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攪拌槽內에서의 高分子 添加物에 의한 流動摩擦 減少 効果

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Drag Reduction Effect of Polymer Additives in a Tank of Rotating Disk With Short Rim

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要 約

극소량의 고분자물질을 첨가하여 회전원판이 장치된 교반조내에서의 유동마찰 감소 현상에 관한 연구를 시도하였다. Torque의 최대 감소를 주는 고분자물질의 농도는 폴리에치렌옥사이드의 경우 10 wppm 이었고 폴리아크릴아마이드의 경우에는 40 wppm 이었으며, 이때의 유동마찰감소는 약 24% 에 달하였다. 실험결과를 동력함수와 레이놀스수로서 연관시켜보았는바, 최대 torque 감소가 생길때의 기울기 값이 거의 일정하게 나타나는 현상이 관찰되었다. 회전원판계에서의 유동마찰계수의 감소도는 보고된 관내에서의 실험치 보다는 비교적 작은 값을 보여주었으며, 높은 전단응력에 의한 고분자물질 용액의 퇴화현상이 다소 일어남도 관찰되었다.

Abstract

A system of a rotating disk in a tank was devised to investigate the drag reduction phenomenon by the small amount of polymer additives. The optimum concentrations for the maximum torque reduction of about 24% were determined to be 10 wppm and 40 wppm for polyethylene oxide and

polyacrylamide solutions, respectively. These data were correlated in terms of power function and Reynolds number giving nearly the same slope at the maximum drag reduction. The extent of drag reduction in a rotating disk flow system was found to be relatively low in comparison to those reported for the pipe flow systems. The degradation of polymer solutions by high shear stress was also observed.

1. Introduction

The discovery and gradual realization in recent years of the phenomenon of drag reduction in a turbulent flow due to small amount of certain additives was a landmark event in the fluid dynamics community. Drag reduction may be achieved with several types of additives. The most spectacular drag reduction is obtained through the addition of small amount, usually order of ppm. of soluble linear polymers of high molecular weight and this has been the subject of intensive research during the last decade. Polymer solution drag reduction may occur from one of two effects, the extension of laminar behavior to abnormally high Reynolds number, or the reduction of friction factor in fully developed turbulence. Several extensive review papers of the subject have appeared in recent years, emphasizing different aspects of the phenomenon by White[1], Lumley[2,3], Patterson et al.[4], Hoyt[5] and Bark.[6]

Drag reduction occurs in turbulent flow so that it is of great potential value to the processing industry to save power consumption, where most flows are turbulent. Extensive use of drag reduction additives has, however, been made only in pumping water and oil particularly for petroleum production operation[7]. Promising applications of drag reduction are in long crude petroleum product pipelines, in water and sewer systems, in fire-fighting hoses, in sprinkling irrigation, and on ships and ship model testing. In addition to the polymer solutions mentioned above soap solutions[4,8] and solid particle suspensions[9-11] are effective in drag reducibility although in less extent than the former.

Drag reduction is defined by Little[12] as a lowering of wall shear stress in comparison with that of pure liquid upon addition of small amount of polymers or other additives. Seyer and Metzner[13] defined the fractional drag reduction as $(f_0-f)/(f_0-f_L)$ where f is the friction factor of the solution, f_0 is that which would be observed at the same Reynolds number in the absence of drag reduction and f_L is that calculated from Poiseuille equation $f_L=16/\mathrm{Re}$. This may alternatively be written as $(\Delta P_0-\Delta P_A)/\Delta P_0$, where ΔP_0 is the pressure loss due to friction per unit length of pipe with solvent only and ΔP_A is that with drag reducing materials.

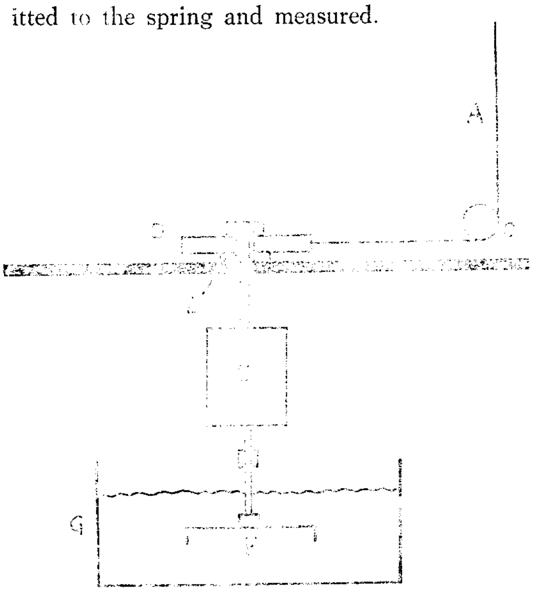
The mechanism underlying the drag reduction phenomenon has not yet been fully understood. Viscosities of highly dilute polymer solutions of order of ppm are known to be nearly the same as that of pure liquid and the unusual behavior of the drag reducing solutions are not explained by ordinary flow theories. The drag reduction phenomenon is observed to occur usually in thermodynamically dilute solutions of long, flexible, expanded, high-molecular weight, linear polymers. It appears that the polymer molecules interfere with the production of turbulence. According to Goren and Norbury[14] molecules either individually or in groups decay eddies near the solid boundary and they tend to store kinetic energy through elongation and deformation, thus suppressing turbulence near the wall.

Most of the drag reduction experiments were performed in turbulent pipe flow. In this experimental study the torque measuring device was employed and torque on the surface of the rotating disk was measured to examine the drag reducibilities of two most effective polymers, namely polyethylene oxide WSR-301 and polyacrylamide ET-597, for various concentrations and rotational speeds of the disk as an initial investigation in this field.

2. Experiments

Apparatus

A dynamometer is employed to measure the torque on the surface of the rotating disk with cylindrical cuplike short rim. The schematic diagram of the apparatus is shown in *Fig.* 1 and its dimensions are given in *Table* 1. When the disk rotates the liquid opposes the disk by the law of action and reaction. This is transmitted to the spring and measured.



A: spring scale B: thrust bearing
C: frictionless pulley D: pulley
E: D.C. motor F: disk
G: tank

Fig. 1. Schematic diagram of experimental apparatus.

Table 1. Dimensions of the experimental apparatus.

Diameter of disk	15.0 cm
Depth of disk rim	1.5 cm
Thickness of disk	0.2 cm
Diameter of tank	35.0 cm
Disk distance from the bottom of tank	5.0 cm

Preparation of polymer Solutions

One of the polymers used is polyethylene oxide manufactured by Union Carbide with the commercial name of Polyox WSR-301. Its approximate molecular weight is 4×10^6. The other is polyacrylamide, Separan ET-597 manufactured by Dow Chemical. Since the degree of drag reduction depends on the procedure of solution preparation and storage the following scheme was adopted in order to maintain the consistency of sample preparation.

a) Add predetermined amounts of polymer to the surface of water sprinkling uniformly.
b) These solutions were allowed to stand for 24 hours. The polymer was dissolved by diffusion during this period.
c) These solutions were poured into the tank filled with distilled water to give desired concentration.
d) It was then stirred for 3 minutes at 200 rpm by a 4 blade turbine propeller.

The solution viscosity was measured by Cannon-Fenske viscometers and is given in *Table* 2.

Table 2. Relative viscosity of dilute polymer solutions at 18°C.

wppm	Polyox	wppm	Separan
5	1.001	20	1.162
10	1.015	40	1.309
20	1.044	80	1.662
40	1.103	160	2.853

3. Results and discussion

A noticeable increase in rotational speed and a significant decrease in torque are observed in comparison to the case of pure water system. Measured torque is plotted against rpm in *Figs.* 2 and 3 for Polyox WSR-301 and Separan ET-597, respectively. Both show that the reduction of torque tends to increase as the rpm of the disk increases. For the dimensional analysis of the system it is assumed that the power P required to rotate the disk depends only on the variables of rotational speed of the disk N rpm, diameter of the disk D, density ρ and viscosity μ of the liquid and the gravitational acceleration g. Further assuming that the linear dimensions of the tank are all strictly related to the diameter, the dimensionless power number N_p can be expressed as[15]

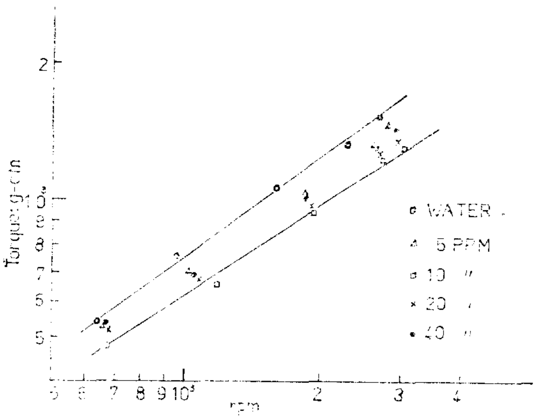


Fig. 2. Torque vs. RPM of the rotating disk in Polyox solution.

$$P/\rho N^3D^5=C(\rho ND^2/\mu)^x(N^2D/g)^y \quad (1)$$

where C is an overall shape factor which represents the geometry of the system, x and y are constants. A power function ϕ which corresponds to the drag coefficient is defined by

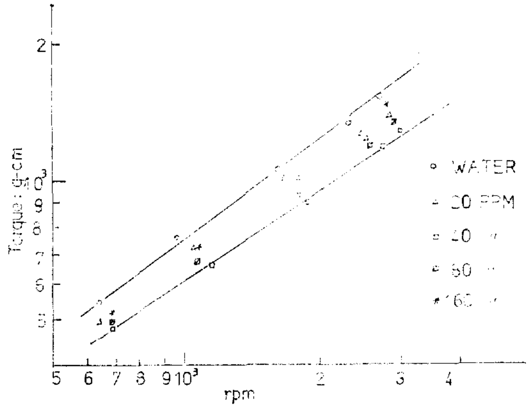


Fig. 3. Torque vs. RPM of the rotating disk in Separan solution.

$$\phi=N_p/(Fr)^y=C(Re)^x. \quad (2)$$

For nonvortexing system the exponent y of the Froude number is zero as in the case of negligible gravitational field. The power curve which is the plot of ϕ *vs.* *Re* on log-log coordinates is shown in *Figs.* 4 and 5 for the respective cases. It is noted that, the higher the Reynolds number becomes the more the drag

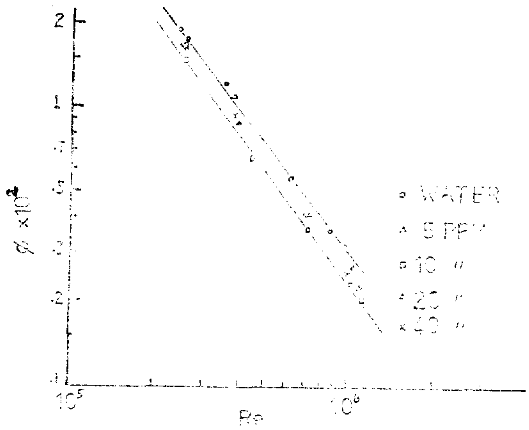


Fig. 4. Power function variation with Reynolds number in Polyox solution.

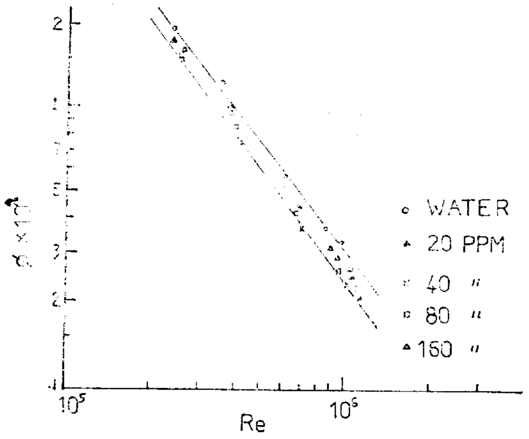


Fig. 5. Power function variation with Reynolds number in Separan solution.

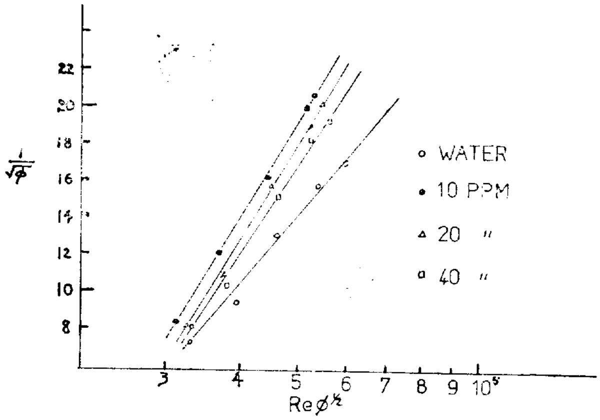


Fig. 6. Correlation of $1/\sqrt{\phi}$ vs. $Re\sqrt{\phi}$ according to Eq. (3) in Polyox solution.

reduction grows. The onset Reynolds number of the system cannot be detected in the above figures and unfortunately the experimental apparatus could produce only the range of Reynolds numbers shown above beyond a certain low limit.

An alternative attempt is also made to correlate the power function by the formula

$$\phi^{-\frac{1}{2}} = A \log_{10}(Re\ \phi^{\frac{1}{2}}) + B \qquad (3)$$

and the same data are plotted in *Figs.* 6 and 7 accordingly. In case of Polyox the maximum torque reduction reached 24% at concentration of 10 wppm and the maximum slope A equals to about 51.0. Similarly the 40 wppm Separan solution gave the maximum torque reduction of 23%, when the slope reached 51.8 which was higher than 39.2 of pure water case. The slope values of A in both polymer solutions gave nearly the same numbers as they reached the maxima. When the polymer concentrations increased above those values, the rate of torque reduction effect tended to decrease as can be seen in *Figs.* 8 and 9.

This tendency was also noted in pipe flow cases[3]. The reason for this strong dependency on concentration in the stirred tank system has not been well understood. It is, however, believed that when polymer molecules are present

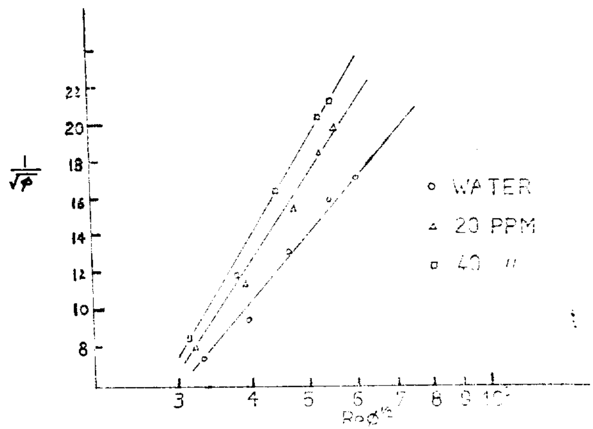


Fig. 7. Correlation of $1/\sqrt{\phi}$ vs. $Re\sqrt{\phi}$ according to Eq. (3) in Separan solution.

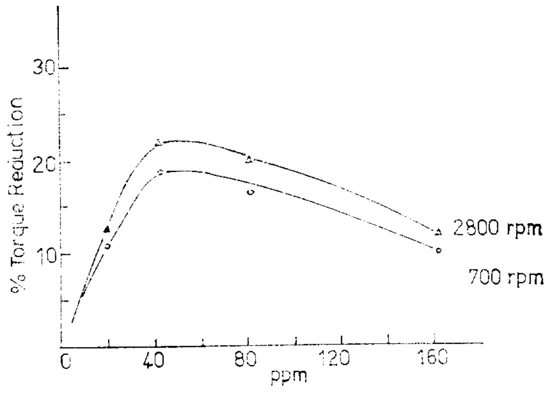


Fig. 8. Dependence of the torque reduction upon polyox additive concentration.

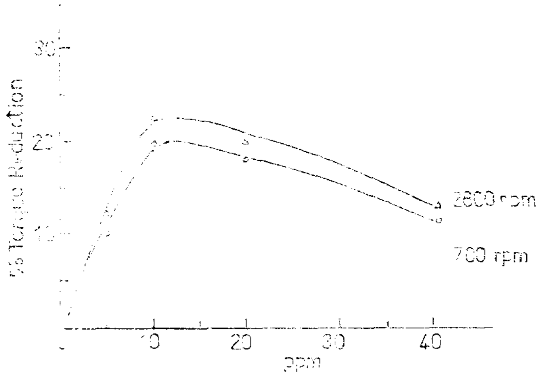


Fig. 9. Dependence of the torque reduction upon Separan additive concentration.

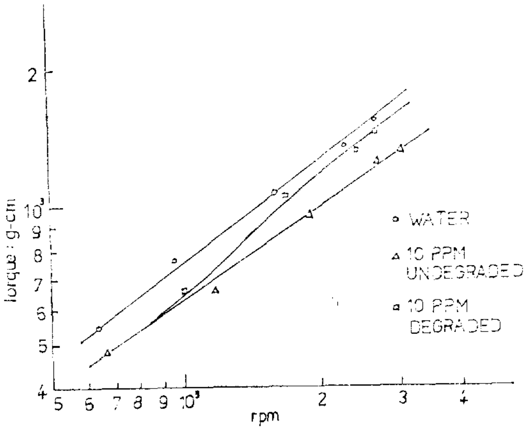


Fig. 10. Trend of degradation of Polyox solution.

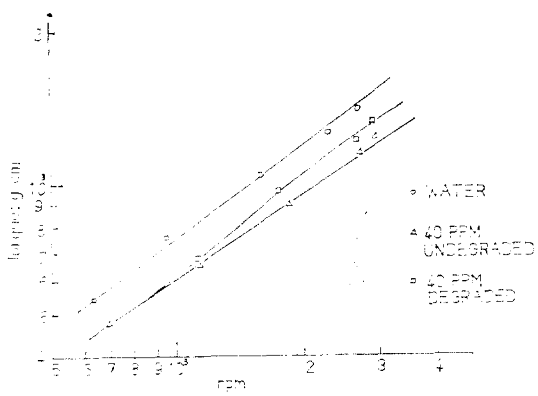


Fig. 11. Trend of degradation of Separan solution.

in solution above certain numbers their coils interpenetrate into or entangle each other, thereby decreasing the drag reducing effect of polymer molecules[16]. It is possible that the stirred tank system which induces the rapid degradation of polymer may have enhanced the tendency.

Once a solution was tested it was discarded and another freshly prepared solution was used for each experiment. To examine the degree of degradation of polymer at high shear stress level caused by the rotating disk an attempt was made. Some selected solutions were run at 1700 rpm for 10 minutes before they were tested for the drag reducibility. It seems that both Polyox and Separan solutions degraded gradually as shown in *Figs.* 10 and 11. Separan solutions seemed to be more resistent to the breakdown of the chain than the Polyox solutions.

4. Conclusions

1) The degree of torque reduction tends to increase as the Reynolds number increases within the experimental range of up to 10^6.
2) The optimum concentrations for the maximum torque reduction were 10 wppm and 40 wppm for Polyox WSR-301 Separan ET-597, respectively. Above these concentrations torque increased as concentrations increased.
3) Polyox WSR-301 and Separan ET-597 solutions degraded by high shear stress and the former degraded more significantly than the latter.
4) A polymer should have a high molecular weight and linear, long chained molecular structure without side chains to exhibit significant drag reduction phenomenon. For further investigations it is suggested to examine this effect not only for a group of polymers which have these structural properties but also for another group of polymers which have not such properties.

Acknowledgement

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