# Effect of Polymer Injection on Frictional Drag in Turbulent Pipe Flow

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**Experimental results concerning the effect of injection of a drag reducing polymer solution along the confining boundary for turbulent pipe flow are described. Tests were made using a 1.625-in.-diam pipe provided with five circumferential injection slots located 6-in. apart. The polymer used was Polyox WSR-301. The effects of variation of Reynolds number, injection rate, number of injection points, and concentration of injected solution were studied. The results of the investigation show that, in general, the trends exhibited for premixed flows are also displayed for the case of polymer injection. It was found that the drag reducing action was most effective when the polymer was injected through the furthest upstream slot rather than being distributed over the test length. For the injection slot design employed in this investigation, a pronounced "injection drag" was measured. This injection drag is thought to be caused by the high viscosity of the polymer solution and the disturbance of the main flow caused by the injection. For the higher solution concentration, a significant residual effect was observed such that a reduction of drag persisted several minutes after injection was stopped.**

## Nomenclature

$C$ = injectant solution concentration, %
$D$ = inside tube diameter
$f$ = Fanning's friction factor, $\tau_w/(\rho V^2/2)$
$f_0$ = measured value of $f$ without injection
$f_{inj}$ = measured value of $f$ with injection
${}_2f_8$ = measured value of $f$ between PT 2 and PT 8, over-all friction factor
$F$ = local friction factor ratio
$L$ = characteristic length associated with $f$
PT = pressure tap (numbered from one to nine)
${}_2\Delta P_8$ = pressure differential between PT 2 and PT 8
$Re$ = tube flow Reynolds number for water, $\rho VD/\mu$
$V$ = average flow velocity through test section
wtppm = weight parts per million of polymer added based upon flow rate of water in the test section, $10^4\, C \times$ Injection Flow Rate/Main Flow Rate
$\mu$ = viscosity of water
$\rho$ = density of flowing fluid
$\tau_w$ = average wall shear stress

## Introduction

IT is now a well established fact that certain long-chain polymer additives can significantly reduce frictional drag in the turbulent flow of water and many other liquids. This phenomenon was first observed by Toms[1] who reported it as a "hitherto unknown feature of the relation between polymer concentration and rate of flow at constant pressure gradient." The implications of Toms' discovery were apparently not recognized immediately. It was not until Fabula[2,3] and his co-workers at Naval Ordnance Test Station became interested in the effect several years later than a systematic study was begun on drag reduction by use of selected additives. Recently, this phenomenon has been the subject of extensive research, and a number of investigators have reported reductions in frictional drag of over 50%.

In spite of the widespread interest in this effect, including a great deal of both experimental and theoretical work, the underlying mechanism of the drag reduction is not well understood. It is obvious, however, and has been demonstrated that a reduction in drag will occur only if the polymer additive is present near the body surfaces in contact with the flowing fluid. This fact, logically, leads to the study of polymer injection along the surfaces of bodies in contact with flowing fluids. Preliminary tests of this type have been carried out by Wells and Spangler[4] for an internal pipe flow and by Vogel and Patterson[5] for flow about a submerged body. In neither of these studies was polymer injection at more than one position examined. In the present investigation an attempt was made to provide more complete data and to study more thoroughly the effect of polymer injection on turbulent drag, including the effect of multiple injection slots.

## Experimental Apparatus and Procedures

Because of its fluid mechanical simplicity, an open circuit pipe flow apparatus was used for this investigation. The main features of the apparatus are shown in Fig. 1. Tap water, the primary fluid, was supplied to a 150 gallon collection tank from which it entered the test section. Under normal operating conditions about one-third of the tank volume was filled with air to suppress water pressure surges. The test section consisted of a 9-ft length of 1.625-in.-i.d.

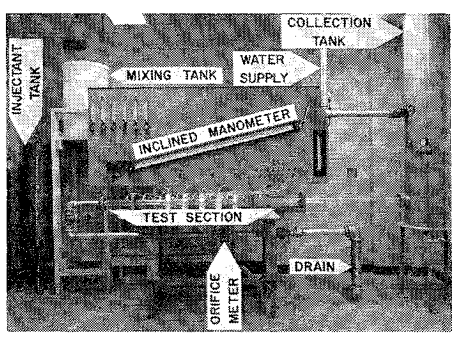


**Fig. 1 Photograph of test apparatus.**

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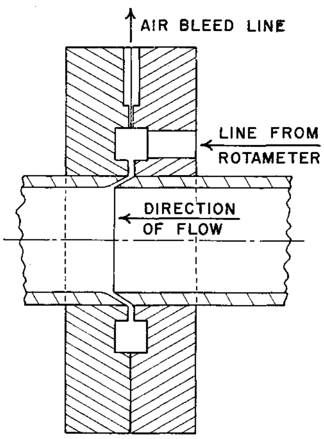


**Fig. 2 Detail of injection collar.**

acrylic pipe. This included a 5-ft entry section, which was provided to insure a fully developed velocity profile, a 2-ft injection region, and a 2-ft downstream region. Standard flow metering equipment was provided downstream of the test section.

The injection region contained five circumferential injection slots spaced at 6-in. intervals. Each of these slots was surrounded by a separate collar. Details of the injection slot and collar are shown in Fig. 2. Each injection slot was 0.050 in. wide and inclined 30° to the pipe wall. The downstream corner was slightly rounded to provide a smooth entry of the injected fluid into the main flow stream.

The injected fluid, either water or a drag reducing solution, was supplied to the collars from a pressurized tank. The flow through each injection slot could be individually controlled and metered.

Nine pressure taps, identified as PT 1 through PT 9 were provided along the pipe. The furthest upstream pressure tap (PT 1) was located 9 in. ahead of the first injection collar. PT 2 through PT 9 were spaced at 6-in. intervals downstream of PT 1. The pressure drop between PT 1 and any of the other eight pressure taps could be measured on the inclined manometer shown in Fig. 1.

The drag reducing agent used in these tests was a polyethylene oxide produced by Union Carbide Company under the trade name Polyox WSR-301. This polymer has a linear, or unbranched, molecule with an average molecular weight of $4 \times 10^6$. It has been used extensively in drag reducing experiments and is one of the most effective drag reducing agents presently in use. As received, this polymer was in powder form.

The drag reducing solution was mixed in a 30 gallon container by sifting the powder onto the surface of water flowing down an incline plane into the container. This method prevented the formation of large globules of Polyox that were very slow to dissolve. After 24 hr, during which the mixture was occasionally stirred by hand, the solution

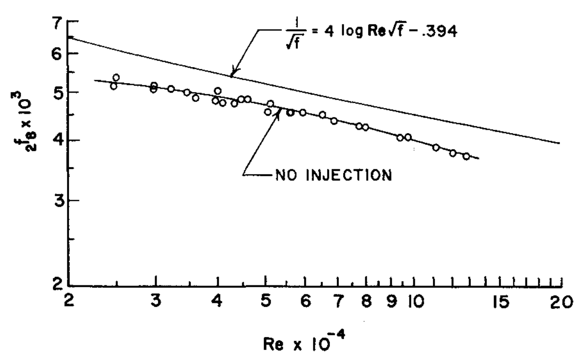


**Fig. 3 Variation of over-all friction factor with Reynolds number for no injection.**

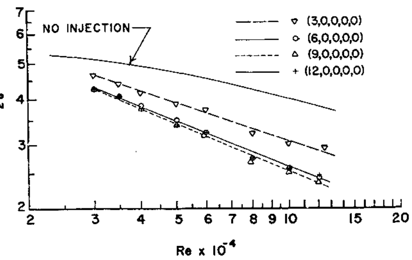


**Fig. 4 Variation of over-all friction factor with Reynolds number for several injection rates.**

was siphoned into the injectant tank and the tests were made. In all cases the solution appeared homogeneous when used.

Recognizing that polymer degradation can be a serious problem with polyethylene oxide solutions, every attempt was made in these experiments to eliminate this factor. Since all solutions were used within 36 hr of initial mixing the effects of aging and/or bacteriological action should have been minimized. Care was also taken not to subject the solution to high shear rates during the mixing process. Some shear degradation undoubtedly occurred during the distribution of the solution to the injection slots. Overall, however, it is believed that the influence of polymer degradation was minor. Unfortunately equipment was not available to provide a good quantitative description of the solution properties.

The difficulties associated with the preparation of identical solutions have been discussed by Lumley.[6] In the present investigation, while the data taken with any particular solution were readily reproduced using that solution, when the test was rerun using a supposedly identical solution some discrepancies were almost always present. Occasionally solutions were prepared, following a routine procedure, that gave results completely inconsistent with the over-all trends observed. These data were discarded and the tests rerun.

## Results and Discussion

In these experiments the effect of three independent variables on the frictional drag was investigated. These independent variables are the flow Reynolds number ($Re$), the injection configuration,‡ and the concentration of the injected solution ($C$).

The results of the investigation are shown in Figs. 3–10 and can be divided into three separate groups. Figures 3–5 show the variation of over-all friction factor with Reynolds number and injection configuration. Figures 6–8 present profiles of the local friction factor along the test section. Figures 9 and 10 show the variation of the over-all friction factor as a function of solution concentration for several injection configurations. The data for Figs. 6–10 were obtained at a Reynolds number of $6 \times 10^4$. The values of $Re$ given are based on tabulated values of the viscosity of water.

Figure 3 shows the variation of the average friction factor between PT 2 and PT 8 as a function of Reynolds number without injection. $_2f_8$ was computed from the relation

$$_2f_8 = D(_2\Delta P_8)/2L\rho V^2$$

A plot of the von Kármán equation

$$1/(f)^{1/2} = 4 \log Re(f)^{1/2} - 0.394$$

for turbulent flow through a smooth pipe is also shown for comparison. The discrepancy between the experimental data and von Kármán's relation is probably due to the

‡ As used here, injection configuration means a combination of injection rates and injection points. Injection configurations will normally be identified by the injection rate in polymer weight parts per million (wtppm) through each of the five collars. Examples are: (9, 0, 0, 0, 0), (5, 3, 1, 0, 0), and (1.8-all).

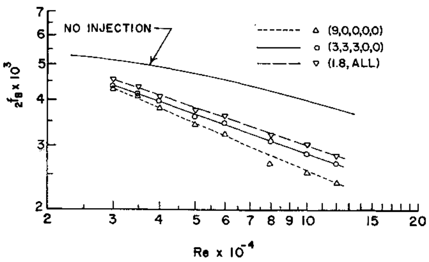


**Fig. 5 Variation of over-all friction factor with Reynolds number for several injection distributions.**

presence of the injection slots themselves. A possible explanation for this effect is that the local skin friction is reduced in the neighborhood of the slots because the flow is not fully attached to the wall. A similar behavior was observed in the data of Wells and Spangler.[4]

Figure 4 shows the effect of changes in the injection rate through the first injection slot on $_2f_8$. The data for this figure as well as for Figs. 5–8 were obtained using Polyox solutions of 0.2% concentration by weight. The general trends exhibited in Fig. 4 are consistent with results reported for premixed flows. The percent drag reduction caused by the polymer additive increases with Reynolds number and with polymer injection rate up to an optimum value. The optimum injection rate was found to be approximately 9 wtppm and independent of Reynolds number. Injection rates of 6 and 12 wtppm gave only slightly less drag reduction, indicating that near optimum drag reduction is possible over an injection rate range of several weight parts per million.

Comparison of the values shown in Fig. 4 with published results for premixed solutions under somewhat similar conditions is inconclusive due to the wide variations of these results. Pruitt and Crawford,[7] for example, have reported the drag reducing effect of Polyox WSR-701 in a 1.624-in. pipe. Polyox WSR-701 has a higher molecular weight and is a more effective drag reducing agent than WSR-301. They found the optimum concentration to be about 250 wtppm. At that concentration they obtained a reduction in drag of about 46% at $Re = 6 \times 10^4$. In contrast to this Goren and Norbury,[8] using Polyox WSR-301 in a 2-in. pipe, found an optimum concentration at about 10 wtppm. At that concentration they obtained a drag reduction of about 61% at $Re = 6 \times 10^4$—more than four times the reduction obtained by Pruitt and Crawford at the same concentration. These wide differences serve to emphasize the difficulty of correlating the drag reducing effects of polymer solutions. The results of the present investigation, using polymer injection, fall between the results quoted earlier. For example, an injection rate of 9 wtppm through the first slot produced a reduction in frictional drag of 31% at $Re = 6 \times 10^4$. This is double the value of Pruitt and Crawford for 10 wtppm but only one-half that of Goren and Norbury.

Figure 5 shows the effect of injecting a total of 9 wtppm using three different injection configurations. Over the Reynolds number range covered, injection of all the polymer through the first slot is more effective in reducing drag. The least effective configuration is equal injection through all five slots (1.8-all).

Additional insight into the reasons for the trends exhibited in Figs. 4 and 5 can be obtained from an examination of Figs. 6–8. These graphs show the variation of the local average friction factor (between adjacent pressure taps) along the test section, for several injection configurations. The data for these figures was obtained at $Re = 6 \times 10^4$, $C = 0.2\%$. The dependent variable $F$ is defined as

$$F = [(f_{\text{inj}} - f_0)/f_0] \times 100$$

where $f_0$ is the measured local friction factor without injection. Thus, $F$ may be interpreted as the percent change

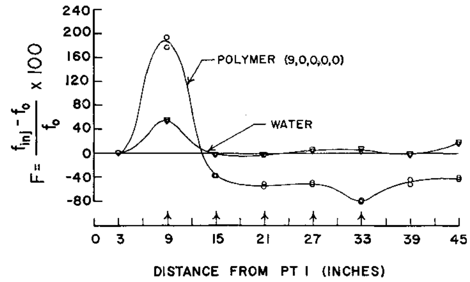


**Fig. 6 Distribution of local friction factor ratio for polymer and water injection. $Re = 6 \times 10^4$.**

in frictional drag due to injection. The five arrows along the horizontal scale of these figures represent the locations of the injection slots.

Figure 6 shows the $F$ distribution for a polymer injection configuration of (9, 0, 0, 0, 0) and for plain water injection at the same flow rate. Since a positive value of $F$ corresponds to an increase in drag, it is evident that the injection alone has the effect of increasing the drag. This is thought to be due to the flow disturbance caused by injection.

It is also clear from this figure that, in the region of injection, the polymer solution causes an increase in drag that is far greater than that for water injection alone. This is probably due to the high viscosity of the concentrated polymer solution. As the polymer solution is diluted by the water of the main flow and subjected to the high shear rates in the sublayers, the drag reducing action begins, causing a net friction reduction over the test section length. It should be pointed out that downstream of the injection region the decrease in frictional drag averages about 55%, which is comparable to the value of 61% reported by Goren and Norbury. Both results, however, are considerably below the maximum possible reduction of about 77% predicted by the empirical curve of Hoyt and Fabula.[3]

An anomalous behavior was observed in the neighborhood of the fifth injection slot. Without injection the value of $f_0$ in that region was about 20% below the over-all average value for the test section. However, for certain injection configurations, the value of $f_{\text{inj}}$ was far below the expected value. This drop was more than enough to offset the low value of $f_0$ and resulted in clearly defined dips in certain curves of Figs. 6, 7, and 8. The reason for this unusual effect is unknown and the validity of the curves in this region is suspect.

Figure 7 shows the effect of changing the injection rate through the first slot on the $F$ distribution. From these curves it is evident that an increase in injection rate causes an increase of injection drag. Thus, even though downstream of the injection region a slight further reduction in drag is produced by an injection rate of 12 wtppm as compared to 9 wtppm, the associated change in injection drag makes 9 wtppm more effective over the test section. Of

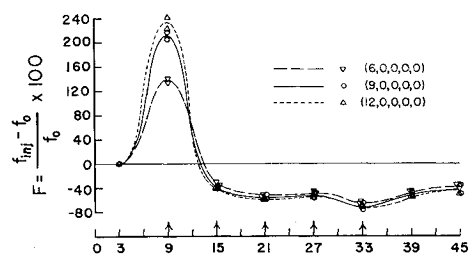


**Fig. 7 Distribution of local friction factor ratio for several polymer injection rates. $Re = 6 \times 10^4$.**

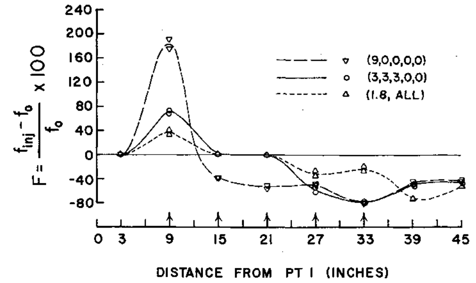


**Fig. 8 Distribution of local friction ratio for several injection configurations. $Re = 6 \times 10^4$.**

course, this result might be changed if a longer test section were used.

It should be noted in Figs. 6 and 7 that downstream of the injection region, ignoring the dip in the vicinity of the fifth injection slot, the percent drag reduction is relatively constant over the remainder of the pipe length, though tending to decrease toward the end of the test section. This behavior would seem to indicate that a significant portion of the polymer additive tends to remain in the vicinity of the wall and not be rapidly diffused into the main flow stream.

Figure 8 shows the effect of distributing the drag reducing solution equally through three and five slots as compared to injection through the furthest upstream slot. From these curves some explanation for the trend exhibited in Fig. 5 can be made. By injecting all of the polymer as far upstream as possible, the drag reducing agent can act over a greater length of the test section, uninterrupted by the introduction of new material that must be diluted and mixed with the sublayer fluid before it is effective in causing further drag reduction.

Note that in Figs. 7 and 8 the curves for configuration (9, 0, 0, 0, 0) are not identical as they were taken during different phases of the experiment. However, considering the wide variation in test results which have been reported, the agreement between the two curves is quite good.

Figures 9 and 10 show the effect of solution concentration and injection configuration on the over-all friction factor at $Re = 6 \times 10^4$. These curves re-emphasize the fact apparent in Fig. 5 that the most effective drag reduction was obtained when the polymer injection was concentrated in the upstream region. This trend is the same for the uniformly distributed injection rates shown in Fig. 9 and tapered injection rates of Fig. 10.

These curves also show very clearly that there is an optimum concentration for the polymer solution. This optimum concentration appears to depend somewhat on the injection configuration but in all cases lies between 0.15% and 0.20%.

It is believed that the optimum concentration is closely associated with the injection drag phenomena. At the low concentrations, for a given polymer injection rate, a relatively large amount of solution must be introduced into the

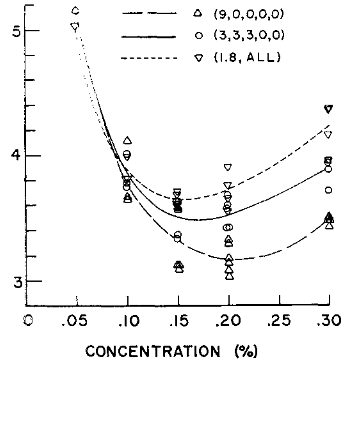


**Fig. 9 Variation of over-all friction factor with solution concentration for three injection configurations. $Re = 6 \times 10^4$.**

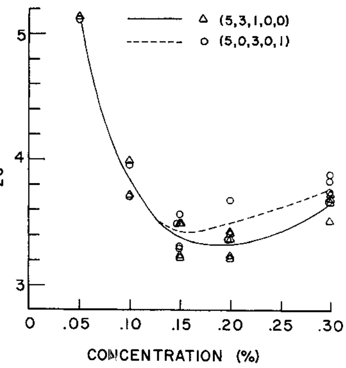


**Fig. 10 Variation of over-all friction factor with solution concentration for tapered injection configurations. $Re = 6 \times 10^4$.**

flow stream. This, of course, produces a larger disturbance in the flowfield causing an increase in injection drag. At the high concentrations, although the injection flow rate is low, the viscosity of the injected solution is very high, again causing a large injection drag. Thus, it would appear that the optimum solution concentration for a particular polymer injection rate is that which minimizes the injection drag.

While obtaining the data for Figs. 9 and 10, an adsorption effect of the type noted by Pruitt et al.[9] was observed. This effect was very significant when, for example, a 0.10% solution was mixed in a container where a 0.30% solution had previously been mixed. A certain amount of polymer from the 0.30% solution was adsorbed on the walls of the container and remained when the solution was removed. Subsequent mixing of a less concentrated solution (e.g., 0.10%) allowed a certain amount of the polymer to be redissolved. This produced a more concentrated solution than that actually mixed. The same effect worked in reverse when a concentrated solution was prepared following a relatively dilute solution. Since each solution was mixed in the same tank and remained there for 24 hr, ample time was available for the adsorption to occur. This effect resulted in the invalidation of certain test runs and may be responsible for some of the spread in data points on Figs. 9 and 10.

A different facet of the adsorption effect was observed with the 0.30% solution. This was in the form of a residual effect such that when injection was stopped, there was an immediate further decrease in the value of ${}_2f_8$. For as long as 12 min after injection ceased, ${}_2f_8$ was below the value for no injection. This persistance of the drag reducing action after injection is stopped was also noted by Kowalski[10] and appears to be the same type of phenomenon reported by Davies and Ponter.[11] Based on this residual effect Kowalski has tested a method of intermittent injection which substantially reduced the amount of polymer required for a given reduction of drag.

## Summary and Conclusions

Data has been presented showing the influence of several variables on frictional drag reduction due to the injection of polymer solutions along the confining boundary for pipe flow. These results show that, in general, the trends exhibited for premixed flows are also found for the case of polymer injection. In particular, the percent drag reduction increases with Reynolds number and there is an optimum polymer injection rate above and below which the drag reduction is less effective. In addition, for the particular test section used in this investigation, it was found that the drag reducing action was most effective when the polymer injection was concentrated as far upstream as possible. Also, it was found that the most effective solution concentration was about 0.2% polymer by weight.

It is argued that many of the trends exhibited in these results are closely associated with the injection drag that is caused by the introduction of a high-viscosity polymer solution into the flow stream. This solution must be diluted by the main flow before the drag reducing action takes effect.

It is recognized that the level of this injection drag is probably strongly dependent on the design of the injection slots. Thus, had a different slot design been employed in this investigation, it is likely that the levels of friction reduction would have been different, and possibly some of the trends would have been changed. It would seem that in order to reduce the injection drag and thereby improve the over-all drag reduction, the polymer solution should be introduced tangentially to the main flow stream at a relatively high velocity. These considerations not withstanding, the results of this investigation indicate that it is unlikely that a significant improvement in drag reduction for internal flows can be obtained by injecting a polymer solution through closely spaced slots.

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