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Eddy Current Drive and Gas Bearing Bob Suspension for Use in Viscometry

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Synopsis

A sensitive concentric cylinder viscometer was developed capable of measuring viscosities of liquids with a precision of 0.2% and an accuracy of 1%. The essential features of this apparatus were a nearly frictionless gas bearing suspension for the viscometer bob and an eddy current torque-sensing device. The viscometer was tested by measuring viscosities of liquids in the centipoise range and determining the elastic behavior of fiber networks suspended in solutions; a torque range of 1–250 dyne-cm. was studied. Based on the results of this work, the apparatus would appear to be an ideal instrument for the study of polymer solutions and particle suspensions exhibiting unusual flow behavior at low shear stresses.

INTRODUCTION

For many years, the concentric cylinder viscometer has been used in determining the flow behavior of solutions and suspensions. Because the rate of shear across a narrow annulus between two cylinders is constant within a few per cent, such an instrument is ideal for the study of shear dependent fluids. Customarily, the bob is either positioned in the apparatus by a vertical shaft mounted in bearings or suspended from a torsion wire. Increased interest in the low stress–low shear rate rheology of certain fluid systems, however, has required more sensitive and versatile viscometer designs.

Scheraga[1] predicted from hydrodynamic considerations that the intrinsic viscosity of a polymer solution would only be constant at low shear rates. Because the relationship between intrinsic viscosity and shear rate is not linear for such solutions, intrinsic viscosities at high rates of shear should not be extrapolated to determine viscosities at low rates. Conway[2] and Eisenberg[3] verified this by studying the viscosity behavior of solutions of deoxyribonucleic acid over a range of shear rates. The Eisenberg study was carried out by using a specially constructed concentric cylinder viscometer[4] capable of operating in the low shear rate range with very good precision.

Maron and Krieger[5] indicated the desirability of investigating the low shear stress behavior of latex suspensions in order to determine how variables such as polymer composition, particle size, and particle distribution affected the rheology of the suspensions. Splitting of ink films in nips has been shown[6] to occur at very low shear stresses. Low shear data on the plastic viscosities and yield points of ink suspensions would, therefore, be extremely useful in explaining some rheological aspects of the printing process. The viscoelastic behavior of such substances as polymers, polymer solutions, and gels has also been studied in a concentric cylinder viscometer. Ferry and Parks[7] showed that the elastic deformation of a polymer could be determined by applying a shear stress to the polymer contained in the viscometer, then removing the stress and observing the elastic recovery.

The requirement of low shear stresses and rates is common to all of these studies. Viscometers employing bobs with rigid shafts mounted in conventional bearings are not suitable for such measurements because of high residual friction in the bearings. A torsion wire would eliminate this friction, but frequent wire change and recalibration would be required to cover more than a narrow range of shear stresses. Furthermore, it would be very difficult to measure the true elastic recovery of a system with this type of apparatus.

In a study of the structural properties associated with suspensions of synthetic fibers,[8] a new type concentric cylinder viscometer (Fig. 1) was developed. This apparatus appears to be especially useful for the study of polymers and other suspensions which exhibit unusual properties at very low shear rates and stresses. The essential features of the apparatus are a gas bearing suspension for the bob and a sensitive eddy current torque-measuring device. The gas bearing virtually eliminates friction in the apparatus, while the eddy current drive permits continuous study over a wide low torque range. In addition, it is only necessary to adjust the gas bearing pressure for studies of fluids of different densities and a simple, inexpensive electrical system is used in the torque measurements. During the investigation of fiber suspensions, torque measurements were made over a range of 1–250 dyne-cm. with a precision of 0.2%. At higher torques, there are indications that the precision of the instrument would be even greater.

PRINCIPLE OF THE APPARATUS

The eddy current drag phenomenon has been used since 1883[9] in such instruments as tachometers and clutches. A magnetic field cutting through a conducting disk generates eddy currents in the disk. These eddy currents, in turn, produce fields which oppose the movement of the original field and thus exert a torque on the disk. The magnitude of the torque is proportional to the speed at which the field cuts the conductor, the strength of the field, and the conductance of the material. The strength of the field may be varied by changing the distance between the magnet and conductor. If the source of the field is an electromagnet, the current to the coils of this magnet may be varied to control the field. Because all these variables may be accurately measured and controlled, this type of torque-sensing device

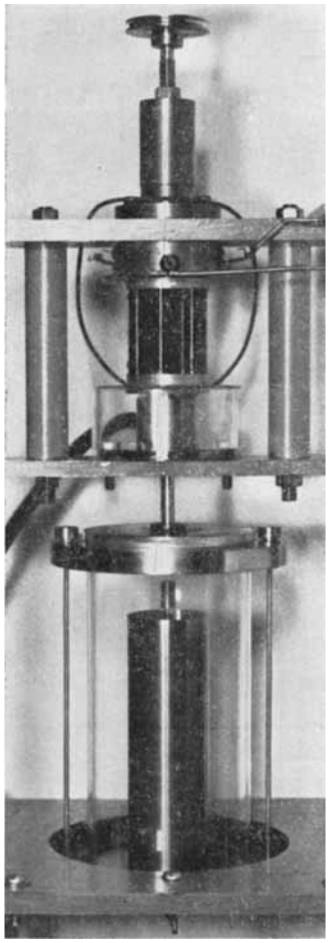

Fig. 1. Concentric cylinder viscometer.

was chosen for this apparatus. In practice, the current to the coils of an electromagnet proved to be the most convenient variable with which to accurately regulate the torque on the bob.

Gas lubrication of bearings[10] has been suggested for use under conditions of extremely high or low temperatures where normal lubricants would be unsuitable. Such bearings have also been used in sensitive instruments[11] where frictional torques of the order of 10^{-3} dyne-cm. were required. The best conventional ball bearings,[4] on the other hand, have residual frictional torques of about 10 dyne-cm. A search of the literature,[12] however, revealed no information which could be used in design of a bearing for a concentric cylinder viscometer. In the present study, a right-angled conical bearing was designed and constructed to give bob support with a low level of friction and satisfactory bob alignment. This bearing proved successful, so other bearing designs were not investigated.

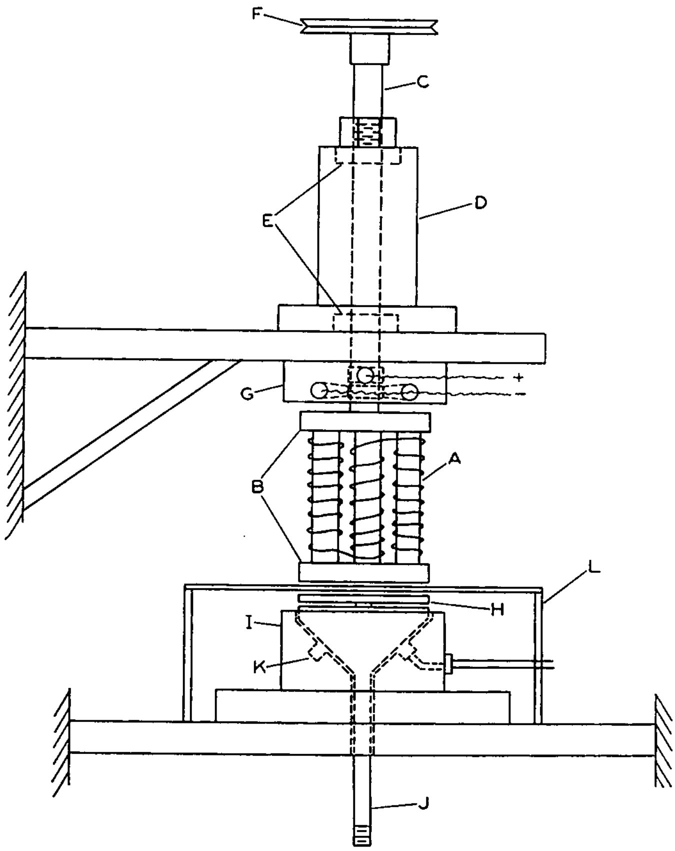

Fig. 2. Detail drawing of gas bearing and eddy current drive section of viscometer shown in Fig. 1.

The eddy current drive and the gas bearing incorporated in the concentric cylinder viscometer are shown in Figure 1; details of the bearing and the eddy current construction are shown in Figure 2.

DESCRIPTION OF APPARATUS

Eddy Current Torque Sensing Device

A rotor section composed of six $^3/_8$-in. diameter, $2^1/_2$-in. long Armco magnet-iron rods, A, spaced at 60° intervals around a $1^1/_2$-in. diameter circle between two magnesium plates, B, was mounted on a vertical brass shaft, C. The shaft was positioned in the bearing housing, D, by two New Departure QOLOO angle contact bearings, E. Pulley wheels, F, of various diameters were attached to the top of the shaft. The coils (25 gage magnet wire, 103 turns on each iron rod) were rotated by a Bodine 1800 rpm synchronous motor at speeds dependent on the pulley wheel diameter.

Current was fed to the coils by means of a slip ring and brush assembly, G, manufactured by the Graphite Metallizing Corp. The strength of the magnetic field was controlled by a Milvay rheostat regulating the current delivered to the coils by a 6-v. storage battery. A Polyranger d.c. ammeter was used to measure the current. Before each run, any residual magnetism in the rods was removed by passage of a.c. current.

A $^1/_8$-in. thick magnesium eddy current disk, H, with the same diameter as the bottom of the rotor was mounted on top of the male section of the gas bearing, I. The top surface of the disk was about $^1/_8$-in. below the rotor. At this distance, small variations in the vertical position of the plate did not noticeably affect the torque output.

Gas Bearing

The gas bearing, I, consisted of brass male and female sections (see Fig. 2). The 90° conical sections of the bearing were identical. A precision fit was insured by turning both sections on the same lathe with identical settings. A cylindrical shaft, J, extended from the bottom of the male section of the bearing. The end of this shaft was threaded, so that either a solid or flexible connection could be made with a viscometer bob. A short cylindrical section at the top of the male portion of the bearing increased the bearing stability. The diameters of the upper and lower cylindrical sections of the female portion of the bearing were such that clearances in the bearing were about 0.002 in.

Gas was fed to the bearing through a channel perpendicular to the conical surfaces. A rectangular groove, K, around the inside of the female section distributed the air evenly throughout the bearing. Gas pressure was controlled by a Conaflow Corp. flow valve (no. 5) and measured with a U-tube manometer. Gas pressures of 0.25–2.5 psig were required to support weights of 75–600 grams. The entire bearing was enclosed in a cylindrical lucite shield, L, to prevent dust and air drafts from disturbing the operation.

Calibration and Operation of Apparatus

The relationship between the torque output of the eddy current effect and the input current to the coils was determined by a static procedure (Fig. 3). Small weights, A, were hung from the end of a nylon filament, B, wrapped around the pulley wheel, C, on the bearing shaft, D. The current in the rotating coils was adjusted so that the bob remained at equilibrium in a position where the supporting filaments, E, formed a 45° angle with the shaft. Under these conditions, the torque from the eddy current effect was exactly equal to that exerted by the weight. Weights of 4–340 mg., equivalent to a torque range of 2.9–230 dyne-cm. were used. Smaller weights appreciably increased the experimental error, while larger weights disturbed the operation of the gas bearing. As will be shown later, the apparatus calibration range may be extended, however, by other procedures.

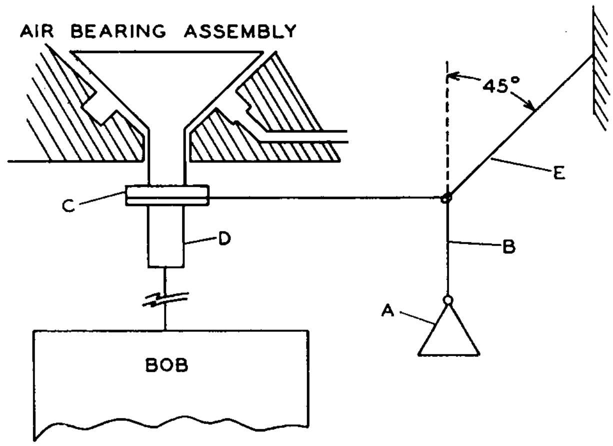

Fig. 3. Static method of calibrating the eddy current drive.

Gas pressures greater than that required to suspend the bob interfered with the operation either through turbulent effects or through an air drive. The pressure required to suspend a given weight was, therefore, determined. This was done by hooking an ohmmeter across the two bearing sections and observing the pressure at which the meter registered infinite resistance for a given load. This pressure corresponded to that required to separate the bearing surfaces. During the use of the apparatus, the pressure–weight relationship was used to eliminate the above effects.

APPARATUS PERFORMANCE

Various liquids and solutions were studied in a concentric cylinder viscometer having a bob length to diameter ratio of 3:1 (bob diameter 2 in.) and an annular gap width of 2.42 mm. The temperature during a measurement was held at 23 ± 0.1 °C. For cylinders of infinite length (no end effects) and very small annulus width, the equation for the torque. T, on the system would be:

$$T = 4\pi h\omega\mu/[(1/r_1^2) - (1/r_2^2)] \tag{1}$$

where h is the bob height, ω is the bob angular velocity, r_1 is the bob radius, r_2 is the cup radius, and μ is the fluid viscosity. By using eq. (1) with the apparatus dimensions and a known fluid viscosity, the torques on a sucrose solution of 1.14 specific gravity and distilled water were calculated and compared with the values obtained in the calibration procedure. The relationship between the two determinations is shown in Figure 4. The slope of the line is about 1% greater than unity. Small changes in the relative motion between the coils and the eddy current disk did not appreciably affect the current–torque relationship, as shown by the excellent agreement between relationships obtained under static and dynamic conditions. End effects encountered with a cylinder of finite length could be

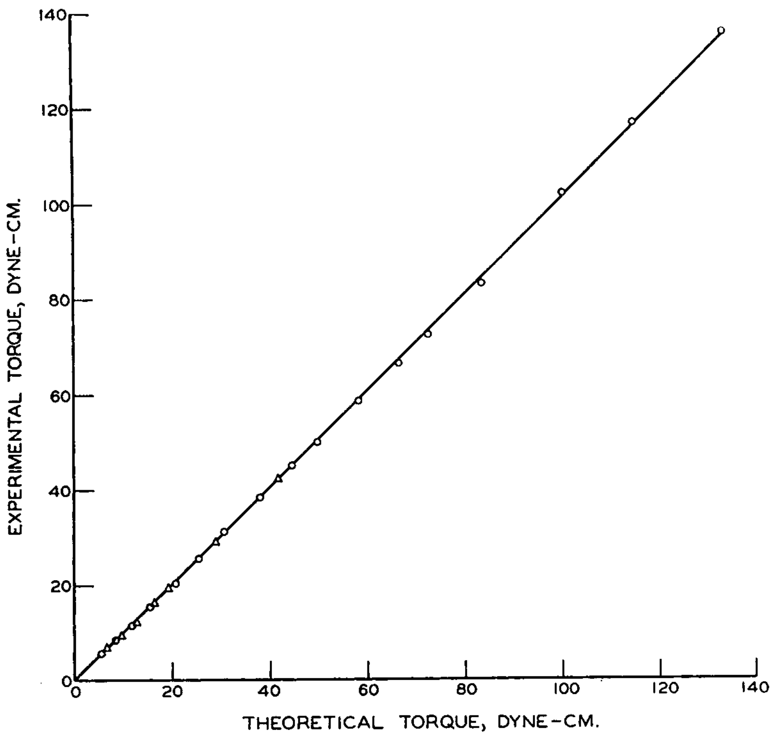

Fig. 4. Relationship between theoretical and experimental torques: (O) water, 23.0°C., μ = 0.933 cpoise; (Δ) sucrose solution, 23.0°C., μ = 3.89 cpoise.

reduced by using a conicylindrical bob and cup combination such as that suggested by Mooney and Ewart.[13] With this modification, it is felt that the apparatus would have sufficient accuracy for use in absolute viscometry. In addition, since the torques determined under static and dynamic conditions are nearly identical, a liquid of known viscosity could be used to extend the range of the instrument calibration.

The stability of flow in the apparatus was studied with fluids of different viscosities, using annuli of different widths. Taylor[14] has shown theoretically and experimentally conditions of maximum stability for a properly designed and precisely constructed viscometer in which the inner bob is rotated. For all combinations of liquids and annulus widths tested, the flow in the apparatus conformed to Taylor's theoretical equations.

The performance of the apparatus in measuring the elastic properties of a nylon fiber suspension is shown in Figure 5. Various shear stresses were applied to the suspension and the resulting deflections were observed. On removing the stresses, elastic recovery was obtained. This behavior is similar to that observed by Ferry and Parks[7] for polyisobutylene. The work reported in this section is preliminary in nature and is intended to indicate some potential uses of this combination of eddy current drive and

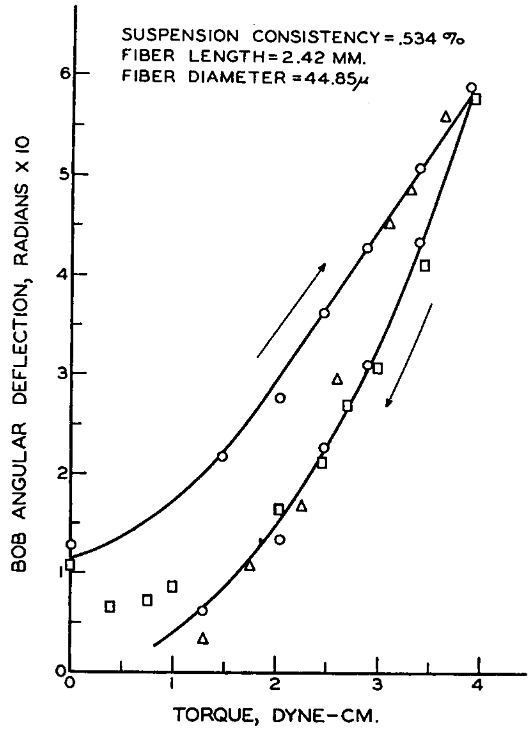

Fig. 5. Shear stress–strain behavior of a nylon fiber slurry, (O) run 1; (Δ) run 2; (□) run 3.

gas bearing in the viscometric investigations of substances such as polymers and suspensions of particles.

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Résumé

On a conçu un viscosimètre sensible à cylindres concentriques capable de mesurer des viscosités des liquides avec une reproductibilité de 0.2% et une précision de 1%. Les aspects essentiels de cet appareil sont une suspension par coussinet de gaz presque sans friction pour le flotteur du viscosimètre et un dispositif à courant de moment de torsion. On a testé le viscosimètre par mesures de viscosité de liquides dans le domaine des centipoises et par détermination du comportement élastique des suspensions de réseaux de fibres en solution. On a étudié un domaine de moment de torsion de 1 à 25 dyne-cm. Se basant sur les résultats de ce travail, l'appareil devrait être un instrument idéal pour l'étude des solutions de polymères et des suspensions de particules présentant un écoulement inhabituel à faible tension de cisaillement.

Zusammenfassung

Es wurde ein empfindliches Viskosimeter nach dem Prinzip der konzentrischen Zylinder entwickelt, das die Messung der Viskosität von Flüssigkeiten mit einer Messgenauigkeit von 0,2% und einer Absolutgenauigkeit von 1% gestatte. Die wesentlichen Bestandteile dieses Gerätes sind eine nahezu reibungslose Gaslager-Aufhängung für die Viskosimetertrommel und eine Wirbelstrom-Drehmomentanzeigevorrichtung. Das Gerät wurde durch Messung der Viskosität von Flüssigkeiten im Centipoise-Bereich und durch Bestimmung des elastischen Verhaltens von in Lösung suspendiertem Fasernetzwerk geprüft; dabei wurde ein Drehmoment-Bereich von 1 bis 250 dyn-cm untersucht. Wie die Ergebnisse dieser Messungen zeigen, ist der Apparat vorzüglich zur Untersuchung von Polymerlösungen und Teilchensuspensionen geeignet, die bei niedrigen Schubspannungen ein ungewöhnliches Fliessverhalten zeigen.

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