Drag Reduction by Microbubbles in a Spatially-Developing Turbulent Boundary Layer: Reynolds Number Effect (HPCMP/CAP)

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INTRODUCTION

Experimental evidence during the past three decades indicates that the injection of gaseous microbubbles (diameter ranging from 1 to 1000 microns, and at a relatively large volume fraction (up to $\Phi_v = 0.7$)) into a liquid turbulent boundary layer over a flat plate[1, 2] or over axisymmetrical bodies[3] can reduce the skin friction by as much as 80 percent from its value without bubble injection. However, the basic physical mechanisms responsible for that reduction were not yet fully understood.

This article discusses the physical mechanisms responsible for the reduction of skin friction in a microbubble-laden, Spatially-Developing Turbulent Boundary Layer (SDTBL) over a flat plate[4], and the effects of increasing Reynolds number on drag reduction.[5] This discussion is based on the results of the author's Direct Numerical Simulations (DNS) of a microbubble-laden SDTBL. These simulations were performed on High Performance Computing (HPC) highly scalable supercomputers (CRAY T3E and IBM Power4+ (KRAKEN)) at the Naval Oceanographic Office (NAVOCEANO) Major Shared Resource Center (MSRC).

MATHEMATICAL DESCRIPTION

Figure 1 shows a schematic of the SDTBL flow where the gravitational acceleration vector is perpendicular to the wall and pointing downward. The DNS used in this simulation employs the Eulerian-Lagrangian approach to solve the fluid continuity and momentum equations in an Eulerian framework. The bubble acceleration equation, on the other hand, is solved for each bubble to track its trajectory in time.[4, 5]

The governing equations of the fluid motion account for the instantaneous local volume fraction of the bubbles. The bubble equation of motion includes terms representing the added mass, carrier fluid inertia, Stokes drag, buoyancy, and lift force. The governing equations[4, 5] were discretized in space using a second-order finite difference scheme—except for the mean advection terms, which were evaluated via a fifth-order upwind differencing scheme.

Time integration in this simulation was performed using the second-order Adams-Bashforth scheme. The discretized Poisson equation for pressure was solved using a cosine transform in the streamwise direction, a Fast Fourier Transform (FFT) in the spanwise direction, and Gauss elimination in the wall-normal direction. The discrete cosine and Fourier transforms were computed using the Fastest Fourier Transform in the West (FFTW) C subroutine library.[6]

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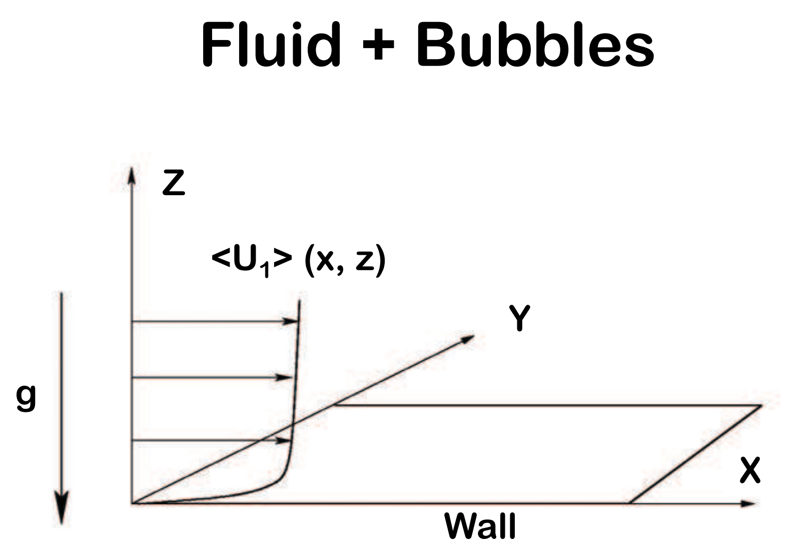

Figure 1. Schematic of microbubble-laden turbulent boundary layer flow over a flat wall.

CAP PARALLEL PERFORMANCE TESTS

During the past four years the authors have used their newly-developed parallel code (DNSBLB, written in FORTRAN 90/MPI), which performs a DNS of a microbubble-laden SDTBL.[4, 5, 7, 8, 9] DNSBLB is parallelized with a One-Dimensional (1D) domain decomposition in the spanwise *y*-direction (*j*) of the three-dimensional computational domain.* DNSBLB was originally written for the CRAY T3E.

During the Capability Applications Project (CAP) 2004, the CRAY T3E version of DNSBLB was converted to run on KRAKEN. The IBM version of DNSBLB is more than ten times faster than its T3E version. The scalability runs of the DNS code were performed using up to 1024 processors for two different computational meshes: a coarse mesh of 256x256x96 = 6x10^{6} grid points, and a fine mesh of 1024x1024x96 = 101x10^{6} grid points; and for four different numbers of bubbles 100 thousand, 16 million, 100 million, and 200 million.

The scalability tests were performed in a one-way coupling regime, i.e., no effects of bubble on turbulence were accounted for. The two-way coupling increases the Central Processing Unit (CPU) time but does not worsen the scalability of the code. Figure 2 shows the CPU time in seconds per processor, per time step needed for the integration of the governing equations of both the fluid and bubbles, versus the number of processors used on KRAKEN. Different lines correspond to different computational meshes and numbers of bubbles. The CPU time monotonically decreases as the number of processors increase (see Figure 2) for all the tests performed.

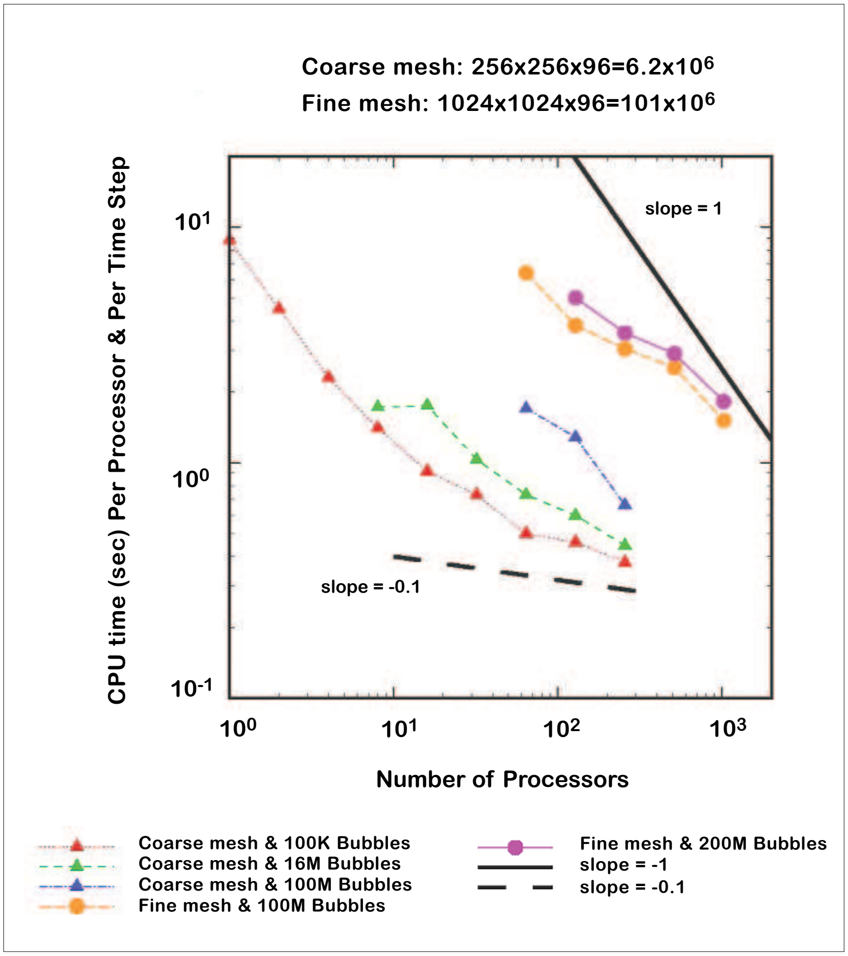

Figure 2. Scalability on IBM P4+ (KRAKEN) of DNS code.

Figure 2 also shows that for the coarse mesh with 100 thousand bubbles, the slope of the line (CPU time versus number of processors) is close to -0.1, whereas for the fine mesh with 200 million bubbles, the slope is close to -1.

The slopes for the other tests are between -0.1 and -1. This means that the performance of the DNS code improves as the number of grid points of the computational mesh and the number of bubbles simulated increase. Furthermore, for the fine mesh the code shows a nearly ideal scalability since the line in Figure 2 has a slope close to -1.

DRAG REDUCTION BY MICROBUBBLES: REYNOLDS NUMBER EFFECT

The DNS results[4] for the microbubble-laden SDTBL for $R_e\Theta = 1430$ with volume fraction ranging from Φ_v= 0.001 to 0.02 show that the presence of bubbles results in a local positive divergence of the fluid velocity, $\nabla \cdot U > 0$. This creates a positive mean velocity, <*U3*>, 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 as in Figure 3. This displacement has two main effects:

- It increases the spanwise gaps between the wall streaks associated with the sweep events and reduces the streamwise

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*If np is the number of processors and *N*, even multiple of *np*, is the number of grid points in the *j* direction, then each processor makes calculation on *N*=*np* planes (*x*-*z* planes) of the computational domain.

velocity in these streaks, thus reducing the skin friction.

- 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.

During CAP 2004 the authors were able to simulate the microbubble-laden SDTBL for $R_e\Theta = 2900$ with volume fraction $\Phi_v = 0.01$ and bubble diameter of 40υm using a computational mesh of 1024x512x128 = 67x10^6 grid points and 29 million bubbles.

The computations were performed on 512 processors of the KRAKEN system. The bubble-laden flow simulations required 9.6 CPU hours per processor and 124 gigabytes of maximum total memory.

The DNS results[5] show that increasing Reynolds numbers from 1430 to 2900 decreases the percentage of drag reduction from 22 to 19 percent. Increasing $R_e\Theta$ "squeezes" the quasi-streamwise vortical structures toward the wall, whereas microbubbles "push them away" from the wall.

The net result of these two opposing effects determines the amount of skin friction reduction by the microbubbles.

The displacement action by the microbubbles is a result of the local positive velocity divergence, $\nabla \cdot U$, created by their concentration gradients. Thus, the volume fraction of bubbles that is responsible for the reduction of skin friction in a low Reynolds number SDTBL is not sufficient to produce the same amount of reduction in skin friction at higher Reynolds number.

SUMMARY

This article has briefly discussed the physical mechanisms of drag reduction by microbubbles and the Reynolds number effect.[4, 5]

Furthermore, it reports some details on the simulations of parallel DNS code and its scalability on the NAVOCEANO MSRC KRAKEN system.

In conclusion, the CAP program has considerably helped the author's drag reduction by microbubbles research to explain the effect of Reynolds number on drag reduction by allowing the use of a large number of processors and extended CPU hours which were not allowed in the "standard" queues.

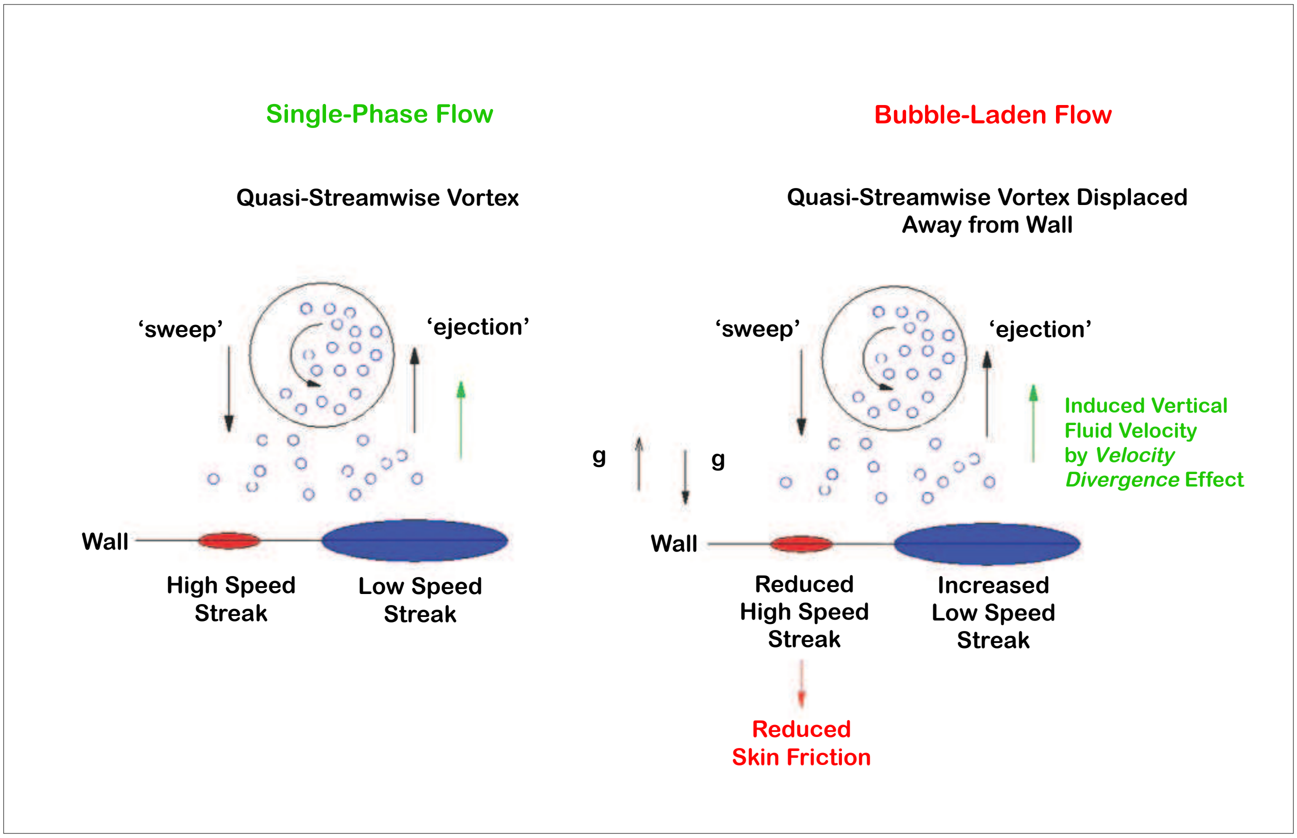

Figure 3. Schematic of the drag reduction mechanism in a microbubble-laden SDTBL.

Acknowledgements

This work was supported by Office of Naval Research (ONR) Grant No. N00014-05-1-0059 under the direction of Dr. Patrick Purtell. The computations were performed on the IBM Power4+ (KRAKEN) located at the NAVO MSRC at the John C. Stennis Space Center (Mississippi), and on CRAY T3E (MD) located at the U.S. Army High Performing Computing Research Center (AHPCRC, Minnesota). The authors thank the outreach group at the NAVOCEANO MSRC and the support group at AHPCRC for allowing jobs with CPU time limits larger than those allowed in the "standard" queues.

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