学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Numerical investigation on large-sized bubble injection for control of turbulent boundary layer -Horizontal channel flow and bubble-induced drag reduction-
(乱流境界層を制御するための大型気泡注入に関する数値計算研究 -水平チャネル流れと気泡による抵抗低減-)

Control of the turbulent boundary layer by injecting bubbles has been researched to improve a lift force or reduce friction drag, and it has many advantages because the bubble consistently modifies the boundary layer by traveling with the main flow and has no damage on environments than other techniques. The characteristics of these bubbly flows change depending on the direction of buoyancy relative to the main flow direction and can be divided into vertical and horizontal bubbly flows, representatively. In the case of vertical bubbly flows, the buoyancy of the bubbles acts along the streamwise direction, resulting in a clear difference in the distribution of the void fraction and flow pattern according to the flow direction. This phenomenon is important for industrial demands related to heat exchangers, such as nuclear reactors and power plants. In the case of horizontal bubbly flows, it has received less attention than vertical bubbly flows because buoyancy acts in the wall-normal direction of the channel so that is unsuitable for the industrial demands and more complex flows. Consequently, air bubbles are present on the upper wall, regardless of the bubble size or void fraction, and hinder heat exchanges or mass transfer between the main flow and the wall. Meanwhile, the horizontal bubbly flow modifies the inner-layer structure of the turbulent boundary layer formed beneath a horizontal flat wall, thus reducing the frictional drag on the upper wall.
This characteristic is called bubble drag reduction (BDR) and is applied to liquid transport in pipelines and ship surfaces in water. In particular, the energy efficiency of large vessels is expected to be promoted by reducing the frictional drag, which accounts for 80 percent of the total drag. Many previous studies of horizontal bubbly flow are based on the microbubble for BDR. Meanwhile, the typical micro-bubbles method applied in industrial fields contains a-few-millimeters bubbles, and they frequently coalesce in the shear layer and become large-sized bubbles in the downstream region. Furthermore, the air film method, which is another method for drag reduction by injecting air on the super-hydrophobic surface to separates the liquid phase of the flows and the wall for drag reduction, is break up and separate into large-sized bubbles from the downstream, however, the critical size of the large-sized bubble has not been determined yet. Such a perspective of view, understanding of large-sized bubbles is essential for the persistency of drag reduction from the downstream. Recently, It has been discovered that large-sized bubbles provided a velocity gradient that calmed the wake region and the performance of drag reduction is dependent on the bubble length.
Interestingly, large-sized bubbles show a common spatial relationship between drag modulation (drag increment and reduction) and the bubble location. However, large-sized bubble dynamics have some open questions, such as the mechanism of drag modulation, as the bubble size causes some large-sized bubbles to increase, rather than reduce, the drag; this results in larger skin friction than that under single-phase flow. Accordingly, the goals of the present study are to numerically investigate the above questions and achieve a comprehensive understanding of large-sized bubble dynamics.
In chapter 1, the background research of BDR and numerical approach are briefly described first, and then the objective and strategy of the thesis are shown last.
In chapter 2, mathematical formulation and numerical detail are described. To achieve our ultimate goal such as modeling large-sized bubble deformation, The author uses the Volume of Fluid method (VOF) methods in order to approach the dynamic motion of bubble interface interacted by a turbulent flow. In this regard, the governing equations in this chapter can consist of the fundamental conservation equations (for mass, momentum) under the one-phase model framework. In the case of the interface sharpening method, the isoAdvector method is introduced as a sub-grid scale model for estimating the intracellular distribution from the given volume fraction and velocity. This sub-grid scale model constructs the interface inside the cell and creates the sub-cells occupied with each volume fraction. This procedure makes it possible that maintain the sharp interface in large deformation conditions. To verify the performance of this method, the most fundamental cases considered pure advection, Rudman-shearing, and Rudman-Zalesak solid rotation test with 2-D calculation domain is performed first. It provides evidence that the current interface sharpening method maintains the interface properly under the pure

advection condition.

In chapter 3, the validation of numerical models is described. Before the validation work, the main part to be modeled is (1) how to generate the turbulent channel flow, (2) how to locate the large-sized bubble inside the channel, and (3) how to maintain the large-sized bubble inside the channel. The procedure of each modeling is described. Then, this chapter mainly shows validation results of a large-sized bubble; validation of modeling for large-sized bubble interface, and for turbulent modulation. In detail, the dynamic distribution of instantaneous momentum flux and skin friction on liquid film is precisely investigated by comparing with the experiment. Based on validation, it is concluded that models for large-sized bubble interface and for turbulent modulation are qualitatively validated.

As result, chapter 4 shows dynamic behavior and drag modulation of large-sized bubbles in the turbulent channel flow by exploring various bubble sizes, and it is defined as Weber number. From here, the numerical method for turbulent flow is changed from Large-eddy simulation (LES) to Direct Numerical Simulation (DNS) to consider the fully resolved boundary layer flow and interface deformation of a large-sized bubble. It is found that the behavior of the bubble interface affects the drag reduction ratio during its deforming, and this dynamic effect on the drag reduction ratio varies with different Weber numbers. In detail, the author observed that drag contour is corresponded with the turbulent flow, beginning from the front side of the liquid film. This region becomes constant as the Weber number increase. In contrast, the absolute value of the skin friction in the spanwise direction is observed to concentrate on the span edge of the liquid film and continue to the secondary flow. This trend might not be important for drag reduction in the streamwise direction; however, the instantaneous contours in the spanwise direction clearly showed that high skin friction corresponded to this trend in the streamwise direction. Indeed, the observed skin friction in the spanwise direction is a good indicator implying that high momentum flux occurred in this region.

In chapter 5, by use of the same computational configuration used in chapter 4, the dynamic behavior of a large-sized bubble on turbulent Couette flow is examined. In order to generate turbulent Couette flow, the source term based on pressure gradient in streamwise direction changed to wall velocity on the upper wall, and it is modeled to have the same frictional Reynolds number as the model of chapter 4. Numerical parameters are selected in order to investigate the motion of a large-sized bubble in an effective way, concluding that the effect of turbulent Couette flow on deformation of large-sized bubbles is significant so that breakup with small daughter bubbles frequently.

In chapter 6, the drag reduction effect on multiple bubbles is investigated as flow conditions(Poiseuille and Couette flow) in order to explain the unsteady phenomena involved in the flow conditions and bubble formation. In this chapter, The time-dependent deformation and behavior of large-sized bubbles are visualized together with the frictional drag distribution. As a result, near-zero skin friction contours on the liquid film of the large-sized bubble are successfully confirmed from both flow condition when the bubble become nearly film states. This phenomenon was experimentally investigated and called relaminarizing flow in the liquid film, and it means the present numerical model is available to reproduce it. Interestingly, this phenomenon is completely different with those occurred in micro-bubble and air-film method.

Finally, in chapter 7, the author reviews the content in each chapter and summarizes the conclusions of this thesis.