PRESSURE DROP REDUCTION IN TURBULENT PIPE FLOW BY SOAP AND POLYMER ADDITIVES

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Introduction

Over the years, numerous approaches have been used to reduce frictional pressure losses in turbulent flows of liquids in pipes and channels, such as boundary layer suction, the use of compliant boundaries, the use of miscible or immiscible fluids of low viscosity injected near the walls, etc. Up to now, however, one of the most promising approaches involves the addition of various drag-reducing materials to the liquid at very low concentrations. Quite remarkable reductions of up to 80% of the turbulent frictional drag in pipe flows may be achieved in this way. The potential importance of such a reduction will be immediately obvious.

Although the drag-reducing properties of certain natural additives has long been known (for instance, Rao [1] has pointed out that H.S. Hele-Shaw carried out such experiments using bile as an additive to water more than seventy years ago), it is only in relatively recent years that this phenomenon has been studied in detail, and it is only now that engineering applications are being investigated. The full practical utilization of the phenomenon of drag reduction by means of active additives has so far been seriously hampered by the lack of a general mechanism to explain all of its effects.

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In the present paper, we wish to review briefly some of the previous work carried out on the turbulent drag reducing effects of certain complex soaps and high molecular weight polymers in very dilute solutions in pipe flows, to present some new friction-factor measurements for such solutions obtained under carefully controlled conditions, and finally, to attempt a qualitative explanation of the observed effects in polymer solutions in terms of an adsorptional mechanism for the phenomenon.

Outline of previous work

Although drag reduction was noted in work carried out during World War II, the earliest work published in the open literature on drag reduction by means of very dilute polymer solutions appears to have been that of Toms [2], and this phenomenon is often termed the Toms effect. Not long after this the occurrence of drag reduction in solutions of aluminium soaps was noted by Mysels [3] and by Agoston, Harte and al [4]. In the last few years a considerable amount of information has been published, and several extensive reviews are available, particularly in the case of drag reduction by soluble polymeric additives [5 to 12].

Here we will consider only work done on drag reduction in pipe flows; much work has also been reported in other geometries, such as in turbulent submerged jets, external flows, etc., and recently investigations have been extended to cover multi-phase systems [13].

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A very detailed survey of the previous work on drag reduction in turbulent pipe flows [14] revealed many disagreements in detail between the results of different workers, due partly to the fact that many of the earlier experiments were carried out at relatively high additive concentrations (up to several orders of magnitude greater than those used in the new experiments discussed below); under these conditions the solutions may become measurably non-Newtonian in their flow behaviour. In addition, many of the early experiments were carried out using recirculating flows of the additive solutions, which, while simulating practical systems, are undesirable since the additives tend to degrade to varying extents on prolonged shearing, making the results very difficult to interpret quantitatively or compare with one another. We have also observed that the manner in which a solution is prepared and its age, storage conditions, manner of dilution, etc., may all influence the degree of drag reduction achieved under given conditions of flow, pipe geometry, and concentration.

In spite of the differences in detail, a broad picture of turbulent drag reduction in pipe flows of dilute polymer and soap solutions can be obtained from the published earlier work. The results of drag reduction measurements can be conveniently compared with those of pressure-drop measurements in ordinary liquids in terms of the dimensionless Darcy friction factor f and the Reynolds number Re, using the wellknown Moody double-logarithmic friction factor plot of the type sketched in Figure 1 a. On this plot, laminar flow conditions are represented by a straight line $f = 16/\text{Re}$, while the conditions for the turbulent flow of ordinary liquids in hydraulically smooth pipes are represented by a curve of decreasing slope towards larger Reynolds numbers; this curve has been well established experimentally, and is shown in all our plots for purposes of comparison.

The general pattern observed in the flow of solutions of drag reducing additives is that the laminar region is unaffected by the presence of the additive, except in tubes of very small diameter [15] or in cases when the solution is strongly non-Newtonian in its flow behaviour, in which case the use of a specially defined Reynolds number [16] will again reduce all results to a common line. In the turbulent flow regime, however, the experimentally determined pressure drop data for the polymer and soap solutions, even when these are not measurably non-Newtonian in flow behaviour, fall considerably below the line for the solvent liquid alone at a given Reynolds number; values corresponding to up to 80% reduction in the frictional drag have been reported repeatedly.

Several interesting effects have been noted in the literature; at risk of oversimplification, these may be summarized as follows:

The effect of additive type (Figs. 1 b, 1 c, 1 d).

Additives of the complex soap type have been mostly observed to produce their drag reduction effect in the part of the turbulent flow region adjacent to the laminar zone [17, 18] by a so-called extension of laminar flow conditions. Above some value of the shear stress, which appears to depend on the type of soap and its concentration, and which is characterized for a given pipe size by a "critical" value of the Reynolds number, the effect tends to disappear, and the experimental friction factor values revert towards the usual solvent line. It is important to note, however, that on reducing the shear stress to below the critical value, the drag reduction effect appears again approximately reversibly. This type of behaviour is sketched in Figure 1 b.

With the soluble, high molecular weight polymer additives, on the other hand, drag reduction may not occur
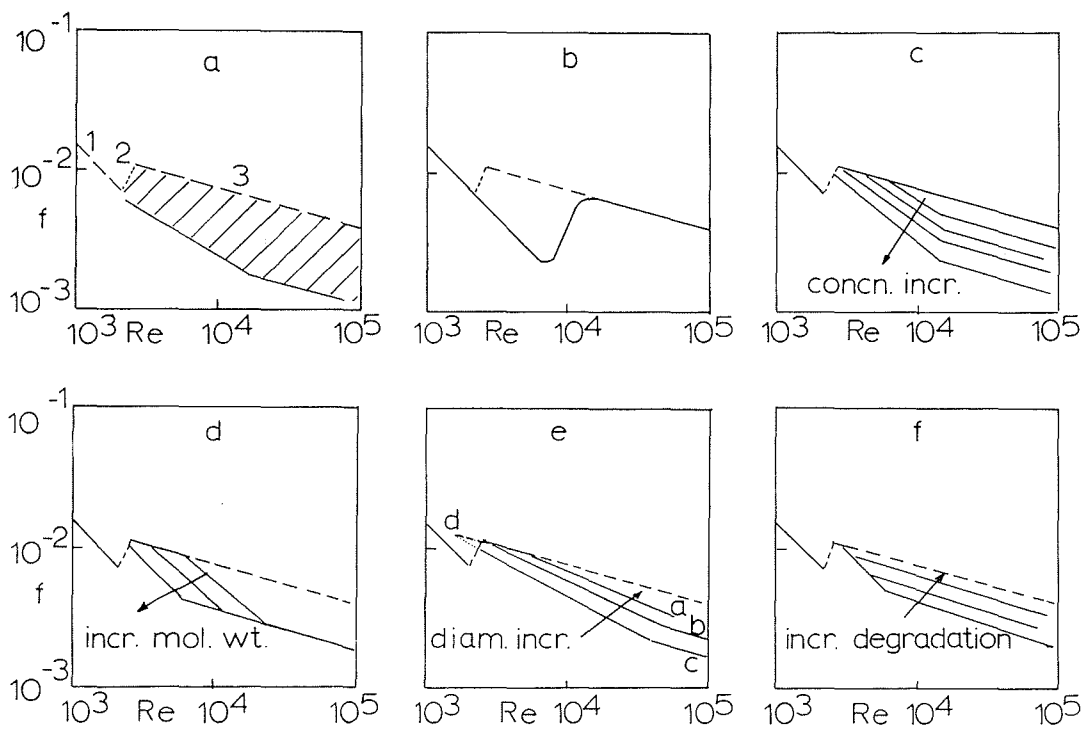
a) Extent of drag reduction: Most experimental results fall in the shaded area, giving reductions of up to about 80% in f; curves 1, 2, 3 represent the results for ordinary liquids in the laminar, transitional and turbulent zones, and are given in each figure as a basis for comparison.

b) Typical results for dilute soap solutions, indicating extension of laminar zone.

c) Typical results for dilute polymer solutions, indicating the effect of increasing the additive concentration.

d) Results for dilute polymer solutions indicating effect of increasing the molecular weight of the additive.

e) The diameter effect with dilute polymer solutions, showing an apparent loss of drag reduction efficacy of a given additive and concentration as pipe diameter increases. Point *d* represents an "imaginary" onset point.

f) Typical results on prolonged recirculation of dilute polymer solutions, illustrating the effect of degrading the additive.

1/ Sketches of friction factor, f, versus Reynolds number, Re, to illustrate various phenomena observed during drag reduction experiments with dilute soap and polymer solutions.

in the low turbulent region (see "diameter effect" below), but only above some "onset Reynolds number" for a given pipe size and polymer as sketched in Figure 1 c. As the mean molecular weight of the polymer increases, under otherwise similar conditions, this onset point moves towards smaller values of Re. As the polymer concentration increases, the magnitude of the drag reduction first increases, then reaches a maximum (at the "optimum" concentration), and then begins to decrease again with further increase of the polymer concentration as the viscosity of the solution begins to increase appreciably above that of the solvent. The maximum drag reduction which can be achieved appears to be relatively similar for different types and molecular weights of additives, though the optimum concentrations required to produce the maximum drag reduction vary widely with molecular weight and type. For instance, we have found drag reductions compared with water of approximately 80% in the cases of solutions containing $\sim$ 150 - 200 parts per million by weight (ppm) of guar gum (a natural polysaccharide of mean molecular weight about 0.25×10^6) or $\sim$ 25 - 30 ppm of "Polyox WSR-301" (polyoxyethylene manufactured by the Union Carbide Corporation, mean molecular weight about 5×10^6) for the same geometry and Reynolds number.

The diameter effect (Fig. 1 e).

One of the interesting effects in polymer solution drag reduction is the so-called diameter effect. As the pipe diameter increases for a given polymer type and concentration, the point at which drag reduction commences shifts to larger and larger Reynolds numbers. Thus, for large pipes it is possible that little or no drag reduction may be observed at the Reynolds numbers which can be reached in a test loop, while for very small tubes the onset of drag reduction may occur before the flow has undergone complete transition to turbulence, in which case an "imaginary onset point" may be found by extending the curves for the solvent and solution to meet at a point such as d in Figure 1 e. In the extreme case, the situation superficially resembles the initial part of the turbulent regime in Figure 1 b, but here there is usually a distinct change of slope at the end of the usual laminar zone. Several subdivisions of these types of behaviour have been discussed in detail by Savins [17].

Degradation effects (Fig. 1 f).

If a dilute drag-reducing polymer solution is subjected to extensive shearing (by being recirculated repeatedly through a test apparatus, for instance), the drag reduction is partly lost, rapidly at first and then more gradually, due to progressive degradation of the polymer, beginning, presumably, with the highest molecular weight fractions, which appear to be the most effective, weight for weight, in reducing drag. (All commercially available polymer additives have a wide to very wide spread of molecular weights about the mean value). This effect is sketched in Figure 1 f, and has been responsible for much of the non-reproducibility of the experimental data on polymer solution drag reduction reported in the literature. The ability of the solution to reduce drag does not appear to be regained on allowing the solution to stand.

Several of these effects will be illustrated quantitatively by the new experimental data presented in section 4.

Hypotheses to explain drag reduction

Several hypotheses have been proposed to explain the interesting phenomena noted above, together with other related effects observed in external flows, flows of submerged jets, and in heat transfer studies in drag reducing solutions. A number of these hypotheses will be reviewed very briefly below.

The effective wall slip theory.

The original explanation of the Toms effect was given by Oldroyd [19], who postulated that the tube walls might induce a preferred orientation of the polymer molecules close to the wall in such a way that an abnormally mobile laminar sublayer could arise. The existence of such mobile layers is known in the case of non-Newtonian suspensions (e.g. suspensions of paper fibers), but has not been demonstrated definitely in the very dilute solutions being considered here. As a mathematical convenience, the existence of a layer near the wall of properties different to those of the bulk solution can be taken into account by means of an effective velocity of slip of the fluid at the wall, though physically it is likely that there is no slip and a change in the boundary layer thickness instead. However, Kozicki et al, have shown [20] that the effective slip approach is capable of explaining the observed drag reduction effects, but it leaves the reason for the effective slip unclear.

Delayed laminar-turbulent transition theory.

By analogy with the small reductions in drag which occur in dusty gases, Savins [21] suggested that drag reduction in polymer solutions might be a result of a delayed laminar to turbulent transition, implying temporary suppression of the forming turbulence. From the Moody-type plots in Figure 1 it can be seen that a delay in transition to turbulence will have the same effect as a reduction of drag in the usually turbulent zone. As already mentioned, some types of soap solutions seem to support this theory, but most of the dilute polymer solutions do not: they have a distinct change of slope in the measured friction-factor—Reynolds number relationship at the usual transition point or, in larger tubes, drag reduction only commences at relatively large Reynolds numbers.

Anisotropic viscosity theory.

Shin [22] postulated the possibility of anisotropic viscosity effects in flowing polymer solutions. If the randomly coiled polymer molecules in solutions were considerably extended into ellipsoidal shapes near the walls in the high shear rate regions of the flow, these aligned molecules could partially block turbulent eddy exchange with the core region of the flow, where the effect of the molecules might be less due to the lack of a sufficiently large mean velocity gradient to cause elongation. In this way a non-isotropic structure could be set up, with the viscosity being no longer a scalar quantity, but a tensor of fourth rank. However, no direct experimental evidence of this type of viscosity behaviour seems to exist at present for very dilute solutions.

Viscoelastic theory.

If the additive molecules (or possibly aggregates of additive molecules) are assumed to be viscoelastic, they will be able to store kinetic energy given up by the main flow as potential energy of elongation or deformation [23]. If the time scale of a turbulent disturbance (given by the dimension of the disturbance divided by its velocity) is less than the relaxation time of the additive unit (the time for the molecule or aggregate to adjust to changes in velocity of its surroundings), which will occur in the case of large additive units, the disturbance flows around the additive molecule, and energy is dissipated, reducing the kinetic energy of the disturbance and therefore damping the turbulent pulsations. If the time scale of the additive unit is small compared with that of the disturbance, the additive molecules will tend to move with the disturbance, and damping will be small or absent, or confined only to the smallest eddies. This type of mechanism can explain many of the drag reduction phenomena, but it has been shown that to be effective, the dimensions of the molecules of the additive would have to be comparable with those of the eddies in the Kolmogorov microscale to provide significant turbulent damping. Even additives of the highest molecular weights (10^6 - 10^7 for polymer additives) do not possess these dimensions in the randomly coiled state in solution, being about an order of magnitude smaller than required theoretically. It has been postulated that the additive molecules may not be randomly coiled in sheared flows, but greatly elongated to the required dimensions. However, recent measurements [24, 25] indicate that actual elongations are much smaller than required by this hypothesis. It has also been postulated that aggregates or tangled networks of additive molecules are actually the active units in drag reduction, which could then well be of sufficient size to make this mechanism possible. Barenblatt et al. [26] have reported the presence of so-called supermolecular aggregates in quite concentrated solutions of carboxymethyl-cellulose, but up to the present their presence in the very dilute drag-reducing solutions has only been inferred. It may also be of interest to note that we, together with most other investigators, have not been able to detect macroscopic viscoelastic properties in the very dilute polymer solutions showing the Toms effect, though the individual additive molecules may possess elastic properties.

Adsorption theory.

Still another possibility is that the additive molecules adsorb onto the pipe walls and modify the part of the flow nearest the wall. El'perin and coworkers [27 to 30] have suggested that adsorption may lead to hydrophobization and an effective slip phenomenon. Alternatively, it can be imagined that the additive adsorbed on the wall will provide a resilient wall layer or appreciably thickened laminar sublayer, which will also have the effect of reducing frictional drag in turbulent flows. Until recently, only Little [24] had reported adsorption measurements with polymeric drag-reducing additives, but we have obtained new information [14, 31] supporting the adsorption mechanism, which we will describe very briefly below, and it will be shown that the adsorption mechanism is capable of explaining the various polymer drag reduction phenomena described above. Other factors suggesting that interaction of the molecules with the walls is important in the case of polymer drag reduction include the "Persistence Effect" noted by Kowalski [32] during intermittent injec-

tion of polyoxyethylene solutions into boundary layers, and the fact that injection into the wall layers seems to have an immediate effect on drag, while injection into the bulk of a turbulent flow seems to have relatively little effect until the polymer has time to diffuse to the wall zone.

Experimental work

Although much experimental work has been published on drag reduction in turbulent pipe flows using a variety of additives, the results are not always in agreement or easily interpretable, for the reasons mentioned earlier, and we thought it useful to carry out some new friction-factor measurements under carefully controlled conditions; these are summarized here. In addition measurements have been carried out for the first time, as far as we know, of friction factors in turbulent pipe flows of mixtures of polymeric and soap-type additives.

Equipment.

The drag reduction experiments were carried out in a tube flow apparatus consisting of a reservoir into which the solution was drawn gently by applying a small vacuum, connected through a manifold and valves to three polymethylmethacrylate tubes of the following internal diameters:

$$\text{Tube I} \dots\dots\dots 0.324 \text{ cm i.d.}$$
$$\text{Tube II} \dots\dots\dots 0.489 \text{ cm i.d.}$$
$$\text{Tube III} \dots\dots\dots 0.946 \text{ cm i.d.}$$

Only one of the tubes was used at a time. The tubes were fitted with pressure tappings at 10.0 and 40.5 cm from the outlet ends, preceded by an "entry section" of length approximately 110 cm to permit full development of the flow before reaching the 30.5 cm zone over which the pressure drop was measured. The pressure tappings were connected through headers and valves to a battery of U-tube differential manometers (filled with mercury, tetrabromoethane or carbon tetrachloride, with densities submerged in water of 12.55, 1.97 and 0.595 g/cm^3 respectively) by means of which the pressure drop could be measured accurately over a wide range of flow rates. The pressure tappings were carefully polished, and were checked for accuracy by measuring the pressure drops for the flows of pure water and comparing the results with the published friction-factor charts.

Flow rate was measured by collecting the efflux from the tube for a known time and weighing it. The flow rate was adjusted by means of a valve at the outlet of the reservoir, which could be pressurized to 80 psig with compressed air to provide large flow rates. In this way pumping of the liquid, which might have led to shear degradation of the additives, was completely avoided. For the same reason, the solutions were discarded after one passage through the apparatus. The temperature of the flowing solution was measured by a thermometer placed in the outlet of the test pipe.

Solution preparation and properties.

In the case of the polymer additives, a master solution of 0.5 - 1.0% by weight was made up in cold water by adding the polymer powder to the water slowly with gentle

stirring carefully controlled to prevent shear degradation of the additive. Heating of the water was found to lead to thermal degradation and non-reproducible results. This master solution was then diluted as required in a mixing tank to provide test solutions of the required concentrations (5 - 150 parts per million by weight (ppm) in water), and the dilute solution was transferred to the reservoir of the test equipment as described above.

Two polymer additives were used in the tests described below, polyoxyethylene and polyacrylamide. The mean molecular weight of the latter (Separan AP-30, manufactured by the Dow Chemical Company) was approximately 3.0×10^6. Two molecular weight grades of polyoxyethylene (manufactured by the Union Carbide Corporation) were used: Polyox WSR-301, mean molecular weight 5.05×10^6, and Polyox WSR-N3000, mean molecular weight 1.45×10^6 for the batches used. Comparative tests using a number of other polymers and several other molecular weight grades of polyoxyethylene are reported fully elsewhere [14].

The soap solutions used contained a complex soap formed by mixing cetyl trimethylammonium bromide (CTAB) and 1-naphthol in water in equimolal quantities. The solutions were prepared as described by White [18], and were diluted to provide 500 ppm test solutions.

Densities of the dilute test solutions differed insignificantly from those of the solvent (water) at the same temperature. Viscosities of all the solution concentrations used were measured on a Weissenberg Rheogoniometer. Since the polymer solutions used were all dilute in the thermodynamic sense (*), their viscosities differed by no more than a few percent, at most from that of water, as expected. Storage of the dilute test solutions for more than a day or two was avoided to eliminate aging effects. The concentrated master solutions appeared to be relatively unaffected by aging (up to 6 months in the case of polyoxyethylene solutions).

Experimental results.

Sample results of the experiments are shown graphically in Figures 2 to 8 in the form of dimensionless friction-factor versus Reynolds number plots. For comparison purposes, the corresponding curves for the laminar and turbulent flow of pure water in the same tubes are also shown. Note that in all cases of water flow and flow of the dilute polymer solutions, the transition to turbulence was found to occur at the same value of the Reynolds number, Re $\cong$ 4,000 (instead of the more usual value of 2,100 - 2,300), as a result of the very smooth inlet conditions.

Figures 2, 3 and 4 show the results obtained using solutions of Polyox WSR-301 of concentrations 5 to 25 ppm in the tubes I, II and III, respectively. The effects of polymer concentration and pipe diameter can be clearly

seen by comparing these figures, as can the phenomenon of onset point shift which was mentioned earlier.

To illustrate the effect of polymer molecular weight, Figure 5 shows the drag reduction obtained with solutions of Polyox WSR-N3000, of molecular weight about one-third that of the WSR-301 grade. Comparison of Figures 2 and 5 shows a decidedly lower drag-reducing efficiency for the lower molecular weight grade, together with a shift of the onset point to higher Reynolds numbers as the molecular weight decreases.

Figure 6, for Separan AP-30 at concentrations of 5 - 150 ppm in Tube I, shows that the drag reduction at a given weight concentration is smaller than in the case of the Polyox. A few data points are given for the most dilute polyacrylamide solution on being passed through the flow loop for a second time, in order to indicate the degree of degradation and loss of drag-reducing ability on even such relatively mild shearing. Subsequent passages through the equipment led to smaller and smaller degrees of loss in the drag reduction.

It may be noted that the maximum drag reduction achieved in Figures 2, 3, 5 and 6 is identical, though different concentrations are required to bring this about with the different polymers. (The maximum was not reached in Figure 4). The effect of increasing the concentration of additive above the optimum can also be seen in Figure 6, where the solution of concentration 150 ppm is seen to produce less drag reduction than the 40 or 60 ppm solutions.

Figures 7 and 8 illustrate the effects of the CTAB soap at 500 ppm, showing the characteristic sharp loss of drag reduction above the critical shear stress, which in Tube II corresponded to a Reynolds number in the region of 10,000. In Figure 7 the results are plotted in terms of a Reynolds number formed from the solvent (water) viscosity, explaining the apparent shift in the laminar region. When the same results are replotted in terms of the Reynolds number formed from the actual measured non-Newtonian viscosity for the soap solution [33] (Fig. 8), it is seen that in the case of the soap solution the drag reduction takes the form of a direct extension of the line for the laminar region, $f = 16/\text{Re}$. Also shown in Figures 7 and 8 are the results for the 10 ppm Polyox WSR-301 solution taken from Figure 3, and the measured results obtained for a solution containing a mixture of 10 ppm Polyox WSR-301 and 500 ppm of CTAB soap. In the case of the mixture, it can be seen that the drag reduction starts in the usual way for the soap solution alone, since at the lower Reynolds numbers this is the predominant effect, then on breakdown of the soap effect, the usual Toms effect of the polymer solution makes itself felt. As far as we know, this is the first time that such mixtures have been investigated, and the results are of interest in that they show that the drag reduction effect from the polymer additives can be extended to cover the entire low Reynolds number region of turbulent flow (where the polymer additives may not be effective) by making use of the soap effect to complement the Toms effect.

In addition to numerous flow and pressure drop experiments of the type reported above, several other types of experiments were carried out to investigate the nature of the additive adsorption effect on the pipe walls. These are reported elsewhere in detail [14], but may be summarized very briefly as:

a) Dilute polyoxyethylene solutions were passed through beds of glass wool and metal powders; effluent samples were collected at different times, and the polymer concen-


(*) The upper concentration limit of a thermodynamically dilute polymer solution may be defined as the concentration at which the polymer molecules suspended in the solvent in their random-coil state just begin to touch each other. In polymer solutions which are dilute in this sense Newtonian flow behaviour is expected, with Newtonian viscosities differing from that of the solvent by less than about 20 %. Strictly speaking, the Toms Phenomenon refers to drag reduction by such dilute solutions only, without additional effects due to non-Newtonian behaviour. (As indicated by Skelland [33], for instance, a type of drag reduction can also occur due to pseudoplastic (shear-thinning) flow behaviour). All the polymer solutions used in the tests were dilute in the sense described here. The soap solution at 500 ppm was very slightly non-Newtonian.
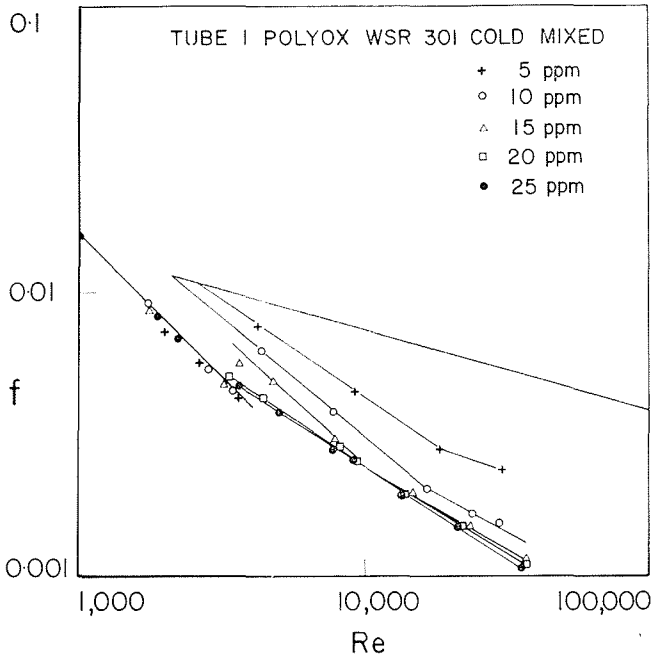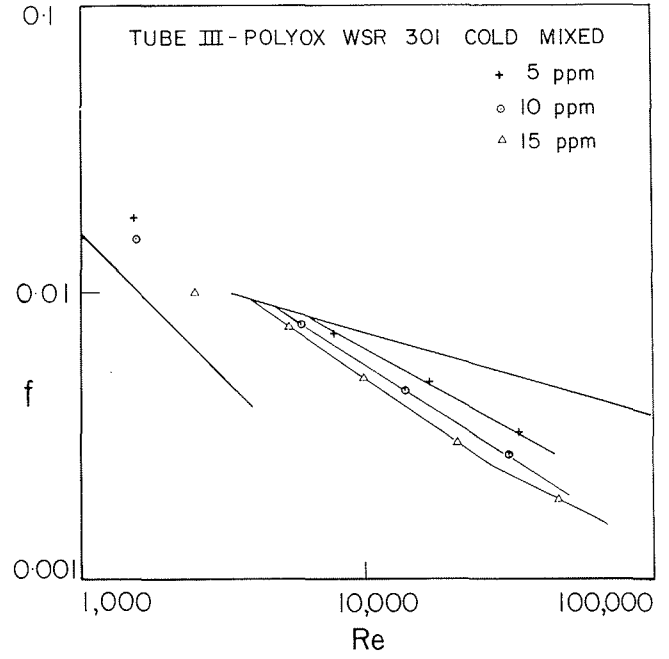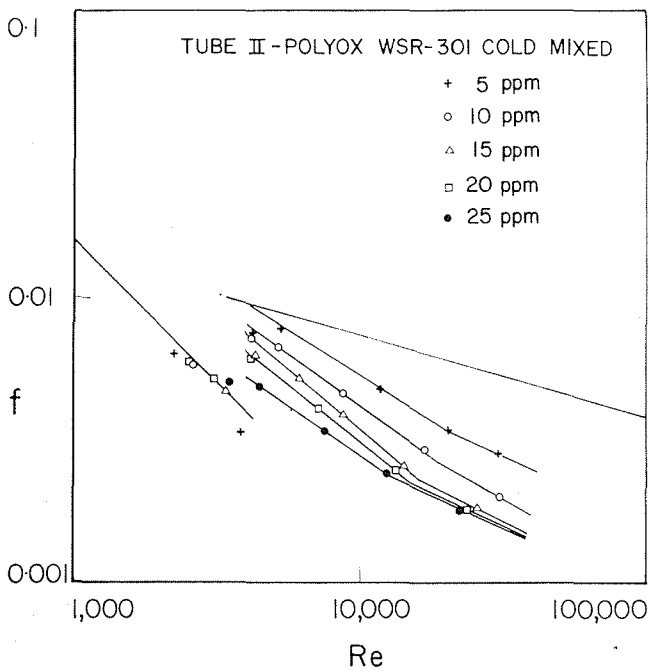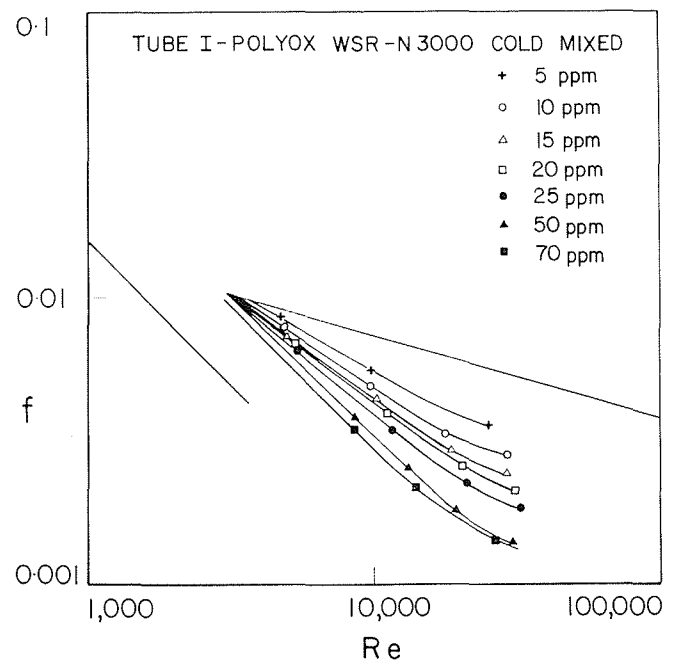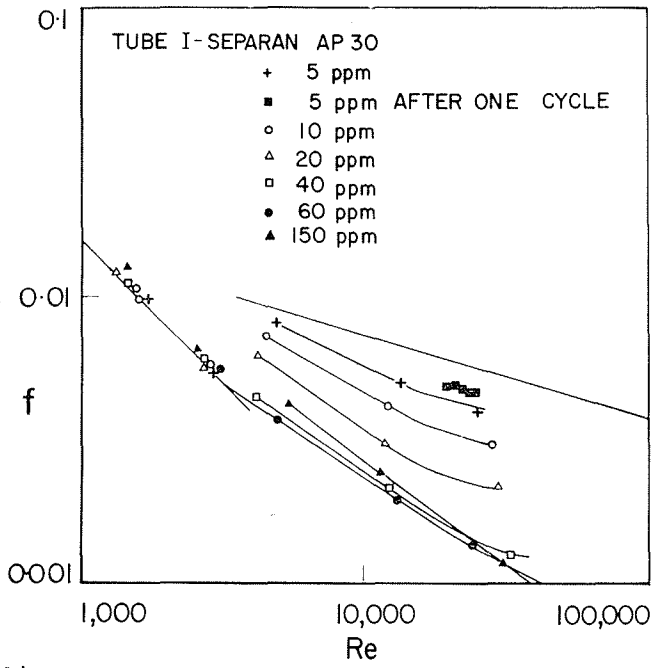
2/ Experimental friction factor data for Polyox WSR-301 solutions at various concentrations in tube of diameter 0.324 cm.
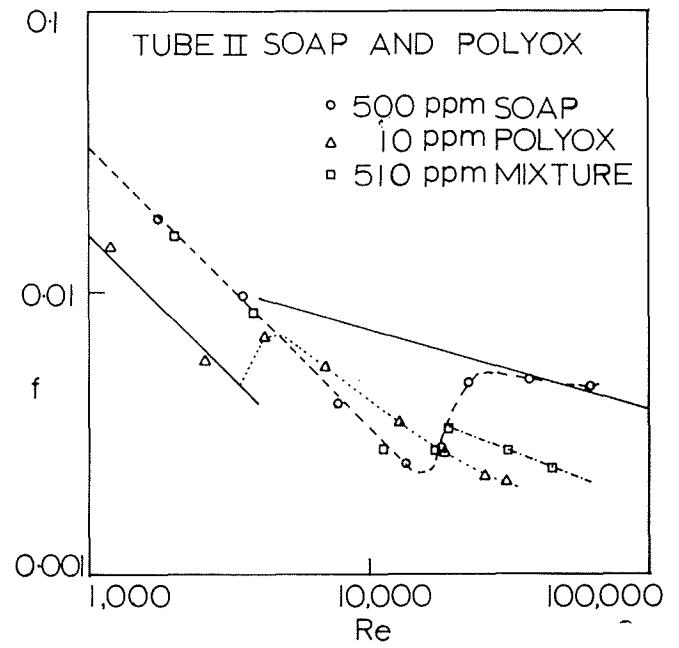
3/ Experimental friction factor data for Polyox WSR-301 solutions at various concentrations in tube of diameter 0.489 cm.

4/ Experimental friction factor data for Polyox WSR-301 solutions at various concentrations in tube of diameter 0.946 cm. In this case laminar zone data are unreliable due to the very small pressure drops to be measured.
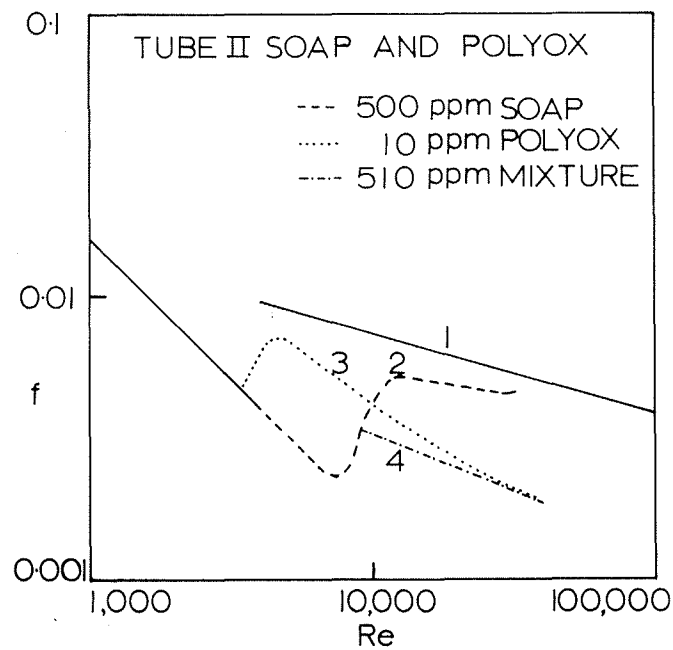
5/ Experimental friction factor data for Polyox WSR-3000 ("low" molecular weight) at various concentrations in tube of diameter 0.324 cm.

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7/

8/

6/ Experimental friction factor data for Separan AP-30 at various concentrations in tube of diameter 0.324 cm. Note decrease in magnitude of drag reduction above 60 ppm concentration.

7/ Experimental friction factor data for 10 ppm Polyox WSR-301 solution, 500 ppm CTAB soap solution and a mixture of both solutions in tube of diameter 0.489 cm.

8/ Data of Fig. 7 re-plotted in terms of Reynolds number taking into account increased viscosity of soap solution over than of water. Curves 1, 2, 3, 4 represent best lines for water alone, CTAB soap solution (500 ppm), Polyox WSR-301 solution (10 ppm), and mixture of 500 ppm soap + 10 ppm Polyox, respectively.

trations were measured by a method accurate to a few ppm. Break-through curves typical of physical adsorption were obtained;

b) During turbulent flow of dilute polyoxyethylene solutions in a 1-inch diameter pipe, samples were taken from the centre of the pipe and very slowly through a wall tapping. Significantly higher concentrations of the polymer were found in the wall samples, in spite of the high degree of turbulent mixing in the main flow;

c) Taylor axial dispersion measurements were carried out in flows of polyoxyethylene solutions (2 - 30 ppm) at Reynolds numbers of 20,000 - 60,000 in a 1-inch diameter pipe, using dilute solutions of common salt (NaCl) as a tracer material. Remarkable increases in the "tailing" of the NaCl tracer residence time curves were obtained with as little as 2 ppm of additive, while the behaviour was entirely normal without the additive. This effect can be suitably interpreted in terms of a slowly moving or adsorbed layer at the pipe wall [14, 31];

d) Analogous tracer dispersion experiments were made in a main flow of pure water using NaCl solution and polyoxyethylene solution as the tracer materials. A normal response was obtained for the NaCl, while the response for the polyoxyethylene was extremely slow and drawn-out, indicating that this material was retarded in its travel along the pipe, probably by an adsorption (followed by slow desorption) at the wall.

Discussion

The results of the additional experiments mentioned above led us to support an adsoption mechanism for explaining the major part of the Toms effect. The specific form of the mechanism is based on the postulation of dynamic adsorption of polymer molecules on the pipe wall. Data published in the literature [34 to 39] suggest that in such cases the molecules are liable to adsorb onto the walls at selected sites along the polymer chains, leaving loops of considerable length hanging loose from the wall; as the bulk concentration in solution becomes greater and the wall tends to become saturated with adsorbed material, these loops tend to protrude farther into the solution. This gives rise, we assume, to a layer at the wall in which the liquid will be greatly retarded by the mass of protruding polymer loops. This will cause a modification of the usual boundary layer in which the average gradient of the mean velocity close to the wall is reduced, and the turbulent drag is thereby decreased. From an evaluation of our tracer response data mentioned above [31] it appears that the effective thickness of this modified layer increases with increasing polymer concentration, and decreases as the Reynolds number of the flow increases; in general, it appears to extend to a distance from the wall corresponding to $y^+ \cong 10$, where y^+ denotes the usual dimensionless distance from the wall. In addition to the effect from the direct thickening of the boundary layer, such an adsorbed layer might be expected to interfere with the usual turbulence generation processes at the edge of the usual viscous sublayer, but it appears that in the case of Toms fluids in pipe flow the greatest part, if not all, of the drag reduction effect can be explained by the sublayer thickening mechanism. Although direct measurements of velocity profiles in drag-reducing fluids are accompanied by a variety of difficulties, measured velocity profiles, for instance by Elata et al. [40], support this view.

The adsorption mechanism also seems to be supported by experiments reported by Barenblatt et al. [41] in which solutions of polyoxyethylene were recirculated in a turbulent jet. Initially there was appreciable drag reduction, which must have been due to a turbulence damping or blocking type of mechanism, since there are no solid surfaces in this case at which adsorption could occur. The drag reduction effect was lost after recirculating the fluid for some time; this was explained as being due to breakdown of the "supermolecular" aggregates of sufficient size to interact with the eddies in the Kolmogorov microscale range. However, on being used for a pipe flow, this "degraded" solution again showed a considerable degree of drag reduction (which then fell off slowly with further recirculation), indicating that some second mechanism, which we feel is probably the wall-adsorption sublayer thickening mechanism, was playing the major part in pipe flow.

The various effects noted experimentally above can be explained qualitatively in terms of such an adsorption mechanism. (Quantitative explanations would require some independent way of predicting the average length of the adsorbed polymer loops under given concentration and shear stress conditions, which does not appear to be available at present.)

The effect of polymer concentration on drag reduction can be explained by an increase in the degree of dynamic adsorption as the bulk concentration increases. This will lead to a gradual filling of the sites on the wall available for adsorption, and hence to a more continuous polymer layer on the wall and a greater extension on the average of the unadsorbed polymer loops into the liquid, giving a greater thickness of the modified wall layer and a greater drag reduction. Eventually all the available sites will be occupied, and once this state is reached negligible further reduction of drag will be possible regardless of the bulk concentration, as indicated by the presence of an optimum concentration in the experiments. On the other hand, if turbulence blocking or interaction of polymer aggregates with eddies were the major mechanism, one would expect that the drag reduction effect would continue to increase monotonically with the additive concentration. The apparent decrease in drag reduction after exceeding the optimum concentration is readily explained as being due to the gradual increase of the solutions at the higher concentrations (usually outside the Toms range).

Similarly, the effect of different polymer types may be explained as being due to different equilibria between polymer in bulk solution and adsorbed polymer at the wall. The same degree of adsorptional covering of the wall may be achieved only at different bulk concentrations for different polymer types, explaining the differences in the "optimum" concentrations of different types of additive noted in the experiments. Since a method for accurately determining the concentrations of polymer in the very dilute solutions involved was available only for polyoxyethylene it was unfortunately not possible to check this point by direct experiment.

The effect of polymer molecular weight can be postulated as being due to the different lengths of free-hanging loops involved; there is some evidence that in theory the loop length may be proportional to molecular weight [35 to 38].

The diameter effect and the onset point shift effect can be considered together. In the case of ordinary turbulent flow in a rough pipe it is well known that when the roughness elements are so small that they remain within

the viscous sublayer of the flow there is little effect of roughness on the pressure drop, and the pipe is said to be hydraulically smooth. In the same way, it is possible that when the effective thickness of the adsorbed layer of additive at the wall is small (or when the thickness of the viscous sublayer is large) the effect of the adsorbed layer will be negligible. If $y^+ = 10$ (or some other similar numerical value) is considered to represent in dimensionless terms the "edge" of the viscous sublayer or layer in which most of the velocity change from the wall occurs normally, and it is remembered thay y^+ may be defined in terms of the actual distance y from the wall and the friction factor f, the pipe diameter D and the Reynolds number Re by:

$$y^+ = (y/D) (f/2)^{1/2} Re$$

(where f may also be some function of Re at moderate Reynolds numbers), it can be seen that as the pipe diameter D increases, the value of y (the actual thickness of the "viscous sublayer" in mm) corresponding to the selected value of y^+ will increase. In other words, to maintain similarity of the velocity profiles at a given Re, the actual thickness of the viscous sublayer must increase with increase of pipe diameter. Thus, if we have a given effective thickness of the adsorbed wall layer, its effect must be expected to become less marked as the diameter increases, as in fact observed.

On the other hand, if we consider a pipe of fixed diameter D, it can be seen that as the thickness of the adsorbed layer increases, due to increase in polymer concentration or molecular weight, the thickness of the adsorbed layer needed to exceed the selected critical value of y^+ will be reached at smaller Reynolds numbers. Alternatively, this thickness will be reached at larger diameter D for a constant Reynolds number, explaining the shifts observed in the onset points as the Reynolds number and pipe diameter are changed.

The CTAB soap results obviously differ considerably from those for the polymer solutions, as already noted by other workers, e.g. White [42]. In the first place, the results suggest an extension of laminar flow, or efficient damping or suppression of eddies in the low turbulent Reynolds number range, followed by loss of the drag reduction effect at a critical value of the wall shear stress. The micellar model for drag reduction by such soap solutions proposed by Savins [17] or Radin et al. [43] provides an attractive explanation of the drag reduction, rather than the adsorption model which appears to explain the various phenomena of the Toms effect.

It is known that above a certain small critical concentration, many soaps in solution form micelles, which are agglomerates of up to many hundred soap residues surrounded by their counter-ions [44]. It has also been indicated that such micelles may further combine into larger structures in gentle turbulent flows [45], providing units of sufficient size to interact with the eddy structure in the microscale. Reversible scission of such structures may occur above a certain shear stress, explaining the sudden loss of drag reduction above a certain critical shear stress for each soap type, and also its re-occurrence once the disruptive stresses are removed (the structures are thought to reform readily). The complete failure of drag reduction to recur when degraded polymer solutions are stored and subsequently re-used (irreversible loss of drag-reducing ability) seems to be an argument against the corresponding "supermolecular aggregate" explanation of the Toms effect. Even if the soap molecules adsorbed onto the pipe walls,

they are relatively so small (molecular weights of only a few hundred) that they could not be expected to produce a significant degree of drag reduction by the sublayer thickening mechanism.

The completely complementary nature of the soap effect and the Toms effect shown by the experiments using the mixed soap and polymer solutions also seems to argue in favour of there being quite distinct mechanisms for the two effects.

It therefores seems that drag reduction may occur in turbulent pipe flows by at least two different mechanisms. In the case of the Toms effect, we have proposed a form of adsorption mechanism which seems to be well supported by experimental data for polyoxythylene. Although more detailed experimental results which will undoubtedly become available in this interesting field may ultimately make this simple mechanism untenable, it is of interest at present since it appears to be capable of providing on a rational basis at least a qualitative explanation of the behaviour of several different polymer additives and the various effects which are observed experimentally in their presence.

Notation

$$D : \text{pipe diameter;}$$
$$f = \tau_w/(\rho V^2/2) : \text{friction factor;}$$
$$Re = VD\rho/\mu : \text{Reynolds number for pipe flow;}$$
$$V : \text{mean velocity in pipe;}$$
$$y : \text{actual distance from pipe wall;}$$
$$y^+ = (y/D)(f/2)^{1/2} Re : \text{dimensionless distance from wall;}$$
$$\mu : \text{dynamic viscosity of fluid;}$$
$$\rho : \text{density of fluid;}$$
$$\tau_w : \text{wall shear stress.}$$

Acknowledgments

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