Abstract of the Dissertation

Reduction of skin-friction in a microbubble-laden spatially developing turbulent boundary layer over a flat plate

by

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Experimental evidence during the past three decades indicates that injection of gaseous microbubbles into a liquid turbulent boundary layer over a flat plate or over axisymmetrical bodies can reduce the skin-friction by as much as 80% from its value without bubble injection. However, the basic physical mechanisms responsible for that reduction are not yet fully understood. The present study is concerned with the direct numerical simulation (DNS) of the effects of dispersed gaseous bubbles on the dynamics of wall turbulence with the objective of explaining the physical mechanisms responsible for the reduction of skin-friction.

First, the DNS of a single-phase spatially developing turbulent boundary layer over a flat plate was performed. A robust method for generating turbulent inflow conditions was developed. The method is a modification of that of Lund, Wu and Squires (1998). This modification is essential for sustaining the production rate of turbulence kinetic energy near the wall throughout the domain. The DNS is validated by comparing the results with the experimental data of DeGraaff & Eaton (2000) at $\mathrm{Re}_\theta = 1430$.

Then, the DNS of a bubble-laden wall bounded turbulent flow was performed using the Eulerian-Lagrangian approach for the two-way coupling case. In addition to the two-way coupling force, all terms of the Navier-Stokes equations of the carrier fluid include the instantaneous local volume fraction of the bubbles. The carrier fluid is laden with microbubbles for different values of the mean void fraction ranging from $\phi_v = 0.001$ to 0.02, while keeping the bubble diameter equal to 2.4 viscous length scales (or wall units). The DNS results show that the presence of bubbles creates a *local* positive divergence of the fluid velocity, $\nabla \cdot \boldsymbol{U} > 0$, generating a positive mean velocity normal to (and away from) the wall which, in turn, reduces the mean streamwise velocity and displaces the quasi-streamwise longitudinal vortical structures away from the wall. This displacement has two main effects:

1. it increases the spanwise gaps between the wall streaks associated with the sweep events and reduces the streamwise velocity in these streaks, thus reducing the skin-friction by up to 20% for $\phi_v = 0.02$, and
2. it moves the location of peak Reynolds stress production away from the wall to a zone of a smaller transverse gradient of the mean streamwise velocity (i.e. smaller mean shear), thus reducing the production rate of turbulence kinetic energy and enstrophy.

Furthermore, for different orientation of the gravitational acceleration vector, buoyancy can enhance (reduce) the '*velocity divergence effect*' by increasing (reducing) the local concentration of bubbles near the plate in the case of plate-on-top (plate-on-bottom), by pushing the bubbles towards (away from) the plate in agreement with the experimental results of Madavan et al. (1984, 1985).