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Skin Friction Measurements in Flows Over Tethered Polymer Coatings

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EXECUTIVE SUMMARY

The effect of a tethered polymer coating on the turbulence production in a turbulent boundary layer was examined. An experimental investigation was carried out in the Naval Ocean Systems Center (NOSC) water tunnel. The aims of the study were to determine the existence of an interaction between the tethered polymer coating and turbulence production at the wall and in the outer layer. Skin friction was measured in a flat plate turbulent boundary layer with and without tethered polymer coating. There were no measurable effects on the turbulent boundary layer skin friction. We should point out the purpose of the tethered polymer coatings is the prevention of biofouling on ships. With this fact in mind it is encouraging that the coating has no deleterious effect on the boundary layer.

INTRODUCTION AND BACKGROUND

The turbulent production process on a hydrodynamically smooth wall ($k^+ < 5$) has been extensively investigated (Kline et al., 1967; Kim et al., 1971; Lu and Willmarth, 1972). The formation of low-speed streaks in the viscous region near the wall, their subsequent lift-up, oscillation, and breakup appears to occur as a reasonably regular sequence of events, called the *burst sweep cycle*. These events appear to be confined to a near-wall layer of thickness less than $100\nu/u_\tau$. Further research, however, indicates there exists a complex interaction between the inner and outer layers (Rao et al., 1971; Grass, 1971). Rao (1971) suggested larger eddies from the outer layer move down in the boundary layer and scour the slow-moving inner layer, creating regions of intense shear. The shear excites and enlarges local instabilities, thus triggering the burst-sweep cycle. The precise extent, and importance, of this interaction is still the subject of intense debate.

We know that on a smooth wall, the effect of non-Newtonian additives is to move the region of maximum shear stress (the buffer layer) further away from the wall into a region of low velocity gradient, thereby reducing the turbulent production (Luchik and Tiederman, 1988). In a fully rough channel flow, where the buffer layer is significantly different than in smooth walls, these additives are still effective in reducing drag (Hendricks et al., 1988). In both smooth and rough wall flows the polymer must be present in a region of high shear to be effective.

Past work in polymer drag reduction was done with the molecules in solution. The novel approach examined in this study is a coating where one end of the polymer molecules is tethered to a coating to restrict the migration of the molecules from the regions of intense shear where they are effective. Such a coating was developed at the National Science Foundation's Industry/University Cooperative Research Center for Biosurfaces at SUNY–Buffalo by Dr. Robert Baier for use as an antifouling coating on surface ships. The SUNY tethered polymer coating is a two-layer coating. The initial layer of the coating is composed of a polyether-type polyurethane cured film, medical grade, and cross linked. The function of the polyurethane layer is to provide a substrate to increase the adhesion of the layer of tethered long-chain polymer. The polymer coating used was called Cardiomat-40. Cardiomat-40 is a acetoxy-cured (infinite molecular weight) polydimethyl-siloxame (medical grade).

The objective of the work reported here is to examine the effect of the tethered polymer coating just described, on the skin friction of a flat plate turbulent boundary layer flow. Specifically, measurements of skin friction in turbulent boundary layer flows with and without a tethered polymer coatings were done.

TECHNICAL APPROACH

An experimental investigation was carried out at NOSC's Hydromechanics Laboratory in the open jet, recirculating water tunnel. The tunnel is a high quality facility with a turbulence level of less than 0.15 percent over the speed range from 0 to 12 m/s. The test section is 1 m long, with a 0.31-m diameter jet. The flat test plate model was mounted on longitudinal supports, outside of the jet in a horizontal position along its centerline. The test plate and its leading edge were separately constructed from type 302 stainless steel. The plate is 19.0 mm thick and 0.58 m wide, with an overall length of 0.86 m. The leading edge piece has a streamwise length of 0.15 m and a width of 0.30 m and was machined to include a rounded edge with a 1.6-mm high forward facing step. The step was designed to act as a tripping device and the leading edge was placed in the water tunnel contraction section to obtain as long a test plate as possible. Figure 1 shows a diagram of the test plate; Re_θ values of about 9000 were obtained at the end of the plate. Velocity field measurements were made using a TSI Laser Doppler Velocimeter (LDV) mounted on a three-dimensional traverse with numerically-controlled positioning. The LDV was operated in the backward scatter mode using a 1-W Argon-Ion laser, velocities measurements could be made as close as 0.05 mm from the plate. Flat plate experiments with four different coatings were done. The coatings are 18 by 24 inches in size and the leading edge of the coatings are located 7 inches downstream from the leading edge of the plate.

Velocity profile measurements made with a control surface (no coating) on the test plate verified the presence of a zero pressure-gradient, fully turbulent boundary layer in the measurement region (see Reidy and Anderson 1988 for details). The local skin friction coefficient, C_f, was calculated from velocity profiles using the Ludwig-Tillman relationship:

$$C_f = 0.246(10)^{-0.678H} Re_\theta^{-0.268}$$

where the displacement δ^* and momentum (θ) thickness, and H $(H = \delta^*/\theta)$ were obtained by integrating the experimental velocity profiles.

Point velocitys were determined by digitizing the analog output of the LDV counter-type processor. Data was digitized at 5000 samples/sec and a running average of the mean and mean square of 2^{17} data samples were used to calculate the mean and RMS velocity at each y profile location.

Velocity profiles were measured at x = 0.625 m, which is near the trailing edge of the test (or control) coatings. Velocity profiles closer to the trailing edge were not used because the small step-down from the coating to the plate might have an affect on the profile shape.

The uncertainties in the measured quantities, velocity and y-position, were used to calculate an uncertainty in momentum thickness of ± 1.1 percent of the measured value. Based on this, the error bands on percent drag reduction (%DR), range from ± 2.5 to ± 2.9 percent, depending on the Reynolds number.

RESULTS

The results of the measurements are summarized in figures 2 through 5. Skin friction measurements were done on a reference surface (uncoated), a surface coated with 10 microns of silicone and two coatings with Cardiomat-40 on them. Measurements were made for a range of Reynolds numbers from $2x10^6$ to $9x10^6$ and for several spanwise locations (figure 2). In summary, the results indicate no measurable affect on the turbulent boundary layer by any of the coatings tested. This result is not an unexpected result for surface # 2 (silicone coated). This coating was tested for completeness and as a validation of the methods. There were some problems manufacturing the Cardiomat-40 coatings and the initial tests on the first Cardiomat-40 coating (surface # 3) indicated no reduction in skin friction. We thought this might be due to the fact surface # 3 had a very rough finish. Consequently, a fourth surface was tested after the manufacturing problems were resolved. Surface # 4 had a flawless finish but nevertheless demonstrated similar performance.

DISCUSSION AND CONCLUSIONS

The repeatable baseline measurements of C_f (surfaces 1 and 2) agree with past researchers values for skin friction on flat plates and are an important validation of the methodology. The results for the Cardiomat-40 coatings are not unexpected. Although the polymers are tethered and prevented from migrating out of the high shear layer of the boundary layer, they are shorter in length than one might expect to be necessary to reach the buffer region of the turbulent boundary layer. The lack of success in reducing C_f drag by the tethered polymer coating should not be viewed as a negative result. The primary purpose of these coatings is to prevent fouling on ships. Note, these coatings add no skin friction drag penalty when applied to a flat plate and could be expected to perform similarly on any ship.

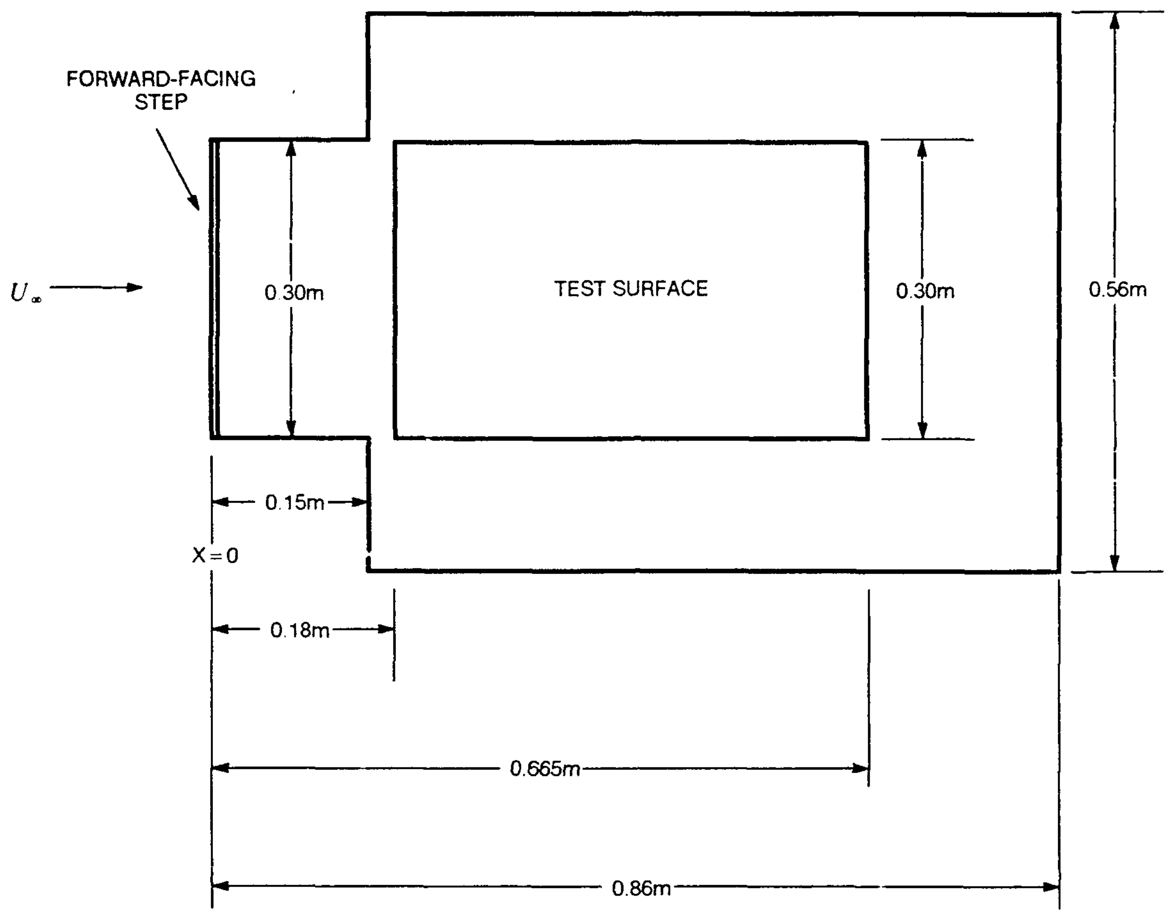

Figure 1. Test plate.

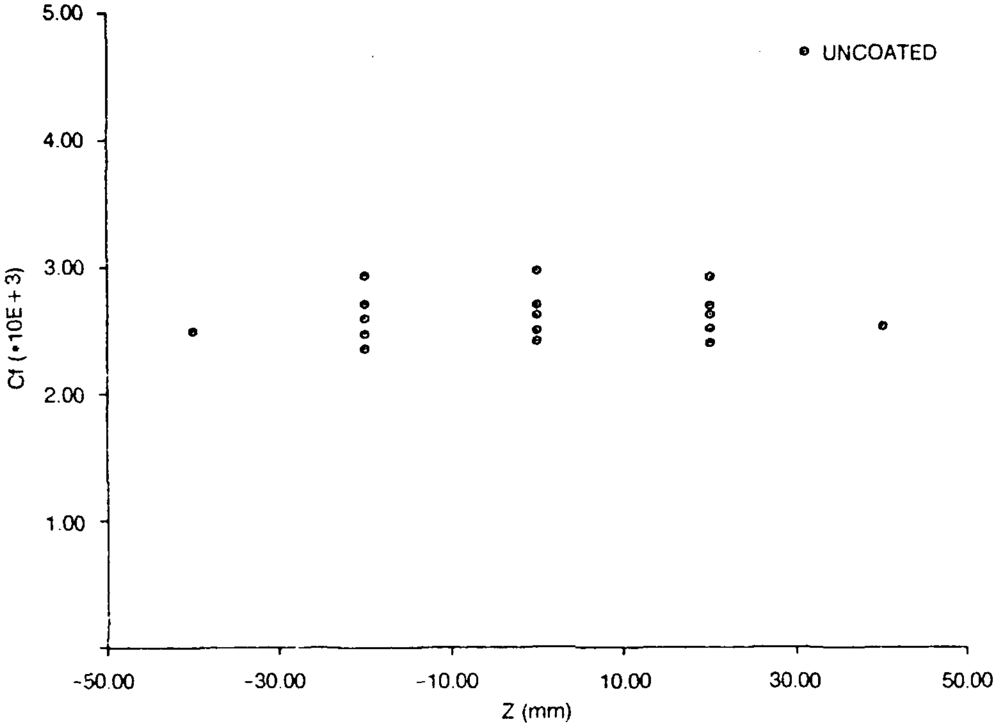

Figure 2. Baseline spanwise measurements.

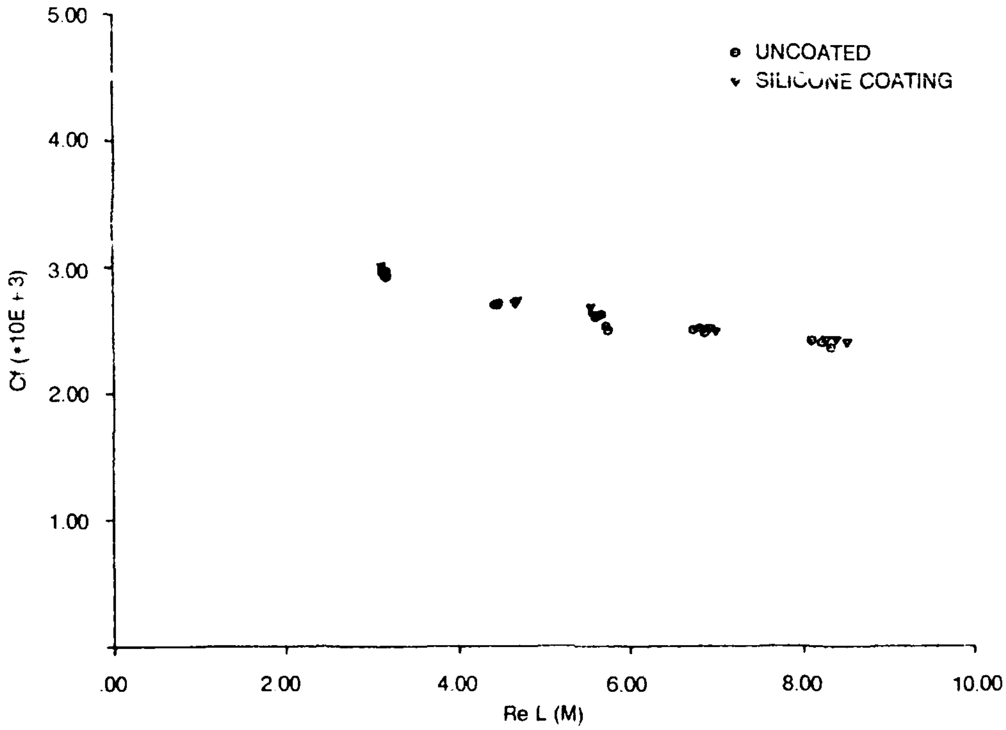

Figure 3. Silicone coating.

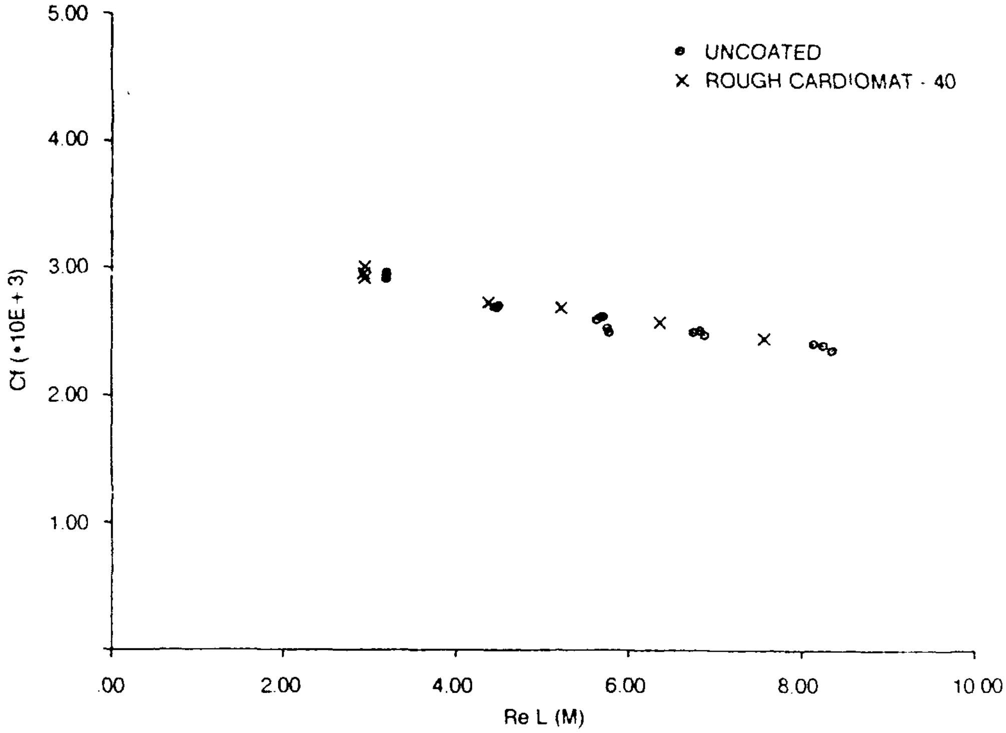

Figure 4. Rough Cardiomat-40 coating.

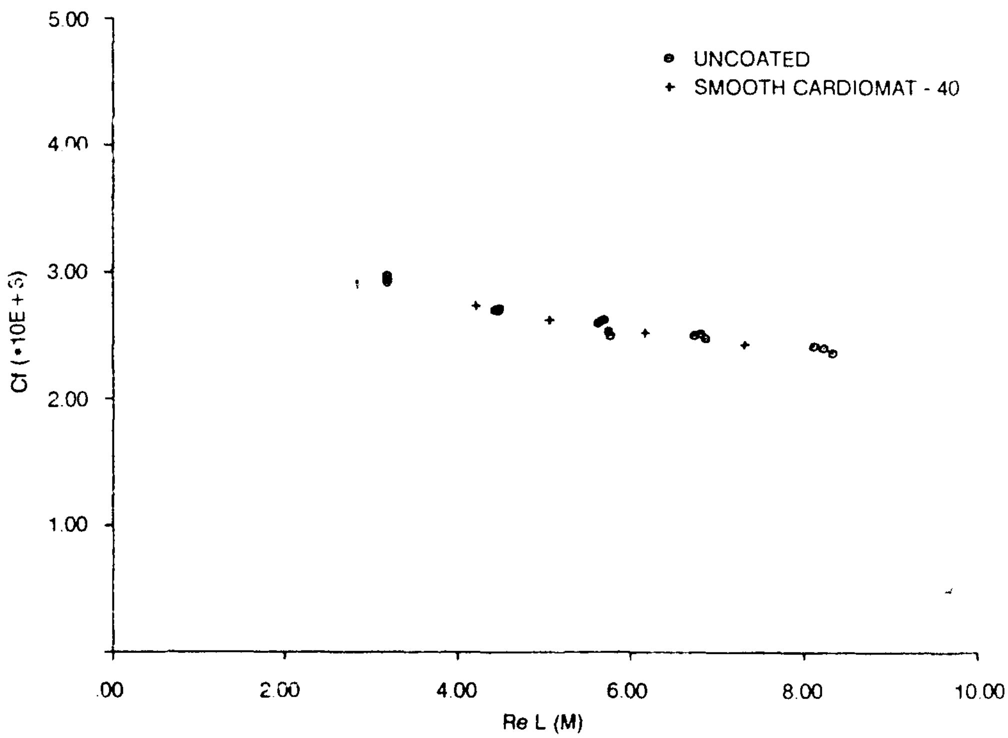

Figure 5. Smooth Cardiomat-40 coating.

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