【主論文の要旨】

学位報告４

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主　論　文　の　要　旨

論文題目　Numerical simulation of gas–liquid two-phase flow by a semi-Lagrangian–Lagrangian approach
（セミ Lagrange−Lagrange 法による気液二相流の数値シミュレーション）

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論 文 内 容 の 要 旨

Gas–liquid two-phase flows around rigid obstacles are observed widely in engineering applications, such as shell and tube heat exchangers, steam generators, and condensers. A comprehensive understanding of the phenomena of gas–liquid two-phase flows around obstacles would allow for improved design and control of related engineering devices. This has attracted the attention of many scientific and engineering researchers. In the era of digital development, numerical simulation is an effective tool for discovering knowledge about the characteristics of bubbly two-phase flow. In computational fluid dynamics, there are three different approaches that have been used to simulate the bubbly two-phase flows around obstacles, namely, Eulerian–Eulerian; Eulerian–Lagrangian; Lagrangian–Lagrangian. In this study, a semi-Lagrangian–Lagrangian approach composed of a vortex-in-cell method for the liquid phase and a Lagrangian description of the gas phase was developed for the simulation of the bubbly flow around a rigid obstacle.

In the first simulation, the evolution of an annular bubble plume was investigated to clarify the characteristics of the bubble dynamics and the induced-liquid flow of an annular bubble plume. The bubbles, released from the annulus located at the bottom of the domain, rise owing to the buoyant force. These released bubbles have diameters of 0.15–0.25 mm and satisfy the bubble flow rate of 4.1 mm^3/s. A new phenomenon of the fluid dynamics was discovered. The bubbly flow enters a transition state with the meandering motion of the bubble plume after the early stable stage. A vortex structure in the form of vortex rings of various scales is formed because of the inhomogeneous bubble distribution and the fluid-surface effects. The vortex structure of the flow deforms as

three-dimensionality appears in the flow before the flow fully develops. Moreover, the superior abilities of the semi-Lagrangian–Lagrangian approach to analyze the vortex structure of the flow and supply physical details of bubble dynamics were demonstrated in this investigation.

In the second simulation, the interaction between a vortex ring and a bubble plume was investigated to clarify the efficiency of bubble transport by the vortex ring, the mechanism of bubble motion under the effects of a vortex, and the effects of entrained bubbles upon the vortex structure. Small bubbles are released into quiescent water from a cylinder tip. They rise under the buoyant force, forming a plume. A vortex ring is launched vertically upward into the bubble plume. It was found that the vortex ring can transport the bubbles surrounding it over a distance significantly depending on the correlative initial position between the bubbles and the core center. The motion of some bubbles is nearly periodic and gradually extinguishes with time. These bubble trajectories are similar to two-dimensional-helix shapes. The vortex is fragmented into multiple regions with high values of Q, the second invariant of velocity gradient tensor, settling at these regional centers. The entrained bubbles excite a growth rate of the vortex ring's azimuthal instability with a formation of the second- and third-harmonic oscillations of modes of 16 and 24, respectively.

In the third simulation, the bubbly flow around a circular cylinder was numerically investigated to better understand the characteristics of flow around a rigid obstacle. The semi-Lagrangian–Lagrangian method was combined with a penalization method to account for the cylinder inside the flow. Additionally, the slip condition of the bubbles on the cylinder's surface was enforced, and the outflow conditions were applied to the liquid flow at the far field. The bubbles were shown to move around and separate from both sides of the cylinder, due to entrainment by the liquid shear layers. Once the bubbly flow fully develops, the bubbles distribute into groups and are dispersed downstream of the cylinder. A three-dimensional vortex structure of various scales was also shown to form downstream, whereas a quasi-stable two-dimensional vortex structure was observed upstream. Overall, the proposed method captured the characteristics of a bubbly flow around a cylinder well.

To sum up, a semi-Lagrangian–Lagrangian composed of a vortex-in-cell method for the liquid phase and a Lagrangian description of the gas phase was successfully developed to simulate the gas-liquid two-phase flows around an obstacle. The characteristics of the evolution of annular bubble plume, the interaction between a vortex ring and a bubble plume, the bubbly flow around a circular cylinder were clarified in this study.