ST. ANTHONY FALLS HYDRAULIC LABORATORY

Reprinted from: VISCOUS DRAG REDUCTION
(Plenum Press, 1969)

TECHNICAL PAPER NO. 35 SERIES A

DRAG REDUCTION ON A ROTATING DISK USING A POLYMER ADDITIVE

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ABSTRACT

The characteristics of frictional drag on a disk rotating in an enclosure filled with water containing various concentrations of guar gum have been investigated.

Measurement of driving torque provided a sensitive means of evaluating the frictional drag reduction relative to water. Reductions ranged up to 60 percent for a smooth disk. Tests with a rough disk showed the expected increase in friction with roughness, but tests with the guar solutions showed approximately the same order of frictional benefits on both the smooth and rough surfaces.

Pitot velocity profile studies of the spiraling boundary layer near the edge of the disk showed significant shifts in the chamber core flow with the addition of guar. While profiles were similar in shape, increasing additive concentration diminished the thickness of the boundary layer. Secondary studies established that the influence of the guar on the Pitot coefficient was negligible.

Studies were made of the durability of the guar under disk shear by operating the disk continuously for extended periods and observing the increase in torque as a function of time. Limited tests indicated that the drag increased gradually for some time before reaching a stable plateau of residual benefits.

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INTRODUCTION

This paper summarizes the results of a thesis study (Ref. 1) to better define the frictional drag reduction which can be obtained when a disk rotating in a finite chamber or enclosure filled with water is treated with various additive concentrations of guar gum.

Guar gum solutions were selected for these tests because a considerable fund of information was available on their general characteristics. This information included the fact that the solutions are good drag reducers, are fairly durable under high shear, and are relatively immune to serious instrumental distortions in Pitot velocity evaluations.

The boundary layer of a rotating disk was selected for these drag reduction studies because of certain unique features and potentials of disk systems. These systems are unique in that their boundary layers normally include the possibility of concurrent laminar, transitional, and turbulent conditions in the modest space which exists between the hub and the edge of the rotating disk. Moreover, these boundary layers may achieve relatively high shear rates and Reynolds numbers in a laboratory facility having relative physical simplicity and modest energy input. In the case of the enclosed disk, there are additional advantages in that the boundary layer is quite accessible and observable, environmental conditions are quite controllable, and only small quantities of additive are necessary for tests. Although disk studies have only an indirect relation to naval hull drag reduction problems, enclosed rotating disks are a common component of many forms of conventional hydraulic machinery and disk friction losses are significant to machine efficiencies. The reduction of these losses by polymer lubrication is an intriguing application possibility.

Boundary layers on enclosed rotating disks have had considerable study in the past. The most pertinent and extensive studies in water are those conducted by Daily and Nece (Ref. 2) at MIT. The only known previous studies using rotating disks with polymer water solutions are those by Hoyt and Fabula (Ref. 3) at the former Naval Ordnance Test Station, Pasadena. The latter studies were confined to torque evaluations with a large tank or unconfined disk and did not include detailed studies of the boundary layer. The present study provides an extension of and a tie between these two earlier studies.

In examining the boundary layers of a rotating disk for insight into the mechanism of dilute polymer solutions, it must be recognized that these boundary layers differ dimensionally in character from those common to pipe flows or flat plates. Fluid elements adjacent to the surface of a rotating disk experience not only the shearing forces of the tangential motion, but are also subject to the radially outward pressure forces of a forced vortex system. In consequence, fluid confined in a cylindrical chamber with a rotating disk boundary at one end and a stationary disk boundary at the other end will experience forces which vary with both the y distance from the face of the disk and the radial distance, r, from the center of rotation. The end result is that near the disks the boundary layer motion is primarily a two-dimensional spiral which is outward-flowing on the rotating disk and inward-flowing on the fixed disk. Between these boundary layers may exist a cylindrical core flow primarily tangential in direction. Superimposed on this core flow is a modest axial flow which moves from the rotating disk toward the fixed disk near the outer wall of the cylinder and in the reverse direction near the cylinder axis.

Daily and Nece (Ref. 2) distinguished four separate regimes in disk flows of this type depending on the axial spacing, s, between disks and the disk Reynolds number ($Re = \omega a^2/\nu$, where ω is the angular velocity, a is the disk radius, and ν is the fluid kinematic viscosity). For low values of Re and s/a, the two boundary layers are laminar and merge together. For larger values of s/a, the two boundary layers are discretely separated by a core flow. At other combinations of Re and s/a, merged and separated turbulent boundary layers may occur. In the study described herein the parameter s/a has been arbitrarily confined to the single value of 0.217 and boundary layer probing has been confined to a region near the rotating disk at an r/a position of 0.765. For these test conditions, the subject boundary layer proved to be of the discrete spiraling turbulent character phasing to a tangential core flow with increasing y values. The tests indicated that, in general, all of the disk was not covered by a turbulent boundary layer but was laminar for an appreciable radial distance outward from the axis.

In the material which follows, the physical test apparatus is described, the drag reduction as measured by torque is evaluated, and the directions and magnitudes of the boundary layer velocity probings are graphically summarized for various speeds and additive concentrations. While most of the tests relate to a smooth boundary, comparative tests with a rough boundary were included to augment the very limited information available on polymer flows with rough boundaries. Additional duration tests were included to evaluate the rate at which the polymer degraded under sustained shearing exposure.

TEST APPARATUS

The experimental apparatus consisted of a machined and polished aluminum disk of 1/4 inch thickness and 19-5/8-inch diameter, rotating within a plexiglas cylinder of 19-3/4-inch inside diameter. The end walls of the enclosing cylinder were spaced 2-1/8 inches from the faces of the disk (s/a = 0.217) as shown in Figure 1. One fixed end wall of plexiglas served for visual observations and support for the instrument probes. The opposite wall was of aluminum and served to transfer heat from the chambered test fluid to an external controlled circulation of coolant water which held test temperatures to a measured range of 45°F to 55°F.

The disk was rotated by a 10 HP electric motor providing selected speeds in a range from 600 to 1800 rpm. Speeds were measured to the nearest 10 rpm by a photoelectric tachometer and torque was measured by a reaction dynamometer to the nearest 0.023 foot-pound. A tare torque measurement permitted suitable torque deductions for shaft, seal, and bearings.

Most of the tests were conducted with the smooth disk, but in one series, roughness material was cemented to one face of the disk. The roughness consisted of "Scotch Tred," made by Minnesota Mining and Manufacturing Co. The uniform roughness had a measured peak to valley height of 0.018 inch.

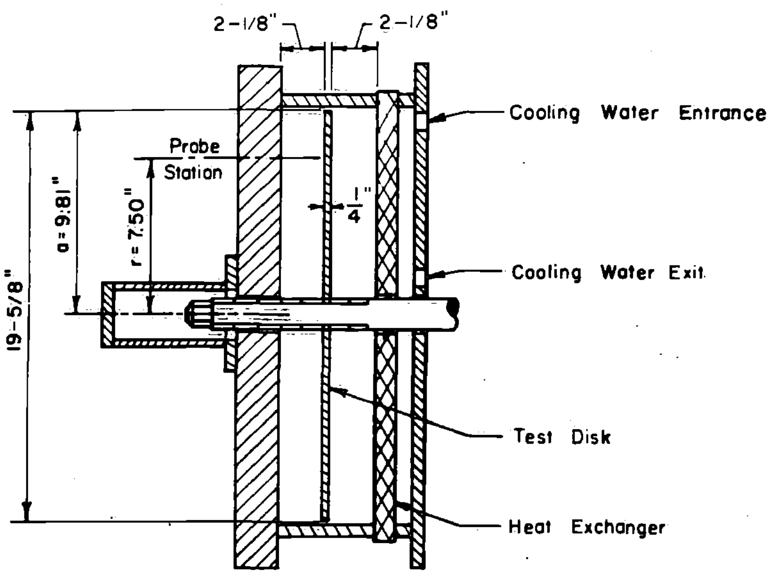

Figure 1 Test Chamber

Measurements of the magnitude and direction of the velocity of the disk boundary layer flow were made at a test station located 7-1/2 inches radially outward from the shaft axis ($r/a = 0.765$). These measurements were made at a y distance from the face of the disk varying from 0.037 to 1.200 inches using separate directional and Pitot-static probes. Determinations of direction were made first followed by magnitude measurements with the aligned Pitot-static probe.

The Pitot-static probe was separately calibrated in the submerged jet issuing from a flow nozzle attached to a head tank. The speed of the test jet was inferred from the measured gravitational head in the tank. The calibrations, which were conducted with both water and guar solutions, are discussed later.

The relative drag reducing characteristics of the guar solutions were evaluated by expelling a test sample through an 0.054-inch diameter capillary tube of 1,000 diameters length under measured pressure conditions. The apparatus and test procedures are described more fully in Reference 4.

The guar gum employed in these tests was Westco J2-FP as manufactured by the Western Company.

RESULTS

Torque Measurements

Measurements of the torque on the disk were obtained for water and six guar gum concentrations using the smooth disk. The guar gum solutions ranged in age from 1 to 3 days. These results, along with torque measurements for water and a solution of 125 ppm using the rough disk, are plotted in Figure 2 using a Reynolds number based on the viscosity of water. For simplicity only the mean line values for the data are shown. Relative values of the torque are represented by a coefficient used by Daily and Nece (Ref. 2) which is

$$C_m = \frac{2M}{\rho \omega^2 a^5}$$

In this, M is the torque, due to two faces of the disk, and ρ is the density. In Figure 2 the rough disk data have been adjusted to account for the actual presence of the roughness on only one side of the disk.

The smooth disk results are comparable to the results that Hoyt and Fabula (Ref. 3) obtained using an unconfined disk. The data describe a fanlike pattern of lines. For the lower concentrations

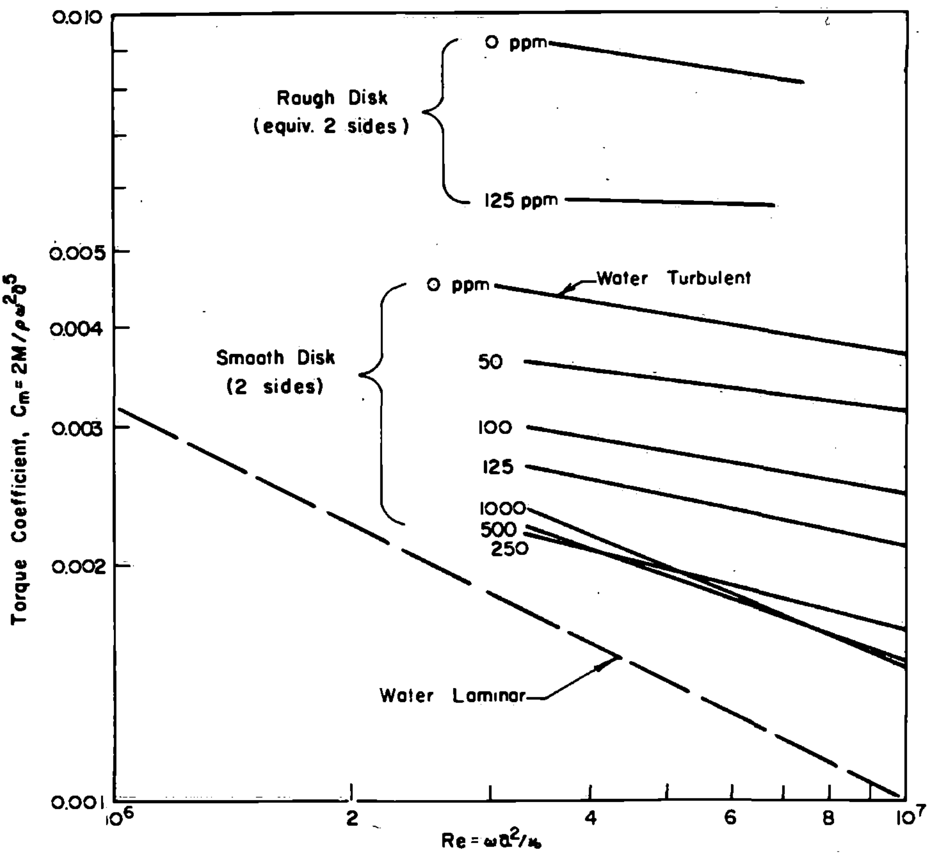

Figure 2 Summary of Torque Measurements

the lines are approximately parallel to the turbulent water line, but for the higher concentrations the data are about parallel to the laminar water line, which has been extended so as to appear in Figure 2. Hoyt and Fabula found that for concentrations below 311 ppm the data approximated the turbulent water data in slope, while for concentrations above 621 the lines were roughly parallel to the laminar water data. These limits seem consistent with the results shown in Figure 2.

The change in slope of the torque data occurs through a range of concentrations that includes the optimum drag reducing concentration. In Figure 2 this concentration is seen to depend on the Reynolds number and varies from 250 ppm to 1000 ppm. For the Reynolds number corresponding to the velocity tests--about 4×10^6--the optimum concentration is about 500 ppm. This optimum value agrees with that yielding a minimum boundary layer as shown in the results of the velocity magnitude tests to be described later. For a Reynolds number of 10^7 the drag reductions obtained in the smooth disk experiments are shown in Table 1.

TABLE 1

Concentration (ppm)	Reduction (%)
0	----
50	14.8
100	33.2
125	42.8
250	54.9
500	58.7
1000	59.4

Figure 2 also shows the rough disk torque measurements. In this case the increased vibrations of the experimental apparatus severely limited the range of Reynolds numbers tested. It is obvious that although the total drag is increased by the roughness, the relative drag reduction is apparently little affected by the addition of roughness to the disk.

Shear Degradation Measurements

Shear degradation tests were conducted for a solution of 500 ppm using the smooth disk and for 100 ppm using both the smooth disk and the rough disk. The results of these tests appear in Figure 3 in terms of the torque coefficient, C_m, and show what apparently is a termination of shear degradation after a given time period. For the smooth disk, this time period is about 30 hours for 500 ppm and about 11 hours for 100 ppm. The rough disk data for 100 ppm showed a greater initial rate of degradation than for the smooth disk, followed by a decrease in the rate of degradation similar to the smooth disk data. However, the testing time period in this case was not long enough to reach a termination of the shear degradation.

The degradation tests indicate a possibly valuable aspect of guar gum solutions in that many degraded molecules can produce a stable drag reduction which is comparable to the initial drag reduction of a lesser concentration of undegraded molecules. For instance, in Figure 3 the 500 ppm solution after 30 hours still has the drag reducing capability of a fresh solution of 75 ppm, as shown in Figure 2, at the same Re. Similarly, the 100 ppm solution after 11 hours compares to a fresh solution of 50 ppm.

Velocity Directional Measurements

Figure 4 shows a mean line summary of the directional data obtained with the smooth disk for guar solutions ranging from 1 to 2 days in age. The data are plotted with angular values

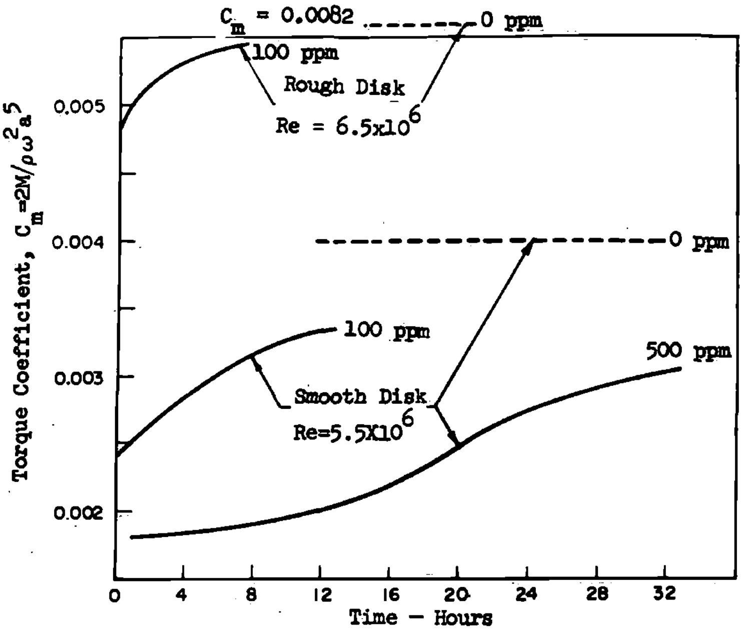

Figure 3 Degradation Measurements

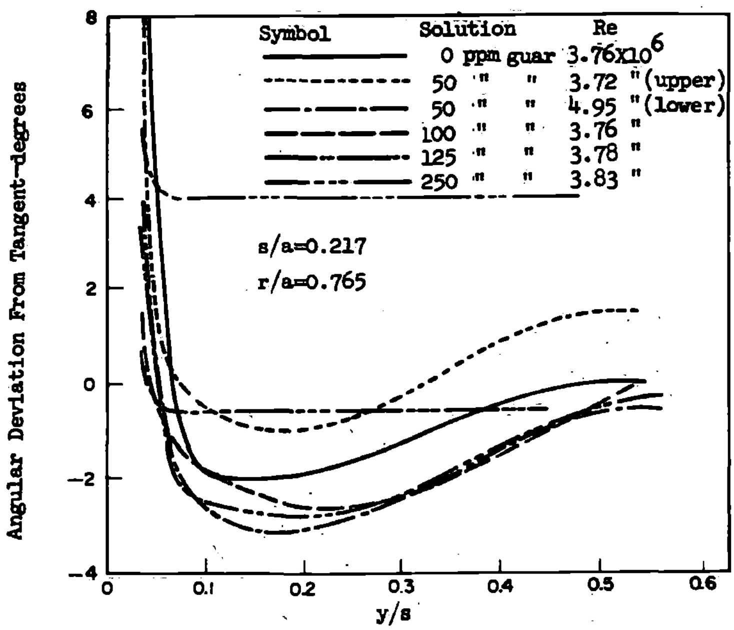

Figure 4 Summary of Directional Tests

referenced to the tangential direction as zero and with values increasing as the radial direction is approached. For the guar gum solutions, the data of this figure show what appear to be the varying effects of transition from laminar to turbulent flow somewhere radially inward of the directional probe. Both the 50 ppm and the 250 ppm solutions yielded data that fell on two separate curves, separated in the core region by 2° for 50 ppm and 4-1/2° for 250 ppm. Tests with 500 ppm and 1,000 ppm both resulted in a complete scatter of data. From these results, it appears that an increase in the concentration of guar gum resulted in increased instability in the flow. Two exceptions to this trend are the 100 ppm and 125 ppm solutions. In each of these cases, the data fell on one curve, indicating either that the instabilities were not present for these solutions or that the instabilities were of sufficiently long time periods so as not to be detected during the tests.

The instabilities seem to be a result of the transition from laminar to turbulent flow on the disk with the region of transition moving radially outward with increasing concentration. During periods of instability, the directional probe could have been sensing either values directly in the transition region or values associated with spiral vortices shed from the transition region. The role of the transition region in the creation of the instabilities was indirectly confirmed by testing the 50 ppm solution at a higher Reynolds number. The increased Reynolds number brought the transition region closer to the center of the disk, and the new data fell on only the lower curve that had previously been obtained for 50 ppm.

The second result inferred from the directional data is a decrease in the thickness of the radial outflow region with increases in concentration. This effect corresponds to the decrease in boundary layer thickness which is also noted later in the velocity profiles of Figure 5.

Velocity Magnitude Measurements

Prior to the measurement of the velocity magnitudes near the disk, the Pitot-static probe was calibrated in the submerged jet from the gravity-fed nozzle. In this calibration the differential pressure coefficient, C_p ($C_p = [h_s - h_o]/V^2/2g$), for the probe was determined for water and for 500 ppm and 1000 ppm of guar gum solutions aged up to 2 weeks. The calibration demonstrated that the effect of 1-day-old guar solutions on the values of C_p was quite small. For 500 ppm the C_p was decreased by 2.8 percent, while for 1,000 ppm, the decrease was 9.4 percent. These effects are much less than those obtained by Wetzel and Tsai (Ref. 5) for an impact probe in Polyox solutions.

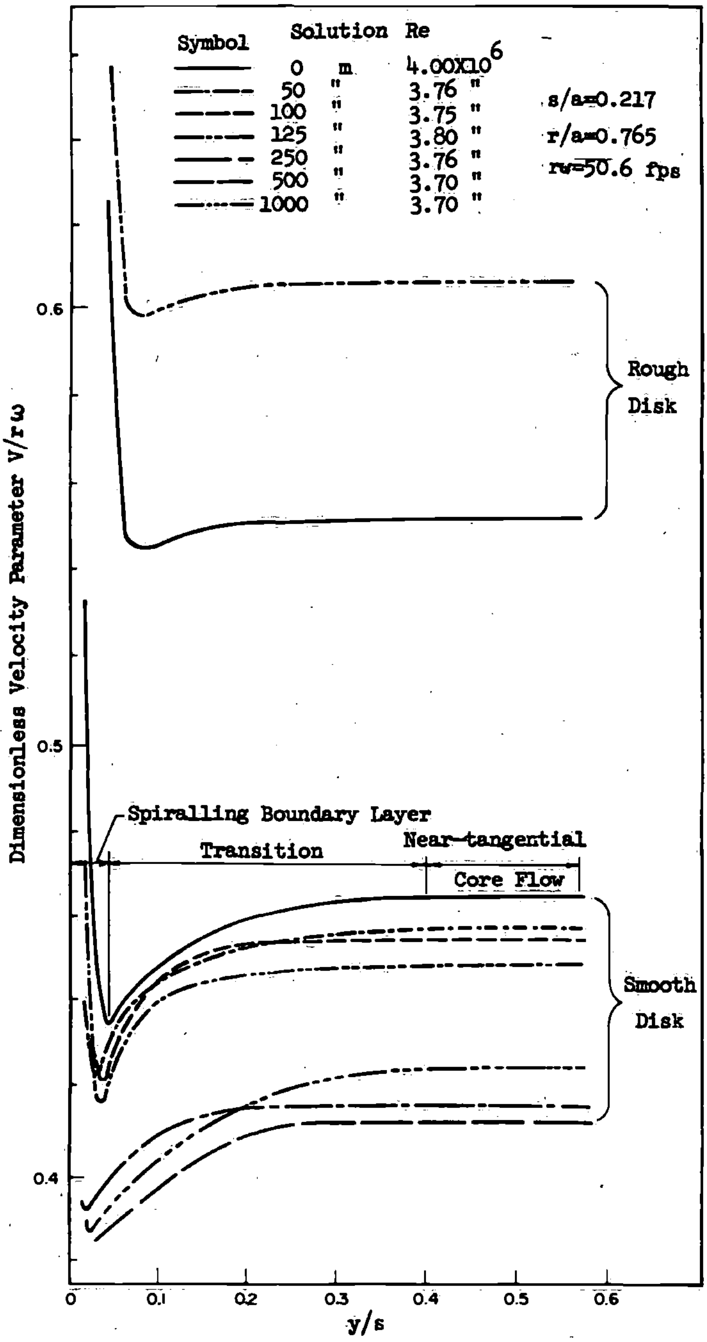

Figure 5 Profiles of Velocity Magnitude

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

St. Anthony Falls Hydraulic Laboratory
University of Minnesota

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

DRAG REDUCTION ON A ROTATING DISK USING A POLYMER ADDITIVE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Paper - May 1967 to May 1968

5. AUTHOR(S) (First name, middle initial, last name)

C. Gorman Gilbert
John F. Ripken

6. REPORT DATE

September 1968

7a. TOTAL NO. OF PAGES

13

7b. NO. OF REFS

6

8a. CONTRACT OR GRANT NO.

N00014-67-A-0113-003, NR 062-388/3-2-66

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

Technical Paper No. 35, Series A

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Disk friction						
Drag reduction						
Polymer additives						

DD FORM 1 NOV 65 1473 (BACK)

S/N 0101-807-6801

Unclassified

Security Classification

A-6

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Office of Naval Research
Fluid Dynamics Branch

13. ABSTRACT

The characteristics of frictional drag on a disk rotating in an enclosure filled with water containing various concentrations of guar gum have been investigated.

Tests with both smooth and rough disks showed the driving torque to decrease up to 60 per cent with additions of guar.

Disk boundary layers diminished in thickness with the addition of guar.

Studies of the durability of the guar under extended disk operation indicated that drag progressively increased with time before approaching a plateau of residual benefits.

The results of the Pitot-static probe calibration changed with the passage of time for a given solution. Calibration tests performed on successive days showed increases in the C_p values until the values of C_p for water were reached. Samples of the solution taken during this time, however, revealed little change in drag reducing ability when tested in the capillary tube rheometer. From these results, it might be inferred that elastic contributions to drag reduction with guar solutions older than 1 day are not appreciable and that the elasticity effects decrease with time. Similar time variance has been reported by Brennen and Gadd (Ref. 6).

The velocity magnitude measurements were performed using both the smooth disk and the rough disk and guar solutions ranging in age from 2 to 5 days. The results of these tests are presented in Figure 5 in terms of a dimensionless velocity parameter. For the smooth disk the velocity profiles show two trends. For concentrations below the optimum drag reducing concentration, increases in concentration yield reductions both in the boundary layer thickness (see Figure 5 for the boundary layer thickness as defined herein) and in the velocity of the core flow. Figure 5 shows that these trends include all concentrations except for the 1,000 ppm solution, indicating that the optimum concentration was less than 1,000 ppm, as noted earlier. The decreases in the boundary layer are observed in Figure 5 by noting that the dip in the velocity profile moves toward the disk as the guar gum concentration increases.

Conversely, the rough disk produced an increase in the core velocity as the guar gum was added. For the concentration (125 ppm) tested with the rough disk, the value of the velocity parameter was 0.61, as opposed to 0.55 for water.

CONCLUSIONS

A smooth disk rotating in a water-filled confined chamber will experience a torque drag reduction of up to 60 percent when guar gum concentrations are increased. The drag reduction is a function of the guar concentration and a Reynolds number. The torque reduction and optimum concentration (500 ppm) were comparable in values to those obtained by Hoyt and Fabula with unconfined chambers.

When treated with guar additive, a rough disk experiences relative torque reduction benefits quite comparable to those experienced by a smooth disk.

When exposed to continuous disk shear, a guar solution evidences a decrease in torque benefits leading eventually to a stable terminal torque benefit. The rate of decrease and the terminal value are a function of the guar concentration and the disk roughness.

Measurements in the boundary layer of a smooth disk indicate that increasing torque benefits are in general accompanied by a decreasing boundary layer thickness, a diminishing angle of spiral in the boundary layer, and a decreasing tangential velocity in the chamber core flow.

The stability of flow in a turbulent boundary layer existing near the edge of the disk depends on the location of the laminar-turbulent transition zone which exists somewhere radially inward on the disk. This location appears to move radially outward as the concentration of guar additive is increased.

The effect of guar additives on the coefficient of a Pitot-static tube is quite minor. For guar solutions that have been aged a few days, this effect on the probe vanishes; but the drag reduction is almost unchanged.

ACKNOWLEDGEMENT

The financial support of the Office of Naval Research, Fluid Mechanics Branch, as a part of Contract N00014-67-A-0013-0003 is gratefully acknowledged.

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