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The effects of microbubbles on skin friction in a turbulent boundary layer flow

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ABSTRACT

The main objectives of the present study are to visualize a bubbly turbulent boundary layer and to investigate the role of the bubbles in frictional drag reduction. The turbulent boundary layer is formed under the surface of a 2-D flat plate. A microbubble generator is used to produce bubbles with diameters in the range 5–100 μm and a mean bubble diameter of 30 ~ 50 μm. The behaviors of the microbubbles are visualized quantitatively by using the conventional PIV technique with a field-of-view of 200 mm^2. The velocity fields of the bubbles show that they reduce the Reynolds stress in the boundary layer. To understand the relationships between the distribution of the void fraction due to the microbubbles and the frictional drag reduction, the shadowgraphy technique was adopted within a tiny field-of-view of 5.6 mm^2. The bubble images are analyzed by performing shadow processing to obtain information about their shapes and speeds. A local 2D void fraction of approximately 3.5% in the buffer layer is found to be highly effective in reducing skin friction by decreasing the Reynolds stress. The 3D void fraction of 1.3–3.0% is also found to reduce skin friction in the present study. The vertical fluctuating motion of microbubbles as well as a high concentration of them in buffer layer is effective in reducing the skin friction in high Reynolds number regime of 10^6.

Introduction

International environmental regulation of the emissions of greenhouse gas has been strengthened by the IMO (International Maritime Organization), and thus the interest in energy saving devices and technologies for use in marine vehicles is increasing. There have been many research attempts to reduce the energy consumption of marine vehicles and to increase their speed, for which decreasing the hydrodynamic drag is crucial. There are generally four kinds of drag that produce resistance against the motion of a body in water: friction, pressure, wave-making, and air drag.

Skin friction is a hydrodynamic drag known as viscous drag because it is most influenced by the fluid viscosity and increases with the fluid flow velocity. There are passive and active methods for reducing the skin friction occurring on the surface of a moving body. Passive methods have attracted much attention because they do not require additional energy. Although active methods do require additional energy to perturb the turbulent flow structure or boundary layer, their drag reduction effects are not small compared to those of the passive method. Active methods such as injecting air layers (Elbing et al., 2008; Sanders et al., 2006; Mäkiharju et al., 2012) or bubbles (Kodama et al., 2002; Kitagawa et al., 2005; Murai et al., 2006) into the boundary layer have been tested with the aim of decreasing the fraction of the wetted area or of changing the effective viscosity and other properties of the boundary layer. Bubble injection was the active method of interest in the present study. Drag reduction with bubbles is generally classified in terms of the bubble size: normal bubbles have diameters of 100 μm ~ 1 mm and microbubbles have diameters of less than 100 μm.

Various studies have examined drag reduction via the microbubble injection method. Hassan and Gutierrez-Torres (2006) studied the drag reduction mechanism to elucidate the influence of microbubbles within the boundary layer, and reported that increases in the microbubble concentration contribute to decreases in the Reynolds stress and turbulence production in the boundary layer. Jacob et al. (2010) also investigated the frictional drag reduction produced by microbubbles with diameters less than 100 μm, which corresponded to the local Kolmogorov length scale within the turbulent boundary layer studied. In their study, by measuring the concentration of microbubbles and characterizing their

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behavior with the particle image velocimetry technique, they found that microbubbles decrease the Reynolds stress and change the flow velocity gradient in the turbulent boundary layer. Hara et al. (2011) applied image analysis to the study of frictional-drag reduction by microbubbles in a turbulent channel flow and found that oscillatory motion in the vertical direction reduces the Reynolds stress near the wall, and that this effect is more relevant upstream than downstream. Fukagata et al. (2002) reported the near-wall Reynolds stress was critical for the prediction and control of wall turbulence affecting skin friction by theoretical method. Ferrante and Elghobashi (2005) studied the Reynolds number effect in a spatially developing turbulent boundary layer with the direct numerical simulation (DNS) method. They reported that an increase in the momentum thickness Reynolds number squeezes the quasi-streamwise vortical structures toward the wall, whereas the microbubbles push them away from the wall. In addition, it was found that an increase in the concentration gradient of the microbubbles produces a local positive velocity divergence in the boundary layer, and finally results in this displacement action of the microbubbles. In the higher Reynolds number regime, a higher bubble volume fraction was found to be required within the boundary layer to achieve the same effect as in the low Reynolds number regime.

Previous studies have generally used electrolysis microbubble generators, and have had difficulties in generating bubbles smaller than 100 μm and high concentrations of bubbles within the inner layer of the turbulent boundary layer. Many of these experiments were performed in the momentum thickness Reynolds number regime of 1000–4000 or for Reynolds numbers (based on channel height) of 3000–5000, and the turbulent boundary layer has been simulated asymptotically at rather low flow velocities. In the present study, a pressurization and dissolution microbubble generator was employed to obtain a high concentration of bubbles in the boundary layer. All our experiments were conducted in a medium-sized cavitation tunnel to achieve high Reynolds numbers of approximately 10^6 (based on the free-stream velocity and the local distance from the leading edge). The Reynolds stress distribution in the boundary layer was investigated by using the PIV technique. Moreover, long distance microscopy (LDM) and the shadowgraphy method were also utilized to obtain a very small field-of-view of a few mm^2 in order to measure the variations with flow speed in the microbubble concentrations in the buffer layer and the viscous sub-layer. The microbubble concentration was found to be the dominant influence on frictional drag reduction in the turbulent boundary layer.

Experimental apparatus and method

The drag measurements for the 2-D flat plate and the flow visualization of the turbulent boundary layer were carried out in the medium-sized cavitation tunnel at KRISO (Korea Research Institute of Ships & Ocean Engineering, formerly MOERI). The dimensions of the rectangular test section were $0.6^{W} \times 0.6^{H} \times 2.6^{L}\ \text{m}^3$. The flow speed in the test section of the tunnel was varied from 1 m/s to 3.0 m/s with an interval of 0.5 m/s. The static pressure in the test section was kept at atmospheric pressure.

A flat plate model was designed and manufactured to investigate the effects on drag of injected microbubbles. The material of the flat plate was black-anodized mild steel. The plates were supported by two struts to maximize their flatness and to minimize twisting or bending effects on the fluid flow, as shown in Fig. 1. The dimensions of the flat plate were $400^{W} \times 10^{H} \times 2000^{L}\ \text{mm}^3$. The origin of the coordinates was located at the leading edge of the flat plate. Two friction sensors were flush-mounted at the locations $X/L = 0.53$ and $X/L = 0.93$ (X is the distance from the leading edge, $L =$ the length of the flat plate) to measure the local skin friction. The friction sensor was the type of underwater multi-beam with ±0.1% accuracy and 20 μs time response. The diameter of the sensing area was 100 mm.

A pressurization and dissolution microbubble generator was used in the present study. The discharge flow rate of the bubbly flow at the end of the nozzle was fixed to approximately 5.77 l/min in this study. The position of the nozzle was at $X/L = 0.23$. Six microbubble injectors were aligned in spanwise direction to provide a satisfactory bubble flow rate (Fig. 2). The microbubble injector has 2 mm diameter and is inclined at an angle less than 15° to discharge the microbubbles into the boundary layer beneath the flat plate, as shown in Fig. 3. The outlet velocity of mixture fluid was

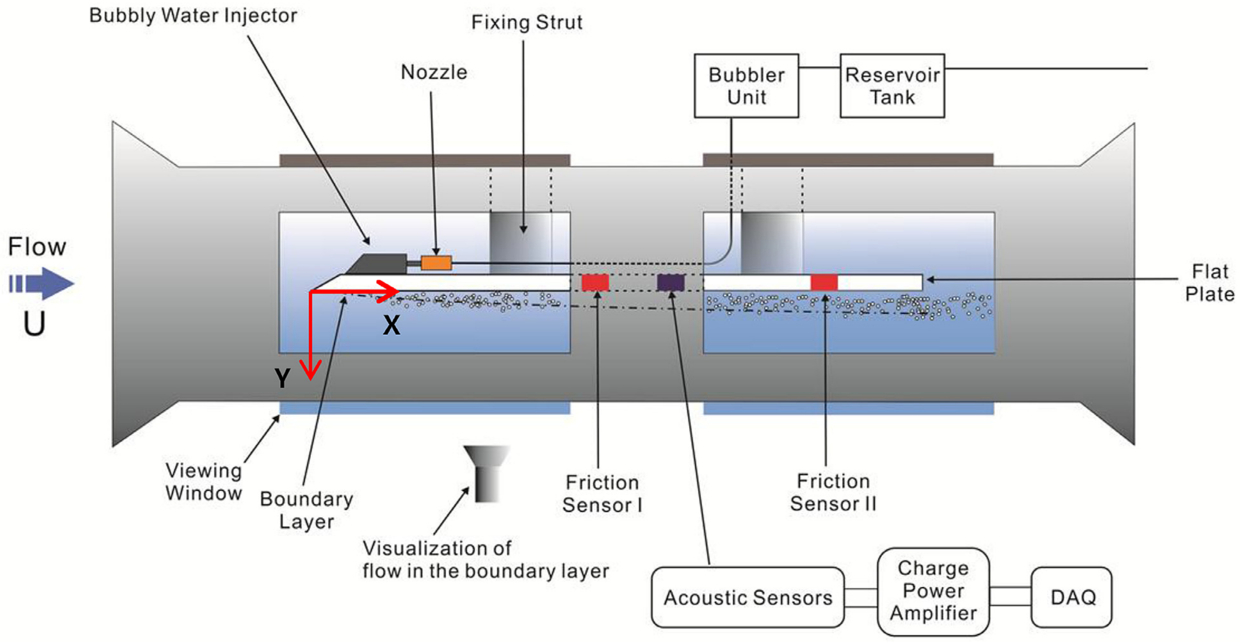

Fig. 1. Schematic diagram of the flat plate model in cavitation tunnel.