Some Storage and Shear History Effects on Polymeric Friction Reduction

A. T. Ellis* and R. Y. Ting†
University of California, San Diego, La Jolla, Calif.
and
R. H. Nadolink‡
U. S. Naval Underwater Weapons Research and Engineering Station, Newport, R. I

The drag reducing properties of two dilute polymer solutions were studied using a simple turbulent pipe flow apparatus under various conditions of storage and mechanical degradation. Aqueous solutions of Polyox WSR-301 (polyethylene oxide) and Separan AP-30 (polyacrylamide) were prepared at 500 ppmw (parts per million by weight) and then diluted into weak concentrations for storage and testing on a day-by-day basis. At concentrations of 10, 25, 50 and 100 ppmw, aged samples showed the same peak effectiveness as freshly prepared ones. However, the aging process reduced the ability to resist mechanical degradation. Anomalies were found in which solutions tend to partially recover from shear degradation under certain conditions, and in other cases tend to improve their friction-reducing efficiency after continuous shearing. Experimental results suggest that entanglement or aggregation of polymer molecules could be one of the important mechanisms involved in friction reduction.

Introduction

THE very dilute aqueous-solutions of some polymers, because of their drag-reducing characteristic in turbulent flows, have drawn considerable interest of many investigators in the past years.[1,2] For lack of sufficient theoretical explanation of the basic mechanisms of drag reduction, most of the studies related to such phenomenon have to rely heavily on experimental work. One of the difficulties usually encountered in these experiments is the so-called degradation of polymer solutions. Specifically, the polymer solutions gradually lost their drag-reducing characteristic under mechanical shearing and the aging process as well. Such behavior ruled out the possibility of using a conventional continuous-flow water tunnel as an experimental facility and previous investigators have had to turn to a once-through apparatus[2] or blow-down type water tunnel.[3] It was therefore intended to systematically study the effect of mechanical degradation and aging on the drag-reducing properties of dilute polymer solutions.

In studying the grid turbulence of Polyox solutions, Fabula[4] observed the raggedness in hot-wire signals displayed on an oscilloscope. This raggedness would decay as the solutions were aged. Brennen and Gadd[5] used a closed-loop system to measure the pitot pressure loss of a pitot tube in Polyox WSR-301 and Separan AP-30 solutions. The decrease in pitot loss with time indicated the degradation of solutions and its effect on reducing the second-normal stress difference to zero. They also reported that viscosity measured by a capillary instrument decreased as the solution was degraded and suggested that turbulence caused macromolecular scission and degraded the polymer solutions. The molecular scission point of view was also shared by Patterson,[6] who determined the molecular weight distribution of Polyox WSR-N80 and Polyox WSR-301 tested in pipe flows, and concluded that the drag reduction phenomenon depends strongly on the concentration of the highest molecular weight species present in the molecular weight distribution. Sherman[7] studied the storage effect on the drag-reducing properties of Polyox WSR-301 and found no significant change in the drag-reducing properties of the solutions. However, it should be noted that his results were obtained by testing the solution with a once-through method. The present work reports some drag-reduction data of Polyox WSR-301 and Separan AP-30 at several different dilutions in distilled water.§ Solutions aged up to 30 days were also repeatedly run through the test apparatus to give a degradation history under high mechanical shearing.

Experimental Technique

1. Solution Preparation

Aqueous solutions of Polyox WSR-301 and Separan AP-30 were first prepared at 500 ppmw and then diluted into samples of weaker solutions at 10, 25, 50 and 100 ppmw. Solutions were designated weak if stored at the concentrations tested, while strong solutions were those stored at 500 ppmw and then diluted to the lower concentrations before testing. Both strong and weak solutions were stored under ordinary laboratory lighting conditions for up to 30 days. The fluctuation in room temperature was very small. The master batches (500 ppmw solutions) were systematically prepared using the techniques outlined by McNally[8] with good success.

Presented as Paper 70-532 at the AIAA/NAVY Marine Systems, Propulsion and ASW Meeting, Newport, R. I., May 4–6, 1970; submitted June 12, 1970; revision received August 9, 1971. The authors are indebted to the Naval Undersea Research and Development Center, Pasadena Laboratory, for the loan of experimental apparatus used in this study. This work was supported in part by the Office of Naval Research, Fluid Mechanics Branch, Contract N00014-69-A-0200-6004.

Index categories: Hydrodynamics; Marine Propulsion; Nozzle and Channel Flow.

* Professor of Applied Mechanics.

† Graduate Research Assistant.

‡ Project Engineer.

§ The choice of distilled water was a consequence of the finding that polymer solution prepared by using local tap water lost its drag-reducing ability after some fifteen hours. It appeared that the high content of chlorides in the tap water might have caused undesirable chemical reactions with polymer molecules and chemically degraded the solution.

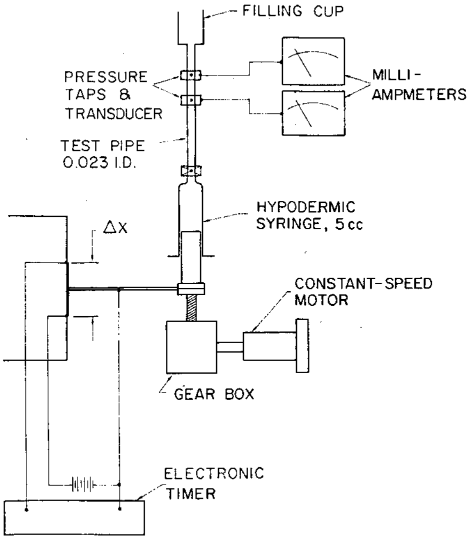

Fig. 1 **Sketch of turbulent flow rheometer.**

2. Apparatus and Procedures

The friction reducing efficiency of the polymer solutions tested in this work was, in all cases, measured with the turbulent flow rheometer pioneered by Hoyt,[9] with certain modifications which are depicted in Fig. 1.

The test fluid was admitted to the filling cup and slowly drawn into the syringe, where upon electrical command the piston was driven through a constant stroke ΔX. The pressure drop due to the resulting turbulent flow in the test pipe was then measured by matched pressure transducers over a three-inch section and the output was displayed on milliammeters, the pressure difference being directly proportional to transducer output current difference. The exact time for each stroke of the piston was known from an electronic timer. The volume of fluid forced through the system was constant for each test.

3. Data Reduction

Since the motor and syringe drive assembly did not provide the same reproducible constant speed for each test, the Reynolds number of the flow varied between 7500 and 8200. In order to compensate for this variation, the friction reduction were always computed in reference to distilled water at an identical Reynolds number. With the present experimental set-up, the following equation was used to calculate the Percent Friction Reduction (PFR) for each point of the data presented:

$$\begin{aligned}\mathrm{PFR}/100 &= [1 - (f\,\text{polymer}/f\,\text{water})]_{\text{const Re}}\\ &= (1 - \{[(\Delta T)^2\cdot\Delta P]_{\text{polymer}}/[(\Delta T)^2\cdot\Delta P]_{\text{water}}\}\end{aligned}$$

$$\begin{aligned}\text{where } f_{(\ )} &= \text{friction factor} = 8\tau_w/\rho\bar{U}^2\\ \tau_w &= \text{wall shear stress}\\ \rho &= \text{fluid density}\\ \bar{U} &= \text{mean velocity}\\ \Delta T &= \text{time for constant stroke } \Delta X\\ \Delta P &= \text{pressure drop across test section}\end{aligned}$$

In all cases the kinematic viscosity and density of water at the test temperature were used for calculation purposes. Total experimental error did not exceed $\pm 2\%$ in the value of PFR. The average Reynolds number for this series of tests was approximately 8000 with values of $\tau_w = 12.6$ lb/ft^2 and friction velocity u^*, defined by $(\tau_w/\rho)^{1/2}$, being equal to 2.53 ft/sec on the average.

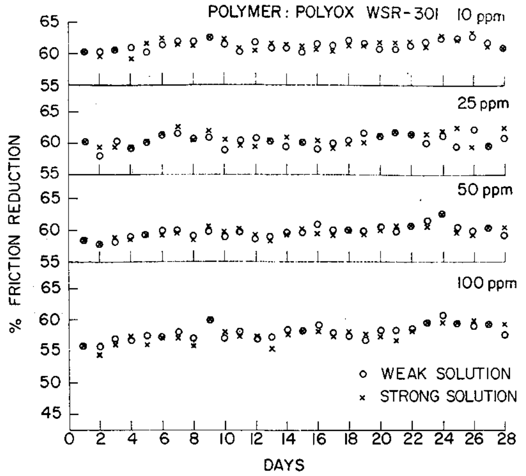

Fig. 2 **Effect of storage on the drag reduction of Polyox WSR-301.**

Results and Discussions

Figures 2 and 3 show the drag reduction data of Polyox WSR-301 and Separan AP-30 at 10 ppmw, 25 ppmw, 50 ppmw, and 100 ppmw. Each data point was calculated based on the measured ΔT and ΔP of the first run on each day. The aged samples showed the same peak effectiveness as freshly prepared ones and resulted in a 60% friction reduction. Only the 10 ppmw Separan AP-30 sample displayed storage degradation after two days in weak solution. The data for 100 ppmw Separan AP-30 stored in a concentrated condition showed slight scattering which was attributed to bad sample-picking from the 500 ppmw storage batch. The results of Polyox solutions agreed well with those of Ref. 7.

The sample solutions were also run repeatedly through the test apparatus and a degradation history was recorded. Figures 4 and 5 show the degradation curves for Polyox WSR-301 and Separan AP-30, respectively. The fresh sample data were compared with those of both strong and weak solutions aged 30 days. In the case of Polyox, the storage condition caused little difference on the shape of the degradation curves, though both strong and weak solutions showed 10% lower effectiveness compared with the fresh samples. The strong samples of Separan showed the same degradation resistance as fresh samples, whereas weak samples displayed less resist-

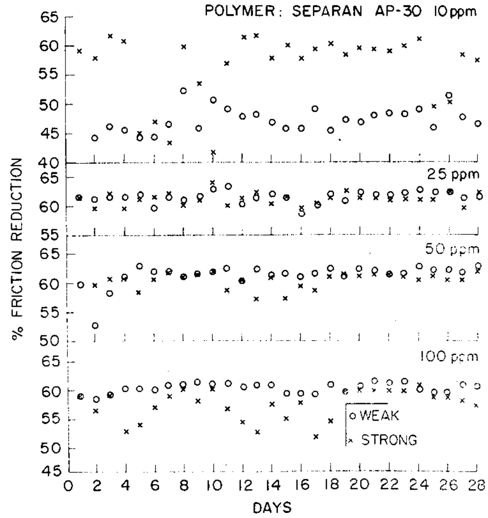

Fig. 3 **Effect of storage on the drag reduction of Separan AP-30.**

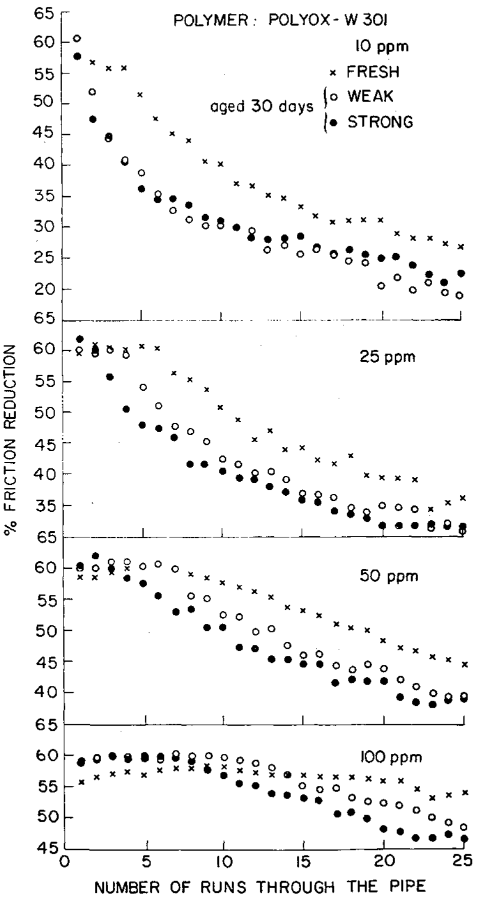

Fig. 4 Degradation curves ofPolyox WSR-301.

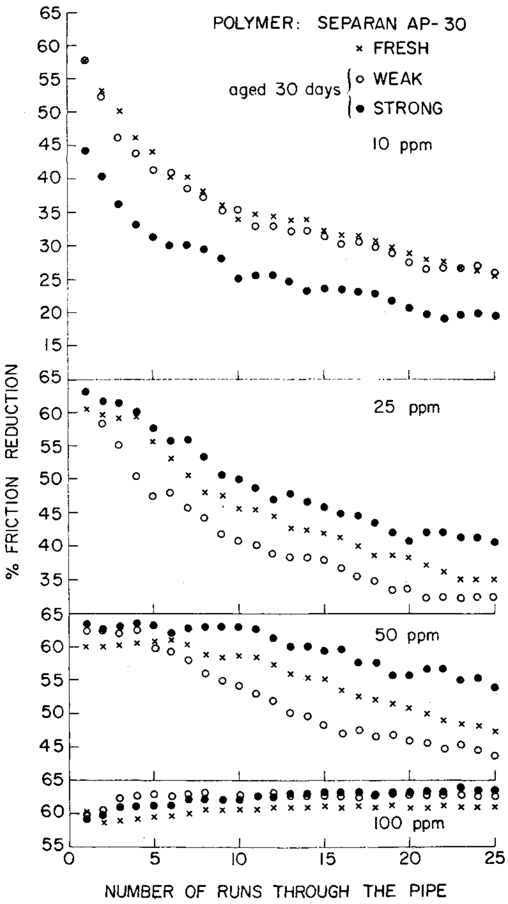

Fig. 5 Degradation curves of Separan AP-30.

ance to shear degradation. The decrease of such ability to resist shear degradation was more pronounced at lower concentration and at later stages of the shearing process. It was especially interesting that the 100 ppmw Separan sample tended to "upgrade" first and then degrade under continuous shearing. Similar observations were indicated by Librovich.[10]

The structure of Polyox molecules is like a very linear long chain, whereas Separan molecules have many branched structures. Such a difference may lead one to the speculation that the mechanisms involved in reducing drag for these two kinds of polymers may be quite different. To support such speculation it was noted that White[11] reported that dilute Polyox solutions reduced drag in rough pipes and suppressed turbulence when impinging a jet obliquely on a flat plate, but guar gum solutions did not exhibit either of the effects, although both solutions were widely-known as very good drag-reducing additives in smooth pipe flows.

Recently Lumley[12] pointed out the possibility of entanglement being involved as one of the responsible mechanisms in reducing frictional drag. By further examining the results obtained in this work, it was believed that the polymer molecules, especially the branched Separan AP-30, were entangled or formed aggregates in the solvent in order to reduce drag. The molecules tend to disperse and the aggregates would break up if aged for a long time. Similarly the action of mechanical shearing, especially since the wall shear forces in the present study were so high, would have the same effect on the molecular aggregates.

It is not clear when and how the aggregates were formed. Fabula[4] and Brennen and Gadd[5] indicated that aggregates only existed in freshly prepared but poorly mixed solutions. However, recently it was reported that Barenblatt[13] passed solutions through a filter with holes so fine that only single molecules could pass. The solutions were then passed through a tube in turbulent flow, producing a reduction in drag, and were immediately passed through the same filter. Very many aggregates failed to pass the second time. It seems to suggest that these aggregates were formed by the turbulent straining. Indeed, in Patterson's measurements,[6] there was a gain of high molecular weight species in the case of Polyox WSR-N80. Recent experiments by Barenblatt showed the existence of so-called globules about 1 mm in diameter.[10] Such a large dimension, approximately three orders of magnitude larger than the diameter of the random coils formed by single molecules, must thus consist of many molecules entangled together.

It is the intention of many investigators to develop appropriate constitutive relations to explain the anomalous drag reducing phenomenon by polymer additivies. If the above speculation is true, then it is obviously necessary to include the effect of molecular interaction between polymer molecules and its strain history in order to accomplish such a task.

Conclusions

Experimental results support earlier notions that entanglement or aggregation of polymer molecules could be one of the important mechanisms involved in friction drag reduction. Solutions of Polyox WSR-301 and Separan AP-30 have no significant change in their drag reducing effect under different storage conditions. Only 10 ppmw Separan AP-30 samples will degrade immediately in storage. Aged solutions also have less resistance to shear degradation than fresh ones. Concentrated solutions tend to upgrade and then degrade under continuous shearing. It is further suggested that the drag-reducing solutions affected by aging or mechanical degradation should be characterized by concentration as well as solution history.

References

[1] Gadd, G. E., "Turbulence Damping and Drag Reduction Promoted by Certain Additives in Water," *Nature*, Vol. 206, 1965, p. 463.

[2] Virk, P., "The Toms Phenomenon—Turbulent Pipe Flow of Dilute Polymer Solutions," Sc.D. thesis, 1966, Chemical Engineering Dept., MIT, Cambridge, Mass.

[3] Ellis, A. T., Waugh, J. G., and Ting, R. Y., "Cavitation Suppression and Stress Effects in High-Speed Flows of Water with Dilute Macromolecule Additives," *Transactions of the ASME Journal of Basic Engineering*, Vol. 92, No. 3, Ser. D, Sept. 1970, pp. 459–466.

[4] Fabula, A. G., "An Experimental Study of Grid Turbulence in Dilute High Polymer Solutions," Ph.D. thesis, 1966, Pennsylvania State Univ., University Park, Pa.

[5] Brennen, C. and Gadd, G. E., "Aging and Degradation in Dilute Polymer Solutions," *Nature*, Vol. 215, 1967, p. 1368.

[6] Patterson, R. W., "Turbulence Measurements in Polymer Solutions Using Hot Film Anemometry," Ph.D. thesis, June 1969, Harvard Univ., Cambridge, Mass.

[7] Sherman, B. A., "Effect of Storage on the Drag Reducing Properties of Polyethylene Oxide WSR-301," TN 303/68, 1968, Admiralty Underwater Weapons Establishment, United Kingdom.

[8] McNally, W. A., "Heat and Momentum Transport with Dilute Polyethylene Oxide Solutions," Ph.D. thesis, 1968, Univ. of Rhode Island, Kingston, R. I.

[9] Hoyt, J. W., "A Turbulent Flow Rheometer," *ASME Symposium on Rheology*, ed. by A. W. Morris, June 1965, pp. 71–82.

[10] Librovich, V. B., private communication, Institute of Mechanical Problems, Moscow, USSR.

[11] White, A., "Studies of the Flow Characteristics of Dilute High Polymer Solutions," *Hendon College Research Bulletin*, No. 4, 1967, p. 113.

[12] Lumley, J. L., "Drag Reduction by Additives," *Annual Reviews of Fluid Mechanics*, ed. by W. Sears and M. Van Dyke, Vol. 1, 1969, p. 367.

[13] Barenblatt, G. I., "Turbulence of Anomalous Fluids," *Heat Transfer-Soviet Research*, Vol. 1, 1969, p. 102.

JULY 1972 J. HYDRONAUTICS VOL. 6, NO. 2

Effects of Distributed Injection of Polymer Solutions on Turbulent Diffusion

Robert R. Walters* and C. Sinclair Wells Jr.†
Advanced Technology Center Inc., Dallas, Texas

Part of an extensive experimental investigation of the mechanics of turbulent diffusion is described for uniformly distributed injection of a polymer solution through a porous wall adjacent to a fully-developed turbulent pipe flow of water. The diffusion data were obtained over an active porous wall section and throughout the region immediately downstream of the porous wall. The previously recorded wall friction anomalies recorded in the region of distributed polymer injection are shown to depend on the viscosity of the resulting polymer solutions near the wall associated with reduced diffusion. Empirical diffusion coefficients give a quantitative determination of the effect of the polymer in reducing turbulent diffusion for the present case. The transitional sublayer was identified from these data as the boundary-layer region requiring polymer to effect wall friction reduction.

Nomenclature

A_i = active porous wall injection area, ft^2
ΔB = defined by Eq. (1) using f based on pressure drop only
C = time averaged local concentration of injected tracer in the stream, ppb
C_i = concentration of injected tracer at the wall, ppb
$\bar{C}$ = average bulk concentration of tracer in the stream, $(\dot{w}_i/\dot{w}_t) \times C_i$, ppb
$\bar{C}_p$ = average bulk concentration of the polymer in the main stream, ppm $(\dot{w}_i/\dot{w}_t) \times$ (concentration of polymer injection solution)
D = tube diameter, $2R$, ft
$\mathfrak{D}$ = molecular diffusion coefficient ($\mathfrak{D}_w$ denotes wall condition), ft^2/sec
E_D = total diffusivity of mass, $\mathfrak{D} + \epsilon_D$, ft^2/sec
f = friction factor, defined as $(R/\rho\bar{u}^2)dP/dx$
g = gravitational constant, ft/sec^2
$\dot{m}_0$ = mass flow rate toward tube centerline per unit area at the wall, $(\dot{w}_0/g)$, (lb) (sec)/ft^3
P = static stream pressure, psf
R = tube radius, ft
Re_D = Reynolds number, $\bar{u}D/\nu_w$
u = local streamwise velocity, fps
u_1 = stream velocity at tube centerline, fps
u_* = shear velocity, $(\tau_w/\rho)^{1/2}$, fps
$\bar{u}$ = average bulk stream velocity, fps
u^+ = dimensionless velocity variable, u/u_*
$\bar{v}_i$ = average injection velocity through porous wall, fps
w = dimensionless density ratio, ρ_A/ρ, equal to C/C_i
$\dot{w}_i$ = total weight flow rate injected through the porous wall, lbs/sec
$\dot{w}_o$ = total weight flow rate injected through the porous wall, per unit area, 16/ft$^2\cdot$sec
$\dot{w}_t$ = weight flow rate of main stream and injection fluid, lbs/sec
x = streamwise spatial coordinate measured from upstream end of porous wall A, ft

---

Received September 30, 1970; revision received December 1, 1971. This research was supported by the Office of Naval Research under Contract N 00014-69-C-0214 (Mathematical Sciences Division, Fluid Dynamics Program).

Index category: Hydrodynamics.

* Research Scientist, Fluid Mechanics Group. Member AIAA.

† Manager, Fluid Mechanics Group. Member AIAA.