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A STUDY OF THE EFFECTS OF LEBU DEVICES ON TURBULENT BOUNDARY LAYER DRAG

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ABSTRACT

Initial measurements of the changes in local skin friction, velocity profile shape, and turbulence structure which result from the placement of tandem plates parallel to the wall in the outer region of thick turbulent boundary layers have been made. Using a tunnel with a .75 m x 1.2 m x 7.3 m test section, which diverged so as to keep the pressure gradient dc_p/dx less than $2x10^3$ /ft, on the test wall, a skin fiction reduction of approximately 30% was measured at $\xi/h = 62$. This relaxed to a reduction of approximately 16% at $\xi/h = 124$ for $h/\delta_M = .6$. The c_f measurements for both the normal and modified boundary layers were obtained by measuring the slope of the velocity profile within the linear sublayer. Visual results indicated a continued presence of strong large eddy structure downstream of the devices. Local skin friction reduction of 12% at $\xi/h = 62$ was also obtained with the manipulators above the boundary layer at $y/\delta_M = 1.1$.

INTRODUCTION

The concept of achieving drag reduction via the addition of simple flow modifying devices in the outer region of turbulent boundary layers is extremely appealing. They are simple, light weight, inexpensive modifications which have the potential for significant cost savings. Using tandem flat plates, to keep the device drag low, Nagib and Corke (see Corke 1981) .x;Corke 1981examined the overall picture out to 68 device heights and have measured a net drag reduction of approximately 20%. They have suggested that considerations necessary to achieve a net reduction are:

1) The Reynolds number of the turbulent boundary layer at the first manipulator plate must be 2000 or greater;

2) The spacing of the tandem plates must be between 8 manipulator heights (IIT) and 8δ (Stanford);

3) The plates must be $.8\delta$ (IIT) to δ (Stanford) long;

4) The height of the manipulators must be between $.8\delta$ (IIT) and $.5\delta$ (Stanford).

5) The boundary layer must be tripped in a precise way.

Although the net results appear to be sensitive to combinations of these parameters, perhaps the most important question is the nature of the way the modifications relax.

Corke et al have advanced a physical picture which suggests that the manipulators interact with a hypothesized strong motion that results from the transition process. They suggest that this structure (presumably some aspect of individual turbulent spots or combinations of spots) is thought to control the production of new turbulence. The interaction presumably weakens the ability of this motion to bring fluid down to the wall. Evidence shows that 'sweeps' of high velocity fluid moving towards the wall are responsible for the onset of the turbulence production process, although a debate is currently underway concerning the origin and scale of the sweeps, as well as the mechanism by which they act. However, it is clear that interfering with the sweeps should modify the process. (See Cantwell, Coles and Dimotakis 1978 for the spot data, and Falco 1977 for the older large eddy boundary layer data). However, both motions appear to have significant spanwise rotation (for the boundary layer this information comes from correlations, see Townsend 1975). In streamwise planes, large scale sweeps are generated by the convected stagnation point flow field that is established at the upstream side of a large eddy or turbulent spot (Falco 1977). This is an essentially irrotational field. Although space time correlation have suggested that the large scale motions have strong internal rotation, results of conditionally sampled measurements show that there is little wallward motions in the large scale motions.

It has become clear from recent experiments at NASA Langley that attempts to set up "identical" experimental conditions will not guarantee similar results. Apparently, a number of factors which have previously been considered as independently satisfiable, must be considered in relation to each other. Furthermore, others must be very precisely regulated. These include:

$R_{\Theta M}$ -- the momentum thickness Reynolds number at the manipulator;

h/δ_M -- plate height / δ at the first plate;

s/δ_M -- spacing between the plates / δ at the first plate;

η/d_M -- distance of first plate from trip / δ at the first plate;

h_{trip}/δ_L -- trip height/laminar boundary layer thickness at trip;

L/δ_M -- the plate length / δ at the first plate;

trip characteristics;

spanwise uniformity with trip in place--no manipulator;

spanwise uniformity with trip and manipulator in place.

We feel that a systematic exploration of the above parameters is necessary. Clearly, examination by flow visualization can only be used in a broad sense to see if the overall situation has changed significantly, but can not be used to optimize the situation. During the time span of this investigation we have only had time to begin to explore this parameter map.

RESULTS OF OUR PRELIMINARY INVESTIGATION

During the past year we have made a preliminary investigation of the effects of tandem plate manipulators on the drag of a turbulent boundary layer. Using a .75 m x 1.2 m x 7.3 m wind tunnel with .35% free stream turbulence level, measurements were made at 2.44 m and 4.41 m downstream of the manipulators, for a nominal free stream velocity of 3m/s. The plates spanned the 1.2 m width of the tunnel and were put under reproducible tension (measured by strain guages) by supports outside of the tunnel. They were made of .5 mm stainless steel sheet metal. Figure 1 shows the experimental arrangement and position of the measurements. The two dimensionality of the tunnel was qualitatively judged to be good because of the ability to create a laminar boundary layer of the 24 foot length of the tunnel, which when marked with smoke showed no spanwise variations.

A large part of our initial effort was spent on wind tunnel design changes, the writing of software, and in the taking of exploratory velocity profiles and movies to get a feel for the new situation. It became apparent that each of the possible permutations of the parameter set discussed in the introduction could lead to different details. We thus limited our scope to reproduce and varify the results of Corke's investigation. We chose to arrive at those answers via a slightly different avenue. As we shall see, differences were found in practically all of the measures we investigated.

The technique we used was to set the flow speed and do a complete velocity profile first with, then without the manipulator in place. The data was acquired via an LSI 11/23 through a 12 bit A/D converter and stored on disc. The wires were calibrated using a three parameter fitting routine (to a Collis and Williams form of equation -- $E^2 = A + BQ^n$). Eleven thousand data points per position were averaged.

Because the wall slope method can be used to measure the local skin friction coefficient for both normal and manipulated boundary layers, and because it would allow a comparison on a station by station basis, we decided to use it as our primary standard, with the intention of doing a momentum balance to back up the results. The wall slope method, depends upon the existence of the linear sublayer, but does not depend upon the three-dimensionality of the shear layer or any non-uniformities, and furthermore does not depend upon differencing or gap/end plate problems. Unlike surface hot-films, it does not depend on a calibration which is extremely insensitive to small variations (the 1/3 power calibration). It does however, have its own set of demands.

The drawbacks of the technique are all related to the criteria that a thick sublayer is needed. These are: 1) heat transfer from the wire to the wall, 2) the number of points obtainable in the linear region, and the statistical reliability of each point, 3) the accuracy with which we can measure the distance from the wall.

In the thick boundary layer of our tunnel (d = 5 in) we were able to safely get into the sublayer while still keeping our wire more than 100 wire diameters above the wall, beyond the point where heat conduction from the wire to the wall has been determined to be important. We have further lessened the heat transfer problem by using a plywood test wall insert, and by using lower resistance ratios. We have had good results using 1.2, with ambient temperature variations of $\pm 1^\circ$C. Measurements taken in our tunnel using this technique did indicate significant c_f differences from those obtained using Cole's law of the wall and Clauser's fitting technique in the non-manipulated case. Figure 2 shows the statistical fluctuations in individual profiles which are directly attributable to the length of the data records (11,000 data points). However, because of the procedure we used, the differences in the slopes of the lines should only be a function of the changes in drag. It is also important to note that the recent work by Bhatia, Durst and Jovanovic strongly supports our results on wall heat transfer about the small effect of the wall on the hot-wire's response to $y^+ \simeq 2$ if the precautions we have taken are followed. Velocity profiles taken in the Göttingen oil channel (Eckelmann 1974, and subsequent work) have also shown that very accurate results can be obtained with the probe as close to the wall as $y^+ = .8$, when care is taken to alleviate the heat transfer problem is minimized. The potential accuracy of this method is significantly greater than obtainable with surface films because of the 1/3 power dependence of the surface film calibration.

Our study of the modifications to the velocity profiles showed that the presence of the manipulators did effect the logarithmic region of the velocity profile. Figure 3 a and b shows two examples of the changes found. In all cases u_τ was determined by the wall slope method. At both $\xi/h = 62$ and 124 the manipulators displaced the points upward in the logarithmic region (where ξ is the distance of the measurement station from the downstream manipulator plate). It appears from many similar profiles that a straight line region continued to be present. By $\xi/h = 124$ the upward displacement was considerably less. Corke also found the persistence of a linear region in semi-logarithmic coordinates, which was displaced upward. However, when non-dimensionalized by wall coordinates, he found no change in displacement with distance downstream of the manipulator up to 67h, and suggested a new set of log region constants. It should be noted that the constants calculated for our line at $\xi/h = 62$, do not agree with his. Furthermore, we have found that the logarithmic constants change with ξ/h in the range investigated.

In the tunnel that was available this past year we were able with the help of a trip (1.5 mm threaded rod) to obtain boundary layers at R_θ of 2-3,000 with sublayers approximately 1.3 mm thick. This allowed from four to six points to be obtained in the linear sublayer. Figure 4 shows our average results for the % c_f reduction at 62 and 124 device heights. The conditions of the boundary layer just upstream of the first manipulator plate were: $R_\theta = 1200$, $H = 1.461$, $c_f = .00435$. The manipulator was at $h/\delta_M = .6$, $L/\delta_M = 1.3$, and $s/h = 15.15$. It should be noted that at $\xi/h = 62$ our results are consistent with Corke's and also Nagib's (see Appendix B of Corke's thesis) overall C_f values (Corke measured downstream to $\xi/h = 68$, Nagib to $\xi/h \simeq 90$). However, we used different trips, our boundary layer at the manipulator was below the R_θ limit that Nagib suggests would work, and we used a different method to obtain the drag. Furthermore, the conditions that were described above had relatively longer plates and longer distances between plates. Thus we have shown that a manipulator can reduce local skin friction to this level with a weaker set of restrictions (R_θ and trip) and a wider range of plate configurations.

It is of interest to report another experiment that was performed under the same conditions but with the plates at $y/\delta_M = 1.1$. At $\xi/h = 62$, we found 12% local skin friction reduction. The fact that we found an effect is not surprising, because instantaneously many of the bulges extend further out than this, but the magnitude of the effect is larger than would be expected if the mechanism was indeed a reduction in the rotation of the large eddies.

Some preliminary flow visualization experiments were performed to see if overall structural picture of reduced intermittency found by Corke could be reproduced. Using a laser sheet parallel to the flow direction and perpendicular to the wall, we could see the instantaneous boundary layer over the whole length of the tunnel. Both the "live" visual impression and observations viewed in slow motion on film showed that the outer edge was highly intermittent, and it appeared to be similar to the normal turbulent boundary layer. Figure 5 shows two photos of the manipulated boundary layer centered around $\xi/h = 62$. It is clear that the intermittency is very similar to that found in a normal layer. This is in sharp contrast to the visualizations of Corke. In part the different

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impression is a result of our different techniques. Corke introduced smoke directly into the wake of the manipulator plates by placing a smoke wire across the flow, as well as into the boundary layer, whereas we only introduced smoke into the boundary layer. Corke, of course, sees far less intermittency than we do downstream of the manipulator. Although we believe the indications of this visualization better reflect the state of the large eddies, it is clear that simultaneous flow visualization and hot-wire anemometry with Reynolds stress and cross-stream vorticity probes will be needed to determine the changes in the state of the large scale motions due to the presence of manipulators.

CONCLUSIONS

These results in general appear to support those of Corke and Nagib, although they are much less comprehensive, and do not include net drag measurements. However, there are some suggestions that details are different, and would lead to different conclusions. First, we found that the decrease in local skin friction was significantly less at $\xi/h = 124$ then at $\xi/h = 62$. Second, we did not find a constant displacement of the logarithmic region, it relaxed back towards the unmodified layer position. Third, we were able to obtain a skin friction reduction when the plates were 10% higher than δ_{99}. Finally, our flow visualization results were quite different, showing significant intermittency at 62 device heights.

REFERENCES

Bhatia, J. C., Durst, F., Jovanovic, J. 1982. Corrections of hot-wire anemometer measurements near walls. J. Fluid Mech. 122:411-431

Cantwell, B. J., Coles, D. E., Dimotakis, P. E. 1978. Structure and Entrainment in the Plane of Symmetry of a Turbulent Spot. J. Fluid Mech. 87:642-672

Corke, T. C. 1981. A New View on Origin, Role and Manipulation of Large Scales in Turbulent Boundary Layers. PhD Thesis, Illinois Institute of Technology.

Eckelmann, H. 1974. The Structure of the viscous sublayer and the adjacent wall region in a turbulent channel flow. J. Fluids Mech. 65:439-459

Falco, R. E. 1977. Coherent Motions in the Outer Region of Turbulent Boundary Layers. Phys. Fluids 20:S124-132

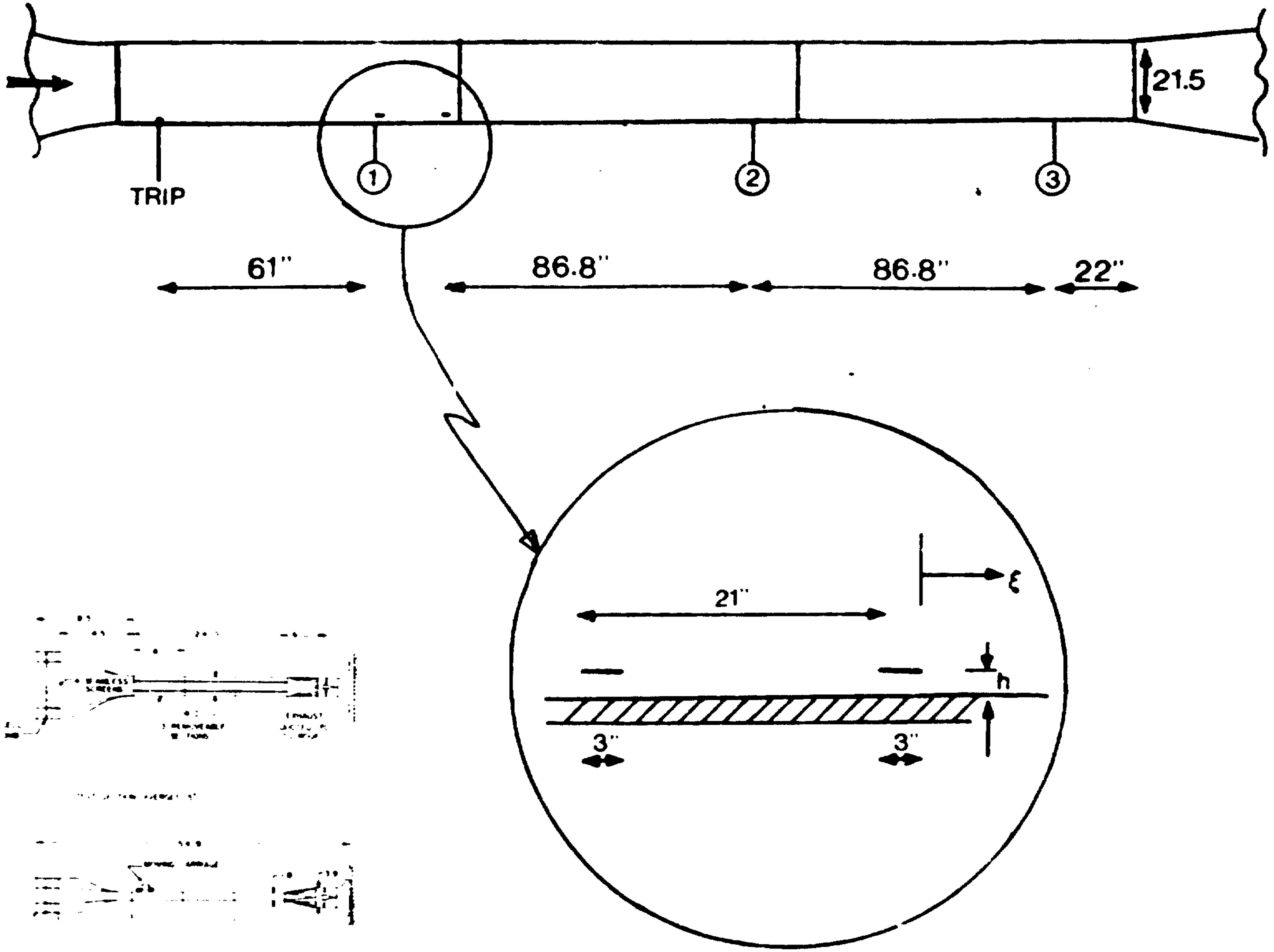

Figure 1. Experimental arrangement and position of the measurements. Stations 2 and 3 were 62 and 124 device heights downstream of the manipulator.

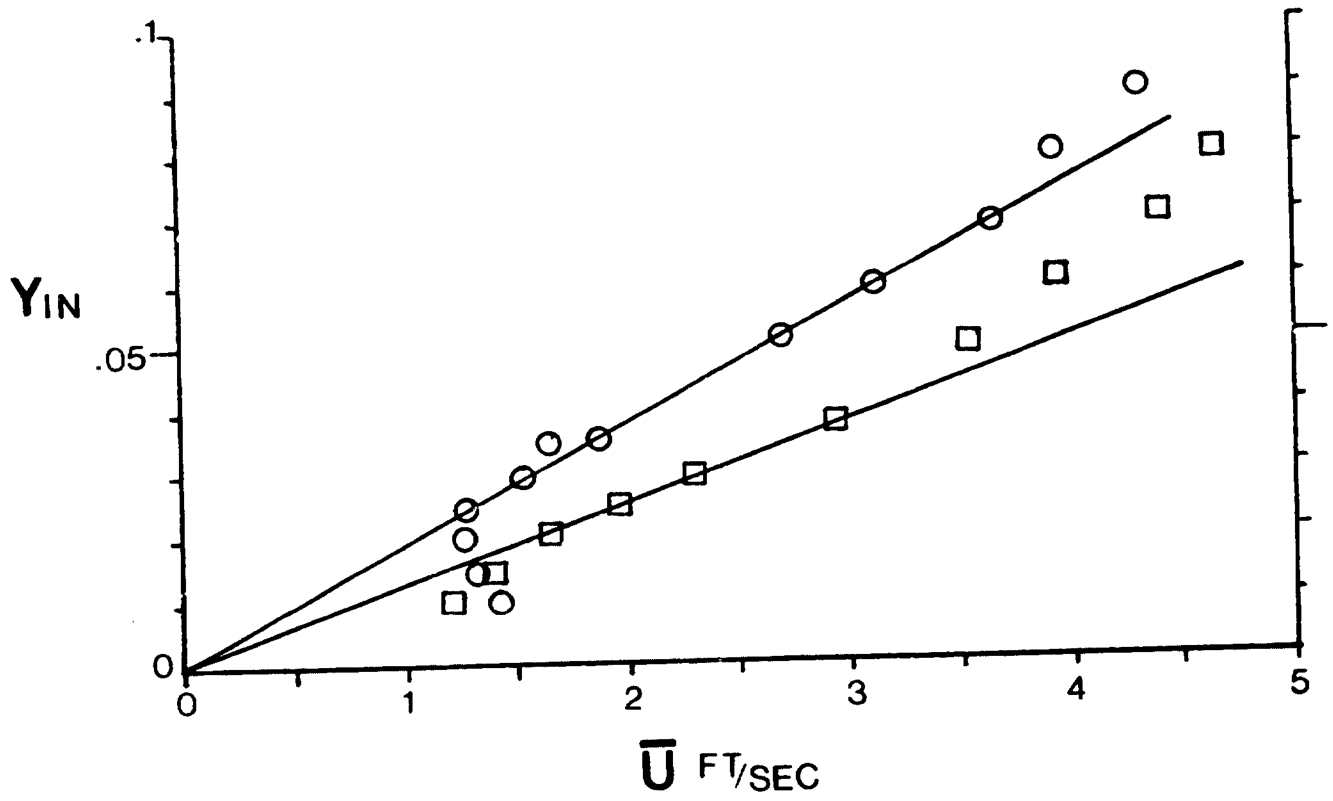

Figure 2. An example of the velocity profiles in the wall region at 62 device heights, showing the curve fit used to obtain $du/dy|_w$. ○ Manipulator; ☐ normal layer.

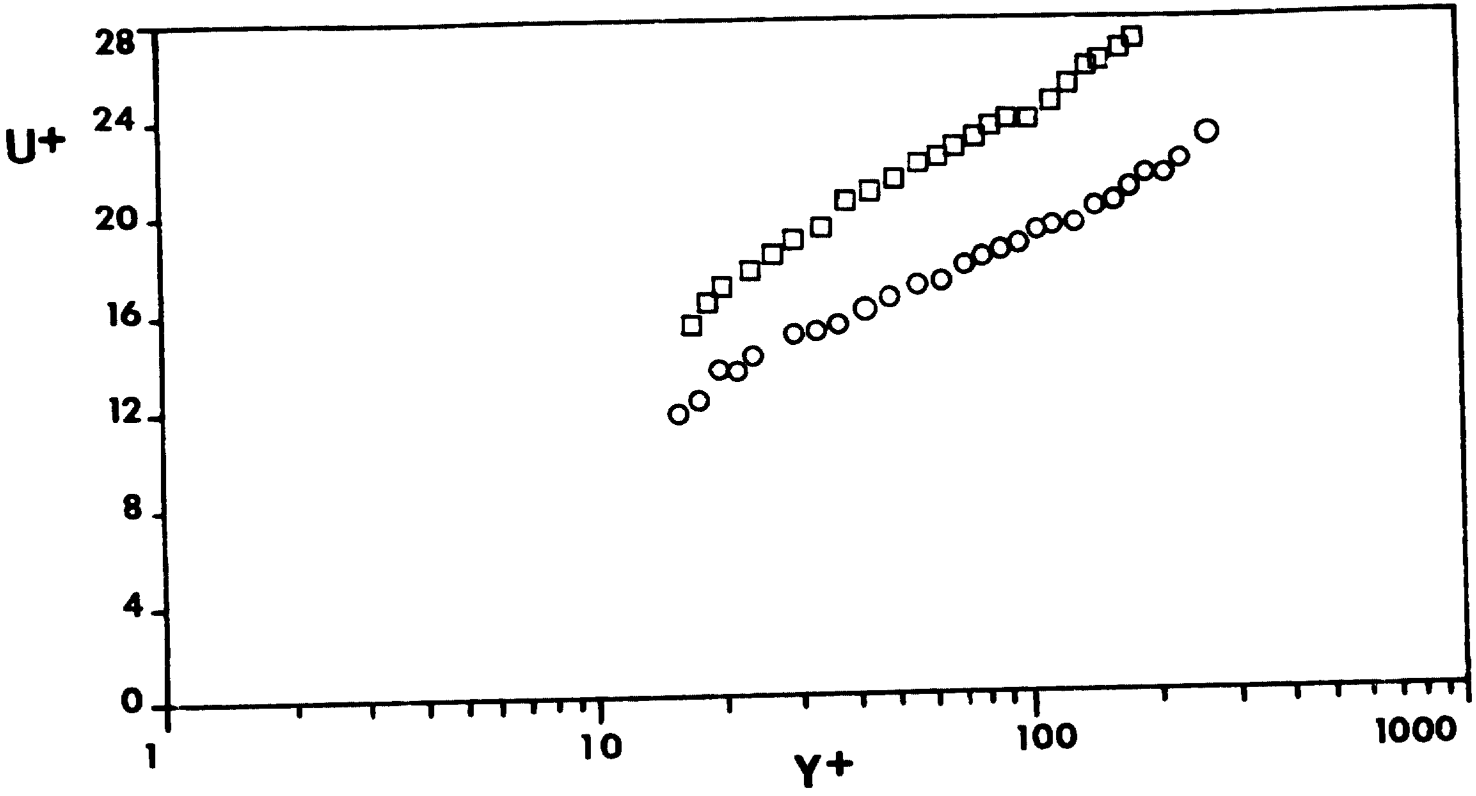

Figure 3a. Mean velocity profiles in the logarithmic region. ☐ Manipulated; ○ normal. For the manipulated case, $\xi = 62h$, $h/\delta = .6$.

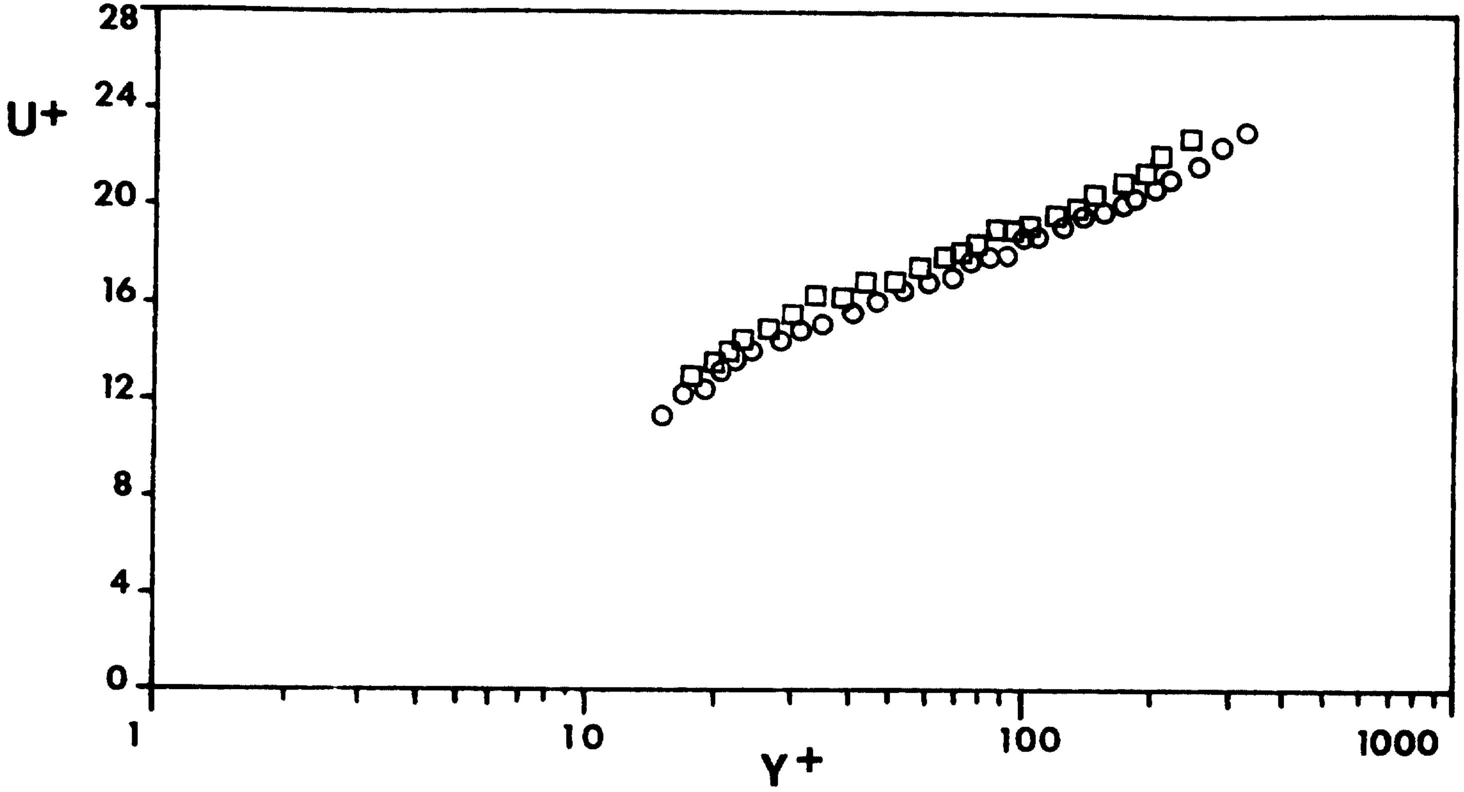

Figure 3b. Mean velocity profiles with □, and without ○, manipulator at ξ=124 h. For the manipulated case, h/δ = .6. Note the relaxation of the line towards the manipulated value.

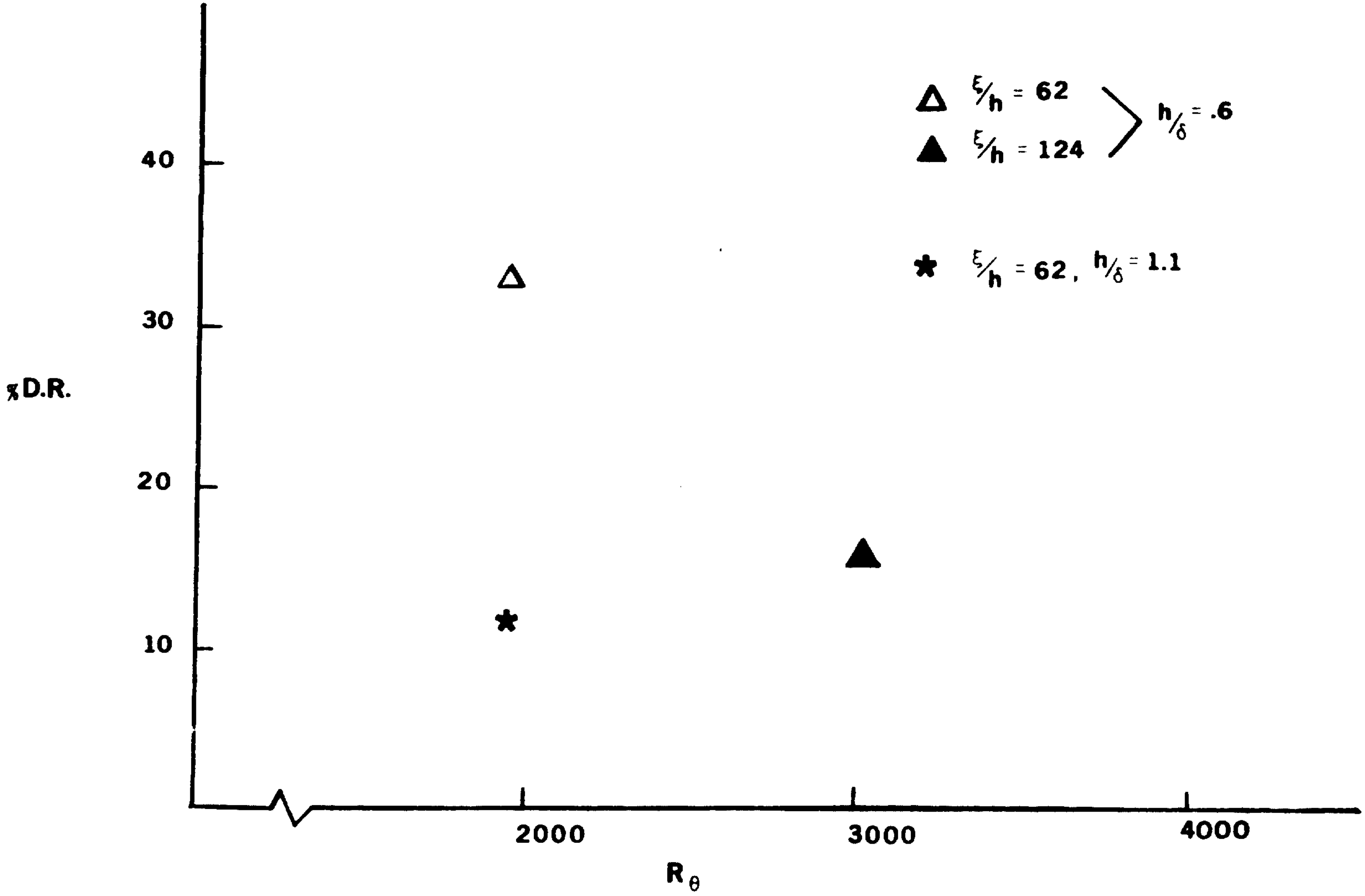

Figure 4. Average results for % local skin friction reduction. Note the decreasing change as we moved downstream from the device. Included is one data set for the case where the manipulator was outside of the boundary layer.

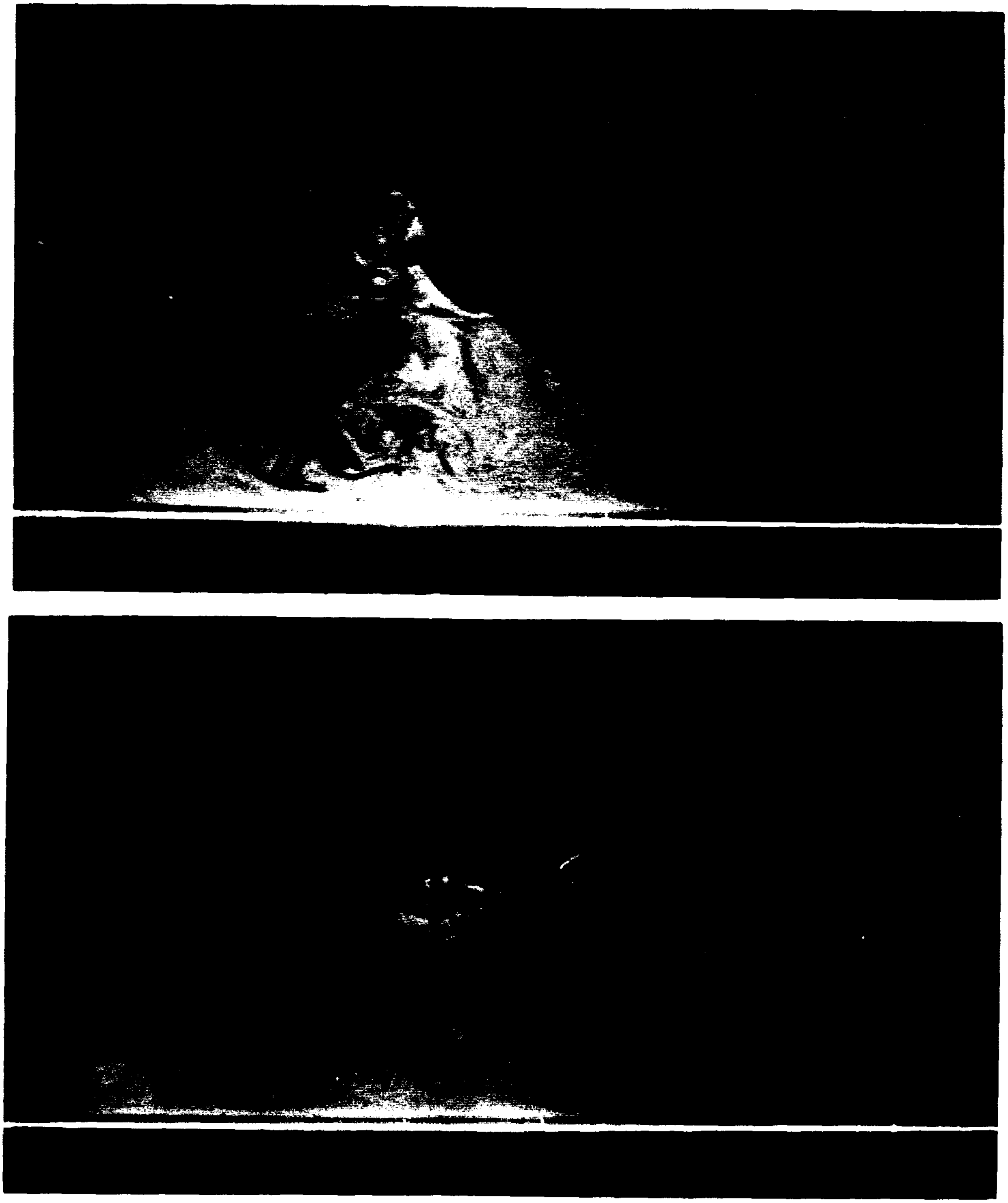

Figure 5. Two photos of the manipulated turbulent boundary layer. They are centered around $\xi/h = 62$. Flow is formed right to left.