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ABSTRACT

The paper reports an experimental study of the flow of homogeneous aqueous polyacrylamide MRL 402 solution over a thin flat plate. Extensive velocity profile data were obtained, using both cylindrical and conical hot-film probes, and used to obtain local skin friction profiles. Direct drag measurements were made over a period of time for concentrations of 0, 25, 50 and 75 wppm and indicated that there was no appreciable degradation of the polymer. Extensive turbulence intensity data were obtained which were contradictory but indicated that the conical type probe is better than the cylindrical type for turbulence measurements and that the turbulence intensity reduced as the fluid progressed along the surface. Results indicate that the form drag is reduced but that the viscous drag is not reduced unless an onset friction velocity is exceeded, which was found to be 0.074 ft/sec for the polymer used.

INTRODUCTION

Under certain conditions dilute polymer solutions can be used to reduce hydrodynamic drag on a body. At the instigation of this research program, little useful data were available on external flows. The majority of data and theories available are concerned with internal flows. Recently, papers by White,[1] Love,[2] Elata,[3] Dove,[4] Emerson,[5] Wu,[6] White,[7] and Kowalski[8] have dealt with external flows. Emphasis has been on injected solution flows in preference to homogeneous solution flows since they have more practical significance. Lang[9] has shown that one of the best methods of improving the propulsion efficiency of submerged vehicles is to reduce their hydrodynamic drag.

To obtain efficient use of injection methods certain criteria must be complied with. Latto et al.[10] have shown that the injection velocity and angle have a pronounced effect on the drag reduction efficiency. Kowalski[8] pointed out that there is a surface seeking behavior of a polymer and that pulse injection of high concentration solutions gives the most efficient results. White[1] has shown that the limiting conditions are not the same for internal and external flows and that there is a limiting Re_x for a given polymer above which drag reduction does not occur. One of the main problems in injected flows is that turbulent diffusion coefficients are not predictable which makes it difficult to estimate concentration level, etc. in the turbulent boundary layer. Homogeneous flows do not have many of the problems associated with injection flows and are one way of estimating injection flow behavior in the absence of diffusion or rigorous injection flow data. The problem of verifying existing theories for injection flows is very large since it is difficult to correlate with any statistically significant available data, there being a large number of parameters which have proven difficult to control such as polymer degradation, the molecular weight distribution of different batches of a given polymer, concentration, injection rates, etc. For these reasons, much more data are needed for both injected and homogeneous external flows.

APPARATUS AND PROCEDURES

Observations were made on a flat plate model constructed of brass structural members with plexiglass surfaces. Direct drag measurements were made on a flat plate 6 inches wide by 3/4-inch thick by 52 inches long suspended between two 3-inch wide side guard plates with berylium copper leaf springs having the largest moment of area in the vertical plane to avoid vertical movement. Movement of the plate due to hydrodynamic drag was measured with a limited differential variable transformer (supplied by Schaevitz Engineering Company). The drag measurement device was calibrated before and after each test run while submerged in quiescent water by applying known weights to a pulley arrangement attached to the plate. Pressure taps were situated at 2-inch intervals along the center line on the underside of of the plate. Symmetrical wedge shaped nose and end pieces 3 inches long were provided to minimize form drag. Inclination, and horizontal and vertical positioning of the plate were adjusted on a carriage situated above the plate which supported the side plates. The plate was located approximately 5 inches above the channel floor with the leading edge between 11 and 15 feet from the flume entrance. Honeycombed filters situated at the flume entrance induced an approximate isotropic free stream turbulence and broke up any entrance contraction vortices.

The major analysis is based on the velocity measurements which were made with constant temperature hot-film probes (TSI type) mounted through the channel floor. The anemometer output, which was fed to a Honeywell 530S digital integrating voltmeter, was greater than 10 volts with an uncertainty of 0.05 volts. The estimated velocity measurement error allowing for calibration errors is 1.5%. The true distance of the probe sensor from the plate was difficult to ascertain. In each boundary layer traverse the sensor was brought into contact with the surface by touch and observation of the reflected probe image. However, the construction of the probe resulted in the sensor being never less than 0.005 inches from the surface. It is doubtful whether data taken closer would have been valid due to the close proximity of the sensor to a solid surface. Thirty-five velocity profiles were obtained along the underside of the plate at 1.5 inch spacings for each concentration, by progressively moving the plate over a stationary probe. A probe was calibrated a number of times during a test in an appropriate concentration polymer solution, using a pitot tube for the high velocities and observation of neutral density particles at low velocities. Agreement between the calibration methods was good. After some periods of continuous use in a polymer solution, the sensor constant velocity output decreased, presumably

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because of contamination, and was rectified by creating a disturbance upstream or by brushing the sensor with a soft brush.

The polymer used, the polyacrylamide, Polyhall MRL 402, (supplied by Stein Hall, Inc.) was sprinkled into the cascading discharge from the flume in a pre-calculated quantity to achieve the required homogeneous concentration in the re-circulating flow system. This method was preferred to that of mixing batches of high concentration solution and diluting. A free stream velocity of 2.21 $\pm$ 0.01 ft/sec was used for all the tests. Normally the solution temperature was between 79 and 82°F during tests and there was no noticeable effect on the calibration when used between these limits.

Variation of drag with concentration and time was measured over a period of three days for the concentrations 0, 25, 50 and 75 wppm. The drag was continuously recorded over a 24 hour period for a given concentration. Polymer was added to previous solutions to achieve the required concentration for each test run and, consequently, part of the final batch was several days old when it was used.

RESULTS AND DISCUSSION

Typical velocity profiles, and momentum growth curves for 0, 25, and 50 wppm are shown in Figures (1,2). For each station along the plate (35 stations for each concentration) velocity profiles of $\frac{u}{U_1}$ vs y were drawn and the smoothed velocity profiles were then transferred to Fortran compatible computer cards, using a Benson Lehner Oscar analogue-digital convertor. These data cards were used in all the subsequent data processing excepting the direct drag measurements. Figures (3,4,5) show the momentum thickness, θ, growth for 0, 25, and 50 wppm. The data points show a distinct fluctuation about fitted curves. This phenomena has been observed by other researchers but little comment made on the subject. It should be noted that the measurements were taken on the underside of the plate in order to reduce the surface wave effects and it was observed that the local free stream velocity U_{1x} still varied as a cyclic function of x having a small amplitude. The concentration of the polymer did not appear to have any effect on the amplitude of these fluctuations. The data for θ were fitted to a polynomial which was subsequently used for C_f computations.

The experimental data were plotted on a graph of U^+ against Y^+, Figures (6,7) and compared to standard equations of the form

$$U^+ = A \log Y^+ + B \qquad (1)$$

and

$$U^+ = Y^+ \qquad (2)$$

For concentrations of 0 and 25 wppm the plots are conventional. The slope A is approximately 2.5 in both cases, but the intercept B was found to be 3.43 and 4.55 for 0 and 25 wppm respectively, which indicates an increase in the thickness of the viscous sublayer for the polymer solution. This is in agreement with the deductions of previous investigators such as Meyer[13] and Latto[10]. It is becoming more widely agreed that equation 1 is not really so universal as previously thought and that even if A is constant B does not appear to be so, (values between 3.7 and 5.5 have been reported for B for pure water). Discrepancy in the data when using a correlation such as a universal log law may be due to the fact that in practice two-dimensional flow is virtually impossible to achieve. Figure 7 shows sample data for the 50 wppm concentration. A single curve is no longer sufficient to describe a velocity profile, and every station appears to have its own correlation. The resulting family of curves have approximately the same slope which is greater than for the 0 and 25 wppm data, but have completely different intercepts which increase as x is increased but are always less than for the previous concentrations. Kowalski[8] observed similar behavior for high concentration injection flows explaining the difference in the profiles as being the result of

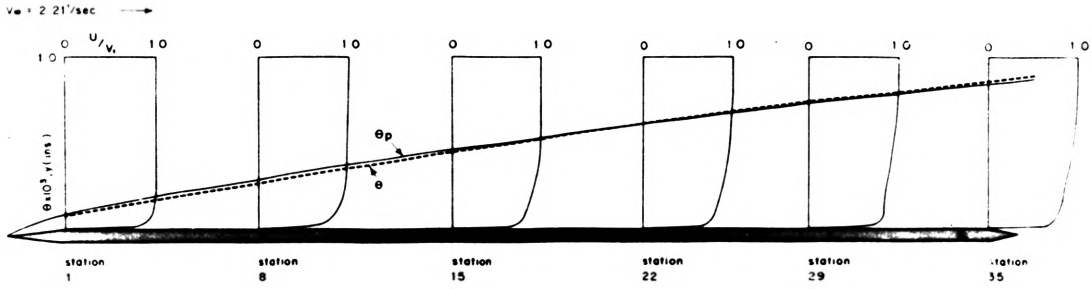

Fig. 1 Selected Velocity Profiles and θ Growth for 25 wppm

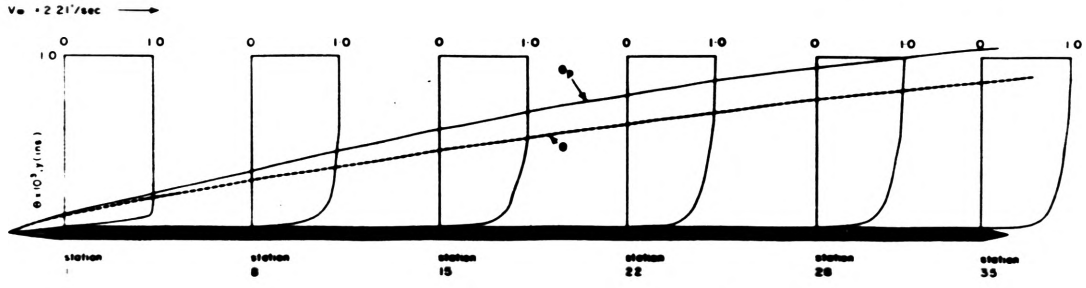

Fig. 2 Selected Velocity Profiles and θ Growth for 50 wppm

diffusion of the polymer solution into the free stream. Latto et al.[10] also observed the same behavior for high concentration injection flows. However, these findings should not be applicable to homogeneous flows unless there is some surface effect which is causing much higher concentrations within the sublayer. It is possible that the flow was developing and not truly two-dimensional, however, this was not born out by any of the profile data that were taken. Figures (8,9,10) give examples of velocity profiles taken at widely spaced positions, showing the actual profile together with standard laminar and turbulent profiles. The profiles are very nearly in agreement with the turbulent profile. It should be noted that the 50 wppm data were obtained with a conical and cylindrical probe, whereas the other data were obtained with cylindrical probes; this matter comes up again in the discussion of the turbulence correlations.

In order to compute the local skin friction coefficient, the von Karman momentum integral equation which under the given conditions reduces to

$$C_f = 2\, d\theta/dx \qquad (3)$$

was used to obtain the curves given in Figure 11. These curves indicate that C_f for 0 wppm is greater than that for 25 wppm but less than that for 50 wppm, however, these curves are misleading when total drag is considered. The form of the C_f curves is in agreement with White's[1] prediction for external flows. It should be appreciated that in external flows the skin friction coefficient C_f should be larger than the onset value, given by

$$C_f^* = 2\left(\frac{U_t^*}{U_1}\right)^2 \qquad (4)$$

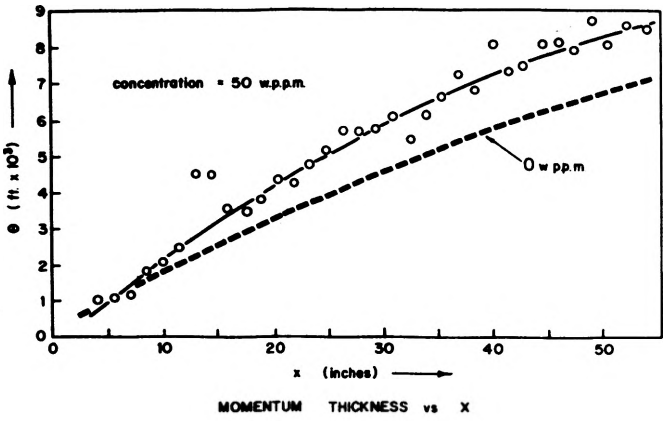

Fig. 5 Momentum thickness θ growth for 50 wppm

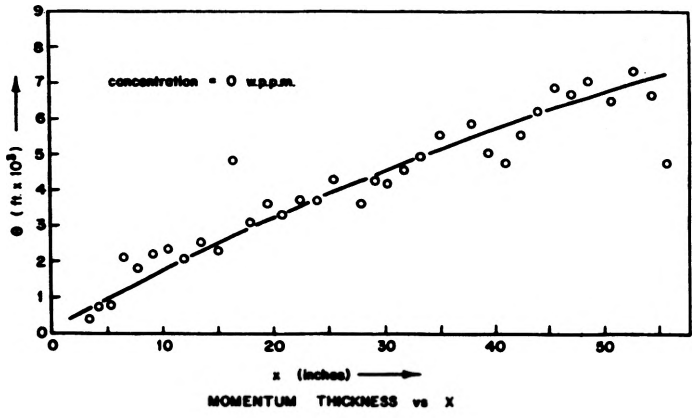

Fig. 3 Momentum thickness θ growth for 0 wppm

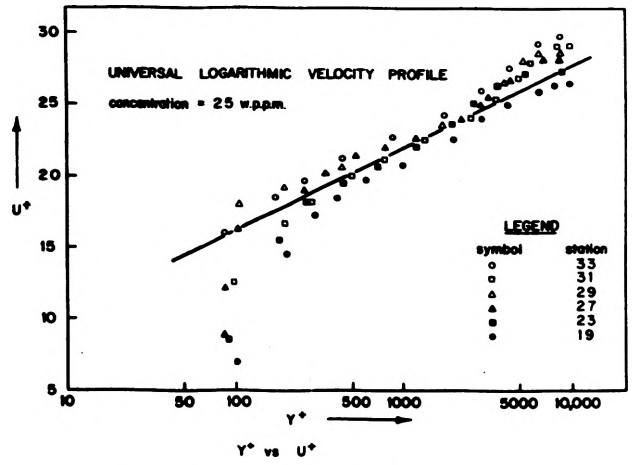

Fig. 6 Universal logarithmic profile for 25 wppm

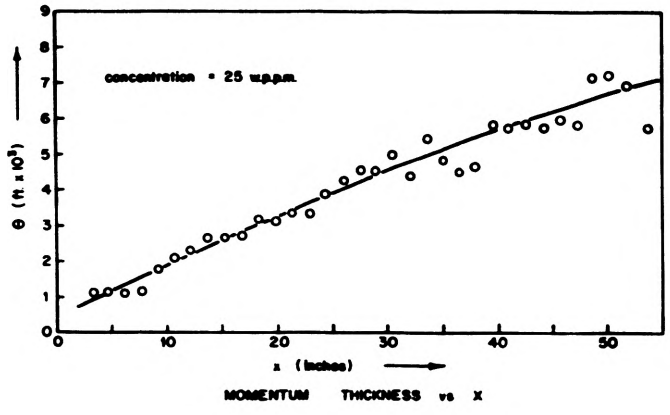

Fig. 4 Momentum thickness θ growth for 25 wppm

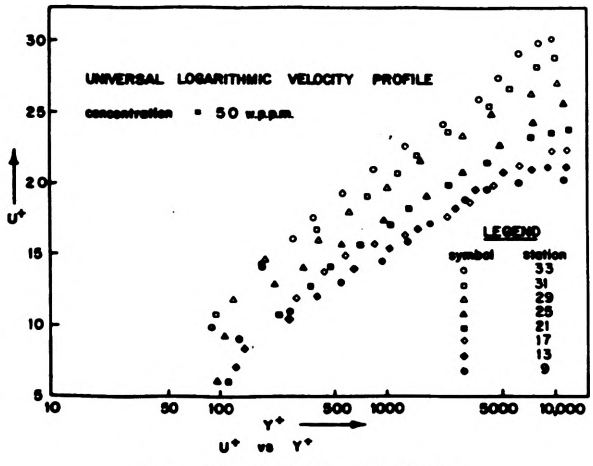

Fig. 7 Universal logarithmic profile for 50 wppm

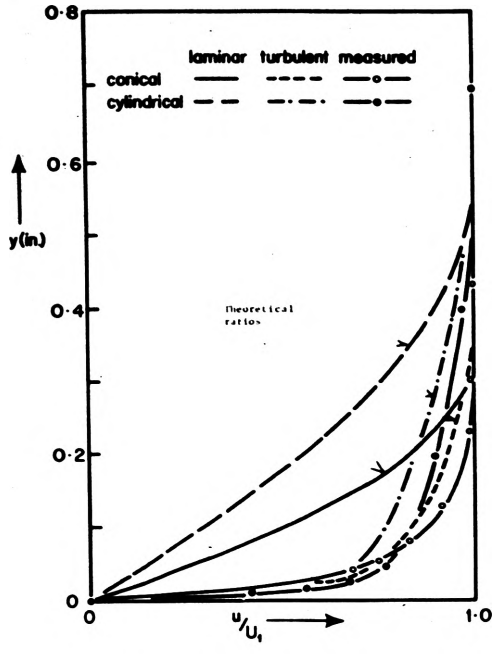

Fig. 8 Velocity Profile at Station 5 (50 wppm)

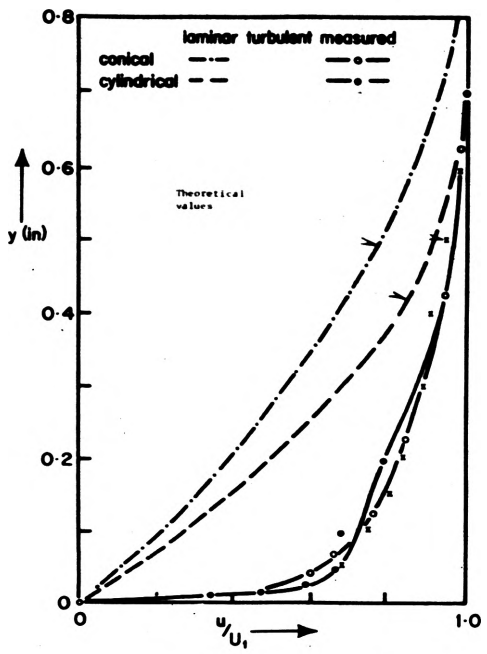

Fig. 9 Velocity Profile at Station 18 (50 wppm)

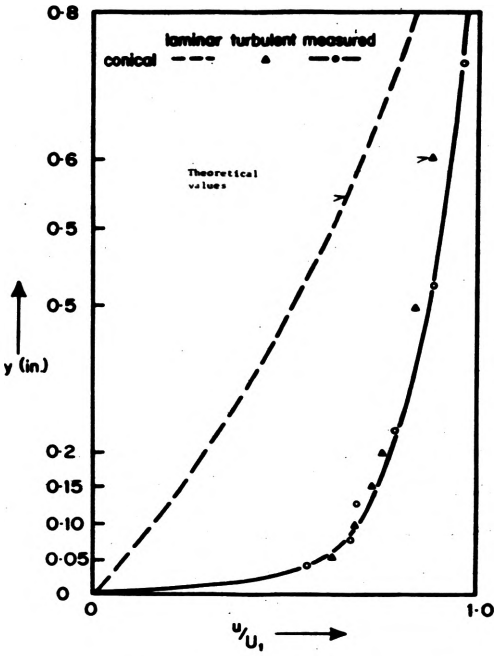

Fig. 10 Velocity Profile at Station 33 (50 wppm)

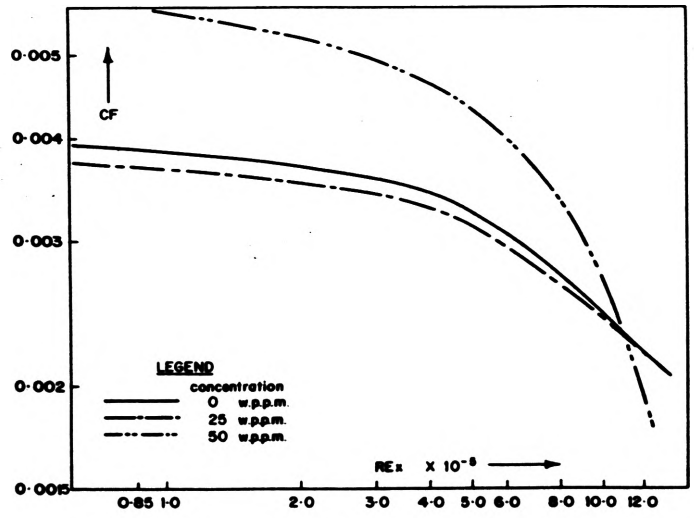

Fig. 11 Local skin friction coefficient versus Re_x

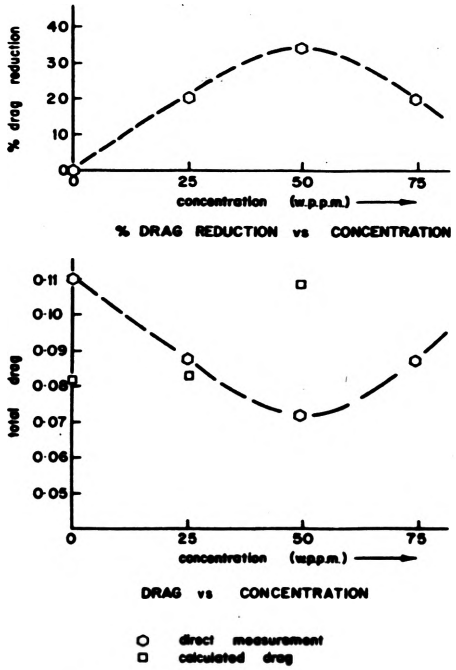

Fig. 12 Drag versus concentration

if drag reduction is to occur. C_f^* is not a constant for a given polymer solution but depends on U_1. The important onset criterion is the wall shear stress τ_o^*, or the friction velocity U_t^*, which are possibly constant for a given polymer.

It can be seen that for the present data C_f^* is approximately 0.0022 which gives a U_t^*~0.074 ft/sec. This corresponds to an onset wave number W* of 7700 ft^{-1} (252 cm^{-1}) for the polyacrylamide MRL 402 which has a molecular weight of about 10^7. At first sight this is not in agreement with Virk et al.'s[12] data for W* of 470 and 530 cm^{-1} for a polyacrylamide having a molecular weight of about 2.5×10^6, which are based on pipe flow data. However, if it is assumed that W* is proportional to $:(MW)^{-\frac{1}{2}}$, then the present data gives an equivalent W*, for MW~2.5×10^6, of 504 which is in fact in agreement with Virk's data.

Directly measured total drag as a function of the concentration is shown in Figure 12 and the form of the curves is as expected. Drag is reduced as the concentration of the polymer increased until a minimum condition is reached and thereafter the drag increased. The drag reduction profile obtained from the velocity profile does not show the same behavior as that obtained by direct measurement. The total drag will be greater than the viscous drag due to form drag. However, for the 50 wppm the viscous drag is larger, which is very suspect. It can be seen that the form drag for the 25 wppm data decreased, which could be expected. In fact, it might be expected that the drag due to turbulent eddy shedding would always be reduced by polymer additives and consequently the total drag on a body of finite thickness would not always comply with the threshold criterion unless only viscous drag is considered.

There are a number of critical points that could be raised when comparing the direct and indirect measurement approaches. With indirect measurement it could

be argued that the calibration procedures are suspect. Furthermore, that the use of the momentum integral equation is not truly valid since it is almost impossible to obtain experimentally a two-dimensional flow, and a three-dimensional flow invalidates the equation. The technique used in the direct measurement is very critical to alignment. Slight misalignments could result in incorrect total drag measurements due to thrust in the vertical plane. Also, the suspension system could be susceptible to oscillation sympathetic to the free stream turbulence. The technique of making a momentum balance downstream of the body and/or drag balance on a support system both have their shortcomings and it is felt that the present technique is more reliable.

Figure 13 shows the distribution of the turbulence intensity with respect to the normal position from the wall at a number of selected stations. The representative data for 0 and 25 wppm are unusual, and are at first sight indicative of developing or transitional flow. However, the velocity profiles were "fuller" than turbulent profiles and completely different from that of expected laminar profiles. For the 50 wppm runs, the turbulence data obtained using a conical probe did not agree with that for the cylindrical probe; but the velocity profiles were in agreement. The conical probe data for 50 wppm were of the generally accepted form and indicated that the turbulence intensity decreased as the fluid progressed down the plate; however, the log law profiles for 50 wppm were unusual. It is difficult to make any worthwhile deductions from these contradictory data but to observe that, as others have found, the conical probes are better for polymer solutions.

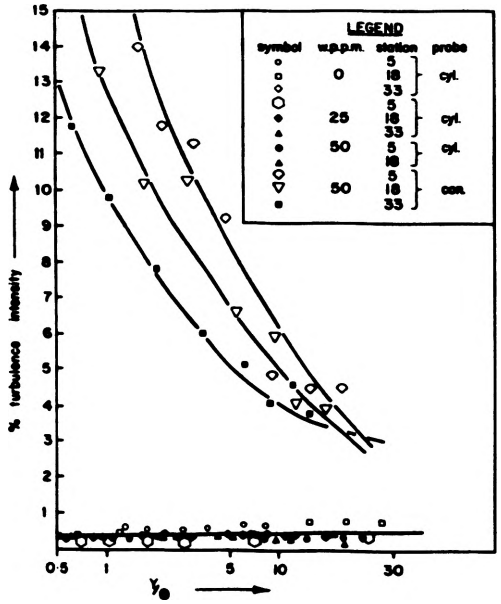

Fig. 13 Turbulence intensity distribution

CONCLUSIONS

1. At Reynolds numbers above the threshold value viscous drag apparently will not be reduced and could be increased in external flows.

2. The onset wave number W* for the polyacrylamide MRL 402 was found to be 7700 ft^{-1}.

3. The form drag appears to be reduced by polymer additives even below the onset Reynolds number Re^*. This in effect can result in reduced total drag at friction velocities below the onset value U_t^* for the particular additive.

4. A maximum total drag reduction of about 30% occurred at a concentration of 50 wppm, however, there was little change in the viscous drag.

5. For aqueous polymer solutions, the turbulent boundary layer profiles were "fuller" than corresponding profiles for pure water.

6. For turbulence measurements conical hot-film probes would appear to be more reliable than cylindrical type probes.

7. The polyacrylamide MRL 402 is apparently quite stable, and exhibited no obvious degradation under the test conditions.

8. The turbulence intensity in the boundary layer appeared to decrease as the fluid progressed down the plate.

SYMBOLS

A	constant in the log law equation
B	constant in the log law equation
C_f	local skin friction coefficient, $\frac{2\tau_o}{\rho U_1^2}$
C_f^*	threshold skin friction coefficient
D	total drag (lbf/ft width)
D_v	viscous drag (lbf/ft width), $\frac{\mu U_\infty}{2} \int_o^{Re_L} C_f \left(\frac{U_1}{U_\infty}\right)^2 d(Re)$
L	length (ft)
Re	Reynolds number, $\frac{U_1 x}{\nu}$
Re_L	Reynolds number, $U_1 L/\nu$
$Re_{(crit)}$	critical Reynolds number
u	velocity in the x direction (ft/sec)
U_1	local free stream velocity (ft/sec)
U_∞	free stream velocity (ft/sec)
U^*	friction velocity (ft/sec), $(\tau_o/\rho)^{\frac{1}{2}}$
U^+	non-dimensional velocity, u/U^*
U_t^*	threshold friction velocity (ft/sec)
W*	onset wave number (1/ft), U_t^*/ν
x,y	coordinates parallel and normal to the plate
Y^+	non dimensional distance, yU^*/ν
ρ	density (lbm/ft^3)
μ	viscosity (lbm/ft sec)
ν	kinematic viscosity (ft^2/sec)
τ_o	wall shear stress (lbf/ft^2)
τ_o^*	onset wall shear stress (lbf/ft^2)
θ	momentum thickness (ft or in) $\int_o^\infty \frac{u}{U_1} \cdot \left(1 - \frac{u}{U_1}\right) dy$
θ_p	momentum thickness for a polymer solution (ft or in)

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