock wave on the wall in the collapse phase of the cavitation bubble exhibited a single-peak pattern, with the peak pressure at 2.930 MPa. In experiment b (Fig. 3.39), the cavitation bubble evolved into a gas-containing cavitation bubble, as shown by the high-speed images above, and shrank to a relatively large minimum volume. In addition, the cavitation bubble did not radiate a shock wave in the collapse phase, as shown by the high-speed images above. However, the measurements of the impact of the cavitation bubble on the wall in the collapse phase of the cavitation bubble showed two small peaks, which were close to each other and measured 0.366 and 0.372 MPa.

In experiment c (Fig. 3.39), the measurements of the impact of the cavitation bubble's collapse shock wave on the wall exhibited three small peaks, which measured 0.309, 0.390, and 0.0119 MPa. These three peaks matched the high-speed images. In experiment d (Fig. 3.39), the cavitation bubble's collapse shock wave was dispersed into two levels, as clearly shown by the high-speed images. The two levels of the wave reached the wall and exerted impact pressures of 0.589 and 0.548 MPa on the wall. In experiment e (Fig. 3.39), in which the air bubble-cavitation bubble distance was large, the cavitation bubble's collapse shock wave exhibited a two-level structure. However, the distance between the two levels was small, and the measurements of their impact on the wall exhibited only one major peak (1.54 MPa). The presence of a second peak following this major peak could be confirmed from the high-speed images. However, owing to the limited frame rate of the high-speed images, the exact value of the second peak was difficult to identify. Because the distance between the two peaks was very small, we were able to estimate that the intensity of impact of the second wave on the wall was approximately 0.257 MPa. In addition, for the duration of the impact of a dispersed shock wave on the wall, the presence of an air bubble led to a slight increase in the duration of impact, as shown in Fig. 3.39b–d.

In experiment f (Fig. 3.39), the high-speed images showed that the shock wave radiated by the cavitation bubble in the collapse phase was similar to that in experiment a (Fig. 3.38). The shock wave did not have a clear stratified structure. The shock wave reached the wall and exerted a peak pressure of approximately 1.58 MPa on the wall. Although the cavitation bubble's collapse shock wave did not have a clear stratified structure in experiment f (Fig. 3.38), the peak impact of the shock wave on the wall was markedly lower than that (2.930 MPa) in experiment a, in which a cavitation bubble evolved near a wall without interacting with an air bubble. As shown in image f6 (Fig. 3.38), the cavitation bubble's collapse shock wave had an integrated nonstratified structure in the area between the air bubble and wall but had a lighter color in the area shielded by the air bubble. This result indicates that at a large air bubble-cavitation bubble distance, an air bubble does not have a considerable effect on the dispersion of the collapse shock wave of a cavitation bubble but does have an effect on the buffering of the impact of the shock wave, thereby resulting in a smaller impact from the shock wave on the wall compared with the impact of the shock wave of a cavitation bubble evolving at the same cavitation bubble-wall distance in the absence of an air bubble.

In the following, we analyze the effect of the air bubble-cavitation bubble size ratio on the collapse shock wave of a cavitation bubble interacting with an air bubble near a wall.

Figure 3.40 shows the evolution of the collapse shock wave of a cavitation bubble interacting with an air bubble near a wall obtained from a series of experiments, in which the air bubble-cavitation bubble size ratio was gradually increased.

In experiment a (Fig. 3.40), the equivalent radius of the air bubble r was very small relative to the maximum radius of the cavitation bubble $R_{\max}$. Throughout the expansion-shrinkage life cycle, the cavitation bubble did not experience considerable deformation. When at the minimum volume, the cavitation bubble radiated a shock wave into the surrounding water. As shown in image a3 (Fig. 3.40), the shock wave consisted of two levels with a very small interlevel distance. As the shock wave propagated outward, the interlevel distance remained very small. The shock wave finally passed through the air bubble and impacted the wall. In experiment b (Fig. 3.40),

Fig. 3.40 Morphology of the shock wave of a cavitation bubble interacting with an air bubble of different relative sizes near a wall

the shock wave radiated into the surrounding water by the cavitation bubble in the collapse phase was multilevel, as shown in image b4 (Fig. 3.40). In addition, the cavitation bubble's collapse shock wave impacted the air bubble surface and was reflected there, generating a rebound wave, as shown in image b5 (Fig. 3.40). Furthermore, the collapse shock wave exhibited a slightly flat shape in the area behind the air bubble, different than the case in experiment a (Fig. 3.40). In experiment c (Fig. 3.40), in which the relative size of the air bubble ε was increased to 0.233, the cavitation bubble radiated a multilevel shock wave into the surrounding water. However, there were no clear high-speed images of the shock wave, in contrast with experiments a and b (Fig. 3.40). In addition, the shock wave behind the air bubble could hardly be identified in the high-speed images. In experiment d (Fig. 3.40), in which the relative size of the air bubble was increased to 0.269, the cavitation bubble also radiated a multilevel shock wave during the course of collapse. However, the brightness of the shock wave in the high-speed images decreased further. Similarly, the cavitation bubble's collapse shock wave could hardly be identified in the area between the air bubble and wall, as shown in image d5 (Fig. 3.40). In addition, in experiments c and d (Fig. 3.40), when the cavitation bubble radiated a shock wave, the air bubble experienced morphological changes to different degrees, with the cavitation bubble side of the air bubble being compressed to different degrees as the shock wave developed, as shown in images c3–c6 and d3–d6 (Fig. 3.40).

Figure 3.41 shows the measurements of the impact of the cavitation bubble's collapse shock wave on the wall obtained from the experiments shown in Fig. 3.40. In experiment a (Fig. 3.40), the shock wave had a two-level structure, as shown in image a4 (Fig. 3.40). However, the two-level structure became less identifiable as the shock wave propagated toward the wall. The measurements of the impact pressure exerted by the shock wave on the wall (Fig. 3.41a) exhibited only a single peak, which measured 2.480 MPa. In experiment b (Fig. 3.40), the cavitation bubble's collapse shock wave had a two-level structure, as could easily be identified in image b5 (Fig. 3.40). The cavitation bubble's collapse shock wave propagated to the air bubble and was reflected there, generating a rebound wave. The rebound wave and the collapse shock wave of the cavitation bubble propagated toward the wall together and ultimately impacted the wall, exerting two peak pressures of 1.420 and 0.308 MPa, respectively. In experiment c (Fig. 3.40), the measurements of the impact exerted by the cavitation bubble collapse on the wall clearly exhibited two peaks, which measured 0.737 and 0.656 MPa and matched the two-level structure, as shown in image c5 (Fig. 3.40). In experiment d (Fig. 3.40), the multilevel shock wave exerted a peak pressure of 0.702 MPa on the wall. As the relative size of the air bubble increased gradually from experiment a to d (Fig. 3.41), the peak impact pressure of the cavitation bubble's shock wave on the wall exhibited a clear decreasing trend, and the duration of the shock wave's impact on the wall gradually increased.

Figure 3.42 shows the relationship between the relative intensity of the shock wave, $P_{\max}/P'_{\max}$ (where $P_{\max}$ is the peak impact pressure on a wall exerted by the collapse shock wave of a cavitation bubble interacting with an air bubble and $P'_{\max}$ is the peak impact pressure on a wall exerted by the collapse shock wave of a cavitation bubble evolving in the absence of an air bubble), and $\theta_{\omega}/\varepsilon\gamma_{bw}$. The figure shows

Fig. 3.41 Impacts on a wall exerted by the collapse shock waves of cavitation bubbles interacting with air bubbles of different sizes

Fig. 3.42 Effect of dimensionless parameter $\theta_\omega/\varepsilon_\gamma$ on the intensity of the impact of a cavitation bubble's collapse shock wave

the combined effect of the air bubble size ε , cavitation bubble-wall distance γ_{bw} , air bubble-cavitation bubble distance ω , and angle θ on the relative intensity of the cavitation bubble's collapse shock wave at a given point on the wall. For a cavitation bubble interacting with an air bubble near a wall, the impact exerted by the collapse of the cavitation bubble on the wall is the smallest when the cavitation bubble has merged with the air bubble. At a small cavitation bubble-air bubble distance, the air bubble serves to effectively reduce the impact exerted by the collapse of the cavitation bubble on the wall mainly through the dispersion of the cavitation bubble's collapse shock wave. At a large cavitation bubble-air bubble distance, the air bubble can retard the direct impact of the cavitation bubble's shock wave on the wall to a certain degree, thereby reducing the intensity of the impact to a certain degree.

3.5 Forced Aeration for Cavitation Erosion Protection of High-Head Dams

For the open-channel discharge structures of high-head dams, the water flow needs to be aerated to protect the channel surface from cavitation erosion. For the air entrained in a high-velocity water flow through surface self-aeration to diffuse across the entire cross-section, appropriate conditions need to be provided, and the channel needs to be long enough to allow streamwise diffusion to occur. Therefore, to ensure the effectiveness of cavitation erosion protection, forced-aeration structures are necessary (Wood 1991; Pfister and Hager 2010). The design of forced-aeration structures is an important task in the cavitation erosion protection of high-head dams.

3.5.1 Mesoscale Mechanism of Forced Aeration

Forced-aeration structures for high-head dams are typically configured at the bottom of flow channels (Fig. 3.43). Such a structure usually consists of a flip bucket, an aerator, air vent holes on the sidewalls of the aerator, and an air supply duct connecting the air vent holes and the environmental air (or the nonwater flow space in the upper part of the channel). When passing through a flip bucket and aerator, a high-velocity water flow separates, resulting in local pressures lower than the atmospheric pressure. Thereby, the air is automatically sucked into the aerator through the air supply ducts, forming an aeration cavity. The air in the aeration cavity is entrained into the water flow, thereby aerating the water flow.

Figure 3.44 shows the mesoscale mechanism of forced aeration. As shown in the figure, when the water comes into contact again with the wall boundary at the wall-attachment point, the intense flow-wall interaction generates a water-air mixed zone. Further observations show that bulky volumes of aerated water gradually emerge

Fig. 3.43 Illustration of aeration through an aerator at the bottom of a water channel

downstream of the wall-attachment point of the water flow. These water-air mixed volumes gradually diffuse into the flow while moving downstream.

As air is entrained into the water at the wall-attachment point, the water flow surface in the aeration cavity becomes unstable and deforms, thereby entraining air into the flow. However, the quantity of air bubbles entrained at the water flow surface is much lower than that at the wall-attachment point. Therefore, forced aeration functions mainly through the air entrainment at the wall-attachment point, with the free-surface aeration in the aeration cavity playing only a minor role.

As shown in Fig. 3.45a, the cross-sectional distribution of the air concentration in the high-velocity water flow at the front of the flip bucket is consistent with that of self-aeration. In the aeration cavity, because the bottom surface of the water flow is also a free surface, the air concentration in that zone is the result of self-aeration at two free surfaces. At the wall-attachment point at the end of the aeration cavity, the bottom part of the water flow cross-section has a high air concentration. As the water flow moves further downstream, the air entrained in the aeration cavity gradually diffuses upward, and the peak air concentration at the bottom gradually decreases.

The mesoscale mechanism of forced aeration can be better understood through the spatial distribution of the air bubble frequency (Fig. 3.45b). In the aeration cavity, the air bubble frequency distribution in the vertical direction exhibits a two-peak characteristic. At the wall-attachment point and in the wall-attachment zone behind it, the air bubble frequency contributed by the bottom aerator significantly increases to a level even higher than that contributed by the self-aeration at the upper surface of the water flow. As the water flow moves further downstream of the wall-attachment zone, the air bubbles contributed by the bottom aerator gradually float upward and diffuses.

Fig. 3.44 Illustration of aeration using an aerator at the bottom of a flow channel

Fig. 3.45 Streamwise evolution of air entrained with a bottom aerator

From the perspective of the air bubble size, experimental observations show that the air bubbles in the vicinity of the wall-attachment point are larger, with a mean diameter d_{mean} above 20 mm (Fig. 3.46). This is mainly because the water flow at the wall-attachment has a high turbulence, resulting in the relatively large air bubble sizes at the wall-attachment point. As the water flow moves further downstream, the air bubble size gradually decreases, indicating that the originally large air bubbles entrained in the water gradually split to form small air bubbles as the large air bubbles move with, float up, and diffuse into the water flow. The air bubbles near the bottom wall maintain stable sizes in the range of 1–2 mm for a long streamwise distance. Figure 3.47 clearly shows the streamwise evolution in the air bubble mean diameter and frequency.

Fig. 3.46 Streamwise evolution of the size of air bubbles entrained through a bottom aerator

Fig. 3.47 Streamwise evolution in the mesoscale characteristics of air bubbles entrained through a bottom aerator

3.5.2 Design Principles of Forced-Aeration for Cavitation Erosion Protection Structures of High-Head Dams

Traditionally, to ensure effective cavitation erosion protection, the forced-aeration structures of high-head dams generally must be designed to be capable of achieving a sufficiently high air concentration. However, as analyzed in the previous sections, the mechanism of aeration-based cavitation erosion protection lies in the ability of the air bubbles to attenuate the collapse intensity, change the direction of collapse, and retard the collapse shock wave of cavitation bubbles. Therefore, for cavitation erosion protection-purposed aeration, the quantity of air bubbles is more important than the air concentration. For a given air concentration, a large quantity of small air bubbles is more effective in cavitation erosion protection than a small quantity of large air bubbles.

For high-head dams, because the high flow velocity makes it difficult for large air bubbles to exist stably in the water, the air bubbles have very small sizes. Under this condition, only if air can be continuously entrained into the water can aeration be effective for protection from cavitation erosion at a very low air concentration.

Therefore, forced-aeration structures for cavitation erosion protection of high-head dams should be designed based on a principle ensuring that aeration channels are unimpeded without being blocked by backwater, aeration cavities maintain their integrity, and the water flow regime is regular.

The above principles can be demonstrated by the engineering practices mentioned in Sect. 3.1 of this chapter.

Traditional aeration structures were built at the bottom of the spillway of a project, but the spillway suffered severe cavitation erosion in a section approximately 400 m long (Fig. 3.48). Repeated investigations of the root cause of the erosion put the focus on the sidewalls at the end of the concave-curve section—a dead corner that cannot be protected by the two aerators nor free-surface aeration. To solve this problem, an

Fig. 3.48 Cavitation erosion of a spillway

Fig. 3.49 Aeration structures built at the bottom and sidewalls of a spillway

aeration structure was built on the sidewalls at the position of the bottom flip bucket, as shown in Fig. 3.49.

However, model tests showed that the flip bucket on the sidewall could be built with only a maximum height of approximately 20 cm. Otherwise, the water flow would jump up due to the lateral contraction, thereby impacting the tunnel roof. Because a small flip bucket can only achieve a low air concentration, then the following question arises: Can such a low air concentration effectively prevent cavitation erosion?

The results demonstrated an affirmative answer. The first solution adopted after the cavitation erosion was repair according to the original design. However, erosion occurred again after 300 h of operation. Since the aeration structures were added to the sidewalls, cavitation erosion has been completely prevented.

3.6 Conclusions

The following conclusions can be drawn based on the analyses in this chapter:

1. The mechanism of aeration-enabled cavitation erosion protection lies in the ability of air bubbles to attenuate the collapse intensity, change the direction of collapse, and retard the collapse shock wave of cavitation bubbles.
2. A forced-aeration structure works mainly by entraining air bubbles into the water at the wall-attachment point of the water flow, with the air entrained through free-surface aeration in the aeration cavity playing only a minor role.
3. Forced-aeration structures for cavitation erosion protection of high-head dams should be designed based on a principle ensuring that aeration channels are unimpeded without being blocked by backwater, aeration cavities maintain their integrity, and the water flow regime is regular. Whenever these conditions are satisfied, the so-called “minimum air concentration” is not necessary for cavitation erosion protection.

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