Journal of Visualization, Vol. 12, No. 3 (2009) 267-274

Regular Paper

Enhancement of Mixing by Microbubble Emission Boiling in a Microfluidic Device

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Received 10 October 2008
Revised 19 January 2009

Abstract : The effect of microbubble emission boiling (MEB) on the mixing of two fluids in a microfluidic device was studied experimentally. When MEB occurred on an electric heater made of a platinum wire with a diameter of 30 micrometers, the mixing of the two fluids increased markedly. However, nucleate boiling had no significant effect on the mixing. A high-speed video showed that the very rapid growth and collapse of micro boiling bubbles on the heater causes the strong mixing of the two fluids. The coexistence of highly superheated and highly subcooled water near the heater seems to be the reason for such enhanced mixing.

Keywords : Microfluidic device, μ-TAS, Microbubble emission boiling, Mixing, Enhance

1. Introduction

The enhancement of mixing is one of the key technologies of microfluidic devices (MFDs), allowing the faster chemical reactions and biological inspections. The flow rate inside a MFD is low and the Reynolds number is on the order of 1; thus, we cannot expect turbulent mixing, which is very effective in normal-size mixing. We thus require devices or methods for enhancing the mixing of two fluids.

There are two types of mixing-enhancement devices, namely, active and passive devices. Many passive devices have a flow channel with a special configuration, such as the split-and-recombine (SAR) structure, to enhance mixing (Hamanaka and Kato (2005), Tan et al. (2005), Chaktranond et al. (2008)). Stook et al. (2003) invented a device that induced a chaotic flow in a microchannel. Many active mixing enhancement devices have been proposed, such as a minute stirrer driven by a magnetic force, magnetic vibration devices that vibrate channel walls, and devices applying electrokinetic instability (Jin, et al. (2008)).

In this paper we present a new mixing-enhancement method using boiling bubbles on a minute electric heater. This method is very effective particularly when microbubble emission boiling (MEB) occurs. Boiling bubbles are often used as a micropump to drive fluids in microfluidic devices (Koizumi et al. (2004)).

Boiling is a major heat transfer phenomenon accompanied by a phase change. It is well known that the pattern of boiling changes from nucleate to transition then film boiling as the heater wall temperature increases. The state change from nucleate boiling to film boiling is known as "burnout", because the wall temperature increases markedly during this phase change. The burnout heat flux is on the order of 1 MW/m² in the case of the pool boiling of water.

When the fluid temperature is less than its saturated temperature, it is in a subcool condition. Recently, it was found that the boiling behaviour markedly changes in highly subcooled water (boiling in low-temperature water). Such behaviour is called microbubble emission boiling. In this case burnout does not occur even when there is a much higher heat flux than the burnout heat flux. The strong ejection of microbubbles occurs from the heater wall (Shoji et al. (2005)).

In the present paper we report the behaviour of microbubbles, which cause the strong micromixing of fluids, observed by a high-speed video.

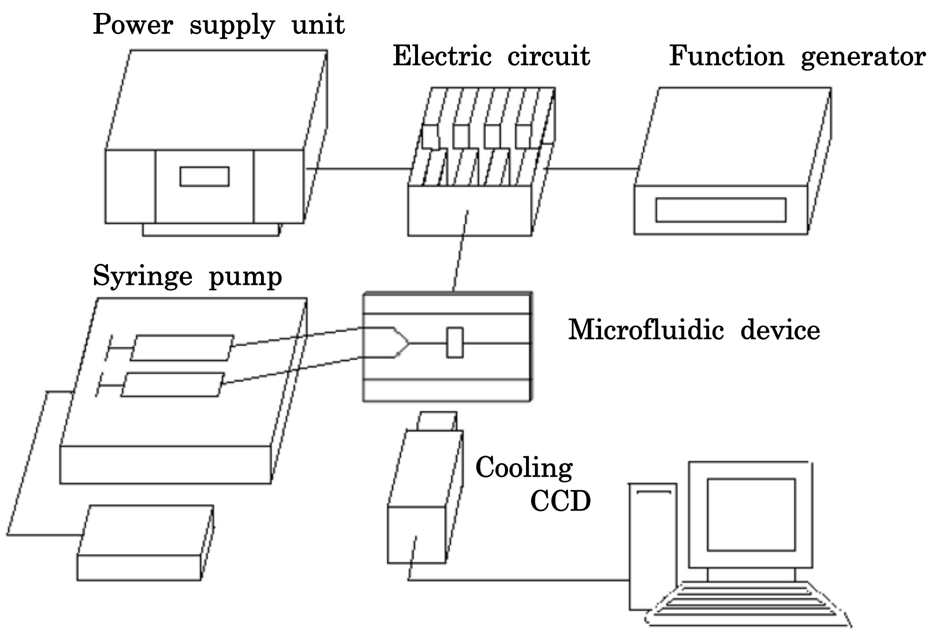


Fig. 1. Experimental apparatus

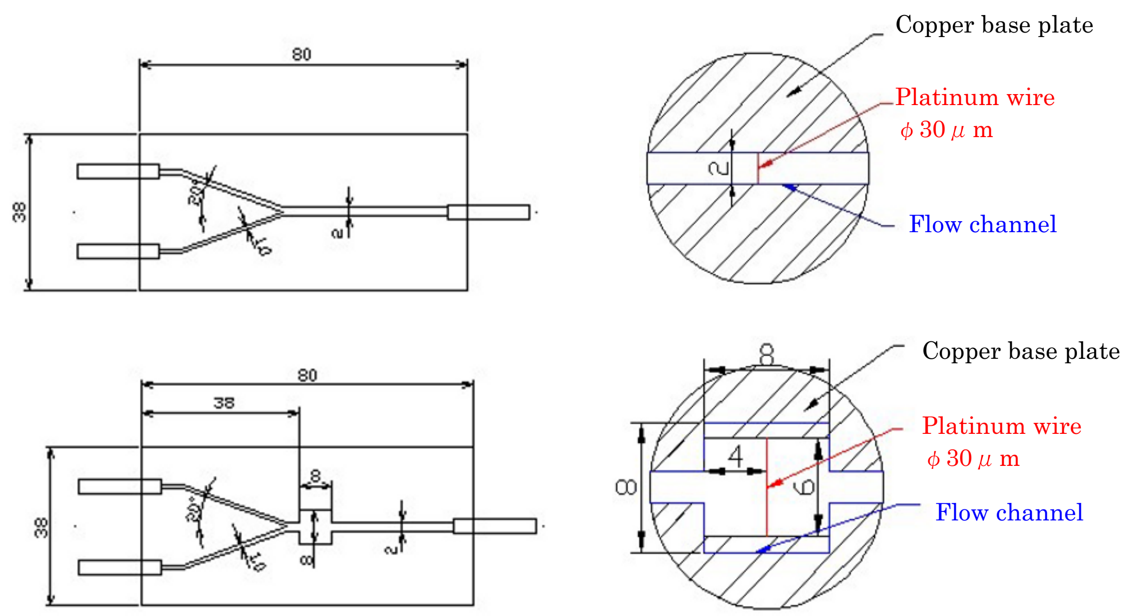


Fig. 2. Microfluidic devices

Above: MFD-A (standard type). Below: MFD-B (with mixing chamber)

2. Experimental

2.1 Experimental Apparatus

Figures 1 and 2 show the experimental apparatus and the microfluidic devices, respectively. MFD-A is a standard device with a Y-shaped structure. The inlet is 1 mm wide and 0.5 mm deep, and the outlet (after confluence) is 2 mm wide and 0.5 mm deep; thus, the mean flow velocity is not changed by the confluence. The MFD was placed vertically as seen in Fig. 1.

Water of two different colors was used for the flow visualization. One weight percent of watercolor paint (black and white; maker: Pentel Co.) was mixed with distilled water. The specific weight of black and white colored waters was 1.006 and 1.009, respectively.

Black and white waters enter the device from two inlet pipes on the left. The flows merge at the confluence point, where an electric heater made of a platinum wire is installed at the flow channel wall. The diameter and length of the wire are 30 μm and 2 mm, respectively (Fig. 2). Two syringes (Hamilton, gas tight syringe, capacity: 2.5 cm^3) driven by a microsyringe pump (Eicom Co. ESP-64, flow rate: 0.0001-99.99 microliters/min) eject two flows of different colored water at a constant flow rate (Fig. 1).

MFD-B has the same dimensions as MFD-A, except that there is a mixing chamber downstream of the confluence point. The size of the chamber is 8 mm x 8 mm and 0.5 mm deep; thus, the average velocity at the heater is one-quarter of that in MFD-A when the flow rate is the same. The length of the heater is 6 mm (Fig. 2). The DC electric current controlled by the power supply unit heated the platinum wire.

At the first stage of experiment, we expected that an intermittent heating might agitate mixing of two fluids, so that we changed the electric current periodically using the function generator. However, such the intermittent heating was not effective at all on the mixing enhancement. Therefore, we discuss only on the result of constant heating in the present paper.

The test conditions of the MFD-A (standard) device are as follows. The electric current supplied to the heater was 0.7, 0.8, 0.9, or 1.0 A, which corresponds to heat fluxes of 1.03, 1.35, 1.65, or 2.04 MW/m^2, respectively. The mean flow velocity was 0.5, 1.0, 1.5, 2.0, 2.5, or 3.0 mm/s.

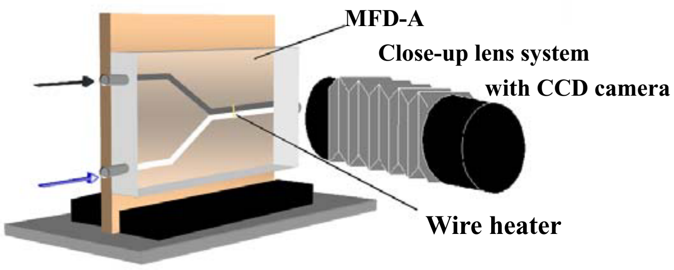


Fig. 3. Observation setup

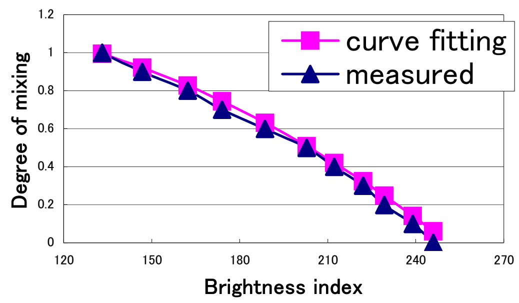


Fig. 4. Calibration curve of degree of mixing

2.2 Experimental Procedure

We observed the flow, particularly that on the heater in the microfluidic devices, using a highly sensitive CCD camera with a cooling device based on the Peltier effect. (Keyence Co., sensitivity: ISO1600). We attached a close-up lens system with a bellows on the CCD camera. The photographing was done under a constant illuminance of 2000 lx at the microfluidic device.

Figure 3 shows the observation setup. We observed the flow while keeping the microfluidic device vertical as shown in Fig. 3. There is a small difference in fluid density between the black water and the white water as mentioned before; thus, a secondary flow is generated when the microfluidic device is horizontal.

We prepared 11 samples with different mixing ratios, from "pure black water" to "pure white water" with 10% intervals, and measured the brightness of each sample using the CCD camera. Figure 4 shows the calibration curve between the brightness and the degree of mixing, where the triangles are measured values and the squares are the result of curve fitting. The images obtained using the CCD camera were processed in a PC and the mean mixing rate M was calculated as

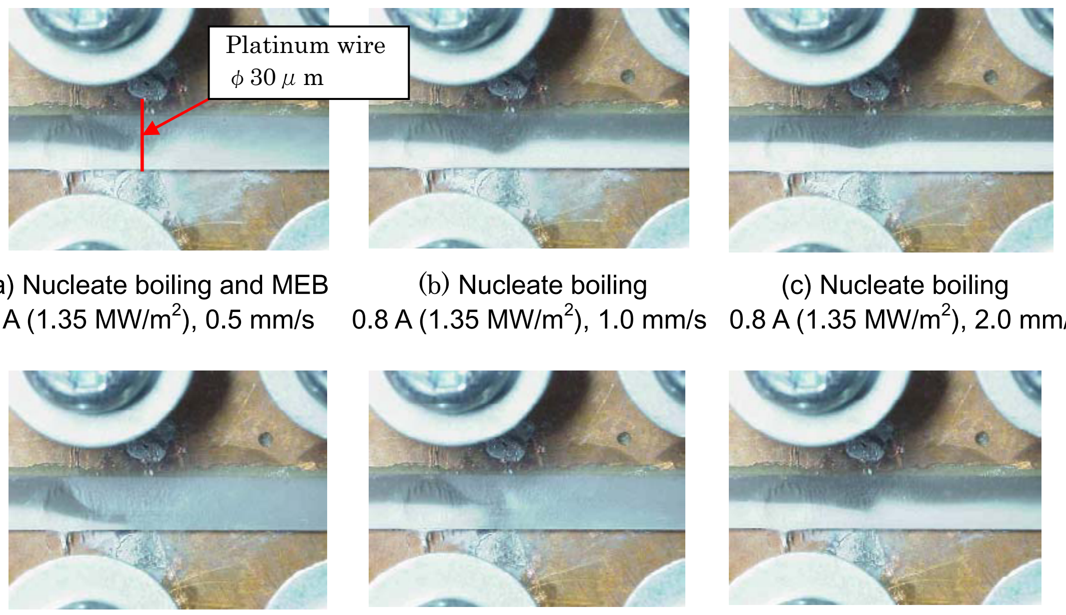
$$M = \left[1 - 1/\overline{C} \sqrt{\sum_{i=1}^{n} (Ci - \overline{C})^2 / n} \right] \times 100$$

where C_i, $\overline{C}$, and n are the degree of mixing at position i, the mean degree of mixing, and the number of measurement points, respectively.

3. Experimental Results and Discussion

3.1 Observation of Mixing

Figure 5 shows photographs of mixing in the MFD-A device after 60sec continuous heating. The electric currents for heating were 0.8 and 0.9 A and mean flow velocities were 0.5, 1.0, and 2.0 mm/s, which correspond to flow rates of 0.5, 1.0, and 2.0 mm^3/s, respectively, because the cross section is 2 mm x 0.5 mm. The flow direction is left to right. We could not see the platinum wire heater, because of colored water. The red vertical line in Fig. 5 (a) shows the position of the wire heater.



(a) Nucleate boiling and MEB 0.8 A (1.35 MW/m^2), 0.5 mm/s
(b) Nucleate boiling 0.8 A (1.35 MW/m^2), 1.0 mm/s
(c) Nucleate boiling 0.8 A (1.35 MW/m^2), 2.0 mm/s

(d) Microbubble emission boiling 0.9 A (1.65 MW/m^2), 0.5 mm/s
(e) Microbubble emission boiling 0.9 A (1.65 MW/m^2), 1.0 mm/s
(f) Nucleate boiling 0.9 A (1.65 MW/m^2), 2.0 mm/s

Fig. 5. Effect of heat flux and mean flow velocity on mixing in MFD-A (standard type) (Flow direction: left to right)

The nominal water temperature was 20 ℃, which is equivalent to 80 degrees of subcooling. The water temperature at the confluence point increased a little because the room temperature was 21-24 ℃. Moreover, the temperature increased much after passing the wire heater, because of high heat flux. Therefore, a pair of vertical recirculating buoyancy flow was observed at the wire heater, which caused mixing even upstream the wire heater as seen in Fig.5. The generation of nucleate boiling and MEB was judged mainly by observation at the preliminary experiment with normal (transparent) water. We can also recognize the generation of MEB by the noise generation.

Mixing did not occur at a low heat flux with a high flow rate (v=1.0, 2.0 mm/s), even though nucleate boiling occurred. The interface between the two fluid layers did not change significantly. In the case of I=0.8 A (q=1.35 MW/m^2), nucleate boiling occurred and the interface became wavy, but the bubbles did not disturb the fluid layers significantly. When I=0.8 A and v=0.5 mm/s, MEB also began to occur on the heater and the mixing increased markedly. The increase in mixing with time is shown in Fig. 6. In the case of I=0.9 A (q=1.65 MW/m^2) and v=0.5 and 1.0 mm/s, MEB occurred, and the flow features changed markedly as can be seen in Fig. 5 (d)(e).

The interface was greatly disturbed by the MEB. The occurrence of MEB was confirmed from the observation as well as by a change in the noise of the boiling. From these photographs, we can easily recognize that MEB occurs at a high heat flux and a low flow velocity.

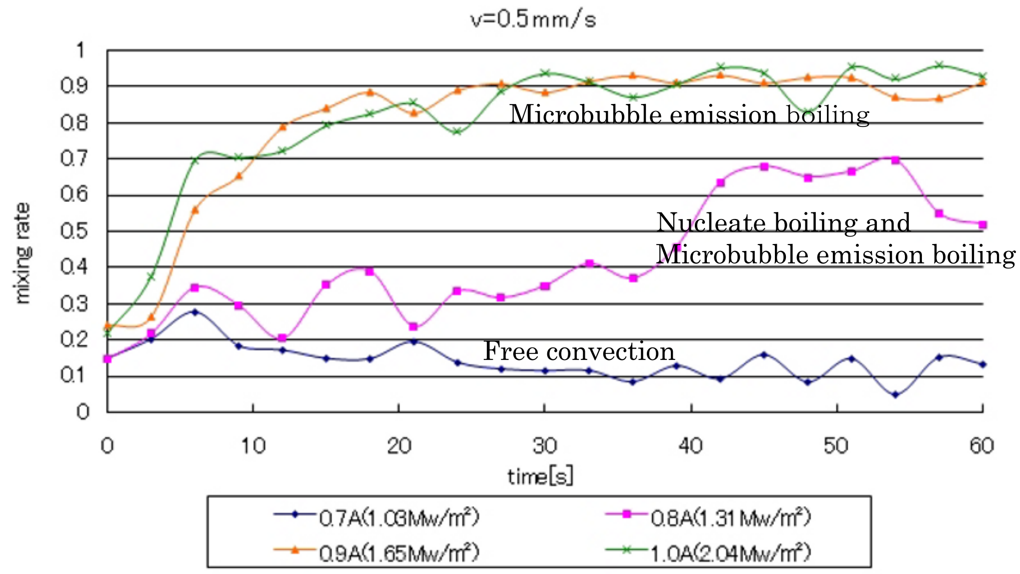


Fig. 6. Increase in mixing rate with time (v=0.5 mm/s)

3.2 Measurement of Mixing Rate

We took a series of pictures every 3 seconds using the close-up lens system with CCD camera under the illuminance of 2000 lx. The transverse images at 5 mm downstream of the wire heater were analyzed as shown below. First the picture was divided into cells of 0.02 mm by 0.02 mm across the flow channel. The total number of cells was 100 because the channel was 2 mm wide. Then the brightness index of each cell was determined using a commercial image-analyzing software, COSMOS. The degree of mixing, C_i was determined using Fig. 4.

Figure 6 shows the increase in the mixing rate after the wire heater was switched on. When the heat flux was low, only free convection occurred and the mixing rate did not increase. In contrast, when the heat flux was high and the MEB occurred, the remarkable increase in mixing rate was observed soon after the heater was switched on. In the case of medium heat flux both the nucleate boiling and MEB occurred simultaneously on the heater and the mixing rate increased gradually as can be seen in the figure. The interface between black and white layers became thicker slowly, which was resembled to a slow turbulent mixing at the interface.

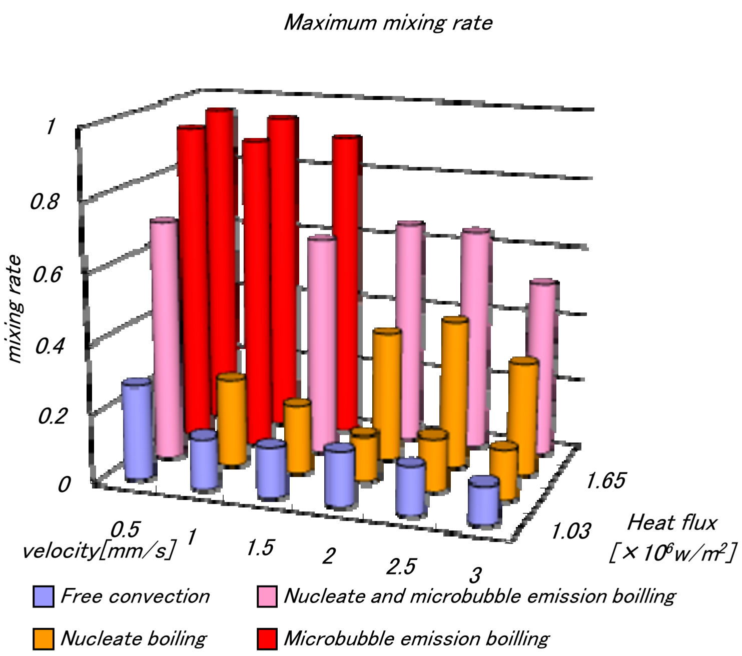
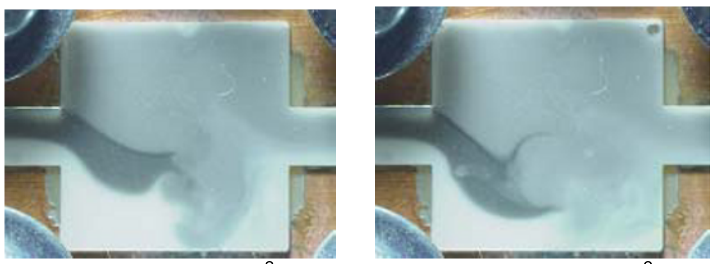


Fig. 7 Maximum mixing rate vs. flow velocity and heat flux



0.8 A (1.35 MW/m^2) 0.9 A (1.65 MW/m^2)

Fig. 8. Effect of mixing chamber at a flow rate of 2.0 mm^3/s (inlet velocity=2.0 mm/s)

Figure 7 shows the mixing rate after 60 sec, which was plotted against the heat flux and the mean flow velocity. The figure clearly depicts the tendency shown in Fig. 5. MEB occurs when the flow velocity is low and the heat flux is high. In the case of nucleate boiling, the mixing rate does not change significantly. In contrast, the mixing rate increases markedly when MEB occurs. It is evident that MEB is very effective for mixing in a microfluidic device.

3.3 Effect of Mixing Chamber

Another point of interest was the effect of the mixing chamber in MFD-B as shown in Fig. 2. A platinum wire heater was positioned at the center of the chamber so that the fluid velocity became much less compared with MFD-A. The Reynolds number was of the order of 1. The flow was viscosity-governed and the flow separation didn't occur in the mixing chamber.

Figure 8 shows photographs of the fluid motion in MFD-B at the same heat flux (1.35 and 1.65 Mw/m^2) and flow rate (2 mm^3/s) as those of MFD-A shown in Fig. 5(c) and (f), respectively. Although the flow rate was the same, the average flow velocity was 0.5 mm/s on the heater of MFD-B and 2.0 mm/s on the heater of MFD-A, because the cross section of MFD-B was 4 times larger than that of MFD-A.

The mixing rate was much greater in MFD-B than in MFD-A. At heat fluxes of 1.35 and 1.65

MW/m^2, nucleate boiling occurred in MFD-A, but the resulting disturbance was limited and the mixing was poor as can be seen in Fig. 5. In contrast, effective mixing occurred in MFD-B, where MEB occurred at the same heat flux and flow rate. It is clear that MEB occurs at a lower heat flux when the flow velocity is low.

3.4 Mechanism of Mixing by MEB

We observed the MEB bubbles on the wire heater by a high-speed video camera (Redlake MASD Motion Scope, maximum frame rate: 8000 fps) with bellows and lens system.

Figure 9 shows the motion of the MEB bubbles in MFD-A. The photographs are reproduced from a high-speed video, which was taken under the conditions of v=1.0 mm/s and a heat flux of 1.65 MW/m^2. The frame rate of the high-speed video was 2000 fps. The flow direction is left to right.

At 0 ms (Frame 1), a small bubble whose diameter was about 60 μm existed on the wire heater surface. It grew gradually first and then began to grow rapidly. The diameter increased more than 200 μm in 3 ms (Frame 7). Then, it burst suddenly and collapsed. A strong wake followed the collapsing bubble (Frames 9 and 11). The movement was so rapid that even the high-speed video could not capture the motion precisely. The inception and collapse of the MEB bubbles were very fast and on the order of 1 ms. The bursting bubble detaches itself from the heater and collapses. A strong wake was observed when the bubble separated from the heater. It was also observed that a nearby bubble was split into a few smaller bubbles by the shock generated by the collapsing of the first bubble.

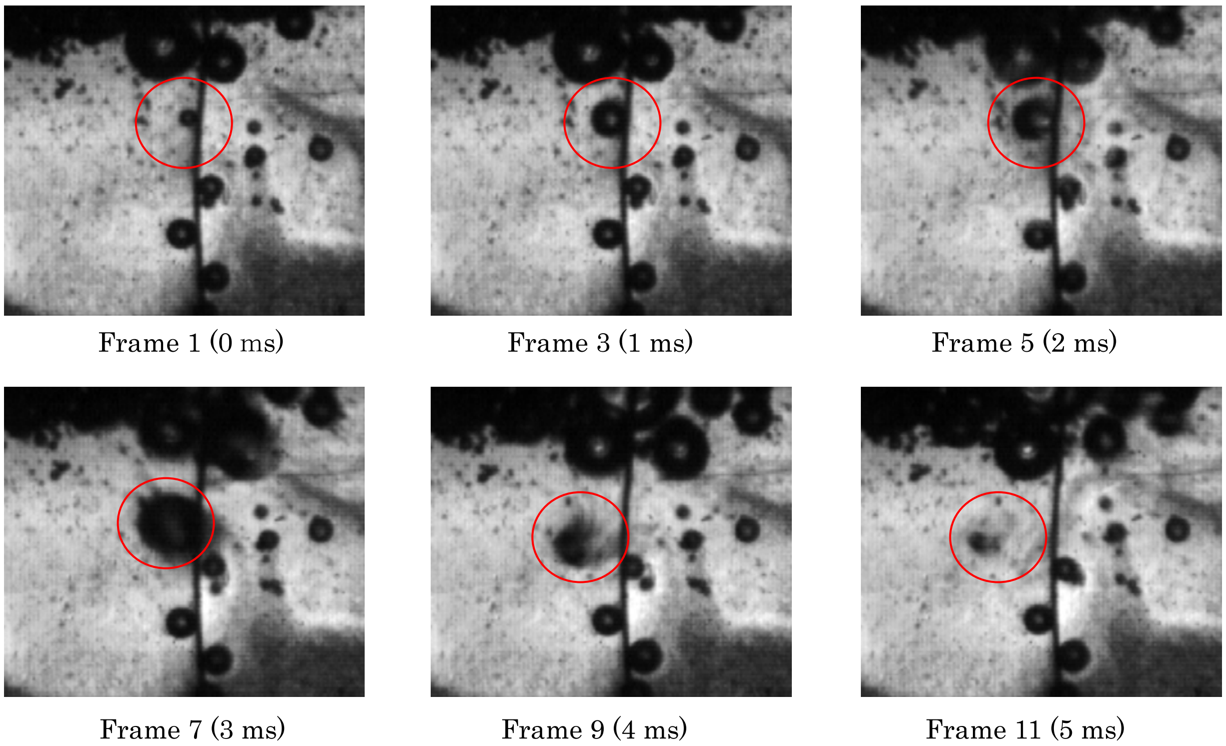


Fig. 9. Behavior of MEB bubbles
V=1.0 mm/s, q=1.65 MW/m^2, subcool= 80 ℃, frame rate=2000 fps. Flow direction: left to right.

Another interesting finding was that there are two types of bubbles on the heater that coexist simultaneously as can be seen in the figure. Several bubbles attached on the wire heater grew very slowly compared with the very fast growing and collapsing bubble. If the heating conditions were the same everywhere on the heater, this could not have happened. One possible explanation is that the water temperature varied considerably near the heater. It can be concluded that the temperature field was turbulent and that a high-temperature field above the burnout temperature existed simultaneously with a low-temperature field of highly subcooled water.

Shoji et al. (2005) observed the splitting of bubbles in the case of MEB under a pool boiling condition. However, the splitting or merging of bubbles was not predominant in the present experiment because the MEB bubbles were very small and of the order of 0.1 mm.

The present method of mixing using MEB is very effective for mixing fluids in a microfluidic device as demonstrated above. This method is simple and convenient. Its shortcoming is that fluids are heated to above their boiling temperature. This may result in some unfavorable effects in biological inspections, even though the amount of superheated fluid is only a small fraction of the total fluid (possibly less than 10%).

4. Conclusion

The following conclusions can be drawn from our experiment on the mixing of two fluids using microbubble emission boiling (MEB).

1. MEB is very effective for mixing fluids in a microfluidic device, whereas nucleate boiling is not effective for mixing. The provision of a mixing chamber also improves the mixing.
2. MEB appears to generate a strong wake when a bubble separates from the heater. This strongly enhances the mixing of two fluids in a microfluidic device.

Acknowledgment

We thank Mr. Yusuke Kariya for the sincere assistance during preparation of the paper.

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