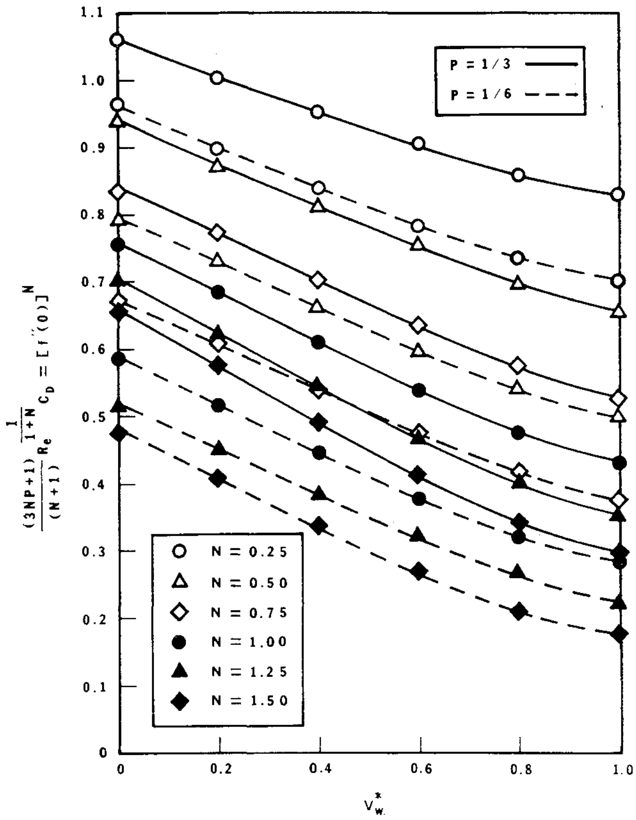

Fig. 3 Dimensionless, scaled drag coefficient.

the strong wall injection, $V_w^* = 1.0$, reduces the drag coefficient 18% for $p = \frac{1}{3}$ and 23% for $p = \frac{1}{6}$. However, for strong viscous effects, $N = 1.50$, the reduction in $[f''(0)]^N$ increases to 48% for $p = \frac{1}{3}$ and 60% for $p = \frac{1}{6}$. It is interesting to note that the variations of the scaled drag coefficient $[f''(0)]^N$ exhibit monotonically decreasing characteristics, with the negative slopes of the curves increasing with the viscous power law exponent N. However, the curves remain parallel to each other for different values of $p = \frac{1}{6}$, $\frac{1}{3}$, separated from each other by the drag coefficient at no wall injection conditions, $V_w^* = 0$, hence indicating that the effect of the wedge angle has small influence on the overall effect of the drag reduction resulting from the wall mass injection.

In summary, it is concluded that the viscous drag of the flow of a non-Newtonian fluid over wedges can be reduced considerably by the wall mass injection, and the degree of the reduction depends on the exponent of the viscous power-law model for the fluid, but not directly on the total wedge angle.

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Effects of Polymer Addition on Friction in a 10-in.-Diam Pipe

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Introduction

It has been well established that friction reductions up to 80% in turbulent liquid flows can be achieved by the addition of small amounts of certain soluble, high-molecular-weight polymers. The greatest effectiveness has been obtained using linear polymers with molecular weights of the order of several million.

Early investigators followed the assumption that the friction-reduction behavior was related to non-Newtonian fluid properties. However, later investigations proved that the friction-reduction effects become more pronounced in relatively dilute polymer concentrations, i.e., < 100 ppm, which show Newtonian behavior. Although a large number of experimental results have been reported, most of these studies have been conducted using pipes 2 in. or less in diameter. Thus, it seemed desirable to obtain some data using a pipe approximately an order of magnitude larger than any previously used.

The studies reported here were carried out in a 10-in.-diam flow facility. To our knowledge, no previous studies in facilities of this size have been reported.

Experiments conducted in large facilities have been handicapped by the difficulties associated with the preparation and injection of large quantities of solutions of friction-reducing polymers. When such polymers are added to water, the wetted particles immediately form a sticky skin, which causes the particles to clump together, rendering further solution difficult. Also, the polymers, having molecular weights of the order of 1,000,000, form extremely viscous solutions at even low concentrations. For example, a sodium salt of polyacrylamide (Separan AP30, Dow Chemical Company), which is an efficient friction reducing material, has an apparent viscosity of 5000 centipoises in a 1% solution.

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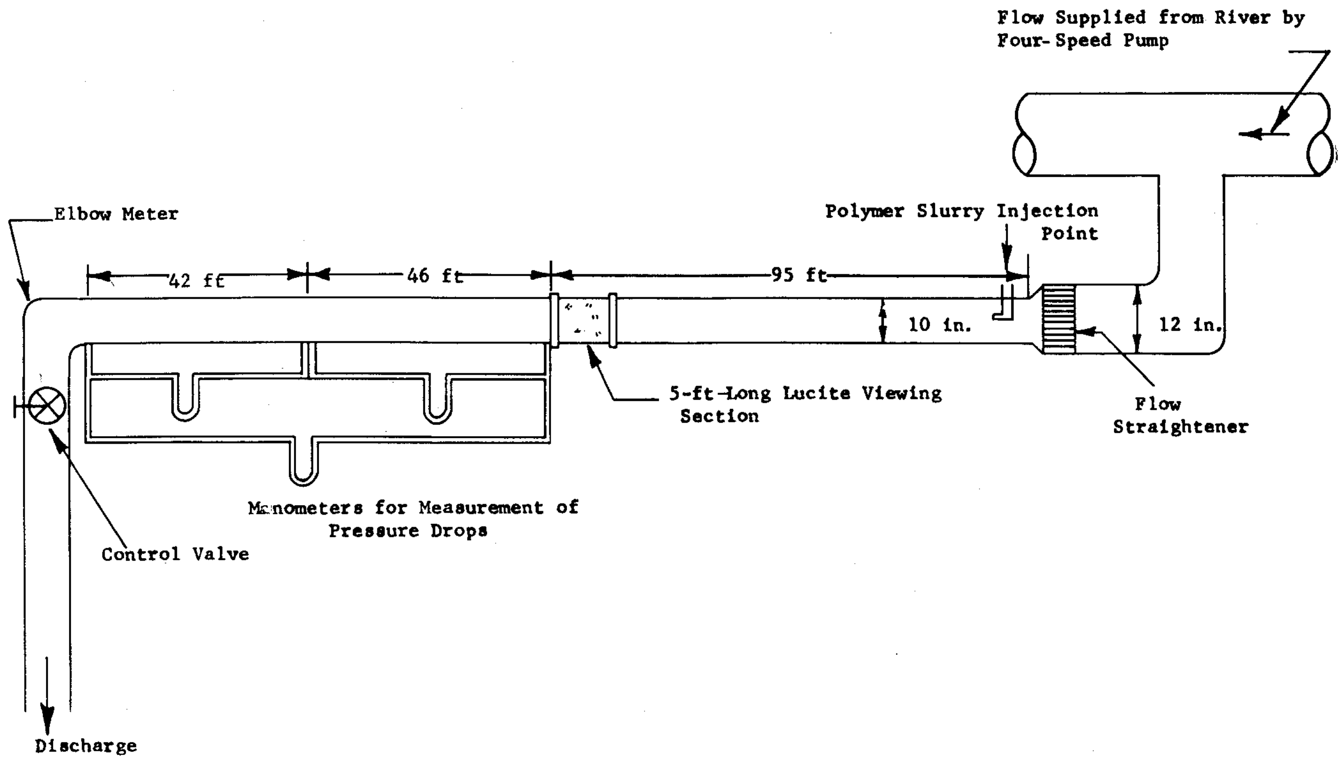

Fig. 1 Sketch of 10-in. water tunnel.

contract with the Naval Ship Research and Development Center, has developed a convenient method of introducing large quantities of linear, high-molecular-weight polymers into water.[1,2] Studies were directed toward the development of concentrated fluid dispersions of drag-reducing polymers in water-miscible liquids that suspend, but do not dissolve, the polymers. Because the polymer is not dissolved, high concentrations can be obtained without intolerably high viscosities. The polymer remains suspended in the liquid as discrete particles until such time as a slurry is injected into, and mixed with, water. The polymer then hydrates rapidly, so that it can effect almost immediate drag reduction. This approach permits the use of high concentrations of polymer particles in a slurry that can be readily pumped and injected into the water. Dispersion techniques are simple, and the storage bulk of the slurries is reduced considerably.

Test Facility

The tests were conducted in a 10-in.-diam water-flow tunnel, shown schematically in Fig. 1. It is a single-pass system, utilizing river water that is passed through the test section and discharged to a water channel.

Concentrated slurry, in which the polymer remains suspended in the liquid as discrete particles until the slurry is injected into and mixed with water, was injected on the centerline of the 10-in.-diam pipe at a station 95 ft ahead of the test section. This upstream injection location was chosen so that there would be sufficient time for the polymer to become fully effective in reducing the friction in the pipe. Tests conducted at North Star indicate that a mixing time of 6 sec is sufficient for this purpose. The polymer slurry injection system is described in detail in Ref. 2. The slurry consisted of 45%, by weight, of Separan AP30 dispersed in urethane grade polypropylene glycol (MW 400).

The 95-ft section of the flow channel was followed by an 88-ft-long test section instrumented so that the pressure drop could be measured over the entire length, the first 46 ft, or the last 42 ft. A 5-ft-long viewing section located 90 ft downstream of the polymer injection station allowed visual observations of the flow patterns. The velocity range for which reliable data could be obtained was from 1.5 fps up to 15 fps. Discharge was measured with a calibrated elbow meter.

Results

The results are shown in Fig. 2, with the Fanning friction factor (f) plotted against the Reynolds number (N_{Re}) based on water properties. The data obtained using the 10-in.-diam pipe plotted in Fig. 2 are for the 88-ft-long test section only, because, for the lowest velocities, it was not possible to obtain accurate pressure drop data for the 46- and 42-ft sections separately. In Fig. 3, the percentage reduction in pressure drop in the 10-in.-diam pipe is plotted as a function of Reynolds number.

Throughout the test program, the following observations were made:

1) In general, the percentage reduction in pressure drop was smaller for the first 46 ft of pipe than for the last 42 ft, indicating that the polymer had either not dispersed to the wall of the pipe or that any resulting change in flow conditions, i.e., change in velocity profile or turbulence characteristics, was not complete. For example, over the last 42 ft of pipe, the friction reduction was 43% at N_{Re} of 7×10^5.

2) By viewing through the transparent section in the channel, fibrous strands could be observed within the flow. The presence of these strands indicated that the polymer was not completely dispersed, thus reducing the effective concentration below 50 ppm (the desired concentration calculated assuming complete solution of the polymer).

3) For most flow conditions, after the polymer was present throughout the entire pipe length, the flow would increase by as much as 20–30% over that obtained using raw water, and the pressure drop would decrease slightly.

Also shown on Fig. 2 are data obtained using the 0.265-in.-diam flow facility at North Star Research and Development Institute.[2] These data were also obtained by injecting polymer slurry into the water flow. Although a polyethylene

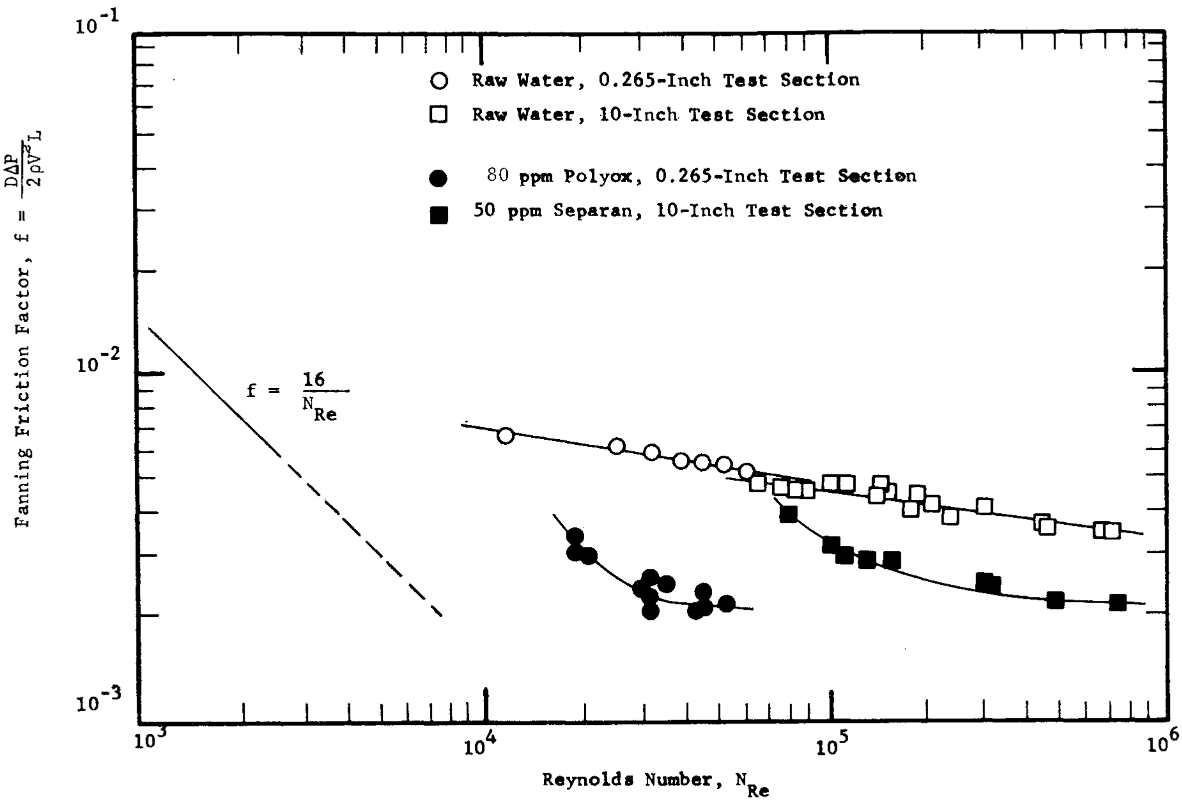

Fig. 2 Variation of friction factor with Reynolds number in small and large test sections.

oxide polymer (Polyox Coagulant, Union Carbide Corporation) was used in most of the tests in the small facility, other tests indicated that the Separan and Polyox Coagulant yielded nearly identical results.

The effect of pipe size on friction reduction has been the object of considerable speculation, with the conclusion that increasing pipe size would greatly reduce the percentage of drag reduction. Extrapolation of the data for the 10-in. pipe indicates that a critical N_{Re} of about 60,000 exists, below which no friction reduction is to be expected. The decrease in the magnitude of friction reduction at the lower Reynolds numbers has been previously observed.[3–5]

Because of the brevity of the test program conducted, many questions remain unanswered, and thus, it is important that additional tests be conducted. It should be stressed that in spite of the fact that the tests left numerous unanswered questions, a reduction in pressure drop in the 10-in.-diam pipe in excess of 40% over the last 42 ft of the

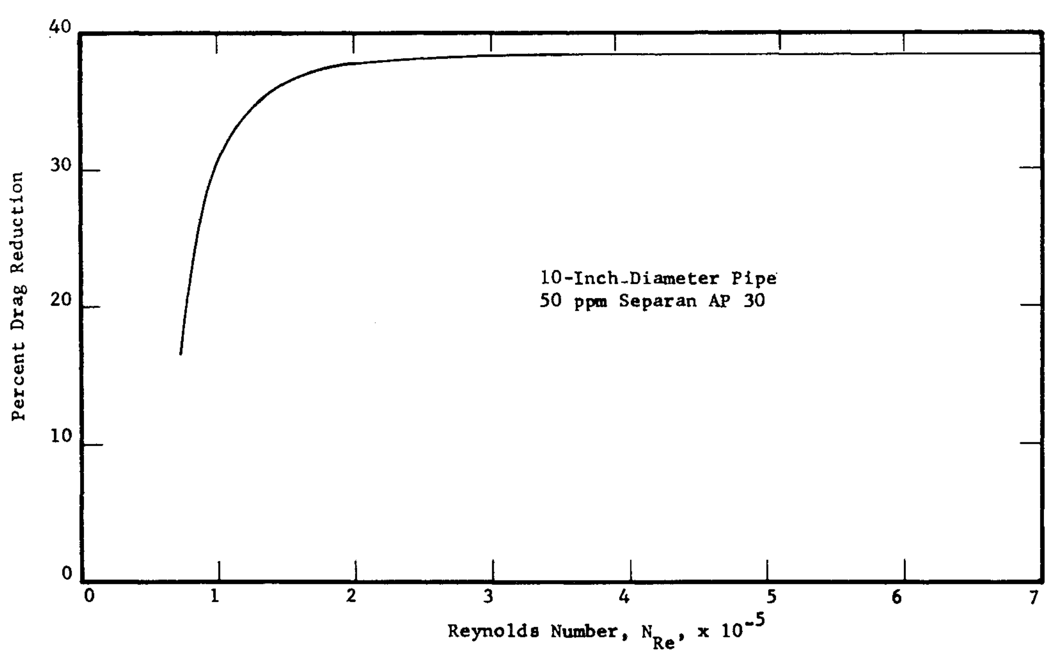

Fig. 3 Variation of drag reduction with Reynolds number.

pipe did occur at velocities of 5–15 fps. Also, indications are that pressure loss reductions as great as 50% may occur in longer pipes.

Conclusions

1) The injection of a high-solids slurry is an efficient and practical method of introducing friction-reducing polymers into water.

2) Significant friction reduction is obtained in large-diameter pipes with friction-reducing polymers. This would have great utility in water-handling systems that are subjected to occasional overloading, such as storm sewers.

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