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EXPERIMENTAL INVESTIGATION OF POLYMER SOLUTION INJECTION ON EXTERNAL BOUNDARY LAYERS[*]

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ABSTRACT

This paper describes an experimental study of the effects of injecting dilute aqueous polymer solutions into a turbulent boundary layer formed on a flat plate immersed in flowing water.

Hot-film anemometer techniques were employed in the measurement of the velocity profiles, turbulence intensities, and lateral correlation coefficients at a number of locations along the plate. Boundary layer growth parameters and the variation of the local skin friction coefficient were computed from the velocity profile data. The effects of polymer concentration and injection velocity on the local drag reduction are also presented.

It was found that momentum diffusivity was smaller than for pure water, and that the presence of the polymer molecules appeared to promote a more uniform distribution of the size of the turbulent eddies. Also, that the injection rate of a polymer solution can have a pronounced affect on the drag reduction.

INTRODUCTION

It has been very well established that dilute polymer and soap solutions reduce hydrodynamic viscous drag on a body. The majority of data and theories available in the open literature have been concerned with internal flows, in pipes for example. Recently, White[1], Love[2], Wu[3], and Kowalski[4] have published papers concerned with external flows, such as over a flat plate.

At the start of the research program described in this paper, very little useful data was available on external flows. There were some available on drag reduction on rotating discs, but due to the complexity of the geometry of the hydrodynamic flow system they are difficult to correlate with other forms of existing data. It is also very evident that although there may be a reasonable amount of data available on internal flows, they cannot be correlated with any accuracy, since there are a large number of parameters which are difficult to control, such as degradation of the polymer, the variation of the molecular weight distribution of different batches of a given polymer, injection rates, concentrations, etc.

EXPERIMENTAL APPARATUS

The basic set-up was a plexiglass plate 1 inch deep by 12 inches wide by 52 inches long positioned in a standard tilting free surface flume. The leading edge of the plate was a wedge having a 20° included angle, (see Fig. 1), with a very thin injection slit 0.01" wide at about 1/2 inch from the leading edge. The injection could be either normal to the free stream or at about 20 degrees to the plate surface in the direction of the main stream flow. Three sets of pressure taps, with tapping points at 2 inch intervals, situated 1 1/2 inches either side of the longitudinal center line of the plate, were used to measure the surface pressure gradients. These taps were scanned using a "scani valve".

The flume had an upstream plenum chamber with a contraction section which led to a set of honeycombed filters which reduced the free stream turbulence and destroyed any entrance contraction vortices.

by separately dissolving a sample of the dry polymer powder in water containing 2% triethylene glycol and 0.01 M neutral phosphate buffer, with an ultimate concentration of 2500 wppm.

The concentration was increased as the experiment proceeded, and the rate of discharge, which was variable, was obtained by taking note of the time elapsed during the experiment and the quantity of polymer solution used. The solution was dyed to observe the injection phenomenon and no check was made on degradation due to bacterial attack or natural degeneration.

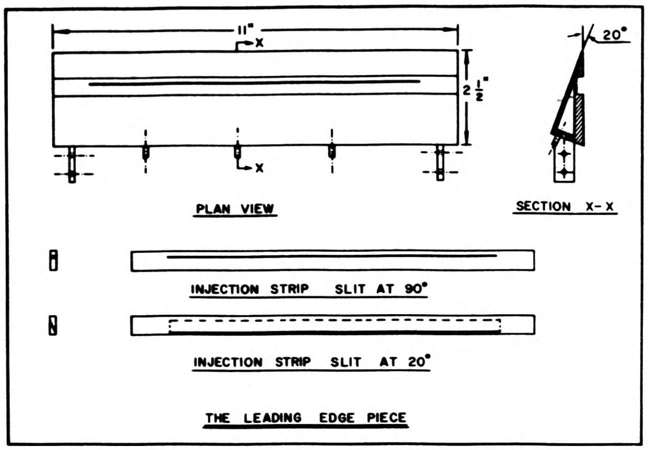

Fig. 1 Leading edge piece

When using injection normal to the surface, back flow or separation was observed and the coloured solution dispersed into the main stream very rapidly, probably due to the upward discharge velocity carrying it into the turbulent core of the boundary layer. Inclined injection gave better results: the solution adhered to the plate surface and there appeared to be no separation. All the experimental results reported in this paper were obtained with the 20° injection slit.

Velocity and Turbulence Quantity Measurements

Since the probes were very sensitive to the fluid temperature, the flow system was allowed to circulate for at least three hours to ensure a uniform fluid temperature before any actual measurement was taken. Velocity profile measurements were executed at several locations along the length of the plate. Before and after each boundary layer traverse, the voltages for the main stream velocity were compared to check any drift in the probe calibration. In addition to the usual gas bubble formation and contamination of the sensor, the polymer molecules affected the normal heat transfer process. Occasionally, the occurrence was indicated clearly by a conspicuous drop in the voltage response and the probe had to be washed with distilled water.

The minimum depth of the water in the channel always exceeded 12 inches, with the plate positioned approximately 5 inches above the flume bed, and 20 feet downstream from the filters.

EXPERIMENTAL PROCEDURES

Three types of hot film probes were used in the experiments, DISA wedge sensor probes, TSI cylindrical sensor probes, and a TSI cylindrical sensor X-configuration probe (type 1241-60W). The probes were calibrated against pitot impact probes in the water channel. The calibration equation used for the hot film probes was of the form

$$E^2 - E_o^2 = AU^n \qquad (1)$$

Throughout the research, the temperature of the fluid ranged from 73°F to 77°F depending on the ambient temperature. The slight change in values of 'E_o' and

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'n' were found to be insignificant compared to the error involved in the velocity voltage read out. It was observed that occasionally there was a change in the value of the constant 'A', and if 'E_o' and 'n' were assumed to be constant, this simply resulted in a parallel shift of the calibration curve in a log-log plot. Since the main stream velocities used in the experiment were known quite accurately, it meant the voltage corresponding to the main stream velocity had to be determined during each experiment and a separate calibration curve drawn.

Polymer Solution: Preparation and Injection

The polymer used was the polyacrylamide Polyhall MRL295 (which was supplied by Stein Hall) which was dissolved in distilled water and thoroughly mixed for 24 hours with the aid of pneumatic stirrers before use. A molecular weight distribution curve for the actual polymer used is given in Figure 2. This curve was obtained by Debell and Richardson Inc., using a gel permeation chromatograph

The velocities in the boundary layer were measured using a TSI 90° probe whose d.c. output voltages were averaged then analysed after the test. The mean value of the longitudinal fluctuating velocity component was assessed directly using the r.m.s. voltmeter on a DISA correlator.

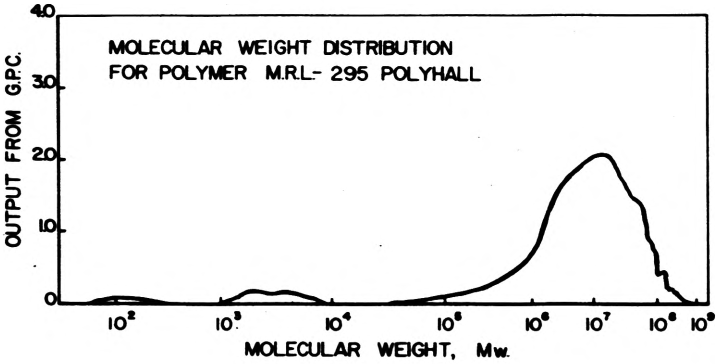

Fig. 2 Molecular weight distribution

The two lateral fluctuating velocity components v' and w' were determined using the X-configuration TSI probe (type 1241-60W) in conjunction with a 90° adaptor. The lateral double velocity correlation coefficient was obtained using a DISA 90° probe and the TSI general purpose probe together. For each position under investigation, the TSI probe was fixed in position while the DISA probe was moved. The correlation coefficient was obtained from the DISA correlator.

The flow system used was a closed loop, and after a number of polymer injections, the water became slightly contaminated with the polymer molecules. Accordingly, the system was drained, whenever considered necessary.

RESULTS AND DISCUSSION

The most critical data measurements obtained during the research were the voltage readings from the anemometer output. Due to the unsteady nature of the quantities that were measured and the frequent contamination of the probes, a high degree of accuracy was difficult to achieve. In each boundary layer traverse, the sensor was brought just in contact with the surface by combinations of the feel of the hand and the image of the probe in the plate. However, because of the construction of the probe and the size of the sensor element, there was still a small gap between the sensor and the surface. This distance could only be estimated from the dimensions of the sensor and the sensor holder. This fact might explain some of the deviations of the points in the viscous sublayer and the buffer layer.

Velocity Profiles

Only two main stream velocities 0.6 ft/sec and 1.6 ft/sec were investigated as at higher velocities vortices tended to move into the test section.

Figures 3 and 4 illustrate the development of the velocity profiles at various stations under various injection conditions. These graphs show that

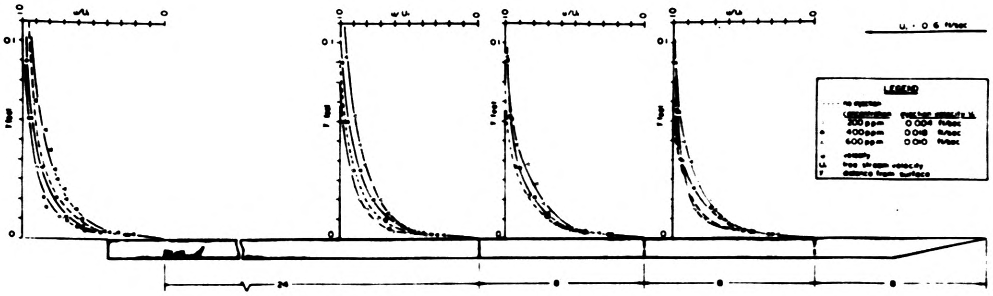

Figure (3) Development of the velocity profiles along the plate

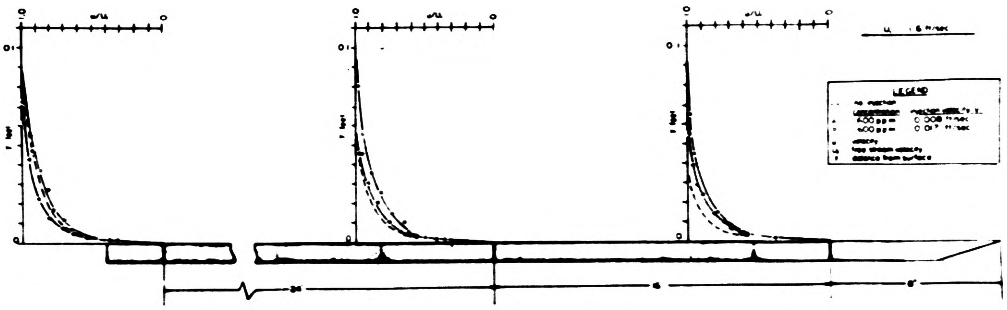

Figure (4) Development of the velocity profiles along the plate for a short distance from the slit the polymer solution was slowly dispersing and gaining speed. Further down the plate, the viscoelastic properties of the polymer solutions appeared to come into play and give rise to the changed profiles. The magnitudes of these effects were consistent with respect to the discharge rates and the concentrations. This trend assumes that the higher the concentration, the higher the fluid viscosity and therefore, the longer it will take to be accelerated and completely mixed.

In calculating the velocities, the calibration curves for pure water had been used even when there was a polymer solution injection. The main reason is that there is, at present, no easy way of determining the concentrations or concentration gradients of the polymer solution in the boundary layer which meant that, even if the probe was calibrated at various concentrations, there would still be no way of applying these curves in the calculations. If uniform mixing in the boundary layer is assumed, which under the given conditions of low velocity and high free stream turbulence may be a reasonable approximation, the maximum concentration would have been a low value of less than 2 wppm. At this level of concentration the effect of probe contamination can be to a large extent avoided, as previously noted in the section "velocity and turbulence quantity measurements". Of course, the concentration across the boundary layer at a given station would not be expected to be uniform and it is most probable that the concentration at the wall would be much higher than in the outer wall region. Consequently, the most likely place of error in the probe reading would have been at the edge of the sub-layer, and this would have minimal effect on the skin friction values obtained using the momentum integral equation. It should be appreciated that there were no quantitative data available and no tests were made at the time to assess the probes performance under similar conditions, to validate the above assumptions. However, subsequent tests with homogeneous solutions have indicated that under similar hydrodynamic conditions a probe's performance is greatly dependent on the type of sensor and that cylindrical sensors appear to be quite useless for turbulence measurements compared to wedge or especially conical sensors.

The velocity profile data were plotted on graphs of U^+ against y^+ together with curves based on the standard equations

$$U^+ = A_1 \text{ Log } y^+ + B_1 \qquad (2)$$

$$U^+ = y^+ \qquad (3)$$

The constants used were $A_1 = 5.85$ and $B = 5.56$ (obtained from reference 8.) There was good agreement between the experimental data for water and equation (2). Figure (5) shows the resulting velocity profiles obtained by injecting pure water and shows that there was good correlation. Figure (6) shows some sample profiles with polymer injections including data points from reference 9. It can be observed that these data agree with available pipe data, in that the polymer appears to affect the thickness of the buffer and/or viscous sub-layer and, also there is the usual ΔB constant shift in the outer wall region. However, it was noted by Fabula et al[10] that apparent parallel upward shift of the curves could not eliminate the possibility of a change in the slope of equation (2); more data are required to support such an assertion. At present it is convenient to say that the viscous sub-layer and the buffer layer seem to have become thicker in a viscoelastic flow.

Attempts were made to obtain local skin friction coefficient Cf data based on the following equation

$$\frac{u}{U*} = \frac{1}{K} \log y \frac{U*}{\nu} + B_1 + \frac{\pi}{K} \omega(\eta) \qquad (4)$$

rearranging

$$\frac{u}{U_1} = \frac{1}{K} \left(\frac{Cf}{2}\right)^{1/2} \log \left(y\frac{U_1}{\nu}\right) + \left(\frac{Cf}{2}\right)^{1/2} \left[B_1 + \frac{1}{2K} \log \left(\frac{Cf}{2}\right)\right] \qquad (5)$$

Since most observers have deduced that K is not changed for dilute polymer solutions, Cf can be obtained from the slope of the U_1^+ against y_1^+ curves. The values computed in this manner were very sensitive to scatter of experimental data and did not give consistent curves even though Cf values were reasonable. The intercept could not be used since B_1 apparently varies with the polymer concentration

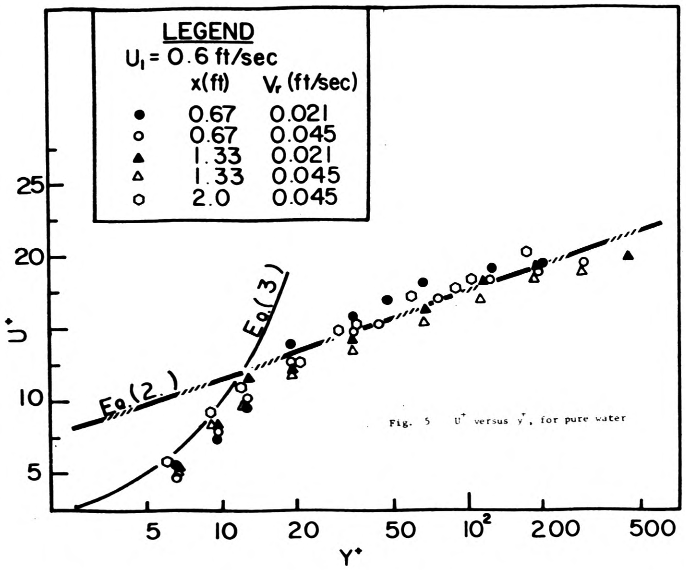

Fig. 5 U^+ versus y^+, for pure water

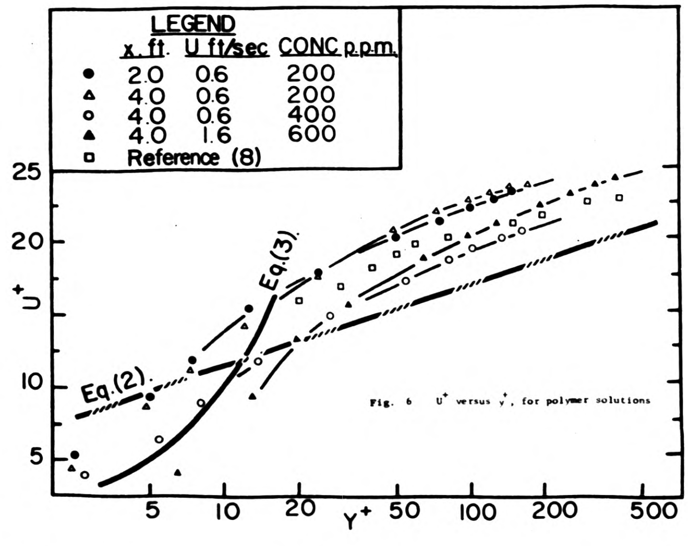

Fig. 6 U^+ versus y^+, for polymer solutions

Turbulence Intensities and Integral Scales

The turbulence intensities in the three directions relative to the local mean velocity are illustrated in Figure 7. The two lateral components are each relatively higher than the conventional results as given by Hinze[11]. There was a small decrease in the turbulence levels close to the plate surfaces when polymer solutions were injected while practically the same turbulence was observed in the rest of the flow regime. This is contrary to the deductions of Johnson et al[12] who did not show any actual data but reported that they had observed that polymer injection increased the root meansquare of the velocity fluctuations in the wall turbulent region. These measurements were all taken at the end of the plate where the solution was assumed to be already fairly well mixed. Consequently, greater suppression would possibly be obtained for

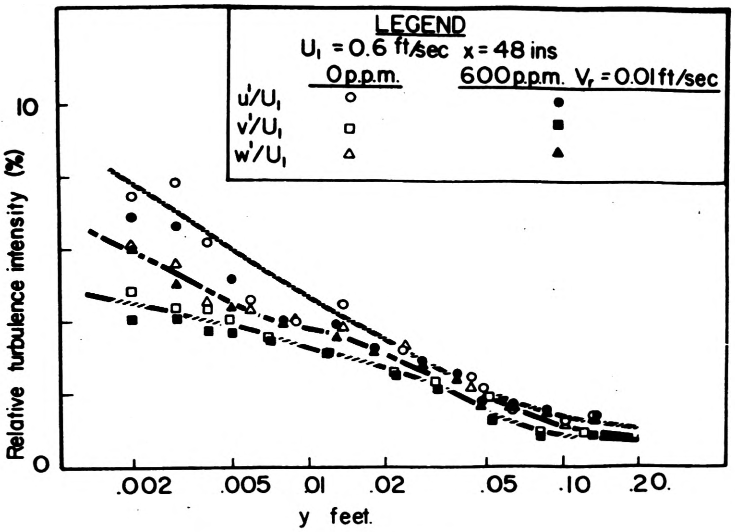

Fig. 7 Relative turbulence intensities

higher concentrations. The decrease in the turbulent kinetic energy suggested that the frequencies of the dissipative eddies had decreased which means that there was an increase in the average size of the eddies responsible for energy dissipation. The observations are in general agreement with the discussions in references 10, 13, 14, 15, 16.

The measurements of the lateral correlation coefficients in the boundary layer are shown in Figures 8 and 9. Because of the configurations of the probes, it was not possible to obtain data for the region r < 0.003 ft. From the curves the lateral integral scales were computed by numerical integration. It can be shown that in a homogeneous isotropic turbulence field[11],

$$L_f = 2\ Lg \tag{6}$$

Equation (6) was used as a reasonable approximation to calculate the longitudinal integral scales in this flow. The values thus obtained are in agreement with data given by Patterson and Zakin[17] which were calculated from the energy spectra in pipe flow.

The integral scales could also be viewed as a measure of the average size of the largest eddies. In the presence of the polymer solutions, the integral scales were reduced signifying a decrease in the size of these eddies. Hence, the apparent effect of the polymer solution is to bring the eddies in a turbulence field to a more uniform size.

Figure (10) shows the distribution of the eddy viscosity across the boundary layer. The points with no injection compare fairly well with Klebanoff and Townsend's data[11]. When polymer solution was injected, the values were smaller and more scattered. Gupta et al[16] found that the heat transfer was lower in a viscoelastic liquid. It appears that the eddy diffusivities for momentum, heat and probably also for mass transfer were lower in the viscoelastic liquid. The slope at the origin gives the value of the flow data. The main points that these curves indicate are that the drag reduction is a function of the injection velocity, initial solution concentration and the Reynolds number or turbulence level. It would be interesting to compare internal and external flow data, especially with regard to the much discussed threshold or onset criteria; however, there is little value in doing so because the Reynolds number or friction velocity cannot be compared in internal and external flows. White[18] has pointed out that there is a maximum Reynolds number for a given polymer solution above which drag reduction does not occur. This is contrary to what occurs in internal flows, which is to some extent born out in this work. Furthermore, the authors cannot agree with the inference of Virk et al[19] concerning the universality of onset criteria when relating internal and external flows.

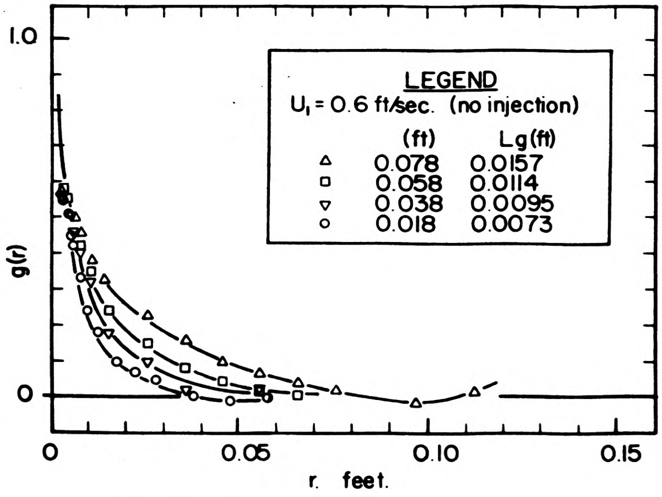

Fig. 8 Lateral correlation coefficient, no injections

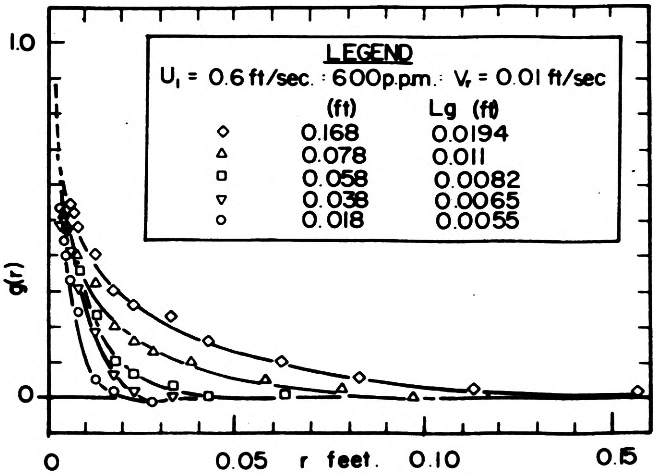

Fig. 9 Lateral correlation coefficient, with injections

CONCLUSIONS

1. Drag reductions of up to 80% can be attained by injecting high concentration aqueous polymer solutions into turbulent boundary layers at low flow rates.

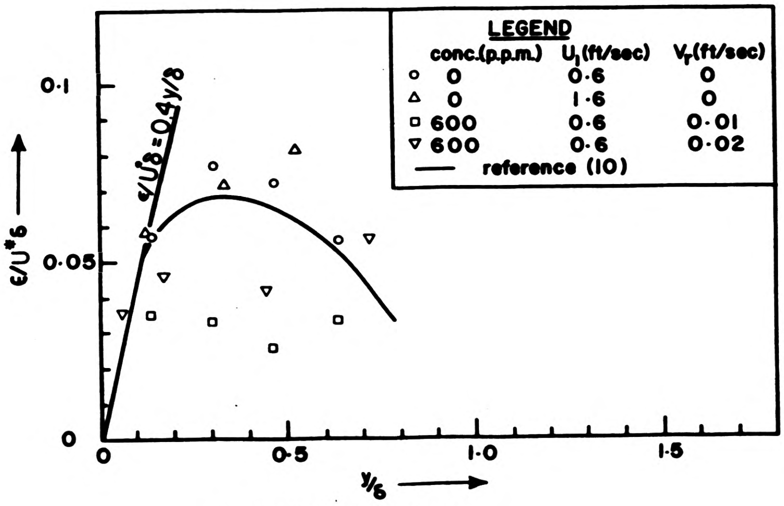

Fig. 10 Eddy viscosity distribution

2. The flow rate, velocity, and angle of injection of the polymer solution can have a pronounced effect on the drag reduction effectiveness. It is desireable to keep the injection velocity as low as possible, and tangential to the surface.

3. The viscoelastic properties of the polymer solution appear to reduce the size range of the turbulent eddies.

4. For turbulent boundary layers the eddy viscosity of a viscoelastic liquid is smaller than that of a Newtonian liquid.

As an overall conclusion, it is felt that there is a need for more mixing length constant k = 0.4. Shaver et al[12] measured the mixing lengths of pseudoplastic fluids and found that the value of "k" had changed. The present data are insufficient to permit any rigorous conclusion.

Figure (11) shows the momentum thickness δ_2, growth curves, computed directly from the velocity profiles. In all cases the growth rates and the actual thicknesses towards the end of the plate were less for water.

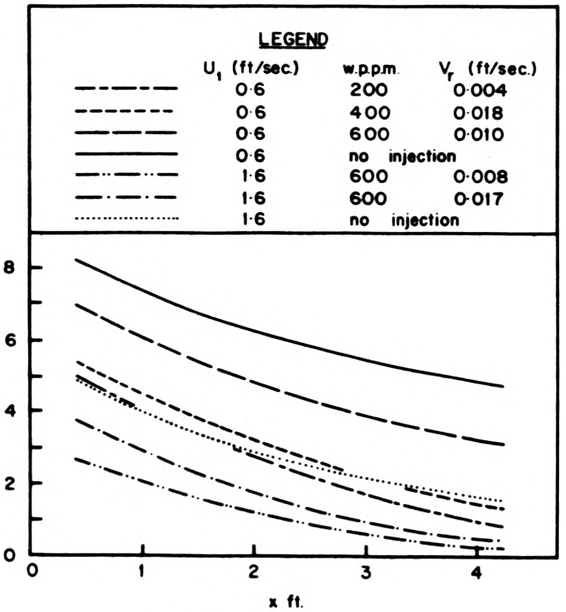

Fig. 11 Momentum thickness growth

Drag Reduction

Since no actual drag measurements were made on the plate other methods were examined to obtain local skin friction data. Even though the velocity gradients at the wall remain approximately constant, higher confidence should be placed on the data obtained in the outer region, where measurements are more reliable. The velocity gradient at the wall was immediately ruled out. The second method, of using equation (4), as previously stated leads to an amplification of the experimental scatter. The method, which was used, was the von Karman momentum integral equation, since under the given conditions it reduces to

$$Cf = 2\, d\delta_2/dx \tag{7}$$

The calculations for the local friction coefficient curves given in Figure (12) were based on equation (7), and the smoothed δ_2 curves given in Figure (11). The resulting curves show a definite reduction in the local skin friction coefficient, and also the drag, for polymer solution injection. The general shape of the curves is in agreement with the available internal flow data.

The curve for 600 wppm and V_r = 0.017 ft/sec, shown in Figure (12) converges with the 600 wppm, V_r = 0.008 ft/sec curve showing that the drag measurements of external flows, in order to verify the general observations which in the majority of cases cannot be correlated with existing internal flow data.

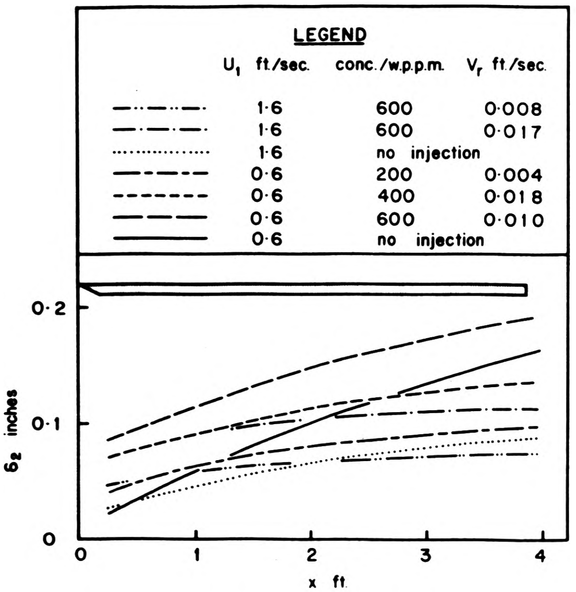

Fig. 12 Local skin friction curves

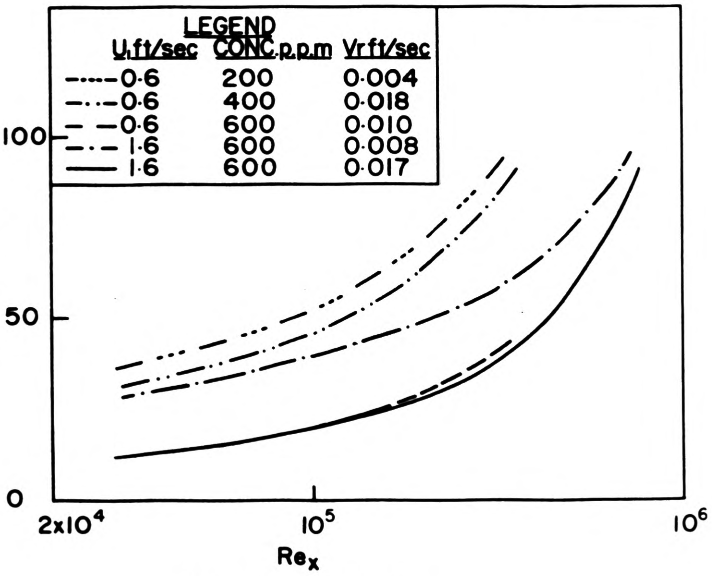

Fig. 13 Skin friction reduction curves

SYMBOLS

A	constant in the hot film probe calibration equation.
A_1	constant in the logarithmic law of the wall equation.
B_1	constant in the universal logarithmic law of the wall equation.
Cf	local skin friction coefficient, $2\tau_o/\rho\, U_1^2$.
E	anemometer output voltage.
E_o	anemometer voltage at zero velocity.
f	longitudinal velocity correlation coefficient.
g	lateral velocity correlation coefficient.
k	Prandtl's mixing length constant.
Lf	longitudinal integral scale, $\int f\, dr$.

Lg	lateral integral scale, $\int g\,dr$.
n	index in the probe calibration equation.
Rex	local Reynolds number, $x U_1/\nu$.
r	distance between two probes in the correlation coefficient measurement.
U_1	local free stream velocity.
U*	friction velocity, τ_o/C.
U^+	non-dimensional velocity parameter, u/U^*.
U_1^+	non-dimensional velocity parameter, u/U_1.
u	local velocity component parallel to the plate surface.
u'	r.m.s. value of the longitudinal fluctuating velocity.
Vr	injection velocity.
v'	r.m.s. value of the lateral fluctuating velocity normal to the plate surface.
w'	r.m.s. value for the lateral fluctuating velocity parallel to the plate surface
$\omega(\eta)$	Coles' wake function
x	longitudinal distance from the leading edge of the plate
y	distance normal to the plate surface
y^+	non-dimensional distance parameter, yU^*/ν.
y_1^+	non-dimensional distance parameter, yU_1/ν.
δ	boundary layer thickness
δ_1	the displacement thickness, $\int_o^\infty (1 - u/U1)dy$
ϵ	eddy viscosity
ν	kinematics viscosity
π	Coles' wake parameter
τ_o	wall shear stress
η	non-dimensional distance from the plate surface, y/δ

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