Destruction of the gas-filled capsule using effects of the collapsing bubble near the capsule

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A new technique to destroy the gas-filled capsule is proposed, making use of the collapsing bubble near the capsule in the ultrasound field. At the moment of collapses under the ultrasound irradiation, the bubble causes flow and acoustic wave radiation. These phenomena are expected to assist the destruction of the capsule. We observed the effect of the bubble on this destruction, using a high-speed video camera which enables the real-time imaging. In this experiment, we use gas-filled capsule made of polyvinyl chloride. When no bubble was near the capsule at sound pressure of 60 kPa, the capsule showed no vibration. However, in the presence of neighboring bubble, the capsule showed the destruction behavior of the deformation and the emission of internal gas. At higher sound pressure such as over 100 kPa, the capsule showed above destruction behavior even if the bubble was not located near the capsule. In the presence of the bubble, however, the capsule was destructed in a shorter time. These experimental results give significant knowledge to a technique manipulating the gas-filled capsule destruction in the drug delivery system.

1 Introduction

A capsule is composed of an internal material covered with a shell. It has the function that can protect internal material from external material, because a shell separates inside and outside of a capsule. In addition, an internal material can be released by destroying a capsule. Currently, a capsule is used as a carrier of an internal material by making the best use of this function in a lot of fields such as medical and industry, etc.

There are various methods to destroy a capsule. We focus on the method to destroy gas-filled capsule in liquid using ultrasound, which has the advantage of remotely-destruction and real-time monitoring of capsule destruction[1]. This method, therefore, is expected to be applied in ultrasound drug delivery system(USDDS) where the capsule is used to be carrier of drugs[2-4]. In medical applications of bubble technique, especially USDDS, shell should prevent internal gas from dissolving in surrounded liquids for a long period. For this reason, the capsule with thick shell was preferably used. However, there is the problem that the capsule with thick shell cannot be destroyed in lower sound pressure. It is necessary to irradiate a strong ultrasound to destroy such a capsule having a thick shell. Considering the safety to the human body, however, it is preferable to destroy the capsule in a lower sound pressure.

To destroy the capsule in a lower sound pressure, we propose a new technique to destroy the gas-filled capsule, making use of the collapsing phenomenon of bubble induced by the ultrasound. A bubble driven by ultrasound shows behaviors such as vibration and collapse, and causes flow and acoustic wave radiation[5-8]. These phenomena are expected to assist the destruction of the capsule, if the collapsing bubble was neighboring the capsule. In this study, in order to reveal the effect of the collapsing bubble on the capsule, we optically observed the capsule and the bubble behavior in the ultrasound field, using high-speed video camera. In addition, we statistically observed the characteristics of the capsule destruction rate by the sound pressure in case of bubble existence or nonexistence.

2 Observation system

An imaging system for observing the capsule and the bubble behaviors is illustrated in Fig.1[9]. This system consists of a high-speed video camera (Shimadzu HPV-1), a long-distance microscope (Quesar QM100), a bubble observation cell, an optical lens, and a xenon lamp (Ushio SX-U1500XQ). We observed the capsule behavior using a shadow graph method.

Figure 2 shows the arrangement of a bubble and a capsule in an observation cell. The ultrasound ware generated by a bolted Langevin transducer (Fuji Ceramics FBL28452HS) with a diameter of 45 mm, which was fixed to bottom of a cylindrical acrylic cell. Both the diameter and height of the cell were 60 mm. The cylindrical cell had two flat quartz windows with a width of 10 mm, which was set parallel to each other for optical observation. The cell was filled with degassed water at room temperature to a depth of 42 mm. The ultrasound was generated by the transducer to form a standing wave field in the cell. A capsule and a bubble were fixed on the transparent tape at the antinode of the standing wave. Here, the initial distance between the center of the bubble and that of the capsule was 200 to 400 μm. The mean radius of the capsule and the bubble was 70 to 100 μm. The behaviors of a capsule and a bubble were observed from top-view. The electrical signal into the transducer was a 10 cycle sinusoidal wave whose center frequency was 28 kHz. Figure 3 shows an example of the irradiated ultrasound waveform, which was measured at observation area. The maximum amplitude of sound pressure P_{max} was 20 to 120 kPa. The observation period with a high-speed video camera is 20 to 420 μs after ultrasonic wave received. Here, 0 μs represents input timing of the electric signal to the transducer. Since the recording rate of high-speed video camera is 250,000 frames/s, we can obtain 9 images during a cycle of ultrasonic wave. In this experiment, we use gas-filled capsule with PVC (polyvinyl chloride) shell (Matsumotoyushi, microsphere F-80ED). The shell thicknesses are approximately 2% of the radius. The Young's modulus and the Poisson's ratio of the shell material are unknown.

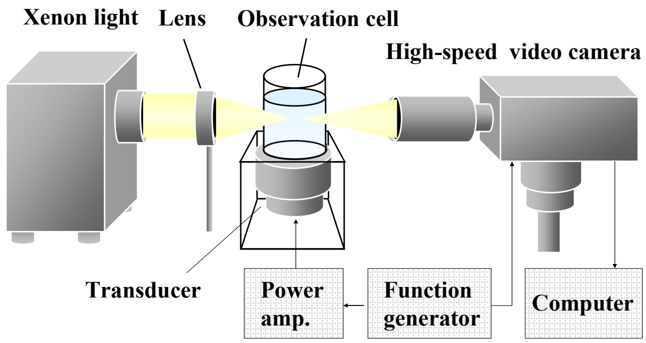

Fig.1 An Imaging system for observing capsule behaviors.

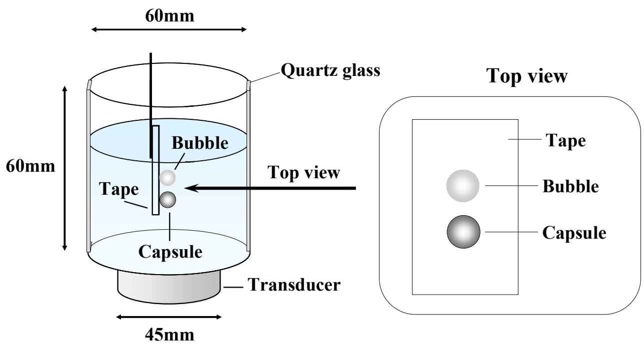

Fig.2 Arrangements of a capsule and a bubble in observation cell.

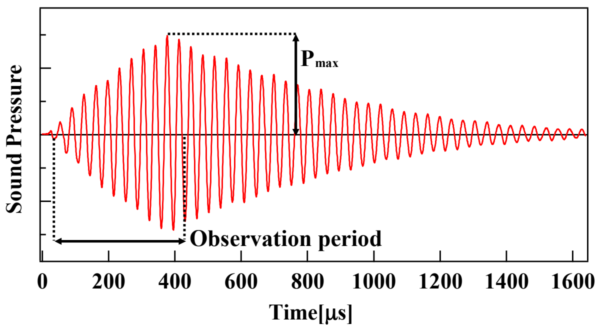

Fig.3 Irradiated ultrasound.

3 Effect of a bubble

We observed three behaviors of a capsule in the following order to clarify the effect of a collapsing bubble.

1st trial; Behavior of a single capsule in the ultrasound field was observed. The initial radius of the observed capsule was 89.5 μm.

2nd trial; We fixed a bubble near the same capsule as 1st trial. The initial radius of the bubble was 88 μm. The initial distance between the center of the bubble and that of the capsule is 278 μm. We observed behavior of the capsule near the bubble in the ultrasound field.

3rd trial; After the bubble removed, we observed behavior of the same capsule in the ultrasound field again.

In above three trial, P_{max} was 60 kPa. Each behavior of the capsule is described below.

3.1 Behaviors in the 1st trial

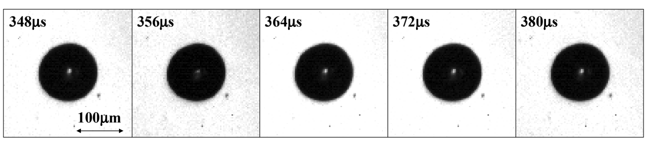

Fig.4 Behavior of a capsule in 1st trial.

In the 1st trial, the capsule showed no significant behaviors though it was driven by ultrasound. Figure 4 shows the behavior of the capsule which observed approximately P_{max}. We can see that the capsule is not deformed and do not vibrates. Previous research revealed that a portion of a capsule shell vibrated locally in the initial stage of a capsule collapse induced by ultrasound[10]. Therefore, we can clearly confirm that the capsule cannot be destroyed only by the irradiated ultrasound of P_{max} = 60kPa.

3.2 Behaviors in the 2nd trial

In the 2nd trial where the bubble was neighboring the capsule, the capsule showed significant behaviors such as deformation and emission of the internal gas. Figure 5 shows the behavior of the capsule and the neighboring bubble under the ultrasound irradiation. The capsule was hardly vibrated immediately after the ultrasound irradiation, whereas the bubble, by contrast, was vibrated clearly [Fig.5(b)-(c)]. When the sound pressure increases, the capsule shell was deformed [Fig.5(d)]. Then, we confirm internal gas emission from the capsule [Fig.5(e)]. Amount of the emitted gas increases as time passes [Fig.5(e)-(f)]. After this observation, the bubble rose up to the surface of the water by the buoyancy.

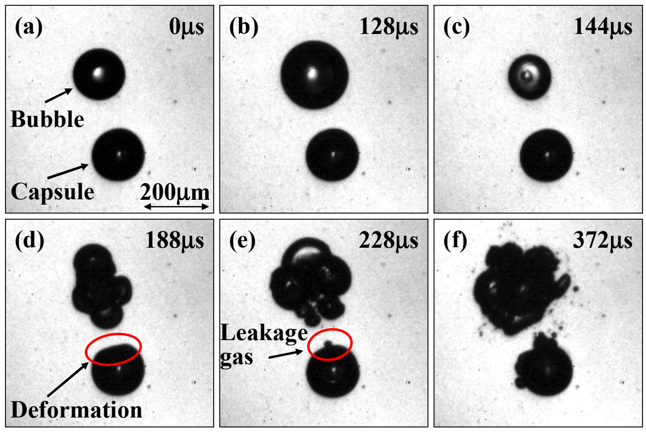

Fig.5 Behavior of a capsule in 2nd trial.

3.3 Behaviors in the 3rd trial

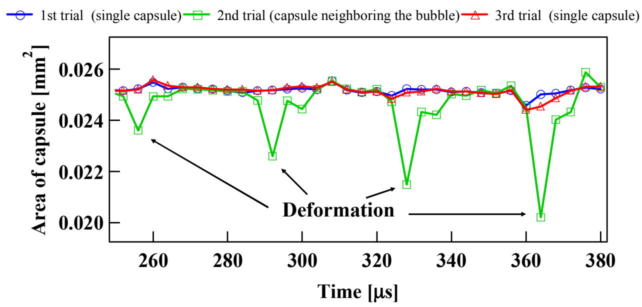

Fig.6 Area change of the capsule.

After the bubble rose up due to the buoyancy, we observed the behavior of the same capsule again, under the ultrasound irradiation. As a result, we confirm that the capsule hardly vibrated as well as 1st trial.

To clarify the effect of the collapsing bubble, we compare the vibration of the capsule in three trials. Figure 6 shows the vibration of the capsule. Here, the vibration of the capsule was evaluated at the shadow area of the capsule (S_c) in observed images. We can find the vibration of S_c in 2nd trial where the capsule is neighbouring bubble. Since Sc decreases in case of deformation as shown in Fig.5, we can understand that this vibration of S_c shows the periodic deformation of the capsule. We consider that the periodic deformation probably decreased the elastic force of the capsule shell. In 2nd trial, additionally, we suppose that the fatigue breakdown of the capsule shell happens because the internal gas of the capsule is emitted. Figure 6, however, shows clearly that the capsule was hardly deformed in the 3rd trial. This result clearly indicates that the collapsing bubble assists the deformation and internal gas emission, which is followed by the destruction of the capsule.

4 Destruction behavior of capsule

In the section 3, we observed the deformation and the internal gas emission of the capsule during the 2nd trial. Based on many observed results, we confirmed that these two behaviors are typical phenomena which occur in case of capsule collapse. In this section, we demonstrate these two behaviors in detail.

4.1 Deformation of capsule

Immediately after the ultrasound irradiation, the bubble started to vibrate whereas the capsule hardly vibrated. As the bubble vibrated more violently due to the increment of sound pressure, a portion of capsule shell started to vibrate locally. Figure 7 shows the typical behaviors of the local vibration. We can clearly find that the portion of a capsule near the bubble contracts locally when bubble behavior changes from contraction to expansion. After this local contraction, the capsule shape returned sphere. We consider that this local vibration of capsule is induced by an acoustic wave radiation and a flow caused by the vibrating bubble, whereas the detailed mechanism is necessary to examined.

Above capsule vibration was occurred synchronizing with the bubble vibration. Figure 8 shows the temporal changes of the capsule and bubble area, respectively. The capsule was deformed every cycle immediately after the bubble changed the behavior from contraction to expansion. Additionally, area of the capsule when deformed becomes smaller as time passes. This is probably considered that the effect from the bubble was increased due to the larger amplitude vibration of the bubble.

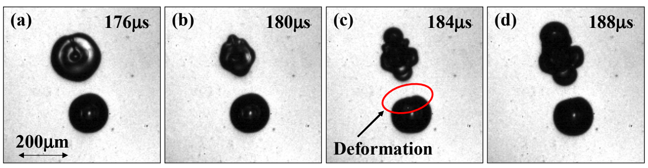

Fig.7 Asymmetric vibration of capsule.

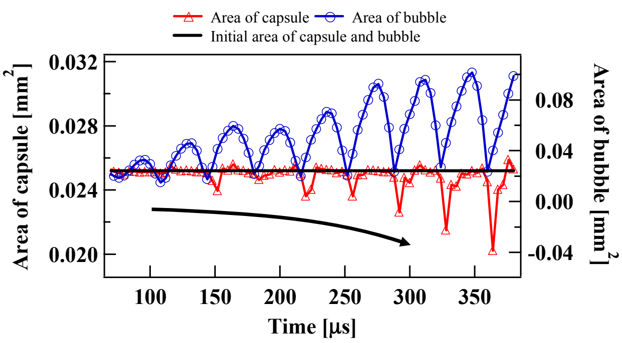

Fig.8 Area change of the bubble and capsule

4.2 Outflow of internal gas

After the repetition of local vibration of capsule, we confirm the emission of the internal gas. Figure 9 shows the typical behaviors of the gas emission from the capsule. When the capsule has changed the shape from non-sphere to sphere, internal gas was always emitted from the portion of the deformation. The elastic fatigue was accumulated to the capsule by repeating the local deformation. Therefore, it seems that the internal gas was emitted from micro-crack which is formed on the shell due to the fatigue by vibration. The emitted gas seems to be flowed into the capsule. Because, it cannot be observed in the Fig.9(d).

Once the emission of the gas occurred, this behavior certainly occurred every cycle. The amount of the emitted gas was increased every cycle[show picture (e) and (f) in Fig.5]. This is because the capsule was affected by the increasing vibration amplitude of the collapsing bubble. Additionally, the accumulate fatigue extended the micro-crack on the shell.

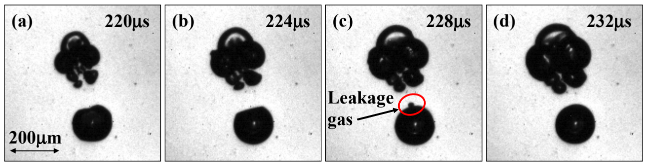

Fig.9 Internal gas emission from the capsule.

4.3 Destruction rate and time

In above sections, the experimental results indicate that the capsule can be destroyed more effectively using the collapsing bubble in addition to the ultrasound irradiation. Therefore, we statically examine the destruction rate of the capsule by the ultrasound irradiation in two conditions. One is the case of the single capsule, and the other is the case of capsule neighboring the bubble. Here, the emission of the internal gas was defined as a destruction of the capsule. P_{max} was changed from 20 to 120 kPa. The mean radius of the capsule and the bubble is 70 to 100 μm. The initial distance between the center of the bubble and that of the capsule is 200 to 400 μm.

Figure 10 shows the destruction rates of the capsule in each sound pressure. Here, the number of sample in each condition is 20 samples. In the range of P_{max} = 60-80 kPa, the capsule cannot be destroyed only by the ultrasound irradiation. On the other hand, in the case of bubble existence, we can destroy the capsule by the ultrasound irradiation. This result shows that the collapsing bubble assists the destruction of the capsule. Over P_{max} = 100 kPa, the capsule can be destroyed if the bubble was not located neighboring the capsule. Even in this case, we can confirm the assist of the collapsing bubble. The effect appeared in the time until destruction of the capsule. Figure 11 shows the time until destruction of the capsule, in the range of P_{max} = 100-120 kPa. We can destroy drastically less time in the case of bubble existence. In this observation, it is clearly indicated that the collapsing bubble assists the destruction of the capsule even in higher sound pressure.

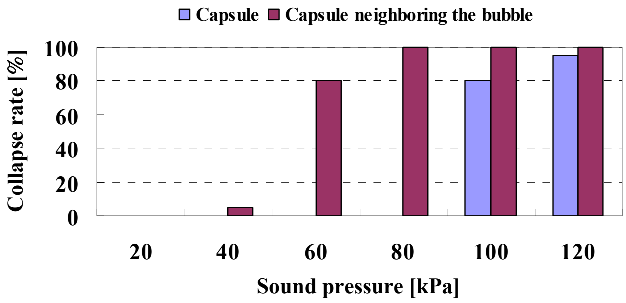

Fig.10 Destruction rate of capsule.

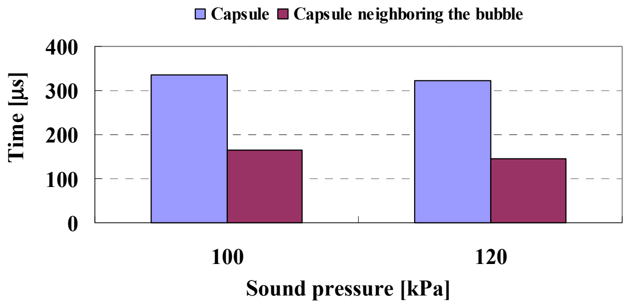

Fig.11 Time until destruction of capsule.

5 Conclusion

To examine the effect of the collapsing bubble on the capsule, we optically observed the real-time behaviors of the capsule and the bubble. As a result, we reveal that the collapsing bubble destroy the neighboring capsule. The capsule was repeating deformation affected by the bubble. The deformation part of the capsule was only the near part of the bubble. Moreover, internal gas was emitted from the same part of the capsule.

Then, we statistically examine the sound pressure to destroy the capsule. At the sound pressure from 60 to 80 kPa, the capsule cannot be destroyed only by ultrasound irradiation. However, the capsule can be destroyed in the presence of the bubble. At higher sound pressure such as over 100 kPa, collapsing bubble reduced the time required for the capsule to be destroyed. These observation results indicates that we can destroy the capsule more effectively using collapsing bubble in addition to the ultrasound irradiation.

Acknowledgments

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