学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Repetitive bubble injection for control of turbulent boundary layers
(乱流境界層の制御のための反復気泡注入法)

Techniques for turbulent boundary layer control have been respected in a long time to improve a lift force or reduce a friction drag, and many techniques have been developed. Comparing with other techniques, a turbulent boundary layer control using injecting bubbles has many advantages because they consistently modify the boundary layer by traveling with a main flow and have no damage on environments. Therefore recently, it is expected to promote the energy efficiency of huge vessels by reducing the frictional drag that occupies 80 percentage of total drag acting on huge vessels.

How do bubbles move within the boundary layer near a wall and how do these bubbles modify the boundary layer? These questions are critical issues in fluid, thermal, and chemical engineering applications where the boundary layer control is required. Characteristics of bubbles in flows change dependency on the direction of buoyancy relative to the main flow direction. Vertical bubbly flows have been targeted for the study in almost cases because of industrial demands for boilers and heat exchangers. On the other hand, horizontal bubbly flows have received less attention than the vertical bubbly flows because they are unsuitable for the industrial demands and more complex flows, multi-dimensionalized irresistibly by buoyancy of bubbles which acts on dispersed the bubbles perpendicularly to the mainstream, than vertical flows. However, the bubbles injected into a horizontal flow can modify and control efficiently a turbulent boundary layer formed beneath a horizontal flat wall because they congregate near the wall and affect the inner-layer structure of the wall turbulence.

According to many previous studies, clout of bubbles to the boundary layer is determined generally by void fraction in the layer. For example, high void fractions which reaches 40 percentage can reduce frictional drag approximately 80 percentage but too much low void fractions cannot reduce the drag. Therefore maintaining high void fractions is required to get good controllability of the boundary layer. However unfortunately a lot of energy for injecting bubbles into the boundary layer is needed to maintain high void fractions and sometimes it is too much high cost comparing with benefits caused by the boundary layer control. It is one of reasons why control of the boundary layer by injecting bubbles is not adopted yet in the industrial fields. Another reason is a low reproducibility of the control. The bubbles change perpetually their behaviors and do not reach at a stable condition when they are traveling in the boundary layer because of the mutual interactions.

In the chapter 1, the author reviews many previous studies for bubbly flows and boundary layer control techniques, and suggests repetitive bubble injection (RBI) to solve problems mentioned above. The RBI is designed to use efficiently air resource to maintain high void fractions locally and avoid low void fractions which have bad controllability of the boundary layer. In other words, the RBI generates bubble swarms with the high void fraction by concentrating the air resource in a short time. Furthermore it is expected that conditions of the bubbles injected by the RBI are maintained statistically at the same phase of the injection period because the RBI generates artificially periodic voidage wave with high fluctuations. The clout to the boundary layer may be more strongly exerted by the high fluctuations of the void fraction because of non-linearity of relationship between the clout and the void fraction. Consequently, the RBI has potentials to enhance efficiency of the boundary layer control and reproducibility of phenomena.

In the chapter 2, information of bubbles traveling in a boundary layer on a horizontal flat plate are investigated using the model ship which installs bubble injection system utilizing an air compressor. From variations of wall shear stress and liquid film thickness obtained by echography, it is confirmed that shear stress is decreased when the film thickness is thin. And from motion analysis of the bubbles, even relatively smaller bubbles with a few millimeter size are hard to change fluid properties such as effective viscosity. In case of continuous bubble injection (CBI) used ordinarily, it is confirmed that voidage wave is generated naturally in the boundary layer by forming bubble cluster. In summary, the bubbles affect the boundary layer by interaction with flow structures in the layer and it is expected that the natural voidage wave helps to maintain the fluctuation of void fraction generated by RBI in a downstream region when artificial voidage wave resonates with the natural one.

In chapters 3 and 4, effects of bubble swarms, i.e., the artificial voidage wave, generated by the RBI on horizontal flows and its controllability are estimated using a 6 m rectangular channel. At first, in the chapter 3, interaction between vortical flow structures near the wall and the bubble swarm in the channel flow is visualized by means of two-color laser-sheet illumination of the wall turbulence with a dilute suspension of flakes. By statistical analysis of visualized images, the author suggests a possibility that streamwise vortices in the buffer layer are swept by the bubble swarm and survive until the swarm is passing above them. In the chapter 4, reproducibility of the bubble swarm, wall shear stress and the velocity vector field in the liquid phase are investigated by a simultaneous measurement system composed by a shear sensor and two ultrasonic velocity profiler (UVP) for estimating effects of the RBI in channel flows. Considering the suggestion in the chapter 3 and results in this chapter, drag reduction effect enhanced by the RBI is caused by air lubrication and by suppression of Reynolds shear stress events in the turbulent vortical structures beneath the bubble swarm. In the final analysis, the RBI is a useful technique to improve efficiency of the boundary layer control and provide the reproducibility of the control.

In the chapter 5, distributions of bubbles in the bubble swarm are investigated statistically at several downstream locations on the channel flows. From the variations of the distributions for size and number density of bubbles in each the location, a tendency is confirmed that large bubbles are traveling with a faster velocity than that of small bubbles. As a result, bubbles are classified according to size when the bubble swarm is traveling with a main flow, and large bubbles are located in a front region of the swarm. From the experimental results, one-dimensional advection model of void fraction distribution of the bubble swarm is established. In industrial fields, it is required to estimate the void fraction distribution in all locations. Therefore this model is expected to help to predict it.

In the chapter 6, the author introduces new echography for measuring bubble information, such as shape of the bubble and liquid film thickness above the bubble, in the boundary layer using ultrasonic pulse dispatched from the UVP. Although it is hard to adopt optical visualizations to measure flow velocity fields and bubbles in industrial fields, ultrasonic echography techniques are still adoptable. This new echography can obtain location of gas–liquid interface and velocity distribution in liquid–phase, simultaneously, because it uses an echo signal which is a concomitant when the UVP measures velocity profiles of liquid–phase in a flow. Therefore it is suitable for industrial needs. Methodology is examined experimentally and numerically, and then demonstrations of the echography are performed at experimental facilities. The author confirm that the new echography is successfully developed.

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