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Application Note

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Life Science

Oscillation Analysis of Water Vapor Bubbles Using High-Speed Video Camera —High-Speed Imaging of Sub-MHz-Order Oscillations—

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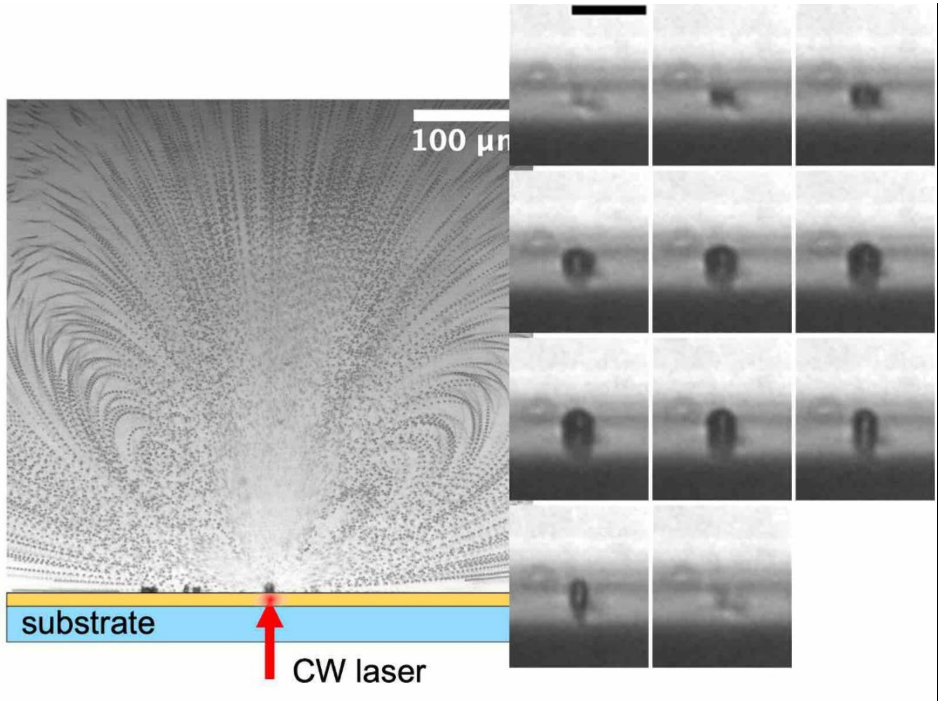

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■ Abstract

Local heating of degassed water generates microbubbles, mainly made of water vapor, and creates strong flows around the bubbles. A High-Speed Video Camera Hyper Vision™ HPV™-X2 was used to record water vapor bubbles oscillating at about 0.5 MHz. This provided valuable insights for investigating the relationship between bubble oscillation and flow generation.

1. Introduction

Devices that handle small amounts of fluid are called microfluidic devices and are widely used in various fields. By reducing the amount of fluid handled, for example, in biochemical analysis, it is possible to quickly perform an analysis with a small sample volume. However, the effect of fluid viscosity is significant at the micrometer scale, so it is still not easy to mix fluids in a narrow channel efficiently.

In recent reports, examples of microfluidic operation using photothermal heating and microbubbles have been reported[1)-3)]. When a laser is focused on a thin film of gold nanoparticles or $FeSi_2$, the light is absorbed and converted into heat. Therefore, the laser spot on the thin film can be used as a local heat source. This heat generates a microbubble in the water, which is then subjected to a temperature gradient. This creates a surface tension gradient on the surface of the bubble, which generates a Marangoni convection current around it. If the water has not been degassed, the resulting bubble is mainly composed of air, with convection occurring only in the vicinity of the bubble. On the other hand, if the water has been degassed, the bubbles generated are primarily composed of water vapor[4)-6)]. And it is found that the convection currents induced around a water vapor bubble are an order of magnitude faster than those generated around an air bubble. The velocity reaches the order of 1 m/s in the very vicinity of the bubble. This phenomenon is expected to be useful as a new microfluidic driving and mixing technique. However, the mechanism by which the convection occurs has not yet been fully elucidated.

One of the sources of convection around water vapor bubbles is the Marangoni force. This is the shear force generated by the surface tension gradient resulting from the temperature gradient. However, assuming that the Marangoni force alone causes convection, a temperature difference of more than 60 K in the diameter direction of the bubble is required. Since the diameter of the water vapor bubble is about 10 µm, it is difficult to maintain a large temperature difference there. Another possible cause of convection is bubble oscillation. It has been reported that bubbles oscillate in the sub-MHz range based on the capture of scattered light from bubbles. To evaluate the strength of convection due to bubble oscillations, it is necessary to know the size and shape of the bubble over time. However, the oscillation frequency of the water vapor bubbles is faster than the speed of a typical camera, making it difficult to capture their movement. In this article, we report on the successful observation of the oscillation of these water vapor bubbles using the HPV-X2, which can capture images at up to 10 Mfps.

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2. Generation of Water Vapor Bubbles and Detection of Bubble Oscillation Using Light Scattering [4), 6)]

First, water vapor bubbles were created by locally heating the degassed water, and convection was confirmed to occur around the bubbles. A gold nanoparticle thin film was deposited on a glass substrate as a photothermal conversion thin film. This thin film was immersed in vacuum ultrasonic degassed water, and a CW laser with a wavelength of 785 nm was focused on the film.

Fig. 1 shows a typical microscopic image of a bubble and convection observed around a laser spot on a photothermal conversion thin film. It was observed from the horizontal direction of the thin film surface. The small black sphere visible above the laser spot, or local heating point, is the generated water vapor bubble, and the dots in the fluid are the polystyrene spheres added to visualize the convection. To visualize the trajectory of the spheres, 100 images taken in 1 second are superimposed and displayed. When the bubble was formed, the degassed water was accelerated in a direction perpendicular to the substrate surface, creating a strong rotational flow.

Next, the resulting bubble was observed under a little more magnification. Using a standard high-speed camera to observe the bubble, the frame rate was set to 100 kfps and the exposure time to about 7 µs. The results are shown in Fig. 2. About 50 µs, after starting the laser irradiation and creating the bubble, the apparent size of the bubble was about 10 µm[6)]. Laser irradiation for more than a minute did not change the apparent size of the bubble. Although the bubble appeared stable, no matter how many attempts were made to focus the light microscope on the bubble, the contour of the bubble did not come into focus, as shown in Fig. 2. This was thought to be because the bubble was oscillating at a period shorter than the camera's exposure time.

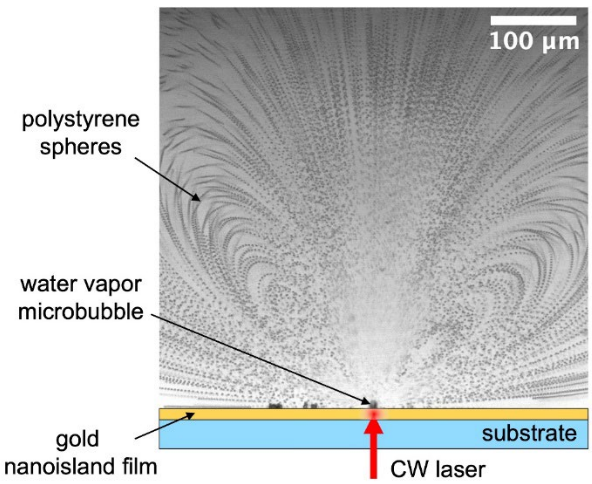

Fig. 1 Generation of Water Vapor Bubbles Using Photothermal Conversion and Surrounding Convection

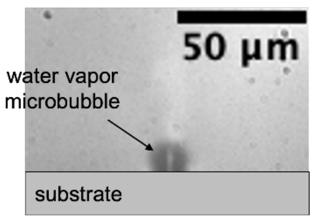

Fig. 2 Microscopic Image of a Water Vapor Bubble (Exposure time: 7 µs)

So first, the light scattered by bubbles was detected to capture the bubbles' oscillations. Fig. 3 (a) shows a schematic of the measurement. A substrate on which a photothermal conversion thin film ($FeSi_2$ thin film, 50 nm) was deposited and degassed water was sealed in a glass cell. Then, a CW laser was focused on the thin film to produce water vapor bubbles. About 10 % of the laser light irradiated to produce the bubbles is transmitted through the thin film and irradiated onto the bubbles. This light is scattered by the bubble, but its direction varies depending on the size and shape of the bubble. Therefore, a photomultiplier tube (R928 manufactured by Hamamatsu Photonics) was installed horizontally on the surface of the substrate through an objective lens. With this photomultiplier tube, the temporal change in the intensity of scattered light entering the objective lens was measured.

The time variation of the detected light intensity is shown in Fig. 3 (b). The X-axis represents time, and the Y-axis represents light intensity. The light intensity clearly changes periodically, with a frequency of 0.26 MHz. If the bubble oscillates at this frequency, this means that the bubble oscillates about twice during the 7 µs exposure time of the camera. In other words, it's reasonable to assume that the bubble oscillations cannot be captured by typical high-speed cameras. Further experiments with different laser intensities and spot sizes revealed that the water vapor bubbles oscillated at frequencies ranging from 0.1 to 0.7 MHz. It was also found that the bubble's oscillation frequency depends on its apparent diameter, and the larger the diameter, the lower the oscillation frequency of the bubble.

In this way, by capturing the scattered light from the bubbles, it was revealed that the bubbles were oscillating and there was a relationship between their apparent size and the oscillation frequency. However, it is not clear how the bubbles oscillate. It is possible that the size of the bubbles does not change periodically but that their shape and position, or all those features, may change at the same time. A frame rate of about 10 times the oscillation frequency is required to capture such sub-MHz order bubble oscillations with a camera. As a result, the HPV-X2, a high-speed video camera capable of recording up to 10 Mfps, caught our attention.

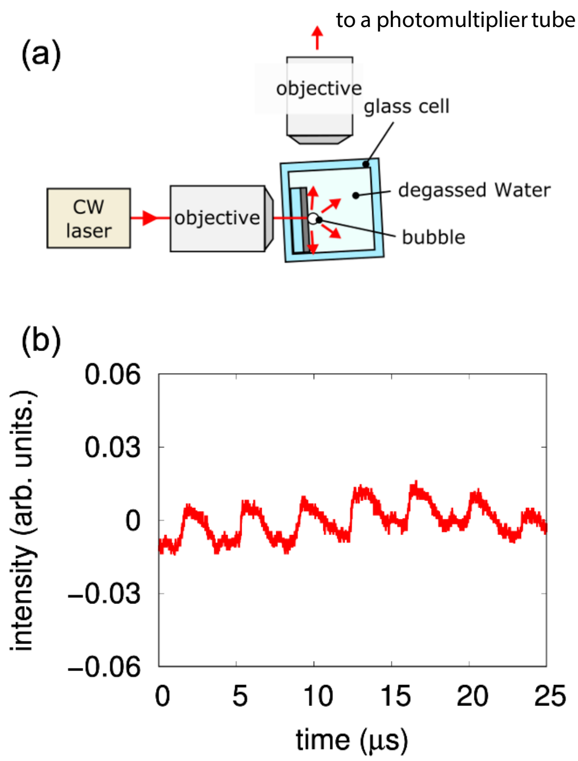

Fig. 3 (a) Schematic Diagram of an Optical System for Capturing Scattered Light from a Water Vapor Bubble
(b) Time Variation of Detected Light Intensity

3. High-Speed Imaging of Water Vapor Bubbles with the HPV-X2

To capture the oscillations of water vapor bubbles produced in degassed water, experiments were conducted to observe the bubbles using an HPV-X2. A schematic of the experimental setup is shown in Fig. 4. First, a glass substrate on which a photothermal conversion thin film ($FeSi_2$ thin film, 50 nm) was deposited, and degassed water was sealed in a glass cell. This was set on a microscope, and a CW laser (Wavelength: 830 nm, Thorlabs FPL830S) was focused on the photothermal conversion thin film from behind the glass substrate. The laser focusing on the thin film was checked using camera 1 (Baumer HXC20) from the direction perpendicular to the film surface. The generated bubbles were observed horizontally from the substrate surface using camera 2 (HPV-X2). The frame rate was set to 5 Mfps. To avoid heating the sample with the illumination light, a pulsed laser (Cavitar, CAVILUX Smart system) with a wavelength of 640 nm and a pulse width of 20 ns was used as illumination light. By connecting an HPV-X2 and a pulsed laser to synchronize the recording and emission timing, bright images could be obtained easily. Furthermore, by utilizing the camera's live mode, the observation position could be adjusted while viewing the sample with the camera, just as when using a standard camera.

High-speed imaging of the bubble was performed a few seconds after the start of laser radiation for bubble generation. Therefore, the observed bubbles were presumed to be in a quasi-steady state.

Fig. 5 shows an image of a water vapor bubble taken with an HPV-X2. The image was taken from the horizontal direction on the substrate surface. A mirror image of the bubble reflected on the substrate surface can be seen below the image of the bubble. Capturing the oscillations of bubbles was achieved by recording at 5 Mfps. The period of bubble oscillation obtained using the HPV-X2 was about 2 μs, which agreed well with the oscillation frequency of the bubble measured using light scattering. Therefore, it is believed that a single cycle of bubble oscillation was captured at a sufficient sampling rate. In addition, this observation showed that the bubbles have a shape that extends laterally to the substrate when they grow (time = 0.0 – 1.0 μs) and a shape that extends perpendicular to the substrate surface when they contract (time = 1.2 – 1.8 μs). It was also found that the size of the bubble varies significantly during the oscillation period, and there are moments when it decreases enough to be invisible to the camera (time = 2.0 μs). These results help to elucidate the oscillation contribution to the formation of convection around bubbles.

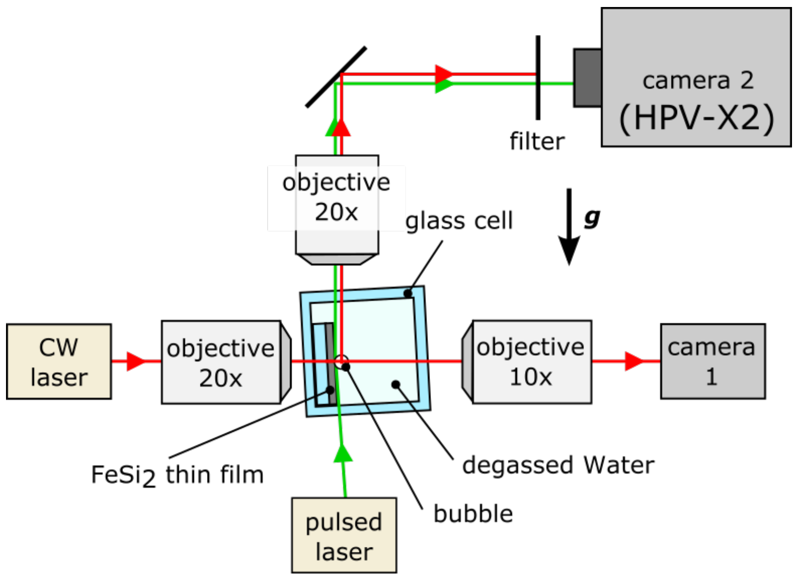

Fig. 4 Schematic Diagram of an Optical System for High-Speed Imaging of the Oscillations of Water Vapor Bubbles

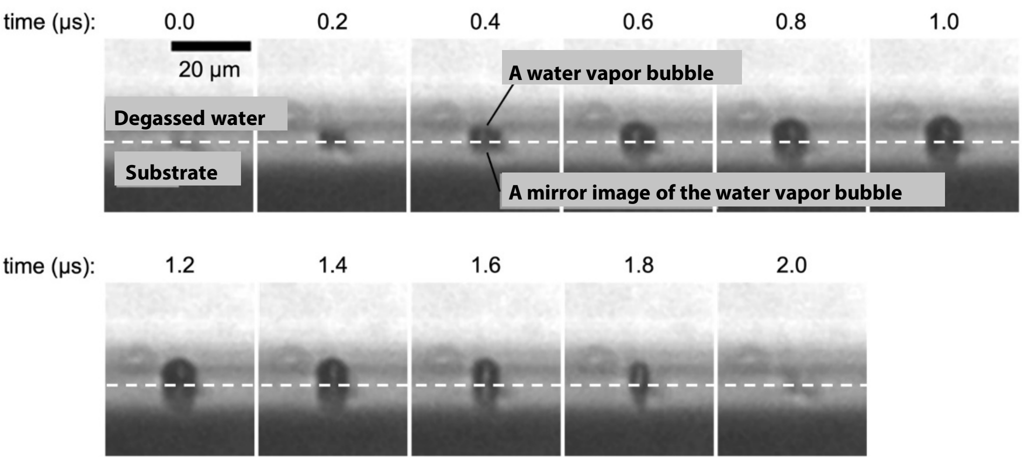

Fig. 5 High-Speed Imaging of the Water Vapor Bubble Oscillation

4. Conclusion

This article described the observation of water vapor bubble oscillations using an HPV-X2 High-Speed Video Camera. The results showed how the size and shape of the water vapor bubbles change during a single cycle of oscillation. This brings us closer to understanding the principle of convection around water vapor bubbles. Further use of the HPV-X2 in the future will enable the elucidation of phenomena that were previously difficult to evaluate, such as how bubbles move when multiple bubbles are generated at the same time and whether there are any interactions between bubble movements. Furthermore, it is expected that this method will be widely used not only for bubble oscillations but also to elucidate flow phenomena at the micro- and nanometer-scale, thereby establishing a new field of research.

Photography cooperation: Department of Micro Engineering, Graduate School of Engineering, Kyoto University

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