A comparison of shear stress fluctuation statistics between microbubble modified and polymer modified turbulent boundary layers

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Shear stress fluctuation statistics, as measured by flush mounted hot film probes, are presented for both microbubble and polymer injection into the same zero pressure gradient turbulent boundary layer. At equivalent values of drag reduction, the moments of the probability distribution are remarkably similar. For drag reductions larger than about 40%, the deviation of the skewness and kurtosis values from their pure water values argue against simple scaling explanations of the drag reduction phenomenon.

I. INTRODUCTION

Previous experimental investigations have documented that injecting either gas to form microbubbles[1–4] or high molecular weight polymer solutions[5,6] into a water turbulent boundary layer, drastically reduces the skin friction drag. Our understanding of drag reduction is somewhat rudimentary. To the level of the mixing length approximation, it seems that both polymer and microbubble injection essentially destroy turbulent production scales in the buffer region,[7,8] effectively increasing the size of the viscous sublayer. Lumley[7] has argued that in the buffer region, in which strain and rotation are not well correlated, polymer molecules would stretch. The resulting relative velocity across the molecule would give rise to an additional drag, which the fluid would perceive as an increased kinematic viscosity. Here, it is important to note that in the sublayer, where rotation and strain are well correlated, polymer molecules will not stretch and the viscosity should remain unchanged. A similar argument has been used by Madavan *et al.*[1] to provide a framework for microbubble drag reduction. Here, the argument goes, the sublayer is unchanged because bubbles are not found there (based on observations), while the concentration of bubbles peaks near the buffer region (for effective drag reduction). The presence of the bubbles introduces a higher dynamic viscosity through an Einstein type of relation, say, while the overall density of the mixture is reduced. Simple computer studies[8] suggest that it is the density change that matters most, but in any event, the result is again an increase in kinematic viscosity in the buffer region and a resulting destruction of production scales in the near wall.

Madavan *et al.*[2] has noted the similarity of microbubble and polymer (as measured by Fortuna and Hanratty[5]) shear stress energy spectra when both are normalized by their appropriate inner scales. The current work extends these observations by employing fluctuating shear stress measurements of both polymer and microbubble additives injected into the same zero pressure gradient turbulent boundary layer, and by comparing the measured higher-order statistics for both over a wide range of drag reduction values.

II. FACILITY AND PROCEDURE

The experiments were conducted on an 1100 mm long flat plate mounted horizontally in the 12 in. diam water tunnel at the Pennsylvania State University. The boundary layer on the flat plate was shown to be a fully developed, zero pressure gradient turbulent boundary layer by a combination of static pressure and LDV surveys.[3] At the most downstream probe location, the momentum thickness Reynolds numbers and the shear velocity varied from 6650 and 0.18 m/sec at a free-stream speed of 4.6 m/sec to 18 500 and 0.5 m/sec at 14 m/sec. A more complete documentation of the flow may be found in Ref. 3.

Both microbubbles and polymers were injected into the boundary layer. The polymers were injected through a 60 mm by 0.6 mm slot, while the gas was injected through a 76 mm by 51 mm, 40 μm porous section. Both the slot and the porous section were located about 260 mm from the plate leading edge, as shown in Fig. 1. All measurements reported here were taken at a tunnel speed of 10.6 m/sec. The measurements made at both lower and higher speeds, which ranged from 4.6–17 m/sec, however, show essentially the same behavior.

Separan (AP 30), mixed in a concentration of 1000 parts per million (ppm) and allowed to sit overnight, was used for the polymer tests. Prior to use, the solution was diluted to 500 ppm. A variable flow rate peristaltic pump was used to inject the solution. Total polymer injection over the course of the experiment was small relative to the volume of the tunnel, so that the base drag state did not change. Injection of tunnel water at the maximum flow rate employed for the polymer studies has no measurable influence on the drag results.

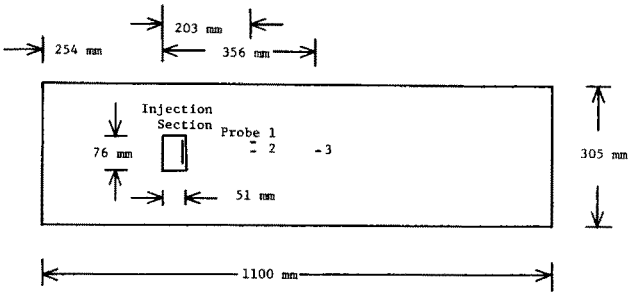

FIG. 1. Schematic of the experimental setup.

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Shear stress measurements on the flat plate were carried out by means of TSI model 1471 W, miniature flush mounted hot film probes. The probes are roughly 400 μm in the flow direction, with an aspect ratio of 2. Data from the films was A/D converted and recorded at 1000 Hz for 2.5 sec on a VAX 11/780. Longer sampling time produced equivalent results. The locations of the films are shown in Fig. 1. As in our earlier microbubble studies,[2] the probes were first calibrated against the known turbulent boundary layer characteristics of the pure water flow. Measurements with additives were then taken, followed by an additional calibration. If the coefficient of the linear least-squares fit between these calibrations was less than 0.98, the entire data set was dropped. We note that it was no more difficult to meet this criterion during the polymer or microbubble tests as it was with pure water. Fouling of the probes resulting from the injection of the polymer (or exposure to air) was not observed.

Justification of the use of flush mounted films for microbubbles is discussed in Ref. 2. We have found that comparisons between drag balance measurements and integrations of flush mounted probe measurements in which the probes were mounted on the balance, agreed to about 10% over the measured drag reduction range. It is well documented that some measurement devices, when inserted in the flow, will give biased readings in polymer solutions (see, for example, Ref. 9). Here the major problems would seem to be potential fouling of the probe or the introduction of a strain field that would cause the polymer to stretch. As we noted earlier, we did not observe fouling of the wall mounted probes. To use the probes, one requires then that the heat transfer and shear stress change in the same way in polymer solution and water. There is some evidence that this is not the case,[10] and one should consider the magnitude of the error that might be introduced. Recently a colleague (Petrie[11]) has essentially repeated a study, using polymers, which is very similar to that done by Madavan *et al.* for microbubbles.[2] They find that the difference between balance and film results on the order of 20%. Differences of this magnitude will not substantially affect the results or conclusions of the current study.

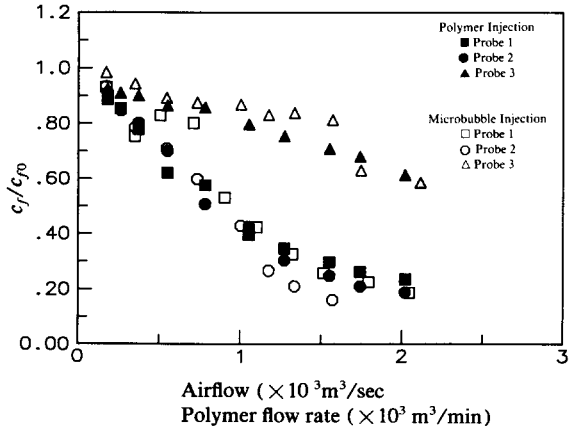

FIG. 2. The drag reduction ratio, c_f/c_{f0} for both polymer and microbubble injection.

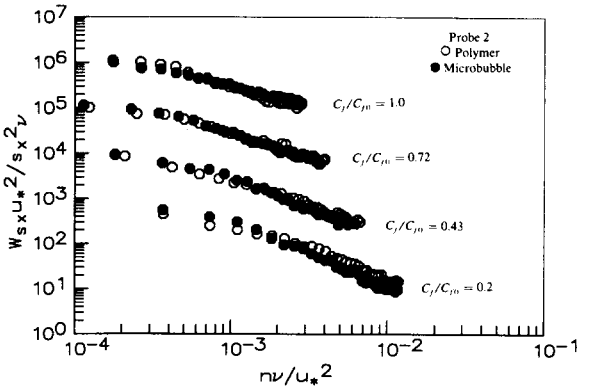

FIG. 3. The energy spectra for polymer and microbubble injection as a function of c_f/c_{f0}.

III. RESULTS

In Fig. 2, we present the ratio of skin friction drag to pure water skin friction drag for both the polymer and microbubble injection as a function of their respective volumetric flow rates. The similarity for the results for the two upstream probes, which are at different spanwise locations, argues for the two-dimensionality of the flow with injection.

Energy spectra for the shear stress fluctuations are shown for both additives, as a function of percent drag reduction, in Fig. 3. When normalized by actual inner variables, as the curves are in Fig. 3, no significant differences between the two cases are apparent. The energy spectra shown also agree very well with that taken by Fortuna and Hanratty,[5] using an electrochemical technique in a polymer solution.

Figure 4 depicts the intensities of the shear stress fluctuations for both cases as a function of their skin friction ratios. The nonadditive value for the intensity is somewhat controversial. For skin friction ratios above about 0.6, we observe values near 0.24, which agree with measurements obtained by Eckleman[12] in an oil channel. While this article was in review, Alfredsson[13] presented an argument for taking this value as 0.4. It is probable that the hot films are averaging over some of the small-scale turbulence for our high unit Reynolds number boundary layers. The value of 0.24 was

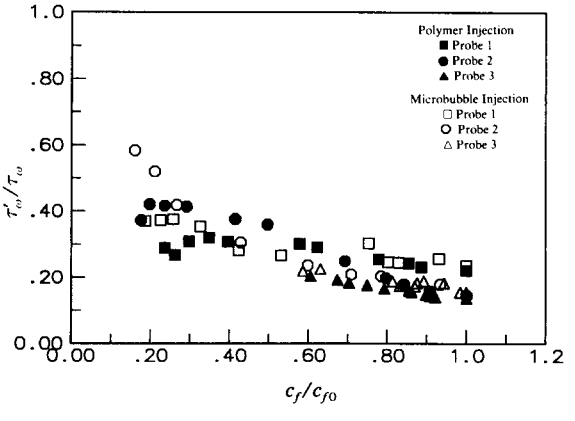

FIG. 4. Intensity of the shear stress signals versus c_f/c_{f0}.

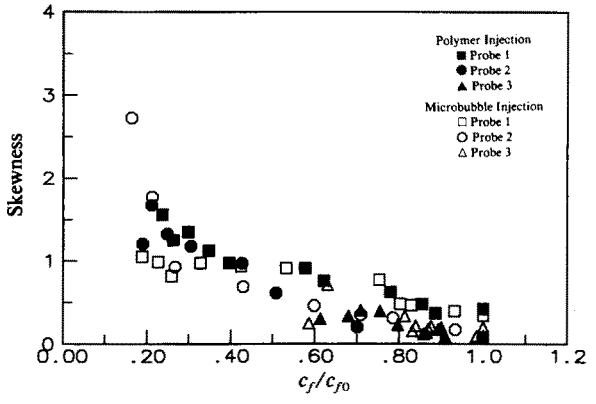

FIG. 5. Skewness of the shear stress signals versus c_f/c_{f0}.

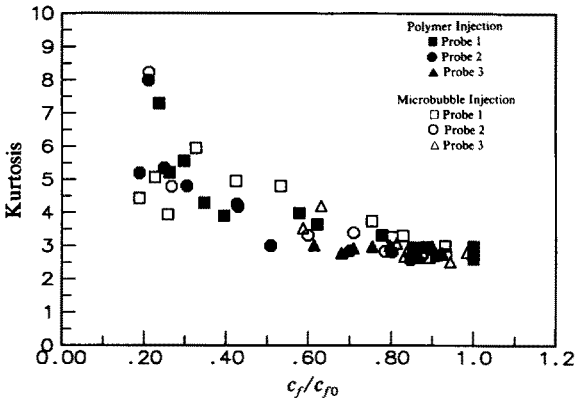

FIG. 6. Kurtosis of the shear stress signals versus c_f/c_{f0}.

typical, however, for our entire range of tests, which covered a range of momentum thickness Reynolds numbers from 4000 to above 18 000, so that it is not entirely clear that averaging can explain these differences. In any event, the absolute value of the intensities will not change the results of this comparative study.

As the skin friction ratio decreases below 0.6, we observe a large increase in the shear stress fluctuation intensity. The deviation from pure water values for skin friction ratios below 0.6 is even more apparent in the plots of skewness and kurtosis of the shear stress fluctuations, which are given in Figs. 5 and 6. For values of the skin friction ratio above 0.6, both the skewness and the kurtosis are only slightly different than the Gaussian values of 0 and 3, respectively. For decreasing skin friction ratios the skewness becomes increasingly positive, indicating that large positive fluctuations from the norm are becoming more prevalent. This is consistent with the kurtosis values that show that the tails of the distribution are becoming more and more important. Note that Madavan *et al.*[1] have presented time traces of the shear stress signal and it is apparent from them that the flow is not relaminarizing, so that the larger values of skewness and kurtosis are not a result of an intermittancy. One gets the picture instead of a turbulence that consists more and more, as the drag reduction increases, of only large eddies. Such a flow is reminescent of, say, the final stage of decay of grid turbulence.

IV. CONCLUSIONS

We have shown, in experiments in which microbubbles and polymers were each injected into the same zero pressure gradient turbulent boundary layer, that at equivalent values of the skin friction ratio, the basic turbulence characteristics of the shear stress signals are essentially the same. We have also shown that for drag reduction ratios greater than about 0.6 the additive flows have essentially the same turbulence characteristic as a pure water flow. This would suggest that simple theories, which essentially rescale the boundary layer on the basis of a reduced friction velocity, are probably reasonable in this range. For larger drag reduction, however, we observed large deviations in the turbulence statistics from their pure water values. This implies a change in the basic nature of the turbulence, and theoretical efforts to explain the drag reduction mechanisms are likely to be much more difficult.

ACKNOWLEDGMENT

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