Numerical Observation of Flow Field around the Water Column behind a Rising Bubble through an Oil/Water Interface

Yoshiaki UEDA,1) Norifumi KOCHI,1) Tomomasa UEMURA,2) Toshio ISHIH3) and Manabu IGUCHI1)  
1) Division of Materials Science and Engineering, Graduate School of Engineering, Hokkaido University, Nishi 8, Kita 13, Kita-Ku, Sapporo, Hokkaido, 060-8628 Japan. 2) Department of Mechanical Engineering, Kansai University, Osaka, 564-8680 Japan. 3) JFE Steel Corporation, 1-1 Minami-Watarida-Cho, Kawasaki-Ku, Kawasaki, Kanagawa, 210-0855 Japan.  
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1. Introduction  
The mass transfer due to entrainment between immiscible two-liquid phases can be greatly promoted by micro droplets.1,2) The passage of a bubble through an oil (upper phase)/water (lower phase) interface starts with an upward lifting of the interface, and the bubble attracts a column of the water phase upwards keeping a film of the water phase around itself.2–4) The film and column then flow back into the water phase, and the parts of them disintegrate into water droplets.2,4) The previous paper3) experimentally demonstrated the five stages (I)–(V) where the rising bubble experiences during the passage through the oil/water interface before the water column disintegrates into water droplets (see Fig. 1). Precisely, at the stage (III) numerous micro water droplets break out from concentric ripples on the outer interface of the ruptured water film around a rising bubble through an oil/water interface.3,5) In addition, the penetration of the water column at the stage (V) was also successfully computed against the experimental results in our associated study.1)  

According to Reiter & Schwerdtfeger,2,4) the water column behind the rising bubble disintegrates into several parts of them after the stage (V). They experimentally measured the height of the water column and total number of droplets into which the water column disintegrates. In this paper, particular attention is given to a still vague phenomenon on the breakup mechanism of the water column after the stage (V), and investigate the key effect to that with the aid of computational fluid dynamics (CFD) which can easily visualize the flow field.  

2. Computational Procedure  
The present paper follows the previous computational procedure1) which successfully simulates the penetration phenomenon of the water column at the stage (V).  
The FLUENT™ numerical code ver. 6.2.16, a commercially available CFD software package, was employed for all numerical predictions on 2.66 GHz Pentium Core 2 Quad processor with 4 GB RAM. GAMBIT 2.2.30 was employed for the establishment of the computational grid. The axisymmetric computational grids were made up of structured elements and a total of 225,736 cells were employed for flow domain, which was based on actual geometry of the preceding experimental setup.3) The computational domain had 30 times of the bubble diameter $d_b$ in width and 34 $d_b$ in height, where the water and oil phases were equally in height ($17 d_b$, respectively). At $t = 0$, the bubble was freely released at 15 $d_b$ below the oil/water interface. In the present computation, the bubble diameter was set at $d_b = 8.31$ (mm) whose volume was 300 (mm$^3$), and the twenty computational grids discretized the bubble. After the bubble was released, it freely rose due to the buoyancy force and reached the interface. To verify the computational results, we took the photographs of the situation after the stage (V) using a similar experimental setup to the preceding study3) and the high-speed camera whose frame rate is 625 frames per second with the shutter speed 1 ms for the resolution $1260 \times 1024$ pixels.  

FLUENT uses a control-volume-based technique to solve the governing continuity and momentum equations. A segregated implicit solver and second-order upwind interpolation scheme were employed for each computational iteration. A time-step size of $\Delta t = 1.0 \times 10^{-4}$ (s) was adopted to achieve a convergence in every time step. Free surface behavior, among the oil (1 cSt viscosity), water and air phases (i.e., three-phase flow), was captured by the Volume-of-Fluid (VOF) model (Geo-Reconstruct). The tracking of the interface between the phases was accomplished by the solution of a continuity equation for the volume fraction of a phase. The interfacial tension of 0.0727 (N/m) for the air/water interface and 0.0527 (N/m) for the oil/water interface were adopted. The convergence of the computational solu-

![Diagram of a rising bubble through an oil/water interface](image-url)
tion was determined based on residuals for the continuity and x-, y-velocities. The residual of all quantities was set to $10^{-4}$. The solution was considered to be converged when all of the residuals were less than or equal to these default settings (see FLUENT 6.2 User’s Guide\(^5\) for more details).

3. Results and Discussion

Figure 2 shows a comparison of the streamlines due to the rising bubble attracting the column of the water phase upwards between before and after the breakup of the column. As mentioned in the introduction, the rising bubble pulls the water phase upwards after the passage through the oil/water interface. The height of the water column then grows up about four times larger than the static bubble diameter $d_b$, and the stretched water column makes a neck around the point C which is depicted in Fig. 2. Around the neck, the water column is observed to break up in the right of Fig. 2. In general, the Rayleigh–Taylor instability is known to account for the breakup of a liquid column due to the interfacial tension.\(^7\) According to Weber\(^8\) who extended the theory of Rayleigh\(^9\) on an inviscid liquid to the viscous one, the viscous liquid column, with a static radius $a$, an initial amplitude of the column $\zeta_0$, and a wave length $\lambda$, splits several parts of them with the length of $l_b = 2a \ln (a/\zeta_0)$ $[\sqrt{\frac{\sigma_c}{\rho_c} + 3 (\text{We}/\text{Re})}]$, where We and Re are the Weber and Reynolds numbers based on the diameter and the injection velocity of the liquid column (see Fig. 3).

Unlike the pure breakup of the liquid column, the present situation gives the fact that the rising bubble attracts the water column upwards with the velocity of 0.158 m/s, and the gravity affects the water column downwards. In the streamlines of Fig. 2, the wake due to the rising bubble can be observed to directly affect the upper part of the water column above the position C and generate the neck (see the left of Fig. 2). Indeed, the velocity inside the lower part of the water column below the position C is downwards due to the gravity, although it is upwards on the centerline of the water column (see the left of Fig. 2). In contrast to the above-mentioned pure breakup phenomenon of a liquid column,\(^8,9\) the present breakup of the water column could be caused by the interaction between the upward hydrodynamic force due to the bubble wake and the downward force due to the gravity.

To precisely discuss the present breakup phenomenon of the water column, we look at the magnified view of the results around the neck of the column. Figure 4 shows the selected snapshots of the shape of the water column and the velocity vectors of the flow. The water column breaks up at $t = t^* - 0.001$ (s) which is shown at Fig. 4(c). It is noted here that the large velocity vectors around the upper field of Fig. 4(a) are due to the wake of the bubble. As also seen in Fig. 2, the velocity inside the lower part of the water column is observed to be downwards near the interface whereas the velocity is upwards in the inner region (see Fig. 4(a)). In addition, the velocity on the centerline of the column strictly changes the direction around the neck due to the wake of the rising bubble before the breakup (One can distinctly see that in Fig. 4(a)). This change in velocity on the centerline of the water column is plotted in Fig. 5 where each plot uses the data of Figs. 2(a) and 2(b) between the points A and B. In Fig. 5, the direction of the velocity varies from positive (around the point A) to negative (around the neck point C) and back to positive (around the point B). Furthermore, the strong downward velocity is induced at $t = t^* - 0.001$ (s) (just before breaking up the neck) and the neck could break up at the position C where the magnitude of the downward velocity becomes maximum. Indeed, just before the breakup at the neck, the strong downward velocity is induced at the neck point C (see Figs. 4(b) and 5) and, in contrast, the velocity inside the upper part of the column is upwards (see Figs. 4(b) and 5) at $t = t^* - 0.001$ (s) so that the water column can break up at $t = t^*$ (see Fig. 4(c)). After the breakup of the water column, the lower part of the water column gradually descends due to the gravity to the static interface level between the oil and water layers (In Figs. 4(d) and 4(e), the strong downward velocity is observed in the lower part of the column). The rim of the water column at the edge of the upper part (see Figs. 4(d) and 4(e)) could retract upward with the so-called Taylor–Culick velocity $U_{bc} = [2\sigma/(\rho e)]^{1/2}$, which is obtained by balancing surface tension force against inertia, where $\sigma_i$ is the surface tension, $\rho$ the den-

![Fig. 2](image1.png) Comparison of a rising bubble attracting a column of the water phase (left) before and (right) after the water column breaks up into parts of them between (top) computational results with the streamline and (bottom) experimental photographs. The velocity distribution on the line between the points A and B is plotted in Fig. 5.

![Fig. 3](image2.png) Sketch of pure breakup of a liquid column due to the Rayleigh–Taylor instability.
4. Concluding Remarks

This study has investigated a breakup phenomenon of the water column pulled by a rising bubble through an oil/water interface, using the previous procedure of the FLUENT numerical code. The wake of the rising bubble distinctly affects the water column attracted upwards by the bubble. The breakup of the water column could be determined by the interaction between an upward hydrodynamic force due to the wake and a downward force due to the gravity, unlike the well-known pure breakup phenomenon of a liquid column due to the Rayleigh–Taylor instability.

The present results obtained compensate for the previous findings which are given before the breakup of the water column (stages (I) to (V)).

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