

A Study of Drag Reduction and Adsorption of Polymer Solutions

P. PEYSER, R. C. LITTLE, AND C. R. SINGLETERRY

*Surface Chemistry Branch
Chemistry Division*

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ABSTRACT

A study was made of the adsorption from aqueous solution of polyethylene oxide (Polyox) and polyacrylamide onto Pyrex, silica, and stainless-steel surfaces. This investigation was undertaken to determine if a correlation exists between the structure of adsorbed polymer films at solid/liquid interfaces and the observed ability of such polymers to reduce the drag in liquid flow systems. In this study the amount of polymer adsorbed by high-surface-area adsorbents was determined by measuring the difference in polymer concentration before and after adsorption. The thickness of adsorbed polymer films on clean, flat surfaces was determined by ellipsometry. It was concluded that Polyox and polyacrylamide molecules adsorbed in thin films, lying relatively flat at the interface with no large loops projecting into the solution.

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A STUDY OF DRAG REDUCTION AND ADSORPTION OF POLYMER SOLUTIONS

INTRODUCTION

The drag in a liquid flow system is substantially reduced by the addition of only a few parts per million of certain flexible polymers of very high molecular weight (1). The mechanism by which such small concentrations of polymer effectively reduce drag is as yet poorly understood. It is generally thought that turbulence begins at the solid/liquid interface of a flow system (2) and that the drag-reducing polymer affects turbulence mainly in the wall region (3). It has also been found that high-molecular-weight polymers absorb from solution onto solid surfaces in large concentrations often with long loops penetrating into solution (4). The absorption of the drag-reducing polymers polyethylene oxide (Polyox) and polyacrylamide (PA) from aqueous solution was therefore studied to test for possible correlations between drag reduction and polymer conformation at the solid/liquid interface. The study involved adsorption measurements using high-surface-area adsorbents and film thickness measurements on plane surfaces by ellipsometry. In addition, the drag reduction of aqueous Polyox solutions was measured with a rotating disk apparatus. The material of the disk and the preconditioning of the disk were varied to see if surface effects could be detected.

EXPERIMENTAL MATERIALS AND TECHNIQUE

The essential characteristics of the high-surface-area adsorbents used are tabulated in Table 1. The stainless-steel slides used for ellipsometry were cleaned by polishing on a rotating Gamal cloth wheel with alumina powder (Linde B, 0.05 micron) until all its surfaces were wetted by distilled water. They were then immediately placed under solvent. The quartz slides were cleaned by heating in a muffle oven at 500°C overnight. They were then cooled to approximately 200°C and immersed under solvent. The solvents were distilled water and spectral grade cyclohexane. The polymers Polyox (mol wt 7×10^6) and PA (mol wt $5-6 \times 10^6$) were obtained from Union Carbide and American Cyanamide Co., respectively, and were used as received. The molecular weight of the Polyox sample was checked by intrinsic viscosity and ultracentrifugation (ultracentrifugation kindly performed by S. Kaufman) and was found to agree with the manufacturer's value.

Adsorption measurements on the powders were carried out by gently shaking the high-surface-area adsorbent with an appropriate aqueous solution of polymer and then removing the adsorbent by centrifugation. The solution polymer concentration after adsorption was determined from either uv adsorption or viscosity. The weight of polymer adsorbed per gram of adsorbent was calculated from the change in polymer concentration in the solution phase.

An ellipsometric technique was used to measure the thickness and refractive index of the adsorbed polymer film (5). The ellipsometer was an O.C. Rudolph and Sons model 43702 designed for measurements on horizontal surfaces. Consider, first of all, a clean substrate. An ellipsometer measures the change in the ratio of the two reflection coefficients ψ and the phase change Δ of light which occurs upon reflection from the substrate

Table I
Some Characteristics of Adsorbents Studied

Type	BET Surface Area (m ² /g)	Average Diameter (μ)	Cleaning Procedure
Cabosil (silica)	150-200*	0.015	Muffle oven > 500°C
Pyrex	≈ 2	< 44†	Muffle oven at 500°C
Fractionated Pyrex‡	≈ 0.90§	< 44†	Muffle oven at 500°C
Stainless steel	> 0.018§	< 44†	Soxhleted 2 days with acetone. Vacuum dried at 50°C

* Manufacturer's specifications.

† 325 mesh.

‡ smaller particles removed by settling in water.

§ BET kindly performed by Dr. V.R. Deitz.

(Fig. 1). The quarter-wave plate is normally set at either ± 45 degrees and the polarizer is then related to Δ and the analyzer to ψ . The cell used is shown in Fig. 2* The cell was first filled with solvent; ψ and Δ were again measured. If the range of the refractive indexes of the adsorbed polymer film was specified (the specification must be small enough so that only one solution exists to the Drude equations of ellipsometry), the change of ψ and Δ which occurred due to polymer adsorption could be related to the polymer film thickness and its refractive index. The product of the film thickness and the concentration (from the refractive index) yields the adsorbance. A computer program (6) was used to perform the complex ellipsometric calculations.

These calculations were based on a model of a homogeneous adsorbed film. In reality the adsorbed film is not expected to be uniform. Probably its concentration will decrease as we move away from the adsorbing surface. This problem was treated by McCrackin and Colson (7). They found that the thickness calculated from an ellipsometric measurement was related to a root mean square (RMS) average thickness of the adsorbed polymer

*This cell offered several advantages over previously used cells:

(1). It was constructed of all glass and hence could be cleaned in an acid bath or a muffle oven.

(2). Essentially no extra birefringence was added to the cell windows by fitting the windows onto the cell. Birefringence of the cell windows is a serious problem in accurate ellipsometric work. The problem, at this time, cannot be eliminated and the best one can do is to find a spot on the cell window through which the measured birefringence is low. A saving grace in polymer adsorption measurements is that, to a first approximation, only a difference in ellipsometer readings is significant. It would be expected, however, that a window under pressure would not possess a birefringence stable with time. For example, a slight change in temperature would affect the birefringence. It is felt that the cell constructed tended to minimize such changes. Indeed, ellipsometric measurements through the cell were found to be unchanging for a period of at least 4 days.

(3). The angle of incidence could be continuously varied from less than 60 degrees to close to 90 degrees.

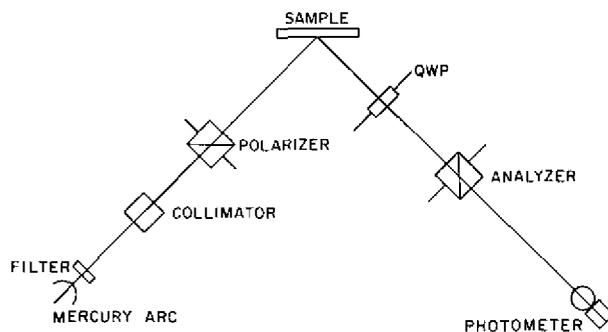


Fig. 1 - Schematic representation of ellipsometer

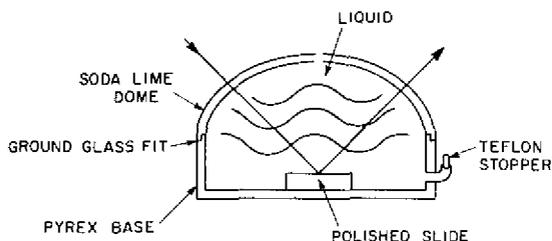


Fig. 2 - Ellipsometer cell

with a linear, exponential, or Gaussian distribution of polymer concentration away from the adsorbing surface by a factor of 1.75, 1.465, and ≈ 1.65 , respectively. An exponential distribution, at this time, is considered to be the most likely distribution of an adsorbed polymer film. We therefore list our polymer thickness as a RMS thickness which is the thickness based on a homogeneous model divided by 1.5.

The adsorption of polystyrene from cyclohexane onto quartz was used to test and compare our ellipsometric system with that of Ref. 8 in which polystyrene was adsorbed on metal surfaces. The many different metallic surfaces reported in Ref. 5 gave essentially the same ellipsometric results; the RMS thickness of polystyrene varied only from 420 to 930 Å. It might be expected that all the metal substrates presented a hydrated oxide surface to the adsorbing polymer. It should be noted that previous measurements of polystyrene film thickness on quartz by ATR in the uv gave thicknesses quite comparable to those measured by ellipsometry on metallic surfaces (9). As seen from Table 5c, our results for 132 minutes and 24 hours agree with those of Stromberg et al. (especially considering that a metallic substrate was used in Ref. 8 instead of quartz.) This is the first known measurement of polymer adsorption onto a glass surface using ellipsometric techniques. The measurement was made possible by a newly constructed, high-sensitivity null detector originally designed by H. P. Layer at the National Bureau of Standards. The results of 52 and 102 minutes are larger than reported earlier, but in view of the thinness of the film, the results lie within the experimental error. The 12-minute result is for a condition far from equilibrium, so that close agreement with other measurements cannot be expected.

The rotating disk apparatus made use of a Cole-Parmer constant speed control unit (model 4420) to rotate a disk at constant speeds from 0 to 3000 rpm. The output of the apparatus, in mV, was proportional to the torque (2.5 mV/in.-oz). A precision stainless-steel shaft with a 1/4 in. diameter and a 10-in. length connected the disk to the chuck of the controller. The disks were 4 in. in diameter and 0.187 in. thick; they were made of

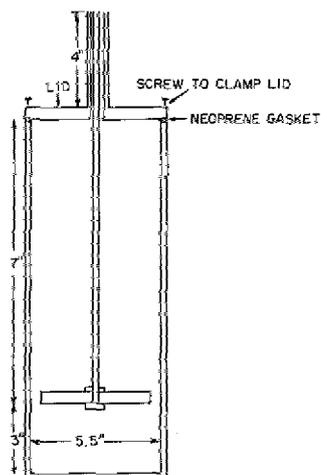


Fig. 3 - Rotating disk apparatus

various materials--stainless steel, Pyrex, nylon, and Teflon-coated stainless steel. The disk and shaft were placed in a Lucite container, shown in Fig. 3, and the entire container was placed in a temperature-controlled water bath. A small difference in mV output for rotation in water was found between the disks which was attributed to slight differences in surface roughness. Drag reduction at a given rpm was detected and measured by comparing the mV output of an aqueous solution of Polyox to that of water alone. Maximum drag reduction was obtained at a concentration of less than 20 ppm Polyox with no increased drag reduction occurring at higher concentrations. At concentrations of 20 to 50 ppm and 25°C a decrease of 39% was measured for the mV output of the apparatus for Polyox solution as compared to water.

RESULTS

Adsorption Studies on Powders

Except for the PA/Cabosil system under acidic conditions, uv analysis of the supernatant was either unsuccessful or of limited success due to dispersion of the powdered adsorbent by the adsorbed polymer even after prolonged centrifugation (Table 2). Meaningful uv data were obtained only for the PA/Cabosil system and are tabulated in Table 3. Concentration analysis of the supernatant by viscosity measurements was not sensitive to the small amounts of adsorbent remaining after centrifugation but was highly sensitive to the molecular weight of the polymer. The relative concentration of the high-molecular-weight polymer in the initially heterogeneous polymeric dispersion may have changed during the adsorption process, due to preferential adsorption and any subsequent shear degradation of the polymer molecules. Both polymers are very sensitive to shear degradation, which tends to make concentration analysis of the supernatant solutions by viscosity very unreliable.

Adsorption of PA from aqueous solution (pH 2.4) onto Cabosil was observed to decrease with increased solution agitation. As the solution "shaking" time increased from 25 to 1133 minutes, the adsorbance decreased from 60 mg/g to approximately 40 mg/g. The decreased adsorbance that occurred with long periods of shaking may be due to mechanical degradation of the polymer. Kuzkin et al. (10) reported a large molecular-weight dependence for the adsorption of PA onto quartz, the higher-molecular-weight fraction adsorbing to a greater extent. A decrease of approximately 10% in viscosity was observed with each pass of an aqueous PA solution, 3.14 mg/ml, through a Ubbelohde viscometer (the maximum shear rate at the wall was 1800 sec⁻¹). In view of these observations, the main cause

Table 2
Maximum Adsorption* of Polymers on Cabosil, Pyrex, and
Stainless-Steel Powders from Aqueous Solution

Polymer	pH	Adsorbent	Adsorbance	
			mg/g	mg/m ²
Polyox (mol wt = 7×10^6)	≈5	Fractionated Pyrex	≤0.9	≤1.0
Polyacrylamide (mol wt = $5-6 \times 10^6$)	2.4 (HCl)	Cabosil	≈60 (see Table 3)	≈0.4
Polyacrylamide	≈5	Fractionated Pyrex	≤0.02	≤0.02
Polyacrylamide	≈2 (HCl)	Fractionated Pyrex	No detectable adsorption	
Polyacrylamide	≈5	Stainless steel	0.017-0.08	—

*As determined from uv adsorption of supernatant.

of the poor reproducibility of the adsorption measurements (Table 3) is probably the variation in the degree of shearing that occurs in preparing the polymer solutions. It would be most difficult to fractionate Polyox or PA without subjecting the polymer molecules to some shearing stress. Moreover, it is seen in Fig. 4 that a lower ratio of adsorbent concentration to polymer concentration gave higher adsorbance values. This effect is most probably due to the broad distribution of polymer molecular weight in the PA. If one fraction of the polymer adsorbed on Cabosil preferentially, it would be expected that at lower ratios of Cabosil to polymer concentration a larger percentage of this species would be adsorbed. The more strongly adsorbing species may be a higher-molecular-weight fraction or a more oxidized fraction of PA. This effect will be referred to as the "adsorbent concentration effect."

In Table 4, there is an apparent decrease in adsorbance with increasing ratio of Cabosil to polymer concentration, when the Polyox adsorption from aqueous solution onto Cabosil was estimated from viscosity changes. The "adsorbent concentration effect" previously postulated for PA adsorption is probably not significant for Polyox adsorption since Howard and McConnell (12) found a very small molecular-weight dependence for Polyox adsorbed onto Cabosil from water. They postulate, and our results confirm, that Polyox adsorbs in a flat fashion onto silica. While no difference in adsorbance exists for different molecular weights of the polymer, it is most probable that the higher-molecular-weight species is preferentially adsorbed (13). Hence, unlike PA, it is believed that the apparent decrease in adsorption of Polyox with increasing ratio of Cabosil to Polyox was due primarily to the *preferential* adsorption of the higher-molecular-weight species and to the sensitivity of solution viscosity to Polyox molecular weight. Similarly any shearing of the polymer during the adsorption experiment would lead to an apparent increase in the adsorbance as determined by the viscosity of the supernatant solution. No suitable quantitative method for determination of the fraction adsorbed is known which is not sensitive to the molecular weight of the polymer and which is not interfered with by small amounts of adsorbent not removed from solution.

Table 3
Adsorption of High-Molecular-Weight PA
onto Cabosil from Aqueous Solution (pH 2.4)

Original Polymer Concentration (mg/100 ml)	Final Polymer Concentration* (mg/100 ml)	Concentration of Cabosil (g/100 ml)	Ratio of Concentration of Cabosil to PA in Original Concentration	Adsorbance (mg/g)
260.9	232.7	0.32	1.23	89.5
246.5	203.0	0.72	2.92	60.4
260.9	195.0	0.91	3.49	72.1
246.5	186.2	1.00	4.06	60.9
260.9	186.0	1.28	4.91	58.4
237.4	178.8	0.97	4.09	60.5
246.5	169.0	1.40	5.68	55.5
246.5	164.6	1.42	5.76	57.6
246.5	162.0	1.54	6.25	54.9
260.9	146.9	1.87	7.17	60.9
198.3	136.8	0.97	4.89	63.2
246.5	136.4	2.38	9.66	46.3
209.1	132.2	1.46	6.98	52.4
178.3	128.9	0.79	4.43	62.8
159.4	114.4	0.98	6.15	46.1
246.5	110.5	2.98	12.11	45.6
246.5	96.2	2.65	10.75	36.3
140.9	89.8	0.96	6.81	53.1
132.7	86.8	1.07	8.06	42.8
103.8	77.3	0.37	3.56	71.5
160.0	66.8	1.82	11.38	51.1
83.8	33.7	1.00	11.94	50.3
111.9†	25.9	2.57	22.96	33.4
68.8	22.7	1.39	20.21	33.2

* Final concentration measured by uv absorption of supernatant.

† Original concentration was from a mixture of previous adsorption runs.

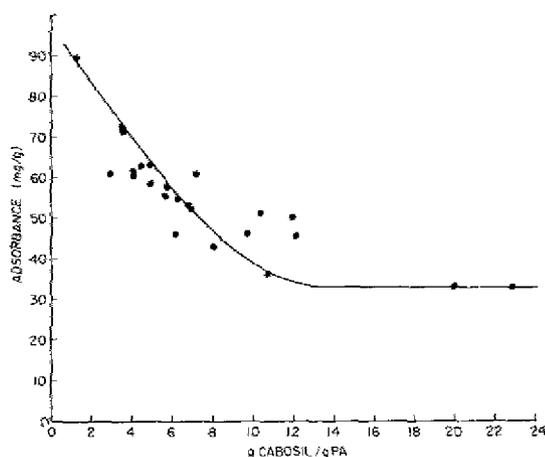


Fig. 4 - Adsorption of polyacrylamide onto Cabosil at pH 2.4 as a function of the ratio of Cabosil concentration to that of polymer in original concentration

Table 4
 Adsorption of High-Molecular-Weight Polyox
 onto Cabosil at 37°C from Aqueous Solution by
 Viscosity Measurements

Original Polymer Concentration (mg/100 ml)	Final Concentration (mg/100 ml)	Concentration of Cabosil (g/100 ml)	Ratio of Concentration of Cabosil to Polyox in Original Concentration	Adsorbance (mg/g)
122.5	87.1	0.229	1.87	154.4
122.5	93.1	0.977	7.98	30.1
122.5	85.7	5.232	42.70	7.27
91.4	64.5	1.165	12.75	23.12
44.4*	40.0	0.024†	5.41	185.4

*From Ref. 6 and personal communication.

†Based on a BET value of 0.089 m²/g for the soda lime adsorbant used in Ref. 11 and a BET value of 150 m²/g for Cabosil. The value given is then the assumed adsorption that would occur with Cabosil based on the adsorption that occurred with 30- μ soda lime glass beads.

Ellipsometric Studies (Table 5)

PA/Water/Stainless-Steel Systems—Convincing results were obtained for the PA/water/stainless-steel system as the reflectance of the surface was high and the adsorbed film was reasonably thick. As expected, the thickness of the film increased with time (8). As compared with the polystyrene system, however, the RMS thickness of approximately 700 Å was much less than expected (\approx 1500 Å) for a polymer with a molecular weight of 45 million. The adsorbance was also low.

PA/Water-pH 2.4/Quartz System—No significant change occurred in the ellipsometer readings of the PA/water/quartz system upon exchange with polymer solution until 12 hours and even then the RMS thickness was less than 100 Å.

Polyox/Water/Quartz System (0.4 and 1.3 mg/ml)—No ellipsometric change was found for a duration of 4 days in the Polyox/water/quartz system. Hence, assuming Polyox adsorbs, it does so either in a very flat configuration (<50 Å for an adsorbance of \approx 1 mg/m²) or the adsorbance is very low (<1 mg/m² for a 50 Å film) or both. This experiment also demonstrates that the changes that occurred in other systems are not due to an alteration of the ellipsometer cell during polymer exchange.

Rotating Disk Studies—Before use, the stainless-steel and glass disks were cleaned in a hot nitric-sulfuric acid solution and the Teflon and nylon disks were washed with detergent solution. All the disks used gave essentially the same drag reduction irrespective of the material of construction. The slight differences in drag reduction that existed between the disks were comparable to the differences that were found between the disks in water alone. Also, no differences in torque output were detected for the rotating 4-in. Pyrex disk when the following variations were tried:

1. The disk was not cleaned before being used,
2. The disk was cleaned in a hot nitric-sulfuric acid solution, rinsed well, and then placed in the polymer solution,

Table 5
 Characteristics of Adsorbed Films from
 Ellipsometric Measurements

Film Concentration (mg/ml)	RMS* Thickness (Å)	Adsorbance (mg/m ²)	Time (minutes)
(a) Polyacrylamide, 0.604 mg/ml of H ₂ O, adsorbed onto a polished stainless-steel slide			
17.0	522.9	1.3	25
16.8	393.2	1.0	
13.3	619.9	1.2	75
15.2	687.3	1.6	
15.7	628.0	1.5	105
17.4	684.9	1.8	
14.3	767.1	1.7	138
16.4	736.2	1.8	
16.4	754.3	1.9	215
18.6	734.2	1.8	
20.2	768.5	2.3	Overnight
17.6	744.3	2.0	
(b) Polyacrylamide, 1.076 mg/ml H ₂ O (pH 2.4), adsorbed onto quartz			
144.6	81.3	1.8	Overnight
150.1	78.9	1.8	
(c) Polystyrene (mol wt - 230,000), 0.255 mg/ml cyclohexane, adsorbed onto quartz			
45.0	255.1	1.7	12
26.5	445.7	1.8	
621.7	158.9	15.4	52
670.1	135.6	8.2	
465.5	116.7	8.2	102
480.4	112.3	9.4	
272.0	138.3	5.6	132
264.6	133.5	5.3	
130.7	287.1	5.6	Overnight
102.7	351.6	5.4	

Note: Data is given in pairs representing the 95% confidence limits of the computer solutions of the Drude equations.

*RMS thickness = Ellipsometer thickness / 1.5.

3. The clean disk was allowed to stand in the polymer solution a few hours before rotation, and

4. The clean disk was rotated immediately upon being placed into the polymer solution. (It requires about 2 minutes after immersion before the disk can be rotated.)

Also no drag reduction was detected for a clean disk which was allowed to stand for a few hours in a polymer solution, rinsed slightly, and then placed into distilled water and rotated. In general, drag reduction decreased with time of rotation. Normally such a decrease with time in drag reduction flow experiments is explained as being caused by the shearing of the polymer and the fact that a higher-molecular-weight species is a better drag reducer. However, to check if the time effect was related to a shearing of the adsorbed polymer the following experiment was performed. After rotation for approximately 1 minute (drag reduction decreasing with time), rotation was stopped for 1 hour. When rotation was again begun, drag reduction continued from the point corresponding to the end of the first section of the run.

DISCUSSION

Our results for PA adsorption agree well with results in Ref. 10, as they also found little or no adsorption of PA onto silicate surfaces (quartz) in neutral media and increased adsorption in acid media. Quartz and Cabosil have similar surfaces. PA is negatively charged in distilled water due to slight ionization of its acid group. Since quartz and Cabosil are both negatively charged little or no adsorption occurs. Acid represses the ionization of polymer and adsorbent and adsorption occurs. The forces of adsorption are strong and the polymer molecules lie predominantly flat on the surface. Stainless steel is not negatively charged and hence adsorbs PA even in nonacid media. The similarly charged polymer molecules do not form a uniform two-dimensional thin film on the steel surface, probably due to repulsion of the like charges. For PA adsorbed onto silica from acidic solution a comparison of Table 2 and Table 5 shows that ellipsometry measures five times more adsorption per unit area than does the powder technique. This apparent difference in polymer adsorption may be due to: (a) the "adsorbent concentration effect" previously discussed; (b) the surface area determined from nitrogen adsorption on the powder being different than that available to the much larger polymer molecule; (c) a roughness factor greater than one for the quartz slide; and (d) shearing of the polymer during the powder adsorption process.

Howard and McConnell (12) measured the adsorption of Polyox from water solution onto a Cabosil. They also encountered difficulty in removing the adsorbent from solutions of the higher-molecular-weight polymer and were only able to measure Polyox adsorption up to a molecular weight of 18,000. Measuring only three molecular weights, they found almost no slope in a plot of log adsorbance vs log molecular weight. In other solvents they obtain large slopes and had no difficulty in removing the adsorbent. They concluded that Polyox adsorbs from water onto silica in a flat fashion. It is believed that extrapolation of their results to higher molecular weights is a reasonable assumption because no system is known where after a zero slope has been obtained a radical change in the slope of an adsorbance-vs-molecular-weight plot occurs. Moreover, our ellipsometric results tend to substantiate the flat configuration they postulated. Such a flat configuration for Polyox adsorption was not anticipated in view of the large affinity the polymer has for the solvent.

Killmann and Weigand (14) studied the adsorption from water of polyethylene glycol (PEG, a low-molecular-weight polyethylene oxide) with molecular weights of 6130 and 40,000 at 25°C onto vacuum-deposited chromium slides by use of the ellipsometric technique. In contrast to our results they measured significant adsorption and a RMS thickness of $\approx 155 \text{ \AA}$ for each of the two molecules of PEG, thereby implying a highly

extended adsorbed polymer. However, two of their observations need explanation: (a) the very large thickness for PEG with a molecular weight of 6130, a value more than twice the end-to-end distance of the polymer, and (b) the fact that no difference in thickness was measured for the two seemingly highly extended adsorbed molecules of PEG. Moreover, Sarkar and Ghosh (15) report that PEG of molecular weight 6000 is associated in solution. Also Killmann and Weigand (14) measured little or no adsorption onto platinum or stainless-steel slides. (The method of cleaning the slides is not described.) Hence, it is suspected that the difference between their work and ours lies in a peculiarity associated either with the differences in molecular weights of the polymer or with the differences between the type or method of cleaning the slides.

Although analyses of the rotating disk experiments are clouded to some degree by the slight differences in roughness between the various disks, the fact that no significant differences in drag reduction were found between the disks is significant. It would be expected that the adsorption capabilities of the high-energy surfaces, such as stainless steel and glass, would be quite different than the low-energy surfaces nylon and Teflon. Indeed, Howard and McConnell were able to detect adsorption of Polyox from water onto Cabosil (12) and were unable to detect a similar adsorption onto nylon (16). Similarly a clean glass surface, which is allowed to stay unprotected in the laboratory or is touched by the hand, becomes covered with organic contaminants so that water does not wet it. Acid cleaning removes the contaminants and the surface is once again wetted by water. Yet no difference in drag reduction was found between a clean and contaminated glass disk. The rate of polymer adsorption has been studied by many researchers (4) and the time dependence of polymer adsorption is demonstrated in Table 5 of the present report. It is expected that the 2 minutes that elapse between immersion of the disk and the beginning of rotation is far from the time of equilibrium adsorption on a clean surface and even further for an unclean surface. Yet the same drag reduction was found irrespective of the time between immersion of the disk and its rotation. In all cases drag reduction data were extrapolated to zero time to correct for the time required to reach equilibrium rotation speed (10-15 sec).

The rate of desorption of polymers from solution is notoriously slow (4) because many adsorbed segments must simultaneously desorb before the whole molecule can desorb. Polyox which has been shown to adsorb from water in a flat fashion should be an especially slow desorber. Hence, it would not be expected that in the few minutes required to rinse the disk and set up the rotation experiment that any significant amount of polymer would desorb. However, no drag reduction occurred for just such a situation.

It is conceivable that if adsorption of Polyox were related to drag reduction the decrease in drag reduction that occurs with time of rotation might be related to a desorption or shearing of the adsorbed polymer due to the shear stress of rotation. However, if such is the case, it would be expected that if the rotation were stopped the system might rejuvenate itself. This possibility was tested and no such effect was found. The remote possibility that drag reduction and polymer adsorption are related, for a brief period, as rotation is started could not be tested with the apparatus described.

CONCLUSIONS

Except for the adsorption of acid PA onto Cabosil the drag-reducing polymers PA and Polyox did not adsorb as much as expected. Ellipsometry showed that the polymers adsorbed in a much flatter fashion than expected. The rotating disk apparatus experiments failed to demonstrate the existence of a drag-reducing layer of adsorbed polymer molecules. It is concluded for the systems studied that adsorbed polymer molecules play an insignificant role in drag reduction, if at all.

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