Center for Fluid Mechanics
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Bubble Friction Drag Reduction in a High Reynolds Number Flat Plate Turbulent Boundary Layer

Turbulent boundary layer skin friction in liquid flows may be reduced when bubbles are present near the surface on which the boundary layer forms. Prior experimental studies of this phenomenon reached downstream-distance-based Reynolds numbers (Re_x) of several million, but potential applications may occur at Re_x orders of magnitude higher. This paper presents results for Re_x as high as 210 million from skin-friction drag reduction experiments conducted in the US Navy's William B. Morgan Large Cavitation Channel (LCC). Here, a near-zero-pressure-gradient flat-plate turbulent boundary layer was generated on a 12.9-m-long hydraulically smooth flat plate that spanned the test section. The test surface faced downward and air was injected at volumetric rates to 0.38 m^3s^{-1} through one of two flush-mounted 40-micron sintered-metal strips that spanned the test model at upstream and downstream locations. Spatially- and temporally-averaged shear stress, bubble images, and impedance-based void fraction measurements are reported here. For the measured flow conditions, the mean bubble diameter was ~300 microns. At the lowest test speed (6 ms^{-1}), buoyancy pushed the air bubbles to the plate surface where they coalesced to form a quasi-continuous gas film that lead to near-100% skin-friction drag reduction and that persisted to the farthest downstream measurement location. At higher flow speeds, the bubbles remained distinct and skin-friction drag reduction was observed when the bubbly mixture was within $300\,l_o^+$ of the plate surface even when the bubble diameter was more than $100\,l_o^+$, where l_o^+ is the viscous wall unit of the equivalent boundary layer without air injection. Skin-friction drag reduction did not persist when shear-induced bubble migration pulled bubbles farther from the plate. The measurements suggest that a combination of density reduction and turbulence modification is responsible for bubble-based skin-friction drag reduction. A simple one-way-coupled bubble-tracking model provides insight into the bubble stratification process near the plate surface.

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