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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034



APPLICATION OF THE STANTON TUBE TO THE MEASUREMENT OF WALL SHEAR STRESS

ON A FLAT PLATE WITH
POLYMER EJECTION

by

William G. Souders

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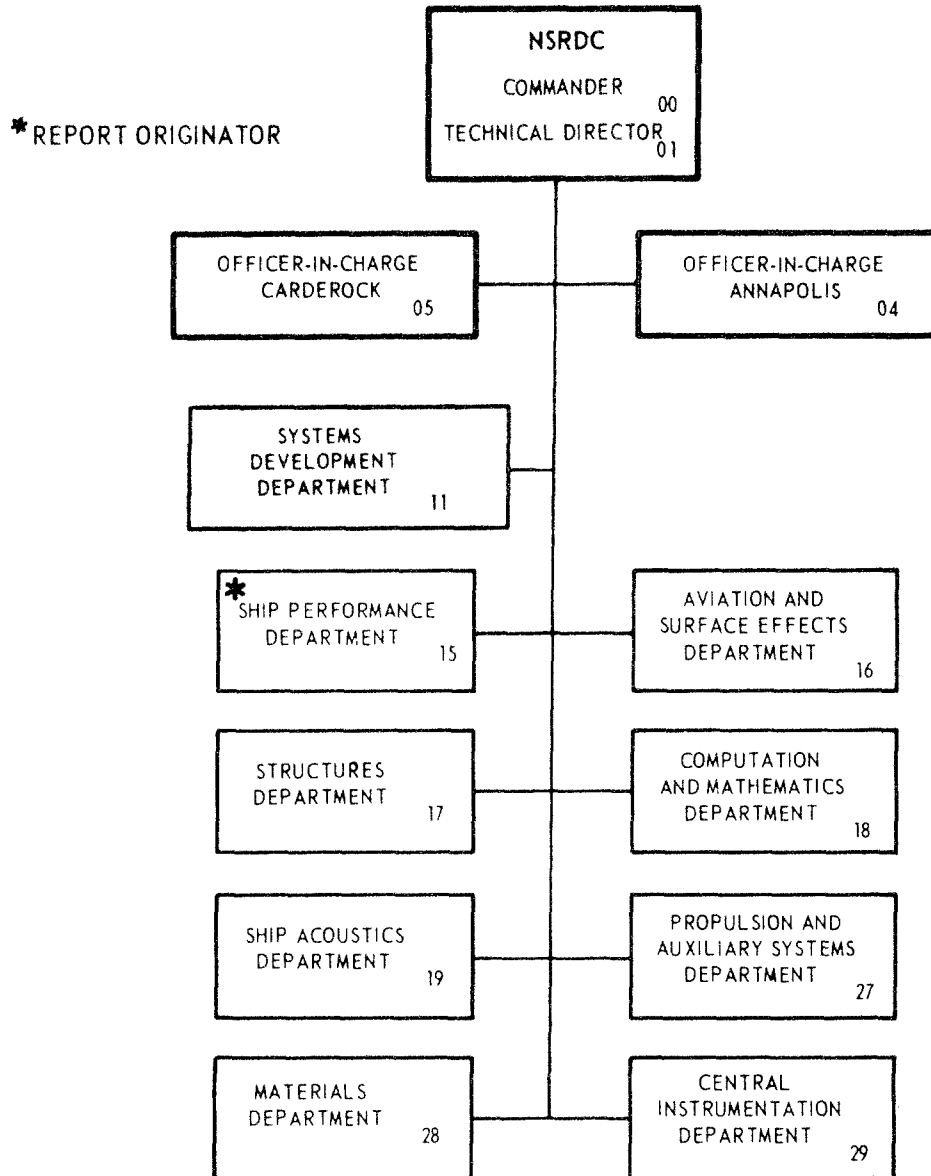
Report 3849

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NOTATION

A	Slope of inner logarithmic velocity law for ordinary Newtonian fluid or $2.3026/K$, Equation (4)
\bar{A}	Slope of logarithmic velocity law for the strongly interactive layer, Equation (3)
B	Constant of ordinary Newtonian inner logarithmic velocity law, Equation (4)
\bar{B}	Constant of the logarithmic law for strongly interactive layer, Equation (3)
c_i	Initial polymer ejection concentration
\bar{c}_w	Local mean wall polymer concentration
c_τ	Wall shear stress coefficient, $c_\tau = \tau_w / 1/2 \rho U_o^2$
D	Pipe diameter, Equation (10)
d_p	Preston tube outside diameter
d_s	Height of Stanton tube above wall
\bar{d}_s	Deviation of effective center of Stanton tube from geometric center
K	Von Kármán constant, Equation (4)
L	Distance between points 1 and 2, Equation (10)
ℓ	Characteristic length scale, Equation (9)
ℓ^*	Nondimensional characteristic length scale, $\ell^* = u_\tau \ell / \nu$
P	Polymer species dissolved in the solvent
P_1	Pressure at point 1, Equation (10)
P_2	Pressure at point 2, Equation (10)
Q_i	Polymer ejection flow rate
q	Dynamic pressure, $q = 1/2 \rho u^2$
R_x	Reynold number based on x , $R_x = U_o x / \nu$

U	Mean velocity at outer edge of boundary layer
U_0	Water tunnel velocity
u	Local mean velocity in direction of flow
u_τ	Shear velocity, $u_\tau \equiv \sqrt{\tau_w/\rho}$
u^+	Nondimensional mean velocity, $u^+ = u/u_\tau$
x	Longitudinal distance along flat plate
x^*	$\log_{10} (\Delta P_p d_p^2/4 \rho v^2)$
y	Normal distance from the wall
y_l	Thickness of the laminar sublayer, Equation (1)
y_s	Thickness of the strongly interactive layer, Equation (3)
y^+	Nondimensional distance from the wall, $y^+ = u_\tau y/\nu$
y_l^+	Nondimensional thickness of the laminar sublayer, $y_l^+ = u_\tau y_l/\nu$
y^*	$\log_{10} (\tau_w d_p^2/4 \rho v^2)$
ΔB	Constant defined in Equation (4)
ΔP_p	Preston tube dynamic pressure
ΔP	Pressure drop along pipe, $P_1 - P_2$, Equation (10)
ΔP_s	Stanton tube dynamic pressure
δ	Boundary layer thickness
ν	Kinematic viscosity of the solvent
ρ	Density of solvent
τ_w	Wall shear stress
Ω	Cole's wake parameter, Equation (5)

ABSTRACT

An experimental investigation was made to determine the effects on drag of injecting aqueous solutions of polyethylene oxide (Polyox WSR-301) into the turbulent boundary layer of a flat plate. The local mean wall shear stress was measured with a Stanton tube located in the laminar sublayer. Diffusion of the polymer in the boundary layer was also investigated by analysis of fluid samples withdrawn from the flat plate surface. In addition, a related but independent experimental turbulent pipe flow study was undertaken to determine any changes in Stanton tube sensitivity caused by the viscoelasticity of the polymer solutions.

The wall friction on the plate was determined with and without polymer injection and the results compared well with available shear data. The measured wall shear stresses showed reductions of up to 50 percent with polymer injection and decreased with increasing mean wall polymer concentration.

ADMINISTRATIVE INFORMATION

The research reported here was sponsored by the Naval Ship Systems Command. Funding was provided under Subproject SF 354 210 03, Task 01710, Element 62512N, Work Unit 1-1508-305.

INTRODUCTION

The possibility of reducing frictional drag by introducing certain long-chain and high-molecular-weight polymers into the boundary layers of ships has recently become of increasing interest to the Navy. The injection of these polymer solutions holds promise of increased speeds, reduced powering requirements, and reduced levels of noise. Potential areas of application include submarines, deep-sea submersible research and rescue vehicles, torpedoes, and certain surface vessels.

Most experimental studies on the use of polymers to reduce frictional drag have been made in smooth pipes with turbulent flows of uniform polymer concentration. The first quantitative study of the drag-reducing characteristics of polymer solutions was conducted by Toms¹ in 1948. Many additional investigations of polymer solutions in pipe flows have since been made, e.g., by Wells,² Fabula,³ Elata and Tirosh.⁴

¹Toms, B. A., "Some Observations on the Flow of Linear Polymer Solutions through Straight Tubes at Large Reynolds Numbers," Proc. First Inter. Congr. Rheology, North Holland Publishing Company, Amsterdam, Vol. 2, pp. 135-141 (1948). A complete list of references is given on page 23.

²Wells, C. S., Jr., "On the Turbulent Shear Flow of an Elasticoviscous Fluid," AIAA Reprint 64-36 (1964).

³Fabula, A. G., "The Toms Phenomenon in the Turbulent Flow of Very Dilute Polymer Solutions," Proc. Fourth Inter. Congr. Rheology, Interscience Publications, New York, Part 3, pp. 455-479 (1965).

⁴Elata, C. and J. Tirosh, "Frictional Drag Reduction," Israel J. Tech., Vol. 3, pp. 1-6 (1965).

Ernst,⁵ Virk,⁶ Tsai,⁷ Paterson and Abernathy,⁸ and Huang and Santelli.⁹ Experimental investigations into the more practical area involving the injection of polymer solutions into developing turbulent boundary layers (nonuniform concentration) are rather scarce, (Wells and Spangler,¹⁰ Wetzel and Ripken,¹¹ and Tullis and Lindeman¹²) and are usually limited to low shear stress or low Reynolds number. The only instance where drag reduction was demonstrated in the more practical range of ship boundary layers is a study by Canham et al.¹³ That polymer ejection trial on the British minesweeper HMS HIGHBURTON indicated the feasibility of using polymer injection to reduce frictional drag on ships, but the measurements were limited to ship powering requirements. Theoretical investigations of external boundary layers with polymer solutions include the work of Granville,¹⁴ McCarthy,¹⁵ Fabula and Burns,¹⁶ and Seyer.¹⁷

The purpose of the present work was to investigate the change in frictional drag caused by injecting polymer solutions into the turbulent boundary layer of a flat plate at high Reynolds number and shear stress. Wall shear stress measurements were made with a Stanton tube located in the laminar sublayer. The mean concentration of polymer in the boundary layer was determined by chemical analysis of fluid samples withdrawn from the flat plate surface. These measurements were made at speeds ranging from 8.5 to 51 ft/sec corresponding to a Reynolds number range of 8×10^6 to 5×10^7 . Aqueous solutions of polymer of 500 and 1000 weight parts per million (wppm) were injected into the boundary layer at flow rates of 0.05 and 0.1 ft³/sec. The Stanton tube used for the shear measurement was calibrated in water using a Preston tube

⁵Ernst, W. D., "Investigation of Turbulent Shear Flow of Dilute Aqueous CMC Solutions," J. Am. Inst. Ch. Eng., Vol. 12, No. 3, pp. 581-586 (1966).

⁶Virk, P.S. et al., "The Toms Phenomenon: Turbulent Pipe Flow of Dilute Polymer Solutions," J. Fluid Mech., Vol. 30, Part 2, pp. 305-328 (1967).

⁷Tsai, F., "The Turbulent Boundary Layer in the Flow of Dilute Solutions of Linear Macromolecules," Ph.D. Thesis, University of Minnesota (1968).

⁸Paterson, R. W. and F. H. Abernathy, "Turbulent Flow Drag Reduction and Degradation with Dilute Polymer Solutions," J. Fluid Mech., Vol. 43, Part 4, pp. 689-710 (1970).

⁹Huang, T. T. and N. Santelli, "Drag Reduction and Degradation of Dilute Polymer Solutions in Turbulent Pipe Flows," NSRDC Report 3677 (1971).

¹⁰Wells, C. S. and J. G. Spangler, "Injection of a Drag Reducing Fluid into Turbulent Pipe Flow of a Newtonian Fluid," The Physics of Fluids, Vol. 10, p. 1890 (1967).

¹¹Wetzel, J. M. and J. F. Ripken, "Shear and Diffusion in a Large Boundary Layer Injected with Polymer Solution," University of Minnesota Report 114 (1970).

¹²Tullis, J. P. and L. F. Lindeman, "Polymer Injection for Drag Reduction," Colorado State University, Engineering Research Center, NSRDC Contract N00014-67-0299-0013 (1972).

¹³Canham, H. J. S. et al., "Boundary Layer Additives to Reduce Ship Resistance," The Naval Architect, No. 2 (Jul 1971).

¹⁴Granville, P. S., "Drag Reduction of Flat Plates with Slot Ejection of Polymer Solution," NSRDC Report 3158 (1969).

¹⁵McCarthy, J. H., "Flat Plate Frictional Drag Reduction with Polymer Injection," NSRDC Report 3290 (1970).

¹⁶Fabula, A. G. and T. J. Burns, "Dilution in a Turbulent Boundary Layer with Frictional Reduction," AIAA Second Advanced Marine Vehicles and Propulsion Meeting, Seattle, Washington (1969).

¹⁷Seyer, F. A., "Friction Reduction in Turbulent Flow of Polymer Solution," J. Fluid Mech., Vol. 40, Part 4, pp. 807-819 (1970).

as a standard. The validity of the Stanton tube results is based on the assumption that the calibration does not change when the fluid is a polymer solution. To confirm this assumption, an auxiliary experiment was conducted in a pipe flow facility where the shear measured by the Stanton tube could be checked by pressure drop measurements.

This report presents the shear stress results in the nondimensional form of shear stress coefficient versus Reynolds number for both water and polymer flows. Mean data on wall polymer concentration are also included. The results are compared with available experimental data.

ANALYTICAL BACKGROUND

The following discussion explains the basis for using Stanton and Preston tubes. The regions of the boundary layer where their use is valid is discussed for both water and polymer flows.

VELOCITY SIMILARITY LAWS

In a recent study dealing with the similarity laws for turbulent boundary layer flow with polymer, Huang¹⁸ compiled and analyzed existing experimental velocity profile data for both internal and external boundary layer flows. The analysis of these experimental data indicated that a four-layer mean velocity profile could be distinguished for turbulent boundary layer flow with polymer solutions. The four-layer nondimensional velocity profile described briefly below is valid for both internal and external boundary layer flows.

Laminar Sublayer

The laminar sublayer is the very thin layer of flow in contact with the wall where viscous effects dominate and the turbulent fluctuations are essentially damped out. In this region, the velocity profile is expressed as

$$u^+ \equiv \frac{u}{u_\tau} = \frac{u_\tau y}{\nu} \equiv y^+ \quad 0 \leq y \leq y_\ell \quad (1)$$

where u is the local mean velocity in the direction of flow,

u_τ is the shear velocity $u_\tau = \sqrt{\tau_w/\rho}$,

u^+ is the nondimensional mean velocity $u^+ = u/u_\tau$,

τ_w is the wall shear stress,

ρ is the density of solvent,

y is the normal distance from the wall,

¹⁸Huang, T. T., "Similarity Laws for Turbulent Flow of Dilute Solutions of Drag-Reducing Polymers," NSRDC Report (in preparation).

y^+ is the nondimensional distance from the wall $y^+ = (u_\tau y)/\nu$,
 y_ρ is the thickness of the laminar sublayer, and
 ν is the kinematic viscosity of the solvent.

This velocity law is considered valid both for flows of Newtonian fluids and for dilute polymer solutions. The nominal thickness of the laminar sublayer y_ρ is generally considered¹⁸ to be

$$y_\rho^+ \equiv \frac{u_\tau y_\rho}{\nu} \leq 11.6 \quad (2)$$

where y_ρ^+ is the nondimensional thickness of the laminar sublayer. Thus from Equation (2), for polymer injection, τ_w decreased as y_ρ increases.

Inner Law or Law of the Wall

This region applies to the flow adjacent to the solid boundary where both viscous and inertial effects are important; for drag-reducing polymer solutions, the law of the wall has two layers, a strongly interactive layer and a weakly interactive layer.

For the strongly interactive layer,

$$u^+ = \bar{A} \log_{10} y^+ + \bar{B} \quad y_\rho \leq y \leq y_s \quad (3)$$

where y_s is the thickness of the strongly interactive layer,

\bar{A} is the slope of this logarithmic law, and

\bar{B} is a constant.

The constants \bar{A} and \bar{B} are determined empirically by the best fit of data in the strongly interactive region and are given as $\bar{A} = 30$ and $\bar{B} = 20.2$. This region is characterized by a smaller Von Karman constant and does not exist for ordinary Newtonian fluids.

For the weakly interactive layer,

$$u^+ = A \log_{10} y^+ + B + \Delta B [\rho^*, \bar{c}_w, P] \quad y_s \leq y < 0.2 \delta \quad (4)$$

where δ is the boundary layer thickness,

A is the slope of the logarithmic velocity law for ordinary Newtonian fluids or $(2.3026)/K$,

K is the Von Karman constant,

B is a constant for the ordinary Newtonian inner logarithmic velocity law,

$\Delta B [\rho^*, \bar{c}_w, P]$ is the friction reduction function,

ρ^* is $u_\tau \ell / \nu$,

ℓ is a characteristic length scale,

\bar{c}_w is the concentration of polymer in the solvent, and

P is the polymer species dissolved in the solvent,

The magnitude of the term $\Delta B [\rho^*, \bar{c}_w, P]$ is a measure of the effectiveness of drag-reducing polymers in turbulent boundary layer flow. The values of the two constants A and B are taken from data for Newtonian fluids, $A = 5.75$ and $B = 5.5$. The universal value for the Von Karman constant K is taken as 0.4.

Outer Law or Velocity Defect Law

At some distance away from the wall, where U is the velocity at the outer edge of the boundary layer, the velocity defect $U-u$ is independent of viscosity or polymer effects and inertial effects dominate. This region can be expressed as

$$\frac{U-u}{u_\tau} = -A \log_{10} (y/\delta) + \frac{\Omega}{K} [1 + \cos \pi (y/\delta)] \quad y_s \leq y \leq \delta \quad (5)$$

where U is the mean velocity at the outer edge of the boundary layer and Ω is the Cole wake parameter. The last bracket of the equation is the Hinze approximate wake function¹⁹ where $\pi = 3.1416$.

DETERMINATION OF WALL SHEAR STRESS

The wall shear stress τ_w or skin friction coefficient c_τ may be determined by direct measurement using impact tubes set flush with the wall surface.

Stanton Tube

The Stanton tube is a specially constructed, narrow type of impact tube adjusted to lie within the very thin laminar sublayer defined by Equation (1). The relation for the Stanton tube in the laminar sublayer is given by Granville²⁰ as

$$\frac{\Delta P_s d_s^2}{4 \rho \nu^2} = \frac{1}{2} \left(\frac{\tau_w d_s^2}{4 \rho \nu^2} \right)^2 \left(1 + \frac{\bar{d}_s}{d_s} \right)^2 \quad (6)$$

¹⁹Hinze, J. O., "Turbulence," McGraw-Hill Book Company, New York (1959).

²⁰Granville, P. S., "The Determination of the Local Skin Friction and the Thickness of Turbulent Boundary Layers from the Velocity Similarity Laws," International Shipbuilding Progress, Vol. 7, No. 69 (1960).

where ΔP_s is the dynamic pressure sensed by the Stanton tube,

d_s is the height of the Stanton tube above the wall, and

\bar{d}_s is the deviation of the effective center of the Stanton tube from the geometric center.

The Stanton tube requires calibration in known shear flows to determine the displacement effects \bar{d}_s due to the finite size of the tube. Reported use of the Stanton tube in the literature is scarce and limited entirely to air flows.

Preston Tube

The Preston tube²¹ has been demonstrated²² to be a reliable and valid means of measuring the local skin friction on smooth surfaces for both air and water flows. It is an ordinary pitot tube mounted directly on the wall and small enough to lie within the inner law region (Equation (4)).

The Preston tube pressure data reported in this paper were converted to shear stress by using a calibration given by Patel.²² An empirical relation which best fits the experimental pipe data is given as

$$x^* = y^* + 2 \log_{10} (1.95 y^* + 4.10) \quad (7)$$

for $3.5 < y^* < 5.3$

or $55 < \frac{u_\tau d_p}{2\nu} < 800$

where $x^* \equiv \log_{10} (\Delta P_p d_p^2 / 4 \rho \nu^2)$

and $y^* \equiv \log_{10} (\tau_w d_p^2 / 4 \rho \nu^2)$

Here d_p is the outside diameter of the Preston tube and ΔP_p is the total pressure sensed by the Preston tube minus the static pressure.

The influence of polymer on the inner law, Equation (4), is contained in the parameter ΔB [ℓ^* , \bar{c}_w , P]. Since ΔB is a function of ℓ^* , \bar{c}_w , and P , different calibrations for each combination of polymer parameters would be required in order to successfully use the Preston tube in polymer flows. Obviously, this is experimentally impractical, and the Preston tube is generally not suited for measurements in polymer flows. However, the velocity law for the laminar sublayer, Equation (1), is unchanged by polymer; thus if properly calibrated, the Stanton tube can be used for shear stress measurements with polymer solutions. In the present

²¹Preston, J. H., "The Determination of Turbulent Skin Friction by Means of Pitot Tubes," J. Roy. Aeron. Soc., Vol. 58 (1954).

²²Patel, V. C., "Calibration of the Preston Tube and Limitations on Its Use in Pressure Gradients," J. Fluid Mech., Vol. 23, Part 1, pp. 185-208 (1965).

study, the Preston tube served to provide shear stress data for water flows and to establish the calibration of the Stanton tube which, in turn, was used for shear stress measurements for polymer flows.

Polymer Viscoelastic Effects

Astarita and Nicodemo²³ have reported that inaccuracies may arise in the measurement of velocity in dilute polymer solutions when conventional impact tubes are used. For ordinary Newtonian flows, the impact tube pressure corresponds to the stagnation pressure; however, for polymer solutions, the pressure is the sum of the stagnation effect and a normal stress difference effect caused by the viscoelasticity of the aqueous polymer solution. This normal stress difference due to elasticity can affect both the static and stagnation pressures and reduce the dynamic pressure or velocity. The limited impact tube data for polymer flow reported by Wetzel and Tsai²⁴ indicated that polymer effects become more significant with increasing polymer concentration and decreasing impact tube diameter. For a tube inside diameter of 0.015 in., e.g., they reported reduced sensitivity for concentrations ≥ 25 wppm. This anomaly could influence the pressure measurements for the present study because of the small size of the Stanton tube. Thus, an investigation was conducted in a 3-in.-diameter pipe to determine any change in Stanton tube sensitivity due to viscoelastic properties of the polymer solutions.

DRAG REDUCTION BY POLYMER EJECTION

TEST FACILITY AND EQUIPMENT

The 36-Inch Water Tunnel

The flat plate study was conducted in the NSRDC 36-in. variable-pressure water tunnel.²⁵ This tunnel is a closed circuit system (Figure 1). Its closed jet test section (circular cross section 18 ft long and inside diameter of approximately 36 in.) was used for the study. The diameter of the test section varies slightly to limit insofar as possible any pressure gradient through it. The maximum water speed through the test section is 80 ft/sec, and the static pressure at the test section centerline can be varied from 2 to 60 psia. Tunnel velocity was determined by a pitot tube suspended from the top of the test section slightly to the rear of the test position as shown in Figure 2c. The tunnel is equipped with a resorber, but it was not installed for this test.

²³Astarita, G. and L. Nicodemo, "Velocity Distribution and Normal Stresses in Viscoelastic Turbulent Pipe Flow," J. Am. Inst. Ch. Eng., Vol. 12, p. 478 (1966)

²⁴Wetzel, J. M. and F. Y. Tsai, "Impact Tube Measurements in Dilute Polymer Solutions," J. Am. Inst. Chem. Eng., Vol. 14, No. 4, pp. 663-664 (Jul 1968).

²⁵Brownell, W. F., "A 36-Inch Variable-Pressure Water Tunnel," David Taylor Model Basin Report 1052 (Jun 1956).

The Flat Plate

Figure 2 shows details of the 11-ft-long stainless steel flat plate and its installation in the water tunnel. The polymer ejector was located 1 ft from the leading edge of the plate and consisted of 15 0.5-in.-diameter holes spaced transversely at 1.5-in. intervals. The ejection holes were drilled at an angle of 45 deg with the flow and all sharp edges were rounded and smoothed. Three 1.5-in.-diameter feed pipes supplied polymer to the ejection chamber, which contained a baffle.

In order to determine whether there was any pressure gradient, four pairs of static pressure taps were located along the plate, 0.5 ft from the plate centerline, at distances of 2.6, 4.6, 6.6, and 8.9 ft from the leading edge. Two sample withdrawal taps were located 0.6 ft off the plate centerline at a distance of 8.6 ft from the leading edge. These withdrawal taps (3/8-in.-diameter holes normal to and flush with the flat plate surface) were used to determine the mean wall polymer concentration for the shear measurements.

Stanton and Preston Tubes

To measure the shear stress on the flat plate, a Stanton tube and a Preston tube were installed at a location just off the plate centerline and approximately 8.6 ft from the leading edge. Both the tubes were built into individual mounting plates which fitted flush into a large mounting plate. The large plate fitted flush with the flat plate. A stainless steel Preston tube was mounted directly on the flat plate surface and was small enough to lie within the inner law region (Equation (4)). The tube had outer and inner diameters of 0.073 and 0.035 in. and square cut ends.

The Stanton tube, a specially constructed total-head type impact tube, was located next to the Preston tube and was small enough to lie within the laminar sublayer (Equation (1)). The conceptual design of the Stanton tube was obtained from Head and Rechneberg.²⁶ The top of this tube consisted of 0.002-in.-thick shim stock which was ground to a knife edge and adjusted to be 0.0015 in. above the flat plate surface. The flat plate surface formed the lower boundary of this tube.

The static reference pressure for both impact tubes was provided by two 1/32-in.-diameter static pressure portals located just to the side of the Stanton tube. Figure 3 shows some details of these impact tubes and their arrangement in the test installation.

ELECTRONIC INSTRUMENTATION

Pressures from the flat plate shear probes were sensed by a variable reluctance pressure transducer (Pace Model PID-1005) which has a full-scale differential pressure range from 0.1 to 500 psia depending on the diaphragm used. Diaphragms whose full-scale values ranged from 0.2 to 20 psi were employed in this investigation. The rated linearity and hysteresis of the transducer is 0.5 percent full scale. The interchangeable diaphragm feature of the Pace transducer permitted pressures to be measured near the full-scale value of the diaphragm, thus increasing obtainable accuracy in the measurement.

²⁶Head, M. R. and I. Rechneberg, "The Preston Tube as a Means of Measuring Skin Friction," J. Fluid Mech., Vol. 14, Part 1, pp. 1-17 (1962).

The analog signals from the pressure gages were conditioned and converted to digital form. The digital signal was then processed on an Interdata III data collector and analyzer and the results displayed by an ASR-33 teletype. Prior to the experiment, the Interdata III was programmed to convert the digital data to physical units. This digital data acquisition and processor system furnished immediate test results which provided much flexibility in the conduct of the experiment. A block diagram of the electronic instrumentation is shown in Figure 4.

POLYMER

Preparation of Polymer

Polyethylene oxide,²⁷ a water-soluble synthetic polymer of high molecular weight was used for the flat plate injection study. It is available commercially from Union Carbide Corporation under the trade name Polyox WSR-301. Concentrated solutions were prepared in a 500-gal-capacity stainless steel dairy tank. To disperse the powdered polymer and prevent the formation of gellike agglomerates which were difficult to dissolve, test solutions were prepared by introducing weighed quantities of dry polymer using an aspiration principle.¹¹ The aspirator, which was connected to a water supply line, ensured that the polymer particles were wetted as individual particles which could be easily dissolved. The dairy tank was equipped with a propeller stirrer which provided a gentle agitation of the Polyox solution during the mixing process. After completion of the mixing process, the solution was left from 8–10 hr, i.e., until complete solution had taken place and there was little evidence of any gellike agglomerates.

The prepared Polyox solution was then transferred to a 200-gal-capacity glass-lined pressure tank. The flow rate of this transfer was limited to a wall shear stress below 30 dynes/cm² to ensure minimum mechanical degradation.²⁷ The tank was pressurized and the flow from the tank passed through a calibrated electromagnetic flowmeter and finally through three 1.5-in.-diameter feed pipes leading to the flat plate ejection chamber. The mixing system (similar to that of Wetzel and Ripken¹¹) is shown schematically in Figure 5a.

Collection of Samples

Samples were collected from the surface of the flat plate. The sample lines were fed out of the tunnel through the aft strut as shown in Figure 2c. The withdrawn fluid represented an average sample by virtue of the turbulent mixing that occurred in the vicinity of the flush-mounted sample tap. The sampling arrangement (Figure 5b) was provided for both sample locations in order to collect fluid with negligible degradation of the polymer:

The 40-psia tunnel pressure provided enough head for sample collection. The procedure for sample collection was to have the capture and flow-rate control valves open and the sample valve closed; after ample

²⁷Paterson, R. W., "Turbulent Flow Drag Reduction and Degradation with Dilute Polymer Solutions," Harvard University, Engineering Sciences Laboratory (Jun 1969).

flush time to ensure steady state-conditions, the capture valve was closed and the sample drained off into the sample bottle. The flow-rate control valve was precalibrated so that the flow in the sampling line was limited to a safe wall shear stress (no degradation of polymer) during sample collection. In addition, the capture valve was placed sufficiently far upstream in the collection apparatus so that any fluid degraded during its closing was not collected.

Analyses of Samples

The polymer concentration in a particular sample withdrawn from the flat plate surface was determined by both the fluorometric and the rheometric methods.

For the fluorometric method, small quantities of a compatible fluorescent dye tracer (Rhodamine B) were added to each concentrated test solution of Polyox. This dye is considered compatible with Polyox in that it is stable and does not influence the drag-reducing properties of the polymer.¹¹ The dye was added to the Polyox mixture just before transfer to the pressure tank in a concentration of 1/1000th of the particular concentration of Polyox. It was assumed that diffusion was the same for the dye and the Polyox. Samples collected from the flat plate surface were analyzed on a fluorometer (American Instrument Company Model 4-702A) using a 10- x 75-mm cell at ambient temperature (60–70 F). All fluorometer measurements were made immediately after sample collection.

For the rheometric method, a turbulent-flow rheometer²⁸ measured the differential pressure in a length of hypodermic tubing at Reynolds numbers above transition. A relative index of frictional drag reduction was obtained by comparing the differential pressure of the test polymer sample with that of a water reference. All rheometer measurements were made within 1–4 hr after sample collection.

EXPERIMENTAL PROCEDURE

The experiment was conducted at a constant tunnel pressure of 40 psia. To determine the pressure gradient, if any, along the plate and the static reference to be used with the Stanton and Preston tubes, tests were run in plain water over a velocity range from 8.5 to 50.7 ft/sec in 8.5-ft/sec increments using the eight static holes shown in Figure 2b. Since the results indicated a negligible pressure gradient, the pressures from the two static taps in the immediate vicinity of the Stanton tube (these agreed with the other static readings) were averaged and used as the reference for both the Preston and Stanton tubes. The Stanton tube was then calibrated by using the Preston tube as a standard. These experiments were run in water over a velocity range from 8.5 to 50.7 ft/sec in 1.7-ft/sec increments.

The final portion of the experiment was conducted with polymer ejection. However, before the use of any polymer, water was ejected at flow rates of 0.05 and 0.10 ft³/sec and tunnel velocities of 16.9 and

²⁸Hoyt, J. M., "A Turbulent-Flow Rheometer," in "Symposium on Rheology," A. W. Morris and J. T. S. Wang, editors, Am. Soc. Mech Eng., New York (1965).

33.8 ft/sec to determine the effect of these variables on wall shear. No changes in the readings of the Stanton or Preston tubes were observed. Polymer ejection tests were limited to tunnel velocities of 16.9, 25.3, 33.8 and 50.7 ft/sec and ejection flow rates of 0.05 and 0.10 ft³/sec. Initial polymer concentrations of 500 and 1000 wppm were used. The majority of runs were limited to the lower concentrations and flow rates. The background level of polymer in the tunnel increased rapidly for the high polymer concentration and flow rates, but this problem was kept to a minimum by periodically draining the tunnel and refilling it with fresh water.

The test procedure for polymer ejection runs was first to take a fluid sample to determine background polymer concentration, if any. Then, with the tunnel at constant velocity, steady-state data were taken before, during, and after polymer ejection. Data were not recorded during the transition phases and fluid samples were collected only during the ejection phase.

RESULTS AND DISCUSSION

The flat plate shear stress results (Figures 6–8) cover a tunnel speed range of 8.5 to 51 ft/sec or a Reynolds number range of 8×10^6 to 5×10^7 (based on longitudinal distance from plate leading edge). The values of mean wall polymer concentration (\bar{c}_w) given for the various runs were determined by the fluorometric method of analysis.

Figure 6 shows the variation of \bar{d}_s/d_s with $\tau_w d_s^2/4 \rho \nu^2$ for the Stanton tube in water flow. Values of \bar{d}_s/d_s were calculated from Equation (6) by using the measured values of τ_w and ΔP_s . The dashed lines represents the mean line through previous experimental data.²⁰ As shown, the values of \bar{d}_s/d_s become quite large for low value of $\tau_w d_s^2/4 \rho \nu^2$.

Figure 7 presents the variation of wall shear stress coefficient C_τ with Reynolds number R_x . These dimensionless parameters are defined as

$$\text{Shear stress coefficient: } C_\tau = \frac{\tau_w}{\frac{1}{2} \rho U_0^2}$$

$$\text{Reynolds number: } R_x = \frac{U_0 x}{\nu}$$

where U_0 is the water tunnel velocity and x is the longitudinal distance along the flat plate.

As expected, results for the Preston tube in water flows indicated a gradual decrease in C_τ with increasing R_x . These are in fair agreement with the empirical equation of Schultz-Grunow; see Daily and Harleman.²⁹ This relation, given as

$$C_\tau = 0.370 (\log R_x)^{-2.584} \quad (8)$$

is included in Figure 7.

²⁹Daily, J. W. and D. R. Harleman, "Fluid Dynamics," Addison-Wesley Publishing Company, Inc. (1966).

Figure 7 also gives the Stanton tube shear results obtained with polymer ejection, C_τ is plotted against R_x for various initial polymer ejection concentrations c_i and flow rates Q_i . Mean wall polymer concentration data are also included. In general, their results indicate the following trends:

1. An average reduction of 40 percent in C_τ over the entire range of test parameters for low concentrations of c_w ; the maximum decrease of 51 percent occurred for a \bar{c}_w of 4.3 wppm.
2. A decrease in wall shear stress with increasing ejection flow rate or mean wall polymer concentration.
3. Lower mean wall concentrations and less shear stress reduction for higher polymer concentrations. This trend has been reported in past studies^{30, 31} and could indicate insufficient mixing of the polymer into the turbulent boundary layer.
4. An increase in C_τ with increasing R_x for all polymer injection concentrations and flow rates.

Figure 8 compares the Stanton tube shear results in polymer flows with experimental data from Huang.¹⁸ Here, the variation of ΔB , Equation (4), is plotted against u_τ/ν for various mean wall polymer concentrations. The Huang data, shown as solid lines on the figure, are expressed as

$$\Delta B = 5.7 (\bar{c}_w)^{1/2} - 25 \left[\log_{10} \left(\frac{u_\tau \ell}{\nu} \right) \right]^2 \quad (9)$$

where ℓ is a characteristics length scale. For Polyox WSR-301, $\ell = 5 \times 10^{-4}$ cm. The results from the present study are shown as individual data points and represent values of ΔB calculated from Equation (9) by using the measured flat plate values of u_τ and \bar{c}_w . Note that the results compare quite well.

STANTON TUBE TURBULENT PIPE FLOW STUDY

To determine whether the viscoelasticity of the polymer solutions caused changes in Stanton tube sensitivity, a study was conducted in the NSRDC 3-in. turbulent pipe flow facility.³²

TEST FACILITY

Shown schematically in Figure 9, this facility consists of a 2400-gal head tank which is connected to a settling tank (4-ft-diameter and 8-ft long) by 12-in.-diameter piping. Water and other solutions are exhausted into a large capacity receiving tank through an exhaust diffuser. The head tank can be either

³⁰Love, Richard H., "The Effect of Ejected Polymer Solutions on the Resistance and Wake of a Flat Plate in a Water Flow," Hydronautics Inc., Technical Report 353-2 (June 1965).

³¹Wu, J. and M. Tulin, "Drag Reduction by Ejecting Additive Solution into Pure-Water Boundary Layer," J. Basic Eng., pp. 749-756 (Dec 1972).

³²Demetz, F. C. and L. D. Cole, "Measurement of the Power Spectral Density of the Fluctuating Pressures on a Rigid Pipe Wall due to Turbulent Flow of a Dilute Polymer-Water Solution," U.S. Navy J. Underwater Acoustics, Vol. 20, No. 2 (Apr 1970).

supercharged with compressed air up to 150 psig or evacuated to a 29-in. Hg vacuum. The initial tank pressure can be maintained constant as the head tank is emptied. All inner steel surfaces in contact with test solutions are treated with three coats of "plasite," an anticorrosion epoxy paint.

The smooth test pipe, which originates at the ball valve, is constructed from transparent Butyrate plastic pipe with a 3-1/16-in. inside diameter and a 0.216-in. wall thickness. A calibrated Foxcroft electromagnetic flowmeter and the test section were smoothly fitted into the test pipe at respective distances of 50 and 100 pipe diameters downstream of the ball valve. For the viscoelastic studies reported here, the 24-in.-long test section of the facility (Figure 9) was constructed from the same stock material as used for the test pipe and was smoothly fitted to the test pipe at each end. Two 1/32-in.-diameter static pressure portals, located 4 1/2 in. from each flange, were used to measure the pressure drop along the test section. The Stanton impact tube was located approximately 2 1/2 in. forward of the downstream test section flange and was built into a plug which fitted flush into the wall of the pipe test section. A 1/32-in.-diameter static reference portal was located within 1/2 in. of the Stanton tube. The static pressure from this portal was subtracted from the Stanton tube impact pressure to obtain ΔP_s .

ELECTRONIC INSTRUMENTATION

The electronic arrangement was similar to that used for the flat plate study (Figure 4). Here, the amplified and filtered analog signals were processed by a Nonlinear Systems Series X-2 integrating digital voltmeter and printer.

POLYMER

Preparation of Polymer

Polyox WSR-301 was also used in this study, but here it was in the form of a slurry, i.e., a mixture of 30 percent by weight of Polyox with iso-propyl alcohol. Polymer solutions were prepared by dissolving the required amount of slurry in 50 to 70 gal of fresh well water. To facilitate homogeneous mixing, the slurry was first mixed into 500 cc of 98 percent iso-propyl alcohol. The alcohol and slurry mixture was then poured into a 75-gal stainless steel tank of well water and stirred gently from 5 to 30 min depending on the concentration. After the mixing process was completed, the solution was allowed to stand (8 to 10 hr) until the polymer was completely dissolved.

The prepared Polyox solution was transferred to the 2400-gal head tank which was under vacuum. The head tank was then pumped full of well water and pressurized in preparation for testing.

Collection and Analysis of Samples

A sample solution was drawn from the bottom of the head tank several times during the testing of each batch of solution to determine the concentration and degree of mixing. This sampling method was used to determine the polymer concentration for all the pipe tests.

The polymer concentrations in the samples withdrawn from the head tank were determined by the rheometric method.

EXPERIMENTAL PROCEDURE

The procedure was similar to that employed in the flat plate study. Before any testing could begin, it was necessary to calibrate the flowmeter. This was accomplished by charging the head tank and exhausting it at fixed pressure through the system and into the receiving tank. The mean pipe flow velocity was obtained from a measurement of the change in volume of the fluid in the receiving tank per time interval of exhaust. The d-c voltage output from the electromagnetic flowmeter was monitored during the exhaust time interval. This procedure was repeated over a range of head tank supercharges and the flowmeter calibration was established.

Water shear stress measurements were then made over an average pipe velocity ranging from 16 to 49 ft/sec. After the head tank was filled with fresh water and pressurized, the gate and ball valves were activated. The flowmeter signal was monitored continuously, and when the flow rate in the test pipe was steady, the Stanton tube pressure, the test section pressure drop, and the flowmeter data were recorded simultaneously.

The test procedure was the same for polymer flow as for plain water except that a fluid sample from the bottom of the head tank was withdrawn prior to a test run to determine the polymer concentration in the head tank. Polymer head tank concentrations up to 110 wppm were utilized for a mean pipe velocity range of 16.3 to 69.7 ft/sec (Reynolds number range from 4×10^5 to 1.7×10^6 , based on pipe diameter).

RESULTS AND DISCUSSION

Figure 10 shows the variation of pipe wall shear stress τ_w with Stanton tube differential pressure ΔP_s (impact pressure minus static pressure). The wall shear stress was determined directly by measuring the pressure gradient along the pipe and was calculated from the equation³³

$$\tau_w = \frac{P_1 - P_2}{L} \frac{D}{4} \equiv \frac{\Delta P}{L} \frac{D}{4} \quad (10)$$

where P_1 is the pressure at point 1,

P_2 is the pressure at point 2,

L is the linear distance between points 1 and 2, and

D is the pipe diameter.

The water results indicate that for the maximum pipe wall shear stress of approximately 6.0 psf, the corresponding Stanton tube differential pressure was 1.4 psi. The variation of τ_w with ΔP_s was approximately

³³Schlichting, H., "Boundary Layer Theory," McGraw-Hill Book Company, Inc. (1960).

linear for τ_w values > 1.5 psi and dropped more rapidly to zero for lower τ_w values. The trend and magnitude of these results are in good agreement with the flat plate calibration of the Stanton tube obtained by using the Preston tube as the standard.

The polymer measurements in the pipe covered a wall shear stress range up to 4.0 psf, corresponding to a Stanton tube impact pressure of 0.9 psi.

For a fixed pipe wall shear stress, the polymer and plain water Stanton tube results were in good agreement for the range of concentrations tested. The curve indicated that the Stanton tube in polymer generally measured a slightly higher pressure than in water. This could be attributed to the possibility that the Stanton tube was not entirely within the laminar sublayer. This can be seen from Equation (2) since the sublayer thickness is defined by

$$y_\ell \simeq 11.6 \frac{\nu}{u_\tau}$$

For the range of wall shear stress investigated ($0.7 \text{ psf} < \tau_w < 4.2 \text{ psf}$) the laminar sublayer thickness is given by $0.0010 \text{ in.} < y_\ell < 0.0023 \text{ in.}$ Since the height of the Stanton tube was 0.0015 in. , there is a chance that the tube was partially outside the laminar sublayer for the higher shear stress.

For the range of wall shear stress and polymer concentration investigated, the turbulent pipe results tend to indicate that the sensitivity of the Stanton tube was not significantly affected by polymer viscoelasticity.

CONCLUSION

The reduction of drag by polymer injection has been demonstrated on a flat plate for a Reynolds number range of 8×10^6 to 5×10^7 . The drag-reducing agent, Polyox WSR-301, was ejected from the plate leading edge into the turbulent boundary layer in concentrations of 500 and 1000 wppm at flow rates of 0.05 and $0.10 \text{ ft}^3/\text{sec}$.

A direct technique was employed to determine the wall shear stress using a Stanton tube located in the laminar sublayer. A Preston tube was used as the calibration reference for the Stanton tube.

The analysis of the flat-plate shear-stress data tend to support the following conclusions:

1. Injection of WSR-301 reduced local shear stress coefficients by as much as 50 percent for a mean-wall polymer concentration of only 4.3 wppm.
2. Wall shear stress decreased with increasing mean wall polymer concentration or polymer ejection flow rate.
3. The higher polymer concentration was not as effective in reducing skin friction as was the lower concentration.
4. Shear stress coefficients increased with increasing Reynolds number for all polymer injection concentrations and flow rates.

5. The shear stress results are in general agreement with the results of available experimental data.

6. The trends established from the shear stress data presented here should be confirmed by a more detailed definition and extended range of the test parameters c_j , Q_j , and R_x .

A turbulent pipe flow investigation indicated that the Stanton tube sensitivity was not significantly affected by the viscoelastic properties of the polymer solutions.

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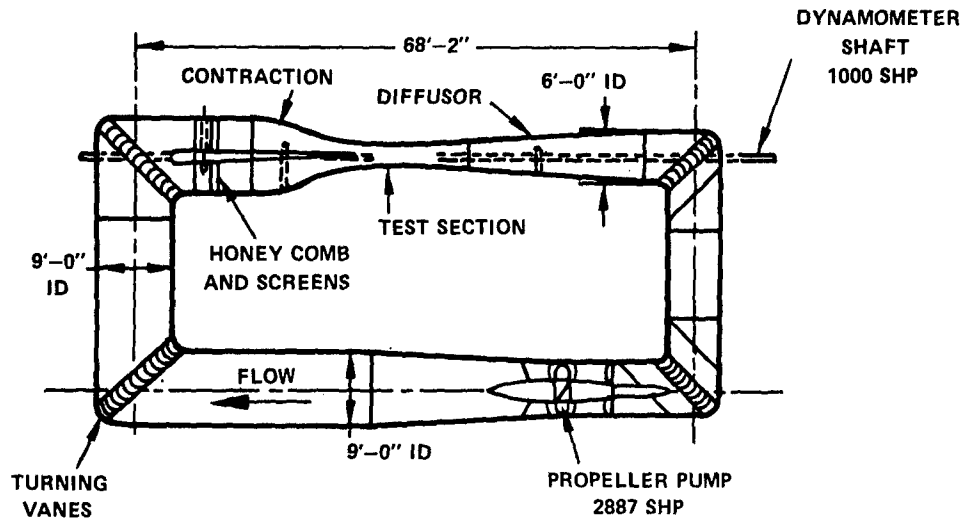


Figure 1 - Vertical Elevation through 36-Inch Water-Tunnel Circuit

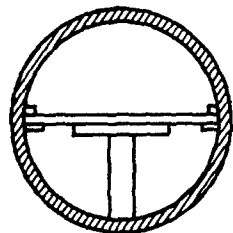


Figure 2a - Front View of Plate Mounted in Water Tunnel Test Section

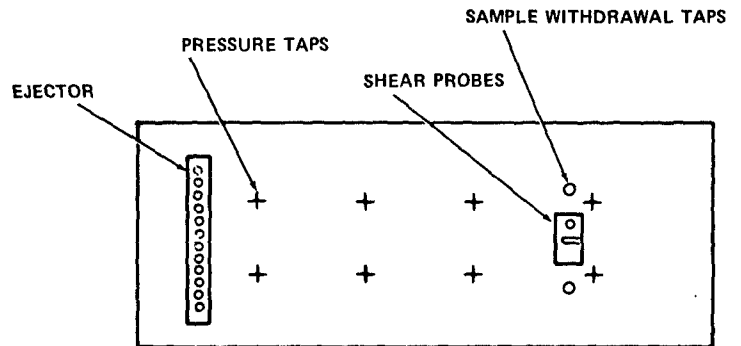


Figure 2b - Top View of Plate

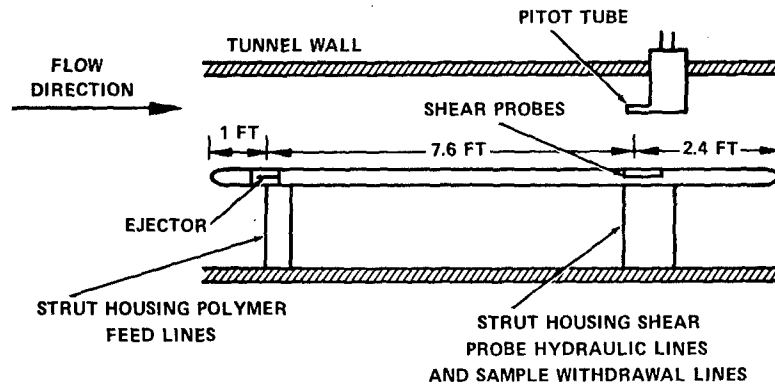


Figure 2c - Side View of Plate Mounted in Tunnel

Figure 2 - Details of Plate and Installation in Test Section of Water Tunnel

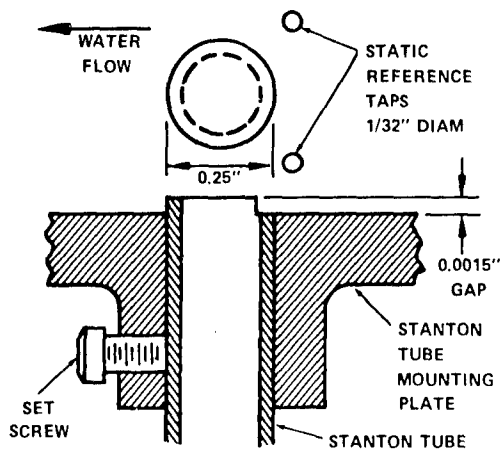


Figure 3a - Stanton Tube Details

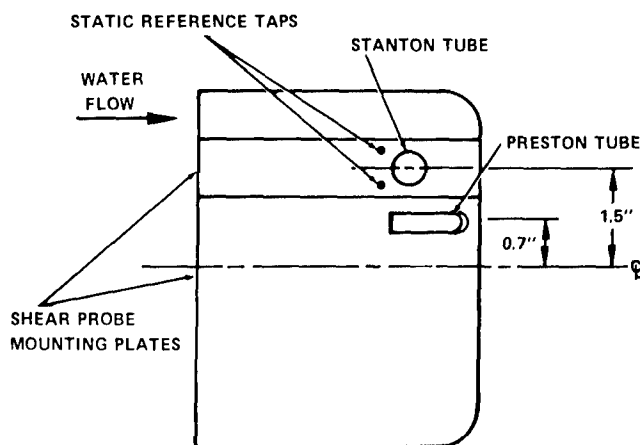


Figure 3b - General Arrangement of Shear Probes

Figure 3 - Arrangement and Some Details of the Impact Tubes and the Shear Probes

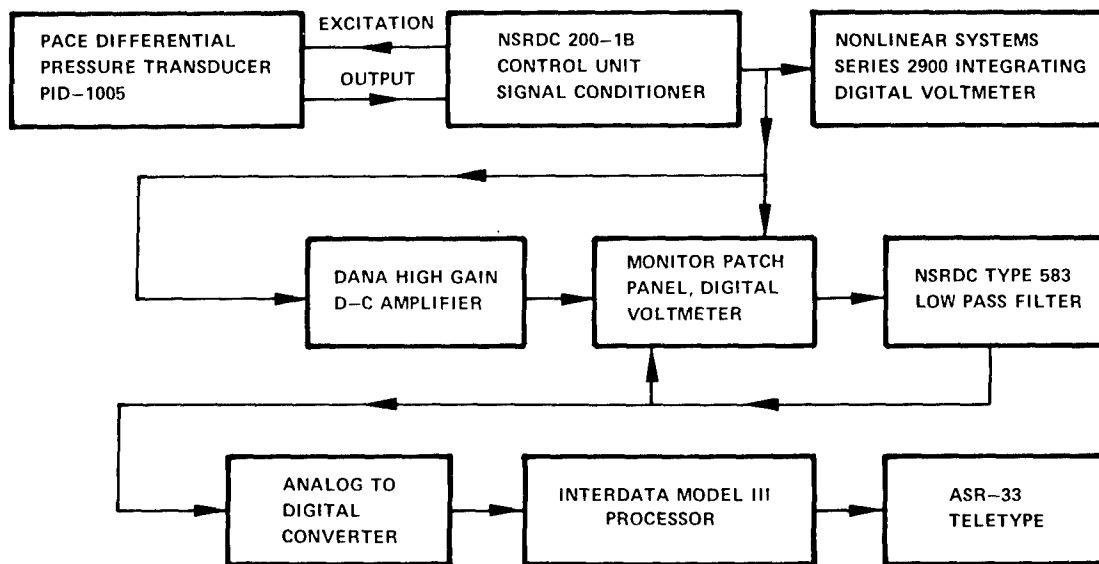


Figure 4 - Electronic Instrumentation

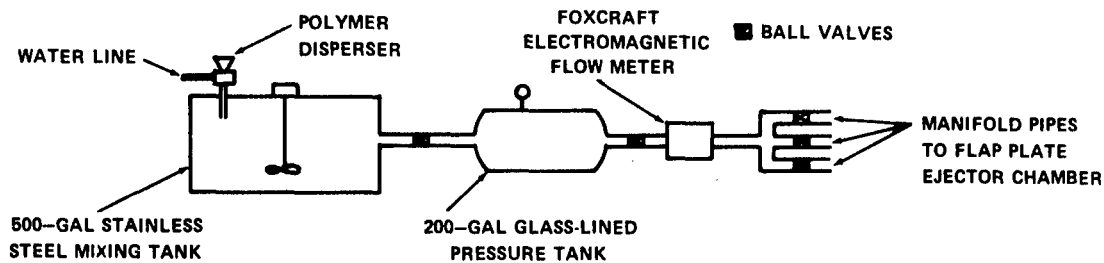


Figure 5a - Polymer Mixing and Transfer Apparatus

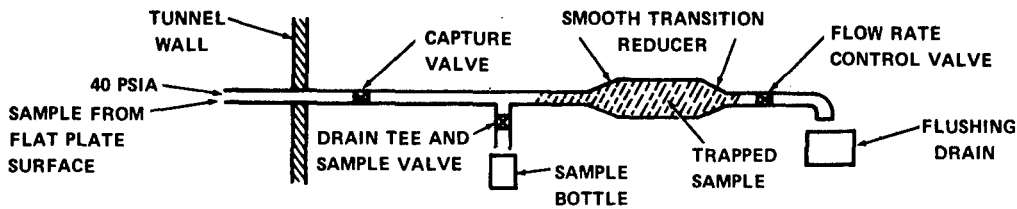


Figure 5b - Sample Collection Apparatus

Figure 5 - Details of Polymer Preparation and Handling

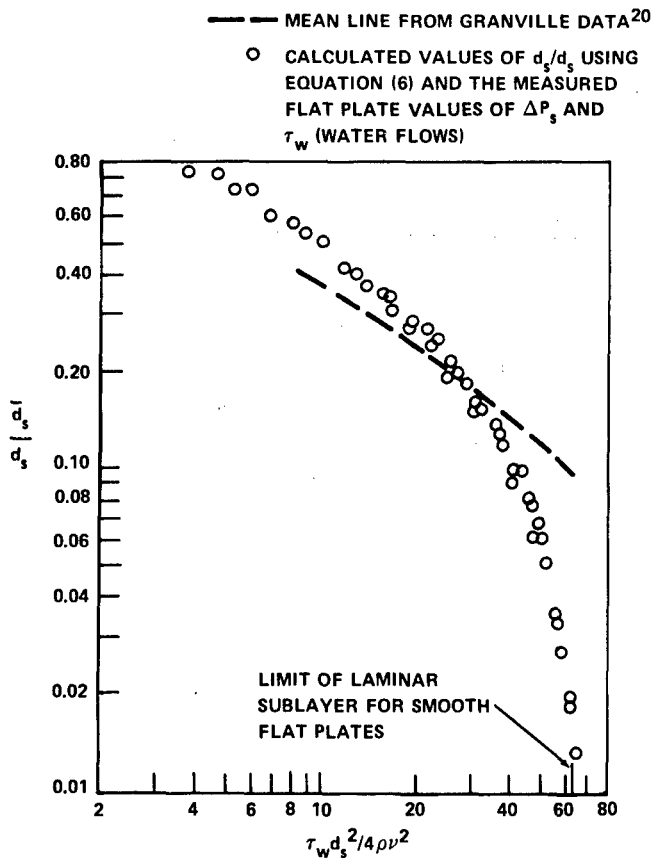


Figure 6 - Displacement of Effective Center for Stanton Tube for Flat Plate Water Flows

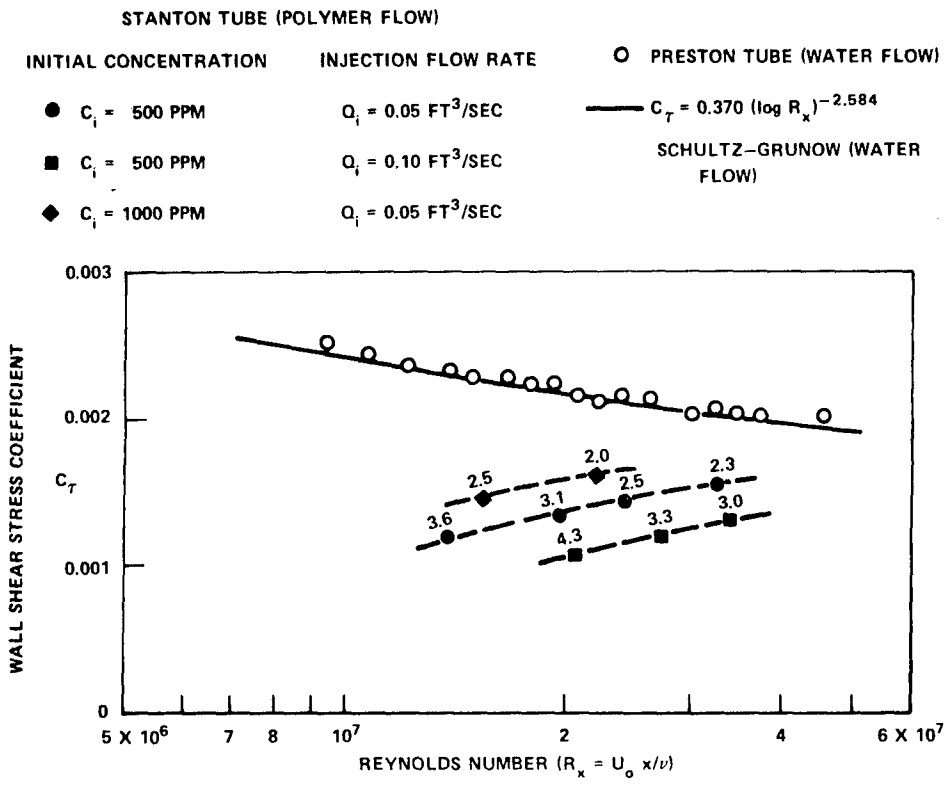


Figure 7 – Variation of Shear Stress Coefficient as Function of Reynolds Number for Water and Polymer Flows

(Numbers adjacent to data points represent measured values of local mean wall polymer concentrations \bar{c}_w)

— MEAN LINE THROUGH HUANG DATA:¹⁸

$$\Delta B = 5.7 (\bar{c}_w)^{1/2} - 25 \left[\log_{10} \left(\frac{u_\tau \ell}{\nu} \right) \right]^2$$

$$= 5 \times 10^{-4} \text{ CM}$$

● CALCULATED VALUES OF ΔB FROM EQUATION (10) AND THE MEASURED FLAT PLATE VALUES OF \bar{c}_w AND u_τ .

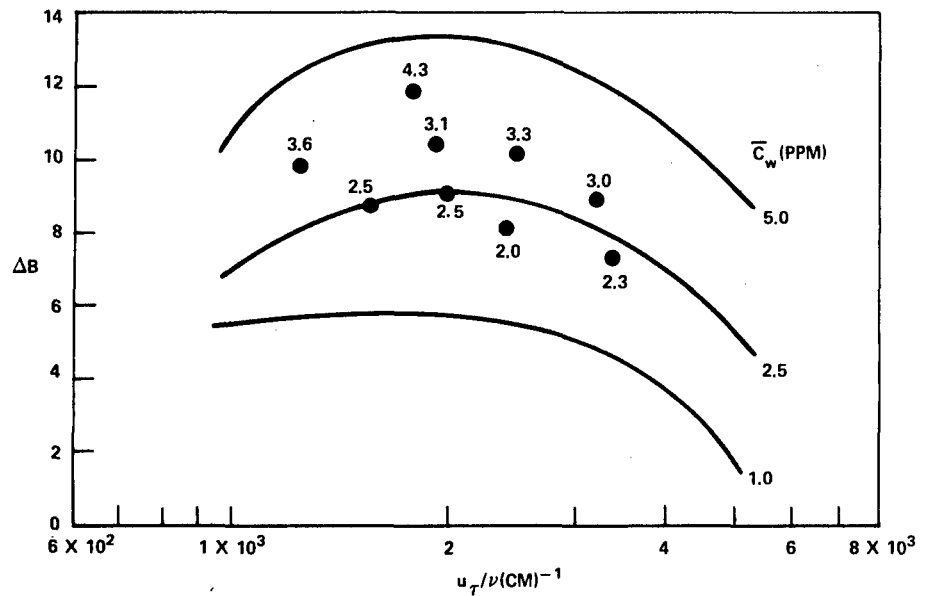


Figure 8 — Flat Plate Drag Reduction Achieved by Various Mean Wall Concentrations of Polyox WSR-301

(Numbers adjacent to data points represent values of \bar{c}_w)

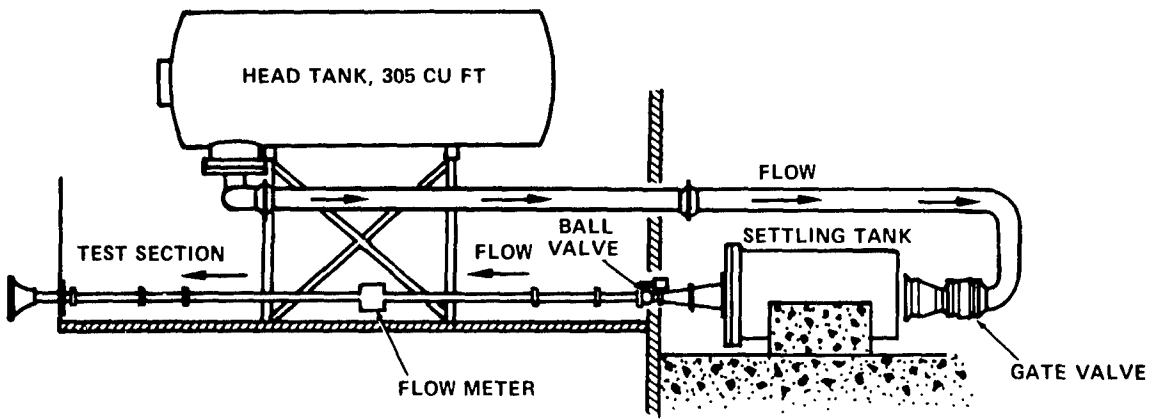


Figure 9 – The 3-Inch Pipe Flow Velocity

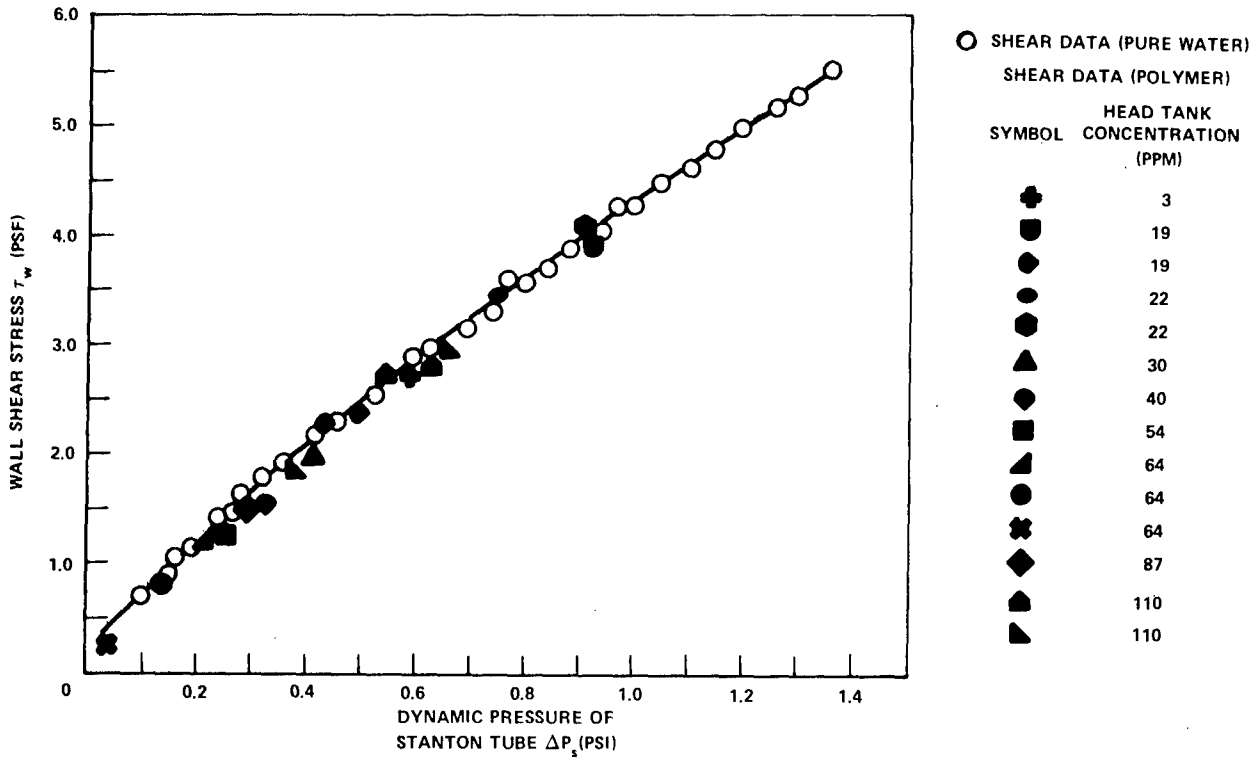


Figure 10 – Effect of Polymer Viscoelasticity on Stanton Tube Differential Pressure

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13. ABSTRACT

An experimental investigation was made to determine the effects on drag of injecting aqueous solutions of polyethylene oxide (Polyox WSR-301) into the turbulent boundary layer of a flat plate. The local mean wall shear stress was measured with a Stanton tube located in the laminar sublayer. Diffusion of the polymer in the boundary layer was also investigated by analysis of fluid samples withdrawn from the flat plate surface. In addition, a related but independent experimental turbulent pipe flow study was undertaken to determine any changes in Stanton tube sensitivity caused by the viscoelasticity of the polymer solutions.

The wall friction on the plate was determined with and without polymer injection and the results compared well with available shear data. The measured wall shear stresses showed reductions of up to 50 percent with polymer injection and decreased with increasing mean wall polymer concentration.

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