01 Sep 1969

Turbulence Measurements in Dilute Polymer Flows

Joseph M. Wetzel

John A. Almo

John M. Killen

TURBULENCE MEASUREMENTS IN DILUTE POLYMER FLOWS*

Joseph M. Wetzel**
John A. Almo+
John M. Killen++
University of Minnesota
St. Anthony Falls Hydraulic Laboratory
Minneapolis, Minnesota

ABSTRACT

A hot-film sensor was flush-mounted in the wall of a four-inch pipe and was calibrated as a function of wall shear stress. Flows with water and with homogeneous aqueous solutions of Polyox WSR-301 were utilized. The heat transfer characteristics of the sensor were reduced for polymer flows. Measurements of the number of zeroes and the frequency spectra for the turbulent fluctuations were obtained for a variety of test conditions. The effects of Polyox WSR-301 on surface pressure fluctuations on both smooth and rough surfaces were also measured.

INTRODUCTION

It has been well established that the addition of relatively small quantities (less than 10 ppmw) of certain high-molecular-weight polymers into a turbulent boundary layer can substantially reduce skin-friction drag. More recently, investigations of a fundamental nature have been undertaken in an attempt to explain the phenomenon of drag reduction as related to the turbulence characteristics of the flow. Measurements of the fluctuating longitudinal velocity component have been made with hot film sensors of a conical shape. Work has also been reported in which a hot film sensor has been flush-mounted on the boundary[1]. Some difficulties have been noted in the use of hot film sensors in polymer solutions, in that the heat transfer rate and thus the calibration has been altered by the polymer[2]. To partially circumvent this problem, the data were presented in a relative form; that is, the ratio of a given quantity in water to that in polymer was used. To our knowledge a calibration of the flush-mounted sensor has not been reported for flows of drag-reducing polymer solutions. In conjunction with some rather large-scale drag reduction tests being conducted at the St. Anthony Falls Hydraulic Laboratory, attempts were made to obtain a calibration of a flush-mounted hot film sensor. It was anticipated that the sensor would prove useful in the measurement of absolute local shear stress levels. Several investigators working with air flows[3,4] have indicated that the power supplied to the sensor was proportional to the cube root of the wall shear stress. For our purposes the sensor was to be used in both water and polymer flows, and it was therefore considered necessary to investigate the possible anomalies that might be associated with polymer addition to the flow. Since the hydraulic gradient of a pipe flow provides a simple measure of wall shear, a gravity flow pipe system was constructed into which polymer solutions could readily be injected. Measurements of the fluctuating component of the sensor output were also made, and the results are discussed in the following sections.

*Sponsored by the Naval Ship Research and Development Center under terms of Contracts Nonr 710(71) and N00014-67-A-0113-0007.

**Research Fellow

+Associate Scientist

++Research Associate

EXPERIMENTAL APPARATUS

Gravity Flow Pipe Facility

A schematic layout of the gravity flow pipe facility is shown in Fig. 1. Fifty feet of 4-in. diameter pipe were laid horizontally, with the test section located 114 diameters downstream of the beginning of the straight reach. Water was drawn directly from the Mississippi River and was discharged to waste under a 50 ft. head. Discharge was controlled with the gate valves and was measured with a calibrated metering elbow. A flow straightener consisting of 3/4 in. tubes about 1.5 ft. long was placed at the pipe entrance to reduce the effects of the upstream elbow. Four 1/8-in. diameter piezometer taps were carefully drilled and deburred at each of the locations shown. Pressure drops used in the calculation of wall shear stress were measured over each of the distances shown as well as over the entire test reach of 10 feet. Preliminary tests indicated that the pressure gradient was constant and the flow was fully developed at the test section.

Aqueous solutions of polyethylene oxide WSR-301 with concentrations of 250 and 500 ppm by weight were mixed in a large storage tank located at a higher level in the laboratory. Gentle agitation was used in mixing. A low head pump was used to transfer the polymer from the tank to the pipe, and the polymer was injected at the low pressure side of the upstream elbow, as shown in Fig. 1. The injection rate was determined by measurement of the drop in fluid level in the calibrated storage tank for a given period of time. The concentration of the homogeneous polymer solution in the test section was calculated from the injected and pipe discharges.

The polymer solutions were analyzed for drag-reducing properties with a capillary tube blow-down rheometer. A sample withdrawn from the pipe at the test section was checked against a sample collected from the storage tank and diluted to the proper concentration. The results agreed satisfactorily, indicating that complete mixing had taken place and that degradation effects were minor.

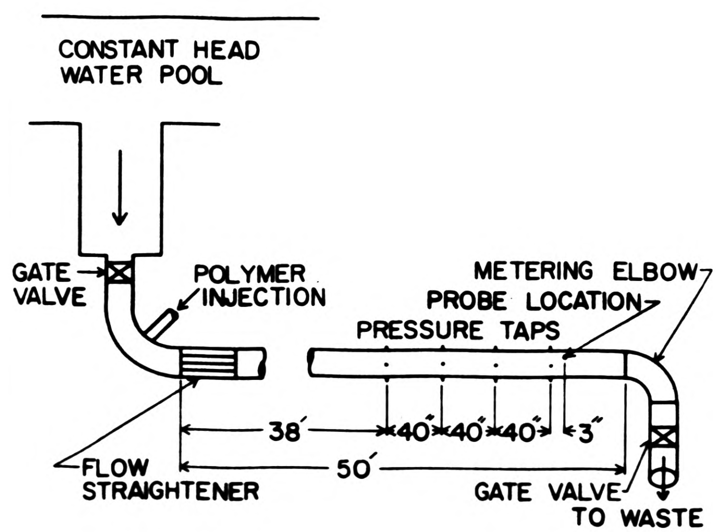

Fig. 1 Four-Inch-Pipe Gravity Flow Facility

Instrumentation

A Thermo-Systems, Inc., Model No. 1236W flush-mounted sensor was installed at the location shown in Fig. 1. The sensor was attached to a traversing mechanism to permit movement in the radial direction as well as rotation about its own longitudinal axis. Radial position was measured with an Ames dial reading to within 0.001 in., and the rotation was measured with a protractor accurate to one degree. The sensor was connected to a Thermo-Systems, Inc., Model 1020A anemometer. The cold resistance of the sensor was measured before and after each test run and was found to be very stable. An overheat ratio of 10 percent was used in all tests.

The output of the anemometer was fed into various electronic components for further processing. Average bridge voltage was measured with a Weston digital voltmeter modified to give a 10-second integrating time. The rms of the fluctuating signal was measured with a Disa Random Signal Indicator and Correlator, Type 55A06, which was also used for direct measurements of the microscale. Frequency analysis was carried out with a Hewlett-Packard 300H harmonic wave analyzer having an 11 Hz effective bandwidth. The signal from the anemometer was also fed into a high-gain amplifier, whose output in turn was connected to a Hewlett-Packard electronic counter. The counter was capable of sensing the number of positive crossings of a zero reference level of the amplified bridge voltage fluctuations per unit time.

DISCUSSION

Friction Coefficient

The measured pressure drops were reduced to wall shear stress and the Darcy friction factor. The experimental data for the friction factor are shown in Fig. 2 as a function of the Reynolds number based on water viscosity. For most runs with polymer injection the friction factor was reduced by varying the injection rate of the polymer solution and thus the concentration. The trends are shown by the dashed lines in Fig. 2. Two tests were also conducted at constant concentrations of 5 and 10 ppmw. The other constant concentration lines have been determined by interpolation between data points obtained with other polymer concentrations.

Sensor Calibration

Before attempting to obtain a calibration curve for the sensor as a function of wall shear stress, considerable effort was expended to determine the influence of the orientation of the sensor with respect to the pipe wall. To this end the radial position of the sensor face was varied and the position of the axis of the heater element was rotated on the face. The most useful signals were obtained when the heated element was placed so that the smallest dimension was parallel to the flow. For the radial position studies the entire sensor was moved systematically into the flow or into the pipe wall, and the corresponding average bridge voltage and rms voltages were noted. These tests were conducted for various velocities in water flow only. It was noted that for each velocity, a small range of radial positions existed for which the bridge voltage and the rms voltage were at a minimum and essentially constant. The width of this region was dependent on velocity, decreasing as the velocity increased. This small radial range of position of the sensor included the flush position as determined visually and by touch. Therefore, for all succeeding tests the sensor was located by simple visual inspection.

The calibration curve is shown in Fig. 3 in the form of the bridge voltage squared against the cube root of the wall shear stress. The open symbols represent data for water, and the filled symbols represent data taken with polymer injection. As the concentration of Polyox was increased, the shear and bridge voltage were reduced, but not in accordance with the relationship obtained with water. At a given shear stress the bridge voltage, and thus the heat transfer, was less than that for water.

In most cases the data were obtained by selecting a particular shear stress for an initial water flow rate and then gradually increasing the polymer injection rate. As a result of friction reduction the system then produced a slightly increased flow rate and average velocity. Thus, the Reynolds number also increased for each particular set of data. Some tests were also conducted in which the concentration was held constant. Flow conditions for water alone were established, and after initiating a predetermined rate of polymer injection, the water control valve was adjusted so that the total discharge was the same as before injection.

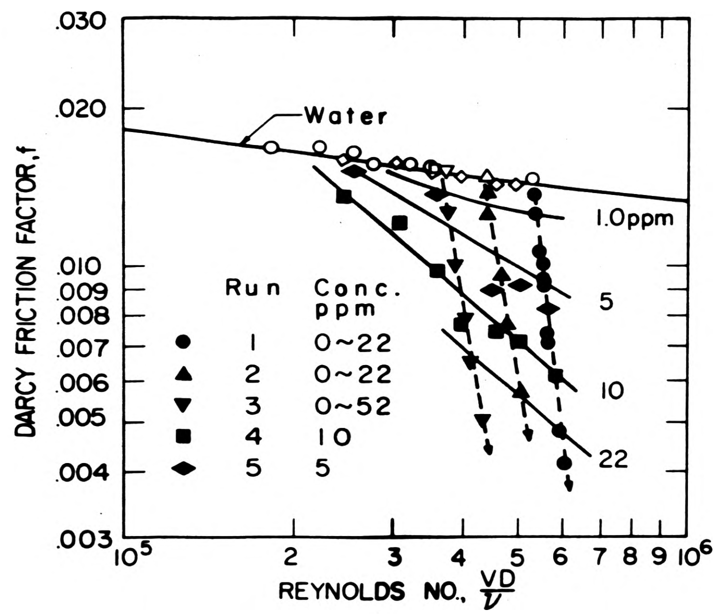

Fig. 2 Effect of Polyox WSR-301 on Friction Factor

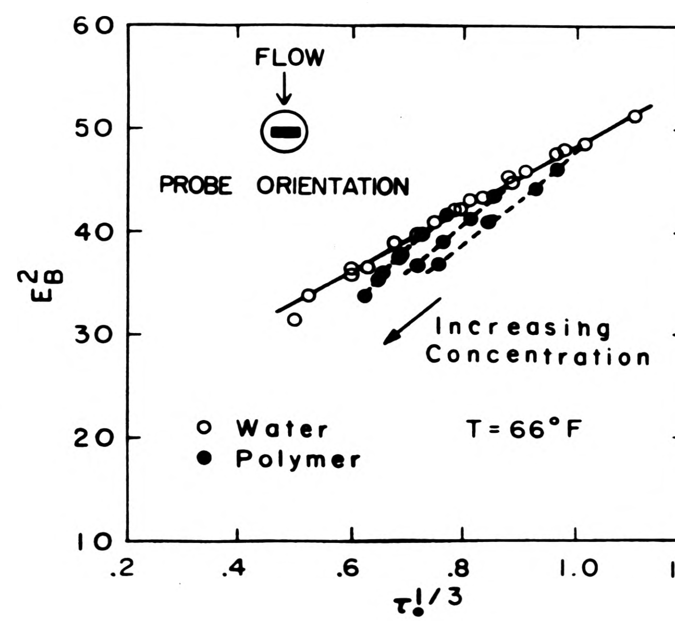

Fig. 3 Calibration Curve for Flush-Mounted Hot-Film Sensor

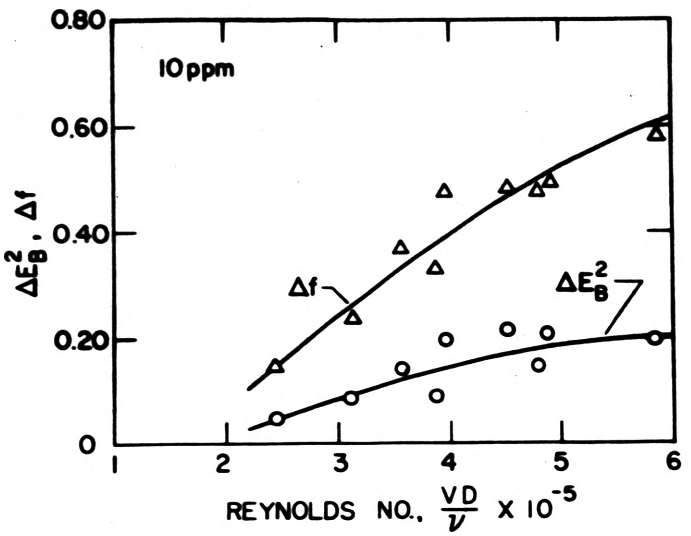

Fig. 4 Comparison of Friction and Heat Transfer Reductions for Hot-Film Sensor

The results for a concentration of 10 ppm are shown in Fig. 4. In the figure Δf and $\Delta E_B{}^2$ are the changes in the friction factor and the bridge voltage squared divided by the corresponding values for water at a given Reynolds number. Curves drawn through both sets of data tend to approach the same critical Reynolds number, implying that drag reduction and reduction bridge voltage or heat transfer are directly related.

Zero Crossings

The number of zeroes of the turbulent fluctuations was determined with the instrumentation described in Section IIB. For more consistent readings, the number of counts was averaged over a one-minute period of time. Armistead and Keyes[5] have shown that the number of zeroes is directly related to the Reynolds number in their experiments with flow of water in a pipe. A similar relationship was noted for the measurements made in the current tests. If the friction factor varies only slightly with Re, then the wall shear stress varies roughly with the square of the velocity. Therefore, the data were plotted against the square root of the wall shear stress, as shown in Fig. 5. For water flow the data could be repeated with fairly good accuracy; all the data points are not shown. As the polymer concentration was increased at a fixed flow rate, the data departed from the water curve until a point was reached at which the zero count was essentially constant. This trend is distinctly shown for two initial shear values in Fig. 5, and final concentrations of 22 and 28 ppm.

It has been shown by others[6] that after making certain assumptions, the number of zeroes is inversely related to the microscale of turbulence and also to the dissipation integral determined from the frequency spectrum. This will be further discussed in a following section.

Frequency Spectra

Frequency spectra were taken for nearly all test runs with both water and polymer flows. Typical trends of the data are shown in Fig. 6 for the power spectral density F(n) on a Db scale as a function of the frequency. The power spectra have been normalized with the mean square voltage integrated over the frequency range of the spectra. The total rms voltage is reduced by increasing the concentration of polymer as indicated in the legend. The higher frequencies, above about 100 Hz, are also attenuated by the addition of polymer.

The power spectra have been plotted in a dimensionless form in Fig. 7 using a Strouhal number based on the pipe diameter, D, and the average velocity, V. The spectra for water (open symbols) collapse very well except at the higher frequencies, where some discrepancies are observed. The same trend exists for the polymer data (filled symbols) at the higher frequencies.

Using the calibration curve shown in Fig. 3 for water, the fluctuating component of the bridge voltage was converted into a fluctuating component of wall shear, ϕ, at any given frequency. A dimensionless plot of the fluctuating shear as a function of frequency is shown in Fig. 8 for two sets of data taken

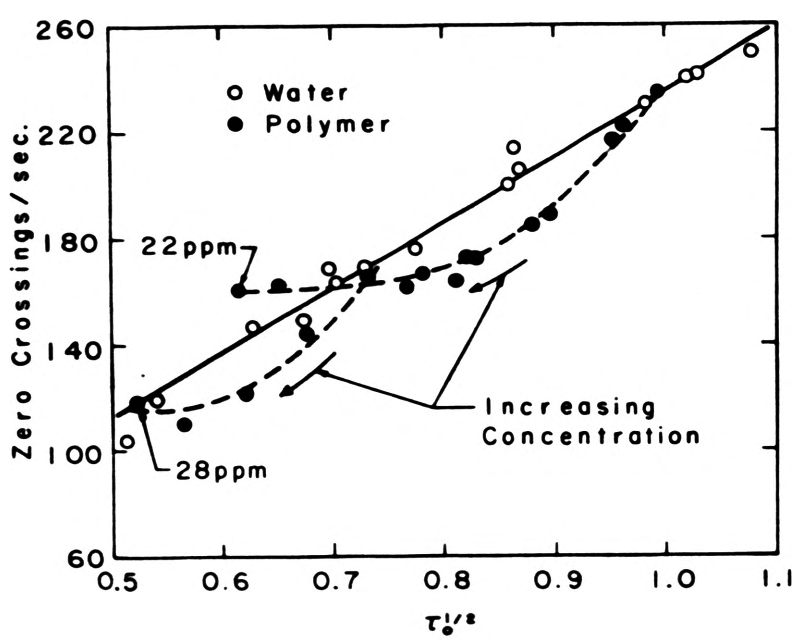

Fig. 5 Zero-Crossing Rate of Fluctuating Sensor Output

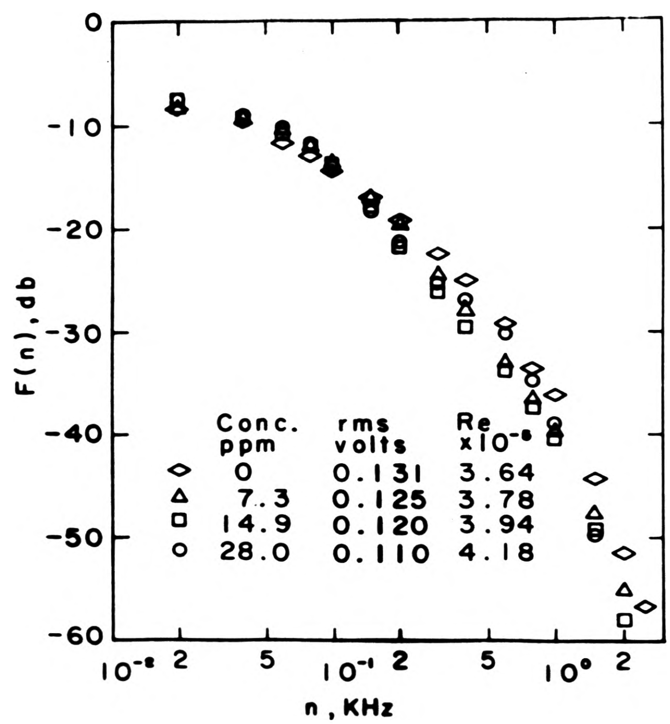

Fig. 6 Power Spectral Density for Various Polymer Concentrations

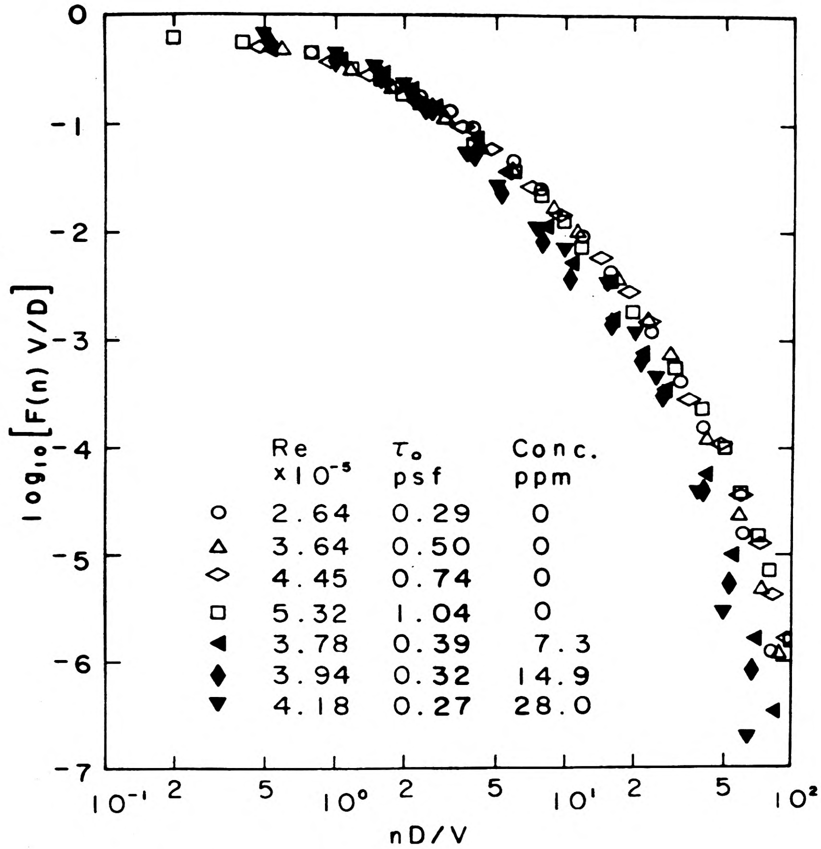

Fig. 7 Dimensionless Power Spectral Density

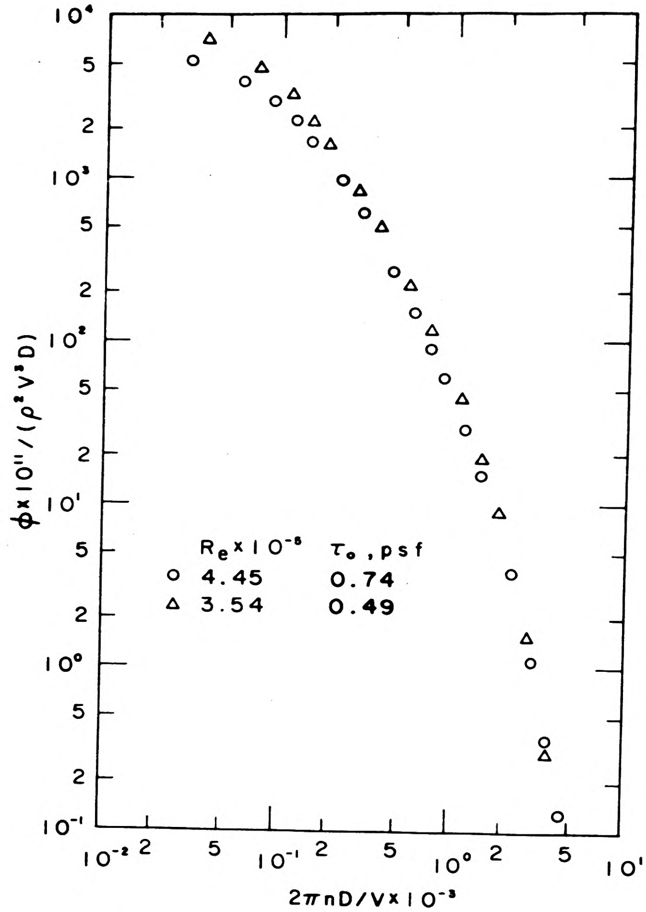

Fig. 8 Dimensionless Power Spectral Density of Fluctuating Shear Stress

with water and different values of the average wall shear stress. The data for the two tests compare very well at the higher frequencies, with deviation being noted at the lower frequencies. This is just the opposite of the trend that has been observed in the plot of Fig. 7. Experimental data for polymer flows have not as yet been reduced in this form, due to the anomalies in the calibration results with polymers.

Microscale

Assuming a Gaussian distribution and isotropic turbulence, the microscale, λ, can be determined for a turbulent fluctuation by several methods.[6] Although it was realized that the assumed conditions might not be satisfied at the boundary, it was of interest to compare the values of the microscale with and without polymers.

If u(t) is the turbulent fluctuation, then

$$\frac{1}{\lambda^2} \approx \frac{1}{U^2 \overline{u^2}} \overline{\left(\frac{\partial u}{\partial t}\right)^2} = \frac{4\pi^2}{U^2} \int_0^\infty n^2 F(n)\,dn = \frac{4 N_o^2 \pi^2}{U^2}$$

Thus the microscale can be found from the derivative of u(t), from the second moment of the power spectra, and from the number of positive going zero crossings in u(t).

A comparison of the values obtained by the various methods as a function of polymer concentration is shown in Fig. 9. The derivatives were measured directly with the Disa Correlator. The velocity, U, was taken as the average velocity in the pipe. With each method the microscale is seen to increase as the concentration is increased, although the percentage change is less with the values taken from the correlator. It also appears that a maximum occurs at a concentration of about 20 ppm, which corresponds to roughly the concentration required for maximum drag reduction. The discrepancy in λ obtained by using the various methods has not been clarified at this time.

As indicated above, the number of zeroes is directly related to the integral of the second moment of the frequency spectra. A plot of the integral versus the number of positive going zero crossings is shown in Fig. 10. The data points for both water and polymer flows tend to scatter about the solid line, indicating reasonable agreement between the two methods.

Surface Pressure Fluctuations

Attempts to measure surface pressure fluctuations in the 4-in. pipe were unsuccessful. Structural vibrations and noise prevented good measurement of surface pressures.

A large amount of surface pressure fluctuation data are available, however, from the rotating cylinder apparatus described in reference 7. The spectra published in reference 7 were presented in terms of the parameters $\phi(\omega)U/\tau_o^2 D_m$ and $\omega D_m/U$, as proposed by Foxwell[8].

Since that time additional work on the data has shown that the parameters $\phi(\omega)/\rho^2 U^3 D_m$ and $\omega D_m/U$ correlate the data at high frequencies ($\log_{10} \omega D_m/U > 0.4$) much better than those proposed by Foxvell. No parameters have yet been found to adequately correlate the low-frequency data. This may be due in part to increased scatter of the data at low frequencies.

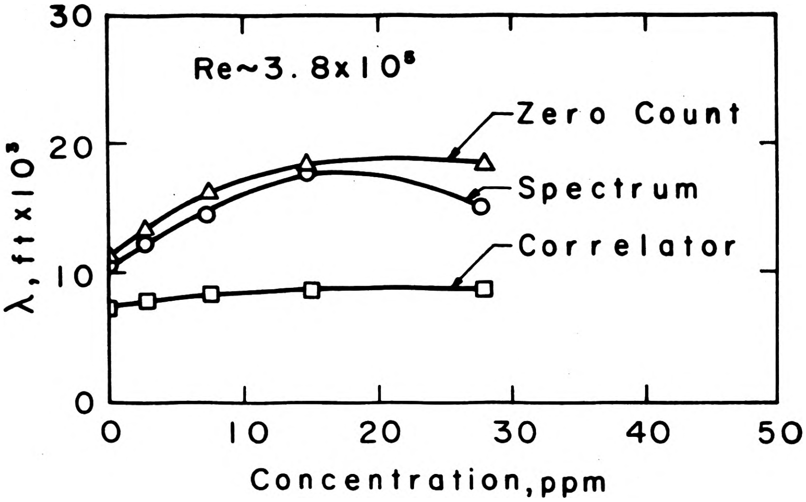

Fig. 9 Effect of Polymer Additives on Microscale

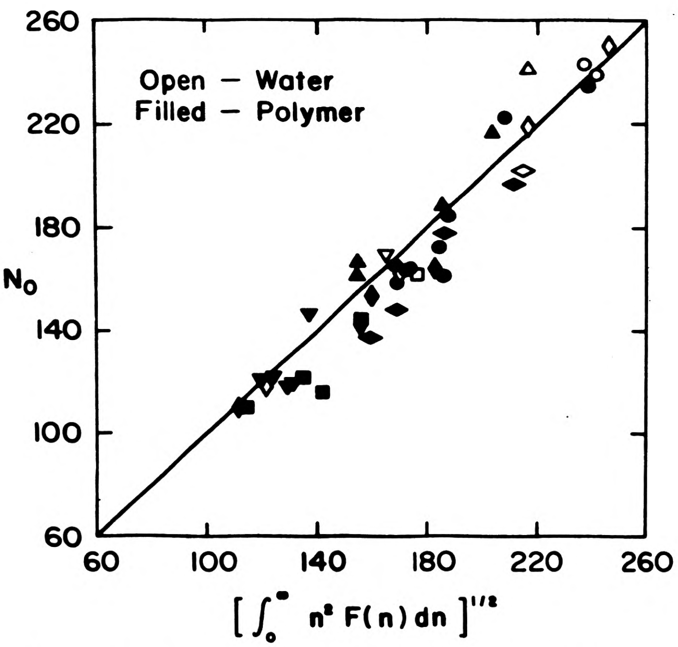

Fig. 10 Comparison of the Integral of Second Moment of Frequency Spectra with Number of Zero Crossings

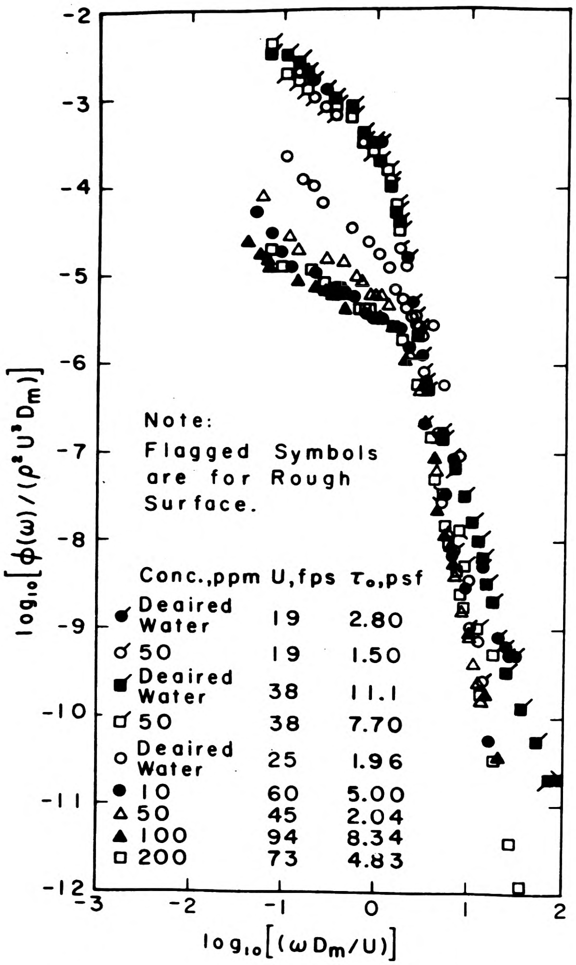

Fig. 11 Surface Pressure Fluctuation Spectrum

Figure 11 shows a representative sample of the smooth cylinder spectra taken from reference 7 and replotted with the new parameters. Additionally, data taken with the cylinder coated with a single layer of closely packed 470-micron-diameter spherical glass beads are shown.

The rough cylinder spectra show three distinct regions: the low-frequency region ($\log_{10}\omega D_m/U < 0.1$), where the departure from the smooth cylinder curve is greatest and where there is apparently the most sensitivity to shear variations; the mid-frequency region ($0.1 < \log_{10} \omega D_m/U < 0.75$), where neither the addition of surface roughness nor the addition of Polyox has much effect; and the high-frequency region ($\log_{10} \omega D_m/U > 0.75$), where the effect of Polyox addition is greatest.

The rough cylinder spectra at high frequencies show a large increase in intensity over the smooth cylinder; however, the addition of Polyox reduces the intensity in this region to that of the smooth cylinder. These reductions in pressure fluctuations can be very large, in some cases as large as 20 to 40 Db.

This high-frequency effect of Polyox on rough surfaces probably explains the apparent discrepancy between the large reduction in radiated flow noise from the "smooth" cylinder with the addition of Polyox and the small effect a similar concentration of Polyox had on the smooth cylinder surface pressure fluctuations as reported in reference 7.

CONCLUSIONS

1. A calibration of a flush-mounted hot film sensor has been carried out in a 4-in. pipe facility. For water flow the square of the bridge voltage was a linear function of the cube root of the wall shear stress. For flows of homogeneous solutions of Polyox WSR-301 the heat transfer from the sensor has been reduced at a given shear stress level.
2. The number of zeroes in the turbulent fluctuations at the wall was related to the wall shear stress for water flow. Again, the addition of Polyox altered the number of zeroes as compared to water for the same shear.
3. Measurements of the frequency spectra indicated that the polymer additive attenuated the high-frequency portion of the spectra. The microscale determined from the second moment of the frequency spectra and also from the number of zeroes was larger for polymer flows than for water.

4. Sufficient concentrations of Polyox reduce high-frequency surface pressure fluctuations on a rough surface to the levels obtained for a smooth surface. At low frequencies, surface pressure fluctuatuions and shear are reduced about equally. A mid-frequency range exists for which roughness and Polyox have little effect on the pressure spectrum.

SYMBOLS

D = diameter of pipe

D_m = diameter of surface hydrophone

E_B = time-averaged bridge voltage

f = Darcy friction factor

(n) = normalized voltage spectral density

n = frequency

N_o = number of positive going zero crossings per unit time in turbulent fluctuation

Re = Reynolds number, VD/ν

U = free stream velocity

V = average velocity in pipe

λ = microscale

ν = kinematic viscosity

ρ = fluid density

τ_o = wall shear stress

(n) = pressure or shear stress squared per cycle

ω = $2\pi n$

REFERENCES

1. Johnson, B., and Barchi, R. H., "Effect of Drag-Reducing Additives on Turbulence," J. Hydronautics, 2, 168-175 (1968).
2. Friehe, C. A., and Schwarz, W. H., "The Use of Pitot-Static Tubes and Hot-Film Anemometers in Dilute Polymer Solutions," Viscous Drag Reduction, ed. by C. S. Wells, Plenum Press, pp. 281-296 (1969).
3. Leipmann, H. W., and Skinner, G. T., "Shearing Stress Measurements by Use of a Heated Element," NACA Tech. Note 3268, 1954.
4. Bellhouse, B. J., and Schultz, D. L., "Determination of Mean and Dynamic Skin Friction Separation and Transition of Low-Speed Flow with a Thin-Film Heated Element," J. Fluid Mech., 24, 379-400 (1966).
5. Armistead, R. A., Jr., and Keyes, J. J., Jr., "A Study of Wall-Turbulence Phenomena Using Hot-Film Sensors," J. Heat Transfer,ASME, 90, 13-21 (1968).
6. Leipmann, H. W., Laufer, J., and Leipmann, K., "On the Spectrum of Isotropic Turbulence," NACA Tech. Note 2473, 1951.
7. Killen, J. M., and Almo, J., "An Experimental Study of the Effects of Dilute Solutions of Polymer Additives on Boundary Layer Characteristics," Viscous Drag Reduction, ed. by C. S. Wells, Plenum Press, 447-461 (1969).
8. Foxwell, J. H., "The Wall Pressure Spectrum under a Turbulent Boundary Layer," Admiralty Underwater Weapons Establishment, Tech. Note 218/66, August 1966.