

<연구논문>

## 회전 Disk계에서 고분자 첨가제에 의한 마찰저항감소 연구

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(1991년 4월 25일 접수)

## A Study of Drag Reduction by Polymer Additives in Rotating Disk Geometry

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(Received April 25, 1991)

### 요 약

적은 양의 분자량이 큰 선형 고분자를 수용액에 첨가함으로써 얻어지는 마찰저항감소 연구가 rotating disk 장치를 이용해 수행되었다. 마찰저항 감소제로 poly(ethylene oxide)와 poly(acrylamide)를 사용하였으며, 고분자 분자량, 고분자 농도, disk의 회전속도 및 온도 등 여러가지 인자에 대한 마찰저항감소의 의존성을 연구하였다. 또한 마찰저항 감소 효과와 고분자 용액의 점도평균 분자량을 동시에 측정함으로써 고분자 퇴화에 대한 연구도 수행하였다.

마찰저항감소는 고분자 농도가 증가함에 따라 임계농도에 도달할 때까지 증가하였고, 낮은 농도에서는 분자량이 큰 고분자일수록 더욱 큰 마찰저항 감소효과를 나타내었다. 마찰감소 진행 중의 높은 전단력에 기인하는 고분자의 분해는 고분자 농도가 낮을수록 더욱 두드러지게 나타났으며, 온도 효과의 연구로부터 poly(acrylamide)가 poly(ethylene oxide)보다 열적으로 안정함을 알 수 있었다.

**Abstract**—Drag reduction achieved by introducing minute amounts of high molecular weight linear polymers into aqueous solutions has been investigated using a rotating disk apparatus. The drag reducers used in the current study are poly(ethylene oxide) and poly(acrylamide). The dependence of drag reduction on various factors such as polymer molecular weight, polymer concentration, rotational disk speed and temperature has also been studied. Further, studies on polymer degradation are given by simultaneously measuring decreases in the drag-reducing effectiveness and the viscosity-average molecular weight of the polymer solution.

Drag reduction is found to increase with polymer concentrations, reaching a maximum at its critical concentration. At low polymer concentrations, polymers of higher molecular weight produce greater drag reduction. Polymer degradation due to high shear force in the process of drag reduction is also found to be more apparent

at lower polymer concentrations. Furthermore, tests on thermal effect show that poly(acrylamide) is more thermally stable than poly(ethylene oxide).

**Keywords:** Polymer drag reduction/Polymer additives/Polymer degradation/Rotating disk apparatus

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## 1. Introduction

It is well known that the presence of very small amounts of high molecular weight polymeric substances can cause drastic reduction in the frictional drag of the liquids in turbulent flow. In 1949, Toms [1] first discovered that addition of 10 weight parts per million (wppm) of poly(methyl methacrylate) [PMMA] to monochlorobenzene undergoing turbulent tube flow resulted in a substantial reduction in pressure drop at a given flow rate. Since then, this phenomenon has been the subject of intensive theoretical and experimental research because of its wide range of application. Many investigators have investigated in large number of polymer-solvent pairs [2-7] and numerous reviews describing the latest research have published [8-12].

Drag reduction is a turbulent flow phenomenon [1, 13, 14], which is only observed when the shear stress at the wall exceeds a critical value. Above this critical point, the drag reduction increases with increasing polymer concentration and molecular weight [M.W.], but it is limited by so-called Virk's maximum drag reduction asymptote below which the value of friction factor doesn't fall. The asymptote depends only on the Reynolds number [18]. It is not a function of the pipe diameter, the polymer species, molecular weight, or the concentration. The maximum per cent reduction reported is typically 50%. This implies that a reduction in drag in the range of 50 percent can be achieved by adding a minute amount of high molecular weight polymer to turbulent fluid flowing through a pipe. By a certain percentage reduction in drag, it is meant that the energy required to move the fluid can be reduced by that percentage.

Since both turbulence and polymer dynamics are not well understood, the simultaneous study of these two is a very challenging problem. Peter-

lin [19] suggested that molecular expansion, resulting in an increase in energy dissipation may occur in drag reducing flows. Assuming that the increased energy dissipation in the highly turbulent inertial sublayer had the effect of increasing the Newtonian viscosity, Lumley [10] predicted that the inner layer of the flow should thicken and that this would lead directly to a decrease in the friction factor.

More reasonable explanation for the mechanism of drag reduction induced by linear polymers involves the idea of molecular stretching. Adopting a simple model to study both the turbulence and dissolved polymer molecules, Armstrong and Jhon [20] related molecular dissipation to friction by constructing a self-consistent method. For the polymer molecules they used a variant of the dumbbell model. And then it has been speculated that the average size of a dissolved polymer molecule increases dramatically when exposed to turbulence, and they have found that a polymer molecule grows by a factor of 10 or more from its equilibrium conformation. The existence of a non-isotropic viscosity [21], the decreased production of turbulence [22, 23] and vortex stretching [24] were also considered to be alternative interpretations of this phenomenon.

The industrial applications of drag reduction can be found in many areas such as transport of crude oil in the Alaska pipeline [15], oil well fracturing operations [16], closed-circuit pumping installations such as central-heating systems [11, 12], sewage systems to prevent overflowing after heavy rain [17], hydraulic transportation of solid particle suspensions [25], fire-fighting to increase the range of the water jets, and in water supply and irrigation systems [11, 12].

The most effective drag-reducing polymers possess a linear flexible structure and a very high

molecular weight ( $M.W. > 10^5$ ). The most commonly used water soluble polymers are poly(ethylene oxide) [PEO], poly(acrylamide) [PAAM] and poly(acrylic acid) [PAA], including their derivatives.

For PEO solutions, Patterson [18] measured pressure drops in a pipe of 0.25-inch-diameter using differential transducers separated by 1327 diameters with the pressure taps spread 10 diameters apart at each station. He observed higher pressure drops at the downstream. These measurements were accompanied by the simultaneous determination of the intrinsic viscosity of samples of solution withdrawn from the apparatus at both stations. He consistently found a lower intrinsic viscosity at the downstream where a significant reduction in drag-reducing efficiency occurred.

For different flow system, Gold *et al.* [26] measured the drag reduction in rotating disk flow using PEO (WSR-301). With various concentrations of polymer solutions, they recorded the torque required to rotate the disk at a rotational speed of 500 rpm. They observed a gradual increase in the required torque which appeared to be approaching a steady value after a sufficiently long time.

Polymers in turbulent flow fields are subject to intense shearing forces, resulting in decrease of molecular weight. This mechanical degradation is accompanied by the decrease of drag-reducing efficiency. Studies of the turbulent pipe flow of various polymer solutions have indicated a perceptible decrease in drag-reducing capability with increased exposure to turbulent flow.

To study flow-induced polymer degradation, Odell *et al.* [27] used the cross-slot device first introduced by Scrivenner [28]. They measured birefringence as a function of elongational strain rate for dilute solution of narrow molecular weight distribution atactic polystyrene circulating through the cross-slot apparatus at deliberately elevated strain rates, showing that an individual molecule broke into two at its center. It was observed that this degradation process until the remaining species are too short to be broken by the imposed strain rate in the cross-slots. Even though their analysis is based on laminar, extensional flow,

their conclusion could be relevant to the explanation of degradation of polymers in turbulent flow (Note that the extensional component in turbulent flow is responsible for polymer coil stretching [20]).

On the other hand, Tabata *et al.* [29] measured changes in the number average molecular weight induced by high speed stirring in a benzene solution of poly(methyl methacrylate) (PMMA) using gel permeation chromatography. They obtained information about specific broken points of either main chains or side chains using an electron spin resonance method combined with a spin trapping technique which was employed to stabilize the unstable scission radicals. They found that at lower concentrations of polymer solution, the molecular weight decreased faster. It was also observed that the main chains of PMMA were ruptured by the high speed stirring.

The objective of the experiments presented here was to study the drag reduction produced by dilute water solutions of PEO and PAAM in the rotating disk system. Note that extensive studies on PAA were carried out at Naval Research Laboratory, Washington D.C. [30, 31]. Experiments were performed to establish the dependence of drag reduction on various factors such as polymer molecular weight and concentration, rotating speed and polymer degradation. Relation between the decrease of drag reduction and that of viscosity-average molecular weight with shearing time and the thermal effect on polymer degradation were also investigated.

## 2. Experimental

### 2.1. Materials

PEO and PAAM were obtained from Scientific Polymer Products Inc. and used as received. The weight-average molecular weights of PEO used were 40,000, 90,000, 4,000,000, and 5,000,000 g/mole.

Solutions were initially prepared in 0.5 wt% concentrations using distilled water and allowed them to equilibrate for 4 or 5 days. 1 wt% isopropanol was also added to prevent chemical degra-

dation [31]. The stock solutions were then diluted to the appropriate concentration as required. Dilute solutions were prepared by injecting carefully measured quantities of stock solution directly into the turbulent flow field.

## 2.2. Measurements

In general, there are two flow forms used to detect the drag reduction phenomenon: the so-called 'external flow' which includes flow over flat plates as well as flow around submerged bodies such as ship hulls of submarine models. The second form, named 'internal flow', includes flow through pipes, ducts and pumps. One typically studies friction drag for the internal flow, whereas one studies total drag (form and friction) for external flow. The rotating disk system is adopted for this study.

The rotating disk apparatus consists of a stainless steel disk of dimension 10.1 cm in diameter  $\times$  0.32 cm in thickness, enclosed in a cylindrical thermostatically controlled container, which is made of stainless steel and has a dimension of 16.3 cm in diameter  $\times$  5.5 cm height (Fig. 1). The whole apparatus is surrounded by a water reservoir whose temperature is well controlled by a constant temperature water circulating system. The volume of polymer solution required to fill the container was approximately 1100 ml. A DC motor generator, coupled with a controller (Cole Parmer Master Servodyne Unit), was used to maintain a preset rotational speed by delivering a variable torque (T) as required by the load on the disk. All exper-

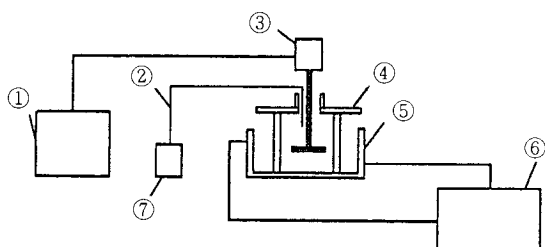


Fig. 1. Schematic diagram of rotating disk apparatus. 1. Controller, 2. Thermocouple, 3. Motor, 4. Solution Container, 5. Water Reservoir, 6. Constant Temperature Water Circulating System, 7. Multimeter

iments were performed at  $25 \pm 0.5^\circ\text{C}$  except those investigating thermal effects. The temperature of the fluid and the rotational speed were measured by a K-type thermocouple and a digital tachometer, respectively. In this system the Reynolds number ( $N_{Re}$ ) can be obtained from the following relationship:

$$N_{Re} = \rho r^2 \omega / \mu \quad (1)$$

where  $\rho$  and  $\mu$  are the density and viscosity of the fluid,  $r$  is the radius of the disk, and  $\omega$  is the rotational speed of the disk respectively.

Unless otherwise specified, all experiments were carried out at a fixed rotational speed of 2800 rpm, corresponding to a water-based Reynolds number of  $8.3 \times 10^5$  in our system.

Drag reduction measurements were undertaken by injecting carefully measured quantities of stock solution directly into turbulent flow field of the rotating disk apparatus. Preliminary flow visualization test using dyed stock solutions indicated that complete mixing was accomplished within several seconds. Confidence in the accuracy with which homogeneous dilute solutions could be produced was further reinforced by the reproducibility of the results and their consistency with results obtained in experiments on homogeneous drag reduction using distilled water and stock solution which were premixed to form homogeneous polymer solution of desired concentration.

Drag reduction characteristics were obtained in all cases by first measuring the torque required to rotate the disk at a given speed in distilled water. The percent drag reduction is then determined by measuring the corresponding torque required at the same speed with a dilute polymer solution.

$$DR(\%) = \frac{T_o - T_p}{T_o} \times 100 \quad (2)$$

where  $T_o$  is the torque measured with distilled water, and  $T_p$  is the torque measured with polymer solution.

In addition, an Ubbelohde viscometer was also used to determine the change in polymer molecular weight as a result of mechanical degradation.

Determinations of intrinsic viscosity  $[\eta]$  were made at  $30 \pm 0.05^\circ\text{C}$  in deionized water, using the following Huggins equation.

$$\eta_{sp}/c \equiv (\eta_p - \eta_0)/\eta_0 c = [\eta] + k'[\eta]^2 c \quad (3)$$

where  $c$  is the polymer concentration in g/dl,  $\eta_0$  is the solvent viscosity,  $\eta_p$  is the viscosity of polymer solution, and  $\eta_{sp}$  is the specific viscosity.

Viscosity-average molecular weights ( $\bar{M}_v$ ) of PEO were then estimated using the following Mark-Houwink equation [33]

$$[\eta] \equiv \lim_{c \rightarrow 0} \eta_{sp}/c = 1.25 \times 10^{-4} \bar{M}_v^{0.78} \quad (\text{at } 30^\circ\text{C}) \quad (4)$$

where the valid molecular weight of PEO in eq. (4) is in the range of 20,000 to 5,000,000.

The experiments were performed for the polymer solutions of two different molecular weights of PEO at a rotational speed of 2800 rpm with a polymer concentration of 300 wppm. Samples of polymer solutions were removed from the rotating disk apparatus periodically during the test.

### 3. Results and Discussion

We will first study the effect of concentration on drag reduction. Concentration effects are determined by two competitive mechanisms. Initially, the drag reduces as the concentration increases due to increases in the number of available drag reducers. However, as the concentration further increases, the solution viscosity increases, leading to an increase in the frictional drag. The existence of a critical concentration at which the drag reduction is maximized is, therefore, anticipated.

Fig. 2 shows the dependence of per cent drag reduction on molecular weight of PEO as a function of polymer concentration at 2800 rpm to illustrate this point. The maximum in the disk flow field is generally fairly broad [34], and the drag reduction effectiveness remains more or less independent of concentration over a wide range of concentrations. It also shows that at low concentrations of polymer solutions drag reduction is greater for higher molecular weight polymers, and that the maximum occurs at lower concentrations

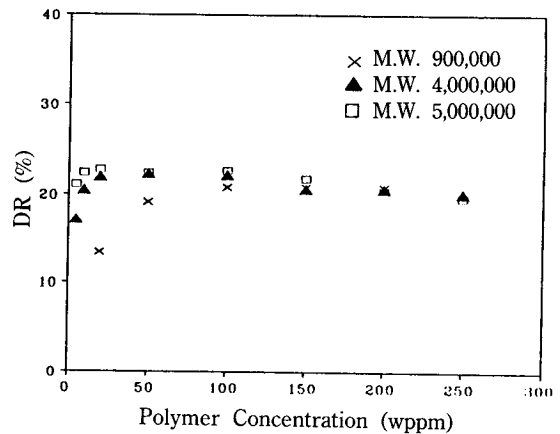


Fig. 2. Per Cent Drag Reduction versus PEO Concentration at three different Polymer Molecular Weights and 2800 rpm.

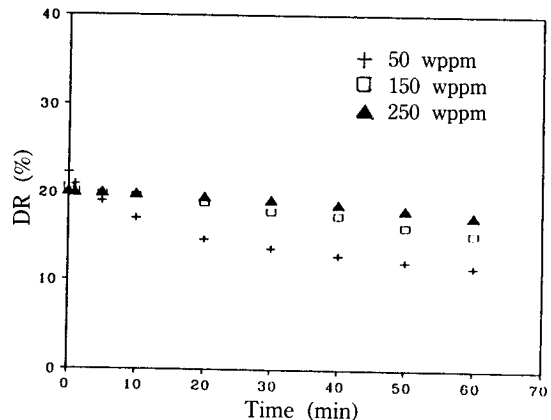


Fig. 3. Per Cent Drag Reduction versus Time at Three different PEO (M.W.=4,000,000) Concentrations and 2800 rpm.

as the molecular weight is increased. However, for the high concentrations of PEO, the molecular weight dependence of drag reduction becomes negligible.

Second, we study the stability or mechanical degradation of polymer chains in turbulent flow. We measured changes occurring in the drag reduction over a period of time to study this effect. Fig. 3 and 4 depict the drag reduction obtained with various polymer concentration as a function of time at a rotational speed of 2800 rpm for molecular weights of 4,000,000 and 5,000,000 respectively. As shown in figures, the drag reduction de-

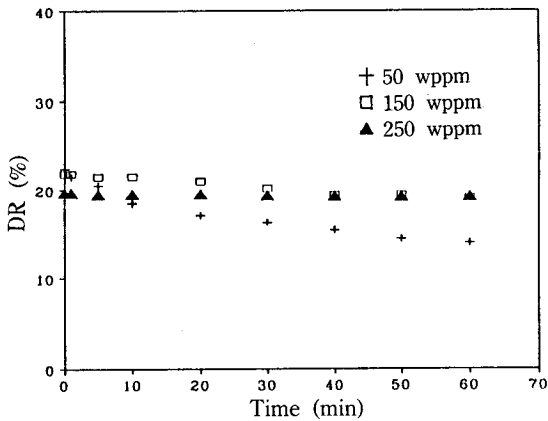


Fig. 4. Per Cent Drag Reduction versus Time at three different PEO (M.W.=5,000,000) Concentrations and 2800 rpm.

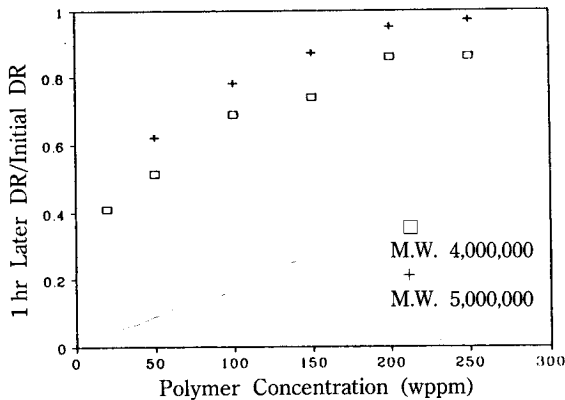


Fig. 5. Dependence of Mechanical Degradation on Polymer Concentration at 2800 rpm.

cays as a function of time and then levels off.

Defining the stability against mechanical degradation as the ratio between 1 hr later DR and initial DR, Fig. 5 shows that the polymer of higher molecular weight gives higher value of stability. Even though higher molecular weight polymer tends to degradation easily, it seems that there exists still higher molecular weight polymer chain even after degradation.

The polymer degradation occurs more rapidly with decreasing polymer concentration, which is consistent with the fact that at a lower concentration of polymer solution, the number-average molecular weight decreases more rapidly as shown

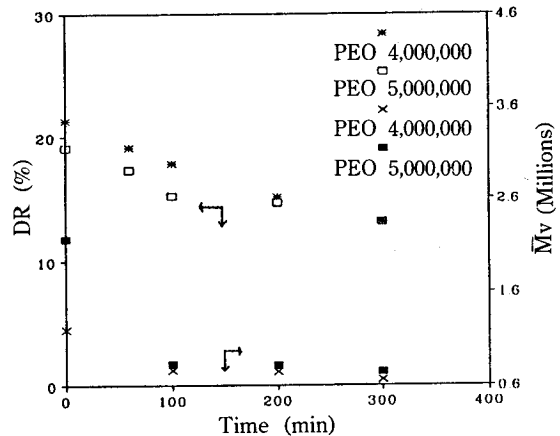


Fig. 6. Per Cent Drag Reduction and  $\bar{M}_v$  versus Time at 2800 rpm with  $c=300$  wppm.

by Tabata *et al.* [29]. To illustrate this point explicitly, we have correlated decrease in the drag reduction and the viscosity-average molecular weight time for the two different molecular weights of PEO (see Fig. 6). The viscosity-average molecular weight can be calculated from the intrinsic viscosity of the polymer solution using the Mark-Houwink relationship as shown in eq. (4). Therefore, Fig. 6 indicates that decreases in the drag reduction are due to the degradation of the polymer molecule. Since there exists some experimental inaccuracies with low polymer concentration to measure the intrinsic viscosity because of too low relative viscosity, we choose 300 wppm of polymer concentration rather than 50 wppm in this experiment. These data also show that higher molecular weight polymers degrade more rapidly over the entire shearing time than those of average molecular weight, as expected, since the force tending to rupture the molecules is higher for larger molecules subjected to the same rotational speed. This implies that drag reduction is largely dependent upon the contributions of the higher molecular weight species in the molecular weight distribution. It also shows that average molecular weight decreases rapidly during the early shearing period (up to 100 min) and then levels off, indicating the existence of a critical molecular weight below which no polymer chain is ruptured by mechanical force. The critical molecular

weight appears to be higher for higher initial molecular weight polymer solutions. This could be explained in light of the dependence of degradation on polymer concentration. That is, as degradation proceeds, the effective concentration of polymers with high molecular weight becomes higher compared to that of low molecular weight polymers, eventually resulting in less degradation. Similar results were reported by Patterson and Abernathy [35], who showed degradation of dilute PEO solutions as a function of time in the 0.248 in. test pipe for various molecular grades. They plotted the ratio of the intrinsic viscosity measured on samples withdrawn at various pipe locations to the intrinsic viscosity of a sample removed from the inlet tank. It is also noted that the degradation phenomenon changes the molecular weight distributions as well as the average molecular weight. The drag reduction is largely due to the contributions of higher molecular weight species in the molecular weight distribution.

In addition, using rotating disk flow, Gold *et al.* [26] also investigated the friction reduction effectiveness with two different sizes of rotating disk. Comparing their results with ours, they obtained rather higher initial percent friction reduction for PEO. It is thought that higher Reynolds number and higher temperature of their experimental conditions were the main sources to produce such higher friction. Further, they mentioned that the onset of friction reduction appears to occur within the transition region and seems to be independent of solution concentration and the onset of degradation also appears to be independent of concentration.

Fig. 7 shows the initial and 1 hr later drag reduction as a function of rotational speed for PEO (M.W.: 4,000,000) solution with  $c=50$  wppm. The data show that the difference between the initial drag reduction and 1 hr later drag reduction gradually increases with increasing rotational speed and thus the initial advantage of larger drag reduction obtained with higher rotational speed is lost after a certain period of time.

So far we have focused on PEO, however, in the following discussion we will compare PEO and

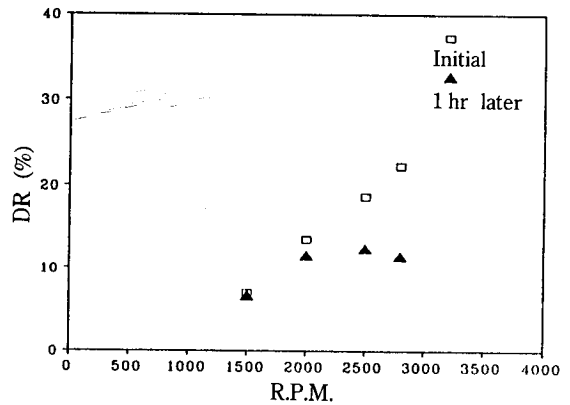


Fig. 7. Mechanical Degradation of PEO (M.W.=4,000,000) versus R.P.M. with  $c=50$  wppm.

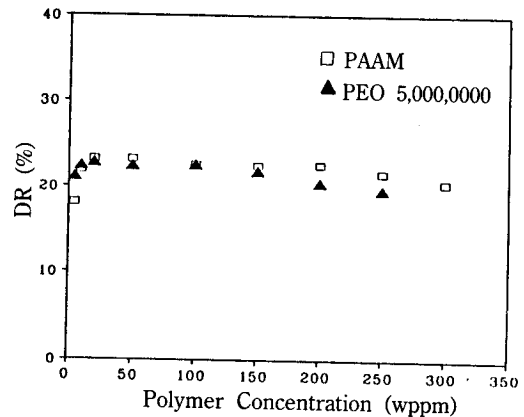


Fig. 8. Per Cent Drag Reduction of PEO and PAAM versus Polymer Concentration at 2800 rpm.

PAAM.

Fig. 8 shows the effect of polymer concentration of PAAM on drag reduction, including that of PEO solution for comparison. The weight-average molecular weight of PAAM used in the following experiments is 5,000,000-6,000,000 g/mole, which is similar to the PEO sample chosen. It is seen that drag reduction increases with increasing polymer concentration, but at some point it reaches a maximum and then remains virtually constant over a wide range of concentrations. It also indicates that for similar molecular weight of PEO and PAAM, PAAM gives slightly higher drag reduction than PEO.

The dependence of drag reduction on rotational

speed for a polymer concentration of 50 wppm is shown in Fig. 9. It shows that drag reduction increases linearly with increasing r.p.m. regardless of polymer type and molecular weight. Since we have performed most parts of this experiment at 2800 rpm, we obtain rather small value of drag reduction. Possible formation of wake in the rotating disk apparatus could also reduce the drag reduction effect.

In polymer degradation experiments using PAAM and a rotational speed of 2800 rpm, decreases in drag reduction as a result of polymer degradation were found to be stronger for lower polymer concentrations. Above a polymer concentration of 50 wppm, however, there was no further decrease as shown in Fig. 10 and 11.

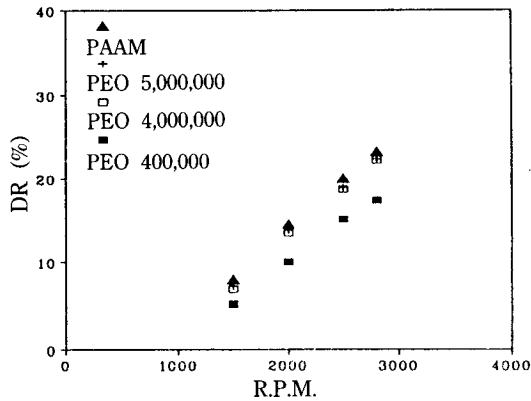


Fig. 9. Per Cent Drag Reduction of PEO and PAAM versus R.P.M. with  $c=50$  wppm.

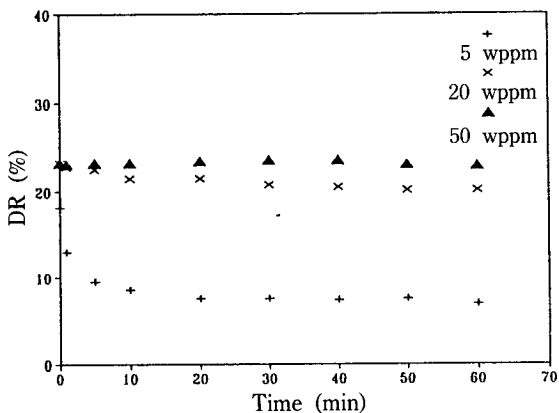


Fig. 10. Per Cent Drag Reduction of PAAM versus Time.

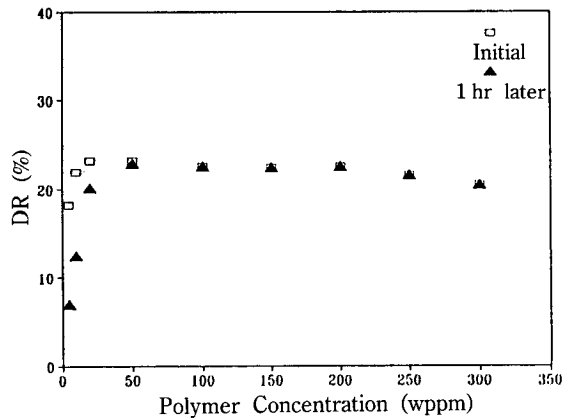


Fig. 11. Dependence of Mechanical Degradation on PAAM Concentration.

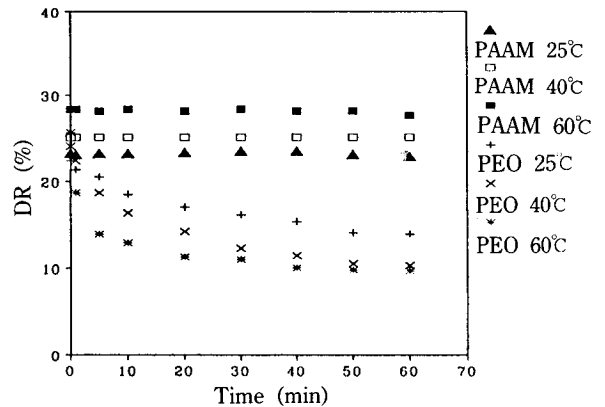


Fig. 12. Influence of Temperature on Drag Reduction as a function of Time with  $c=50$  wppm.

The experiments examining the effect of temperature on drag reduction for PAAM and PEO (M.W.: 5,000,000) were performed at three different temperatures (25°C, 40°C, 60°C) and the results are shown in Fig. 12. For PAAM, temperature elevation results in an increase in the initial drag reduction with no change in the rate of polymer degradation. With PEO, on the other hand, the advantage of larger initial drag reduction with higher temperature is lost due to an increased rate of polymer degradation. It clearly shows that PEO solution is much more susceptible to thermal degradation as well as mechanical degradation than PAAM solution at the same concentration for all of the temperatures examined. One possible exp-



lanation on this thermal effect is based on the glass transition temperature and it is known that PAAM has a higher glass transition temperature than PEO [36].

#### 4. Conclusion

Drag reduction produced by two typical drag-reducing polymers, PEO and PAAM, in a rotating disk apparatus has been investigated experimentally.

The drag reduction increases with higher polymer concentrations until a maximum is reached. The maximum plateau appears broader for PAAM solutions. It is also found that the polymer concentration at which maximum drag reduction is attained, is lower for higher polymer molecular weights.

At low polymer concentrations for higher molecular weights, greater drag reduction is achieved. However, this effect becomes negligible as the polymer concentration further increases. Increasing rotational speed also causes higher drag reduction, but this advantage is lost after a certain time due to an increased rate of polymer degradation. This degradation is more intense at lower polymer concentrations and higher molecular weights. However, this degradation does not always proceed to the complete destruction of drag-reducing effectiveness of the polymer. Rather, a steady state drag-reducing effectiveness is observed. This effect is also confirmed by measurements of the viscosity-average molecular weight of the polymer.

Degradation tests show that although PEO is as effective as PAAM, PEO is much more susceptible to thermal and mechanical degradation. The susceptibility of PEO to degradation increases dramatically as the temperature is increased, while PAAM is stable even at high temperatures. This indicates that PAAM is a promising candidate for high temperature applications and long time transportation.

#### Nomenclature

$c$  : polymer concentration [wppm]

DR(%) : per cent drag reduction  
 $\bar{M}_v$  : viscosity-average molecular weight  
 $N_{Re}$  : Reynolds number  
 $T$  : disk torque measured using polymer solution  
 $T_o$  : disk torque measured using water  
 $r$  : radius of the rotating disk  
PAA : poly(acrylic acid)  
PAAM : poly(acrylamide)  
PEO : poly(ethylene oxide)  
PMMA : poly(methyl methacrylate)  
 $\rho$  : density of the fluid  
 $\omega$  : rotational speed of the rotating disk  
 $\mu$  : viscosity of the fluid  
 $\eta_o$  : water viscosity  
 $\eta_{sp}$  : specific viscosity  
 $[\eta]$  : intrinsic viscosity [dl/g]

#### References

1. B.A. Toms, *Proc. Ist Int. Congress on Rheology*, Vol. 2, 135, North Holland Publish Co., Amsterdam, 1949.
2. R.G. Shaver and E.W. Merrill, *AIChE J.*, **5**, 181 (1959).
3. D.W. Dodge and A.B. Metzner, *AIChE J.*, **5**, 189 (1959).
4. A.B. Metzner and M.G. Park, *J. Fluid Mechanics*, **20**, 292 (1964).
5. J.W. Hoyt, *Polymer Letters*, **9**, 851 (1971).
6. B. Johnson and R.H. Barchi, *J. Hydronautics*, **2**, 108 (1968).
7. M. Walsch, *International Shipbuilding Progress*, **14**, 134 (1967).
8. P.S. Virk, *AIChE J.*, **21**, 625 (1975).
9. J.W. Hoyt, *Trans. ASME., J. Basic Engineering*, **94D**, 258 (1972).
10. J.L. Lumley, *J. Polym. Sci. Macromolecular Reviews*, **7**, 263 (1973).
11. R.H. Sellin, J.W. Hoyt and O. Scrivener, *J. Hydraulic Research*, **20**, 29 (1982).
12. R.H. Sellin, J.W. Hoyt, J. Polleet and O. Scrivener, *J. Hydraulic Research*, **20**, 235 (1982).
13. G.E. Gadd, "Friction Reduction" in N. M. Bikales Ed., *Encyclopedia of Polymer Science and Technology*, Interscience Publishers, New York, Vol. 15, 1971, p. 224.

14. W.D. White and D.M. McEligot, *Trans ASME, J. Basic Engineering*, **92-93**, 411 (1970).
15. E.D. Burger, W.R. Munk and H.A. Wahl, Society of Petroleum Engineers of AIME, Report SPE 9419, Dallas, Texas, 1980.
16. R.S. Ousterhout and C.D. Hall, *J. Petroleum Technol.*, **13**, 217 (1961).
17. R.H. Sellin, and M. Ollis, *J. Rheology*, **24**, 667 (1980).
18. R.W. Patterson, "Turbulent Flow Drag Reduction and degradation with Dilute Polymer Solutions", Engineering Sciences Laboratory, Harvard University AD-693-306, June, 1969.
19. A. Peterlin, *Nature*, **227**, 598 (1970).
20. R. Armstrong and M.S. Jhon, *Chem. Eng. Commun.*, **30**, 99 (1984).
21. G.K. Patterson and J.L. Zakin, *AIChE J.*, **14**, 434 (1968).
22. G.E. Gadd, *Nature*, **206**, 463 (1965).
23. G.E. Gadd, *Nature*, **212**, 1348 (1966).
24. R.J. Gordon and C. Balakrishnan, *J. Appl. Polym. Sci.*, **16**, 1629 (1972).
25. J. Golda, *Chem. Eng. Commun.*, **43**, 53 (1986).
26. P.I. Gold, P.K. Amar and B.E. Swaidan, *J. Appl. Polym. Sci.*, **17**, 333 (1973).
27. J.I. Odell, A. Keller and M.J. Miles, *Polym. Commun.*, **24**, 7 (1983).
28. O. Scivener, C. Berner, R. Cressely, R. Hocquant, R. Sellin and N.S. Vloches, *J. Non-Newtonian Fluid Mechanics*, **5**, 475 (1979).
29. M. Tabata, Y. Hosokawa and O. Watanabe, *Polymer J.*, **18**, 699 (1986).
30. O.K. Kim, T. Long and F. Brown, *Poly. Commun.*, **27**, 71 (1986).
31. O.K. Kim, L.S. Choi, T. Long and T.H. Yoon, *Poly. Commun.*, **29**, 168 (1988).
32. C.W. McCary, *Nature*, **206**, 464 (1965).
33. F.E. Bailey, J.L. Kucera and L.G. Imhoff, *J. Polym. Sci.*, **32**, 517 (1958).
34. J.W. Hoyt and A.G. Fabula, *Proceedings of the 5th Symposium on Naval Hydrodynamics*, Bergen, Norway, September, 947-974 (1964).
35. R.W. Patterson and F.H. Abernathy, *J. Fluid Mech.*, **43**, 689 (1970).
36. J. Brandrup and E.H. Immergut, "Polymer Handbook" 2nd ed., Wiley, N.Y. (1975).