論文の内容の要旨

Abstract of Doctoral Dissertation

Experimental Analysis of Turbulent Frictional Drag Reduction Effect in the Microbubble-laden Channel Flow

(微細気泡による摩擦抵抗低減効果に関する実験的研究)

By

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Drag reduction by injecting bubbles into a turbulent boundary layer is a complex physical phenomenon, which has been studied for many years by researchers in various fields worldwide. The benefits of a success in drag reduction control are enormous. Reduction in drag can increase the range of speed in transportation system, reduce the energy consumption in pumping system such as pipeline, improve systems efficiency, and decrease fuel consumption, which directly leads to cost savings and decrease in pollutants emission. Since the first experimental study was carried out by McCormick & Bhattacharrya (1973), A series of experimental and numerical studies were conducted mainly in USA, Russia and Japan. These studies revealed fundamental characteristics of the phenomenon, and confirmed that as much as 80% of the skin friction drag can be reduced with bubbles (Bogdevich et al. 1976, Madavan et al. 1984, Pal et al. 1988, Deutsch et al. 1990, Clark Ⅲ et al. 1991, Kato et al. 1998). Recently, practical researches on the application to ships have made great progress in Japan. The first successful full-scale experiment was carried out using a cement carrier, and it was reported that approximately 5.3% net fuel consumption was saved by the air injection (Kodama et al. 2008). It is considered that drag reduction by bubbles is a promising engineering method for ships. However, the mechanism of this physical phenomenon has been not fully understood until now. Consequently, it is confronted with many difficulties in making actual design and application to ships and improving the effect of bubbles.

An important step towards the understanding of the mechanism is to find parameters which have significant influences on the drag reduction. In the present research, we put the focus upon the relation between bubble size and drag reduction. The knowledge on the effect of the bubble size especially in the very small bubble size range has been very limited because generating such small bubbles is very difficult.

Therefore, a method for generating very small microbubbles by electrolysis was developed first. Using this technique, a series of experiments were carried out for a fully developed turbulent channel flow in a circulating water tunnel for gaining a new insight into the effect of the bubble size on the interaction between bubbles and turbulence and its contribution to the drag reduction..

In the first set of experiments, the drag reduction effect of small microbubbles generated by electrolysis was measured by shear stress transducers and by a differential pressure gauge. By comparing with the results for large bubbles generated by air injection, it was clearly shown that small bubbles are 10~1000 times more effective in terms of the drag reduction per unit gas volume than large air bubbles. This experiment is described in Chapter 2

In Chapter 3, the bubble size distribution and the void fraction profile were investigated by means of microscope photography. Through the image processing of the microscope photographs taken by a backlight method, the size and position of individual bubbles were recoded. It was confirmed that the diameter distribution of small bubbles peaks around 30 μm, and that small microbubbles are more concentrated near the wall compared with large air bubbles. The ratio of the peak void fraction α_p to the mean value α_m was approximately 7 with small microbubbles, while the value with large air bubbles was about 1.5. The peak of the void fraction was located within 0.25H from the wall with H being the half channel width, while that of large air bubbles was between 0.25H and 0.5H. It is suggested that this difference in the void fraction profiles is one of the reason for the high drag reducing efficiency of small microbubbles.

The relation between bubble size and turbulence statistics was investigated by means of a particle tracking velocimetry (PTV) for smaller bubble size. The mean velocity profiles of the liquid phase without or with microbubbles were almost the same.. Interesting findings were that the mean velocity of microbubbles was smaller than that of the liquid phase, and that the mean relative velocity between water and microbubbles increases with the increasing bubble diameter. It was also found that the velocity fluctuation of liquid phase with microbubbles is smaller than that without microbubbles. The velocity fluctuation of microbubbles was smaller than that of water, and that this tendency has positive correlation with bubble diameters. The Reynolds shear stress of microbubble-laden flow was smaller than that of single-phase flow, and the difference was consistent with the measured drag reduction by direct methods. The correlation of the streamwise and wall-normal velocity fluctuation of microbubbles was smaller than that of the liquid phase, and the difference increases with the increasing microbubble diameter. These results are summarized in Chapter 4.

In Chapter 5, the preferential concentration of microbubbles in the region near the wall was investigated by photography. It was found that the tendency of the preferential concentration is strongly dependent on the bubble size. The preferential concentration was observed by the visualization for microbubbles between 10 and 80μm in diameter. While such behavior was not observed for large air bubbles. The bubble relaxation time normalized by viscous units τ_p^+ ranges between 0.011 and 0.702 when the mean velocity is 1.0m/s, and between 0.020 and 1.288 when the mean velocity is 1.5m/s, respectively.

Based on the experimental evidences obtained in the previous chapters, the mechanism of the drag reduction by very small microbubbles is discussed in Chapter 6. Fugakata et al. (2002) derived theoretically that the reduction of Reynolds shear stress near the wall can induce the drag reduction more effectively. Kim et al. (1971) has shown that this bursting of low-speed streaks contributes the majority of the turbulent kinetic energy produced in a turbulent boundary layer. The near-wall vortices extract a large amount of turbulent kinetic energy from the mean flow (Iwamoto et al. 2002). On the other hand, the large-scale structures also gain substantial energy from the mean flow. The energy is not dissipated by themselves, but transferred to the smaller vortices through the energy cascade. By combining those knowledge on the mechanism of the production of the turbulent energy and the findings of the present study, it is reasonable to conclude that the sharp peak of the void fraction profile and the tendency towards the preferential concentration near the wall are two important reasons for the highly efficient drag reduction caused by small scale microbubbles. The behavior of a bubble in a vortex is strongly dependent on the ratio of the time scale between the bubble and the vortex. It is known that the interaction becomes strong when the time scale ratio is on the order of unity. The large air bubbles, of which diameter is larger than 200 μm, have longer time scale, or relaxation time. Thus they interact with the large scale vortex structure which spans the entire channel width. As shown in Chapter 5, small microbubbles, of which the diameter is smaller than 80 μm, have time scale on the order of unity when scaled in the viscous units. Therefore they interact with the near wall vortical structure which has large contribution to the skin friction. Consequently, as shown in Chapter 2, small microbubbles are two orders of magnitude more efficiently reduce the skin friction than large air bubbles. Although further investigation is desired, the proposed mechanism of the drag reduction by small microbubbles is consistent with the experiments in the past and in the present study.

Finally, Chapter 7 summarizes this study. The findings in the present work are expected to contribute to the development of rational models for predicting the drag reduction, and optimizing its use in practical applications.