Abstract

Dynamics of a bubble in confined space
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Dynamics of a spatially confined bubble is discussed in this thesis. Spatial confinements make the dynamics more complicated, but at the same time more physically rich because of the following three reasons: (i) spatial symmetries such as spherical and circular symmetries of the phenomena are broken, (ii) the number of length scales which characterize the dynamics increases, and (iii) the dynamics is often subject to the existence of liquid thin films. In this paper, we discuss two cases of bubble dynamics in confined space: bursting and rising motion.

(1) Bursting dynamics of viscous film without circular symmetry: the effect of confinement

The goal of this study is to understand how bursting dynamics changes if the bubble is confined in a narrow space of the Hele-Shaw cell. Bursting exhibits two regimes of inertial and viscous regimes. In the viscous regime, bursting proceeds with a small constant velocity (~ 10 mm/s) and the rim formed at the bursting tip does not grow. It is a salient feature of the confined quasi-two dimensional bursting that the fluid is not collected in the rim. This never occurs in the three dimensional bursting in which the circular symmetry of the bursting hole is maintained. We derive the velocity law by clear agreement between theory and experiment: the bursting velocity linearly increases with the cell thickness. As for the inertial dynamics, in the confined case, the bursting proceeds with a large constant velocity (30 m/s). Unexpectedly at a first glance, this velocity is theoretically expected to be equal to the well-known Culick velocity [1] that is observed in the nonconfined-inertial cases. In experiment, we confirmed directly the nonconfined-to-confined inertial crossover with no change in bursting velocity as theoretically predicted when the circular symmetry of the shape of the expanding hole is dynamically broken. The present work raises a possibility for the control of bursting velocity by spatial confinement, and this could make a significant contribution to many research areas such as industrial processes, environmental science, and biology.

(2) Rising bubble confined from two directions: two regimes for rising velocity and bubble shape

Rising dynamics of a bubble confined in a vertical cell with a rectangular cross-section is discussed. We focus on the case in which the viscous and capillary effects are dominant and the inertial effect is negligible (the case of small Morton number and small Bond number). One of

the difficulties for understanding of rising dynamics of a bubble arise from the correlation between the rising velocity and the bubble shape. In this study, we first discuss the rising velocity of a bubble whose width is experimentally selected to a fixed value depending on values of other experimental parameters such as the aspect ratio of the cross-section. By imposing appropriate conditions for length scales, we find the regime in which the dissipation in the gap between a bubble and the side wall dominates the dynamics, and derive a new scaling law for the rising velocity. Then, we study how the width of the bubble rising at a given velocity is selected. We also establish the drag force acting on a rising bubble, which corresponds to a generalization of Stokes' law for a spherical object in viscous fluid. The present dynamics of bubble rising in a cell with a rectangular cross-section exhibits a crossover to that in a Hele-Shaw cell discussed in the previous study [2] by decreasing the ratio of the size of a bubble to the width of a cell. This crossover is demonstrated experimentally both for the rising velocity and the bubble width. We uncover that bubble rising in the present study can be mapped to viscous fingering under a simple transformation associated with the bubble (or finger) velocity and the bubble (or finger) width. This means that the scaling laws we find for rising bubble might provide a new perspective for the study of viscous fingering [3].

In the present study, we deal with systems confined from one direction (Hele-Shaw cells) and two directions (cells with rectangular cross-sections), and reveal a number of different dynamics of spatially confined bubbles. We expect that the present findings give insight into more generalized cases, such as the dynamics of small droplets or thin viscous films.

[1] F. Culick, *J. Appl. Phys.,* **31** (1960)
[2] A. Eri and K. Okumura, *Soft Matter,* **7** (2011)
[3] P. G. Saffman and G. Taylor, *Royal Society of London A*, **245** (1958)