A High Reynolds Number Rotating Disk Rheometer

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SYNOPSIS

The construction and principles of operation of a rotating disk rheometer are outlined as is its use in the study of polymeric fluid drag reduction. The need for a sensitive measuring system under a wide variation of Reynolds numbers has prompted the development of a computer-controlled system that allows a systematic measurement of the turbulent fluid frictional difference between dilute polymer solutions. Also, the long-term drag-reducing stability of macromolecules in a turbulent flow field can be conveniently measured. Representative data from experimental measurements are presented demonstrating the capabilities of this instrument. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

Since the 1940s, the phenomena of drag reduction (DR) in turbulent flow has been investigated yet it is not clearly understood. Small amounts of certain additives can cause a marked reduction in fluid friction when in turbulent flow. High molecular weight molecules, micellar systems, fibers, and other solids have been used to bring about drag reduction; however, despite an abundance of investigation into drag reduction, no comprehensive model exists that adequately explains all aspects of the phenomena.[1,2]

Drag reduction has found practical application in irrigation, fire fighting, drainage control, and marine propulsion. To analyze the drag reduction properties of polymeric solutions under turbulent flow, a high Reynolds number, high precision rotating disk system has been developed. A computer control and measuring system has been interfaced which combines a high data sampling rate with accurate disk rotation speed control to allow fluid friction measurements from below the turbulent transition zone to Reynolds numbers exceeding 1,000,000.

The Reynolds number, N_{RE}, a *dimensionless parameter* which represents the ratio of inertial forces to cohesive forces, is defined for a rotating disk by its angular velocity, Ω, the radius of the disk, R, the solution density, ρ, and viscosity, μ, by the equation

$$N_{RE} = \frac{R^2 \Omega \rho}{\mu} \tag{1}$$

where the *angular velocity* is defined as

$$\Omega = \frac{2\pi N}{60} \tag{2}$$

and N is the disk rotation rate in rotations per minute (rpms).[3,4] The fluid friction factor, f, can be calculated from the torque, T_q, required to rotate the disk.

$$f = \frac{T_q}{\pi R^5 \rho \Omega^2} \tag{3}$$

Plots of the friction factor versus Reynolds number can be used to evaluate the drag reduction efficiency of various solutions.

Large molecular weight, water-soluble polymers have been found to be very effective at reducing fluid drag even at very dilute concentrations. Most of the past *DR* measurements have been made using a tube flow apparatus where turbulence is produced by driving fluid through an enclosed channel.[5] In contrast, with a rotating disk geometry, turbulence is produced by driving a surface located within a fluid. This flow situation is more representative of ship movement. In addition, experiments on turbulent DR made by alteration of surface properties can be more readily accomplished on a disk than on the interior walls of a tube. It is known that the *DR*

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performance of polymer solutions decreases with increasing exposure to turbulence. The rotating disk geometry allows convenient measurement of long-term DR properties of polymer solutions.

MEASUREMENT TECHNIQUES

DR Measurements

If f_s is the measured friction of the solvent and f_p is the measured friction of the solution, then in a system with no mechanical friction, such as a capillary system, $\%DR$ is defined as

$$\%DR = \frac{f_s - f_p}{f_s} \times 100 \tag{4}$$

However, since some mechanical friction is observed from the bearings supporting the shaft and disk, a better estimate of the $\%DR$ is given by

$$\%DR = \frac{(f_s - f_m) - (f_p - f_m)}{f_s - f_m} \times 100 = \frac{f_s - f_p}{f_s - f_m} \times 100 \tag{5}$$

where f_m is the mechanical friction observed in a "dry" system. In a "dry" system only a small amount of solvent is introduced into the system to cover the bottom shaft bearing. At higher Reynolds numbers, f_m is much less than f_s and $\%DR$ may be calculated directly by eq. (4).

INSTRUMENT DESCRIPTION

The rotating disk system consists of three primary subsystems (1) the fluid container, (2) a motor drive unit to rotate the disk, (3) and a computer for control and data acquisition.

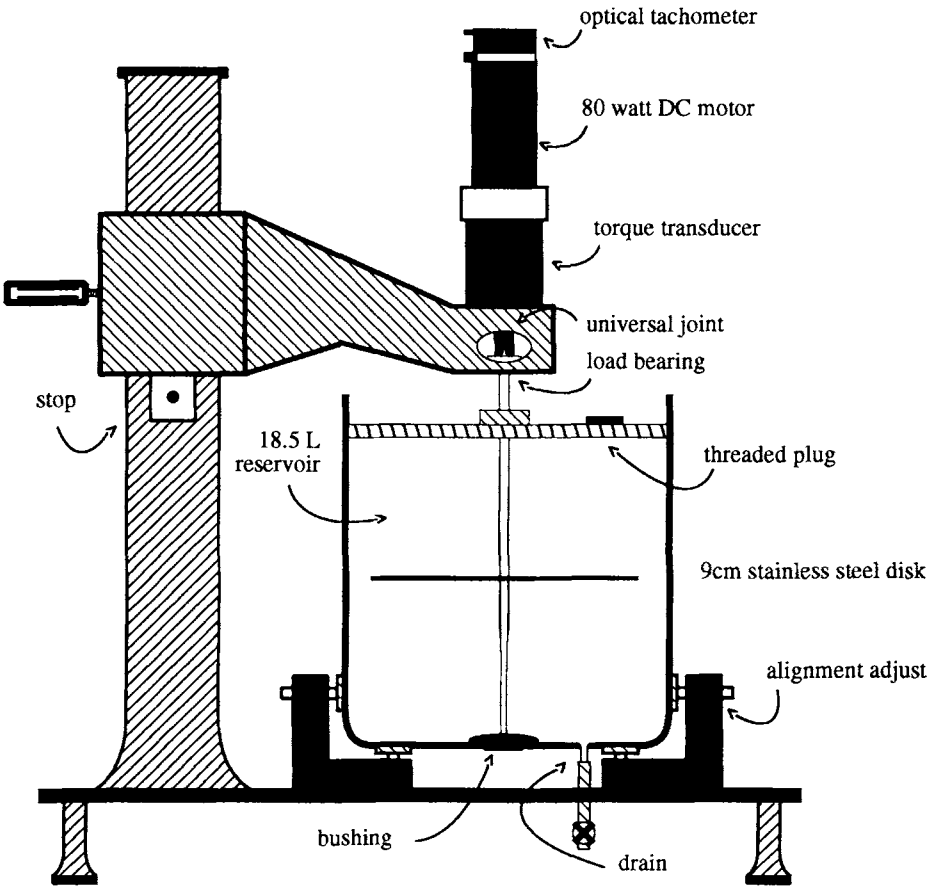

Figure 1 High-precision rotating disk rheometer.

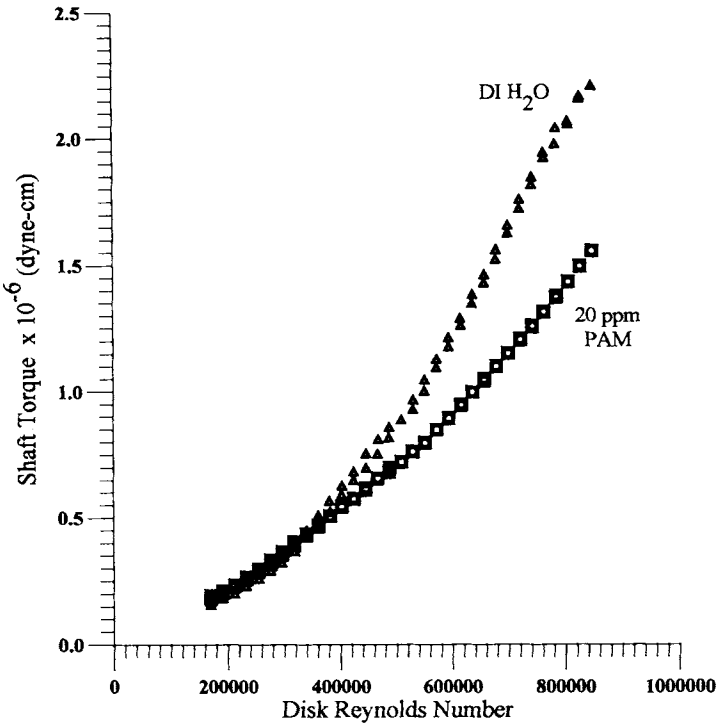

Figure 2 Shaft torque measurement for deionized H_2O and a 20 ppmw solution of poly(acrylamide) in water. PAM sample is American Cyanamid Magnifloc 900N. Molecular weight estimation from viscosity measurements is 2.5×10^6 g/mol. Laminar to turbulent transition Reynolds number is approximately 375,000.

Fluid Container

Figure 1 shows a schematic representation of the existing disk system excluding the computer controller used for data collection and rotation control. The solution is contained in a 18.5-L glass Bell jar (30.5 cm OD, 0.953 cm wall thickness) sealed with a removable 0.635-cm thick polycarbonate lid. The lid eliminates the formation of a vortex at higher Reynolds numbers. The disk is located 15.5 cm from the bottom of the Bell jar or 12.5 cm from the polycarbonate lid. Approximately 18.5 L of fluid are contained within the jar when full. The center of the lid contains a 1.91-cm diameter opening to allow entry of a 1.27-cm diameter stainless-steel shaft which is used to rotate an 18-cm diameter stainless-steel disk having a thickness of 0.152 cm. The 33.0-cm long shaft was made in two parts which allows the removal and replacement of the disk. This design enables future experimentation to be done with coated disk surfaces of varying thicknesses. A 2.54-cm long phenolic sleeve bushing located at the center of the tank base is used to increase the overall stability of the rotating disk.

Motor Drive

An aluminum frame supports the drive motor and insures accurate center and vertical positioning of the shaft with respect to the center of the tank. Four padded alignment pins in the frame allow fine alignment of the shaft with the jar base bushing. By monitoring the shaft torque during alignment, the mechanical friction from this bushing can be minimized.

The motor assembly used to drive the disk consists of a Maxon 80-watt DC motor (model 2260.88-51.216-200) capable of generating disk speeds in excess of 1000 rpm in aqueous solutions. Atop the motor is an HP HEDS-6310 optical tachometer that monitors disk rotational velocity. The motor and tachometer were purchased as a preassembled unit from Maxon. A KEL-F® polymeric coupler joins the motor to a Vibrac TQ-100 transducer capable of measuring 0 to 7.06×10^6 dyne-cm (0–100 oz.-in.) with an accuracy of ±2%.[6] A polymeric coupler was chosen to minimize the influence of motor heat on the performance of the torque transducer. The motor/torque-sensing assembly slides on a square ver-

tical aluminum shaft which allows for disk removal or cleaning of the reservoir without the loss of disk alignment. An interlocking universal joint connects the motor assembly to the disk shaft. The shaft is supported below the universal joint by a MRC H401 stainless-steel load bearing. It was determined experimentally that the polymeric couple between the motor and torque head was insufficient to eliminate all the effects of heat; therefore, the entire motor assembly is wrapped in a water-cooled jacket which maintains a constant heat flux from the motor to the torque measuring transducer. This addition greatly improved the precision of the torque measurements which are used to construct plots such as shown in Figure 2.

Computer Control Interface

The rheometer controller comprises three subsystems in relation to the motor/encoder assembly as shown in Figure 3. The controller system was fabricated for four main functions: (1) to control motor speed, (2) to provide motor speed feedback in digital format, (3) to acquire torque transducer measurements, and (4) to provide motor voltage and current feedback in digital format to be used to calculate torque values by power consumption. This enabled a check on torque measurements obtained from the torque transducer. The first subsystem, the command center, is an IBM PC/XT which contains the command center interface (CCI) (see Fig. 4). The CCI is responsible for the PC bus decode logic, torque transducer output, digital motor speed control, and shaft speed measurement. The motor speed control signal is a 12-bit control word that is converted to an analog voltage by the hardware control assembly (HCA). The control word is adjusted several times per second by the control software to maintain a steady motor rotational speed. The torque measurements received from the torque measurement system (TMS) and rotational speed

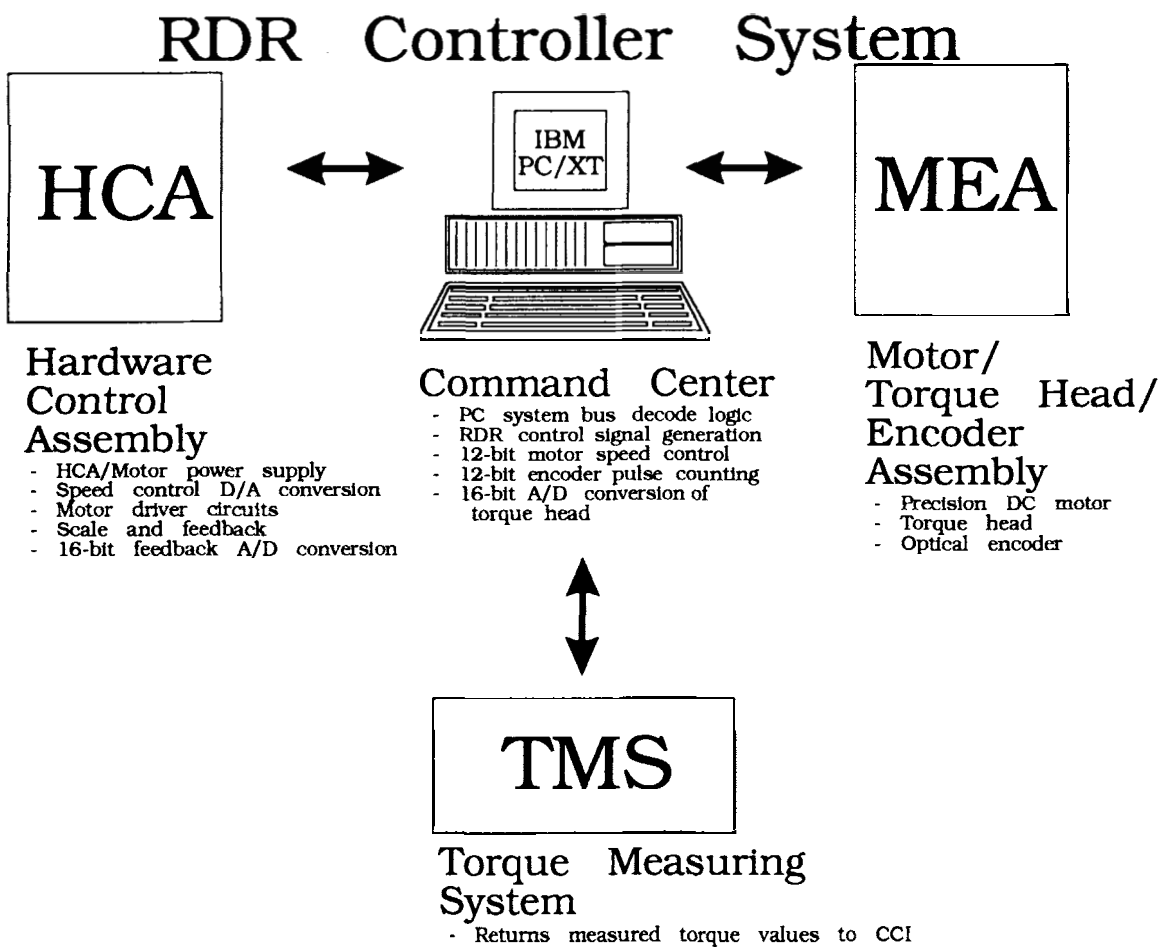

Figure 3 Rotating disk control system.

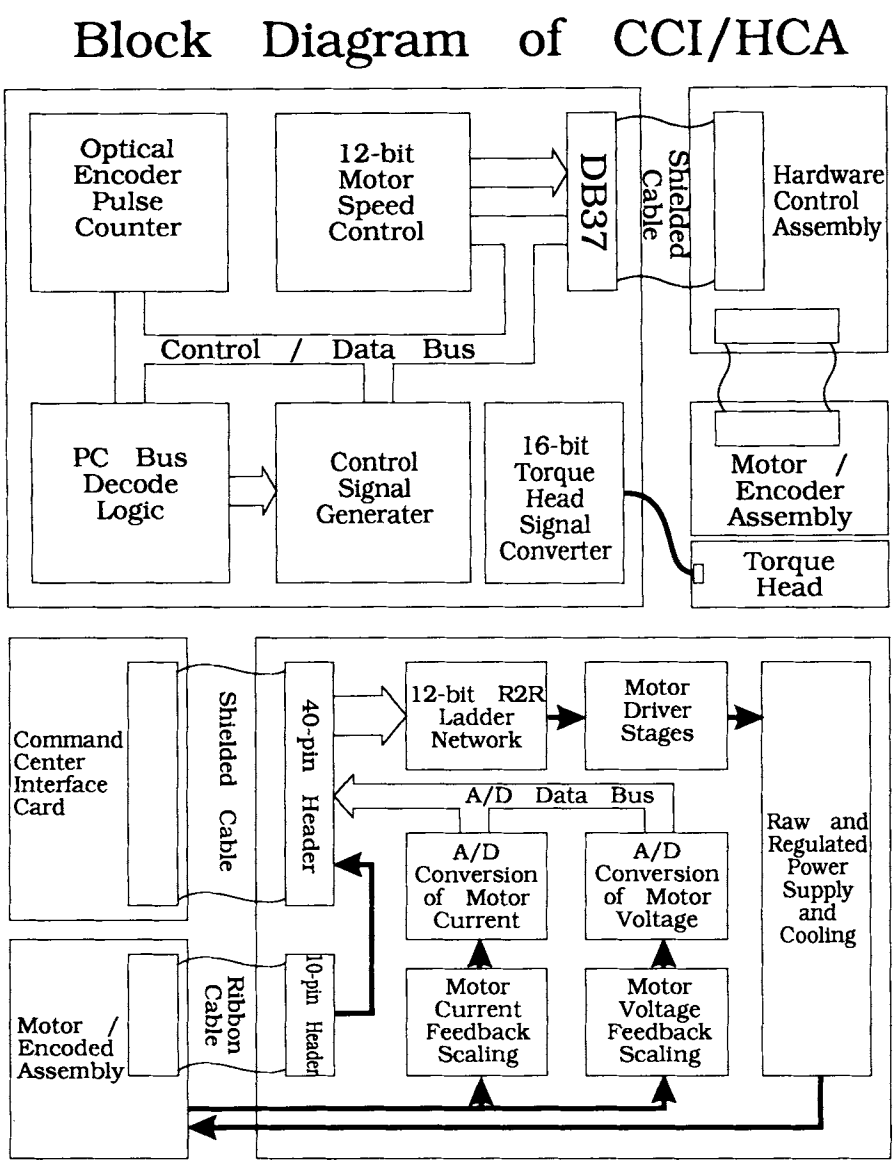

Figure 4 Command center interface (CCI) and the Hardware Control Assembly (HCA).

from the HCA are the only measurements needed for calculating the amount of fluid drag reduction relative to a standard fluid. The motor voltage and current feedback are also returned from the HCA and were used to calculate torque from motor power consumption, but these torque values had a lower precision than those obtained with the TMS.

The CCI communicates directly with the second subsystem, the TMS. The TMS consists of the Vibrac TQ-100 torque transducer and its measurement electronics. The transducer measures torque by optically monitoring the deflection in a calibrated torque bar. The amount of light transmitted by the photocell inside the transducer is directly proportional to the twist angle of the torque bar. The torque bar is known to deflect 0.5 degrees with a torque of 7.06×10^6 dyne-cm, the maximum rated torque for this system. The analog signal from the TMS is sent to an A/D converter located at the CCI.

The CCI also communicates directly with the HCA, the third subsystem. When the 12-bit control word is received from the CCI, it is converted to an analog voltage by way of a R2R ladder. This R2R ladder scales its output between 0 and 5 V in increments of 1.22 mV (5 Volts/2^{12} bits). This output is then sent to the motor driver stages which consist of three LM124AJ operational amplifiers. The purpose of the driver stages is to convert the 0- to 5-V

signal to a 0- to 12-V signal to control the speed of the 80-W DC motor. The motor rotational speed is measured by a HP HEDS-6310 optical tachometer. This tachometer sends 1,000 pulses per revolution. With the onboard system clock in the PC used as a timer, the software converts these pulses to rpm values with a ±1 rpm accuracy.

Computer Control Software and Data Acquisition

Three primary programs have been written to control the operation of the rotating disk system. All programs are written in Modula-II and are specific to the Microsoft MS-DOS® operating system and the IBM-PC architecture. A common "configuration" file is used by all three programs which contains specific information on the mechanical and solvent torque, calibration constants, and data acquisition parameters. A different configuration file is created for each solvent system during calibration and, once created, is changed when the solvent is altered.

To control the system, a data acquisition and control system has been written to supervise the operation of the electronics. Using a multitasking programming structure, rotational speed (and hence N_{Re}) from the optical encoder and torque from the torque head are continually monitored. A feedback loop using the rotational speed is used to control the 12-bit control byte which governs motor power. A deviation between the set rpm value and the measured rpm value invokes an increment or decrement in the control byte which adjusts the motor power to compensate for the measured change. The priority of the updating and measuring routines may be changed to "tune" the system to give high rotational stability. Typical disk speed stability is ±1 RPM. The software also monitors the disk torque when changing N_{Re}s thus allowing the fluid system to come to equilibrium before measurements are made.

The first program of the computer software, CALIB, is used with the solvent only and acquires the necessary information for setting the configuration file constants. *SWEEP* is a multiReynolds number program that allows acquisition over a broad range of Reynolds numbers. Typical data from *SWEEP* is shown in Figure 5. *DEGRAD* is a modification of the sweep program and is used for measuring changes in drag reduction behavior with respect to time. *DEGRAD* runs at a fixed N_{RE} (user selectable) and acquires data of the type shown in Figure 6. The base routines for all three programs are created from common modules, and the Modula-II programming language allows quick and easy modification of the existing programs and the construction of new ones.

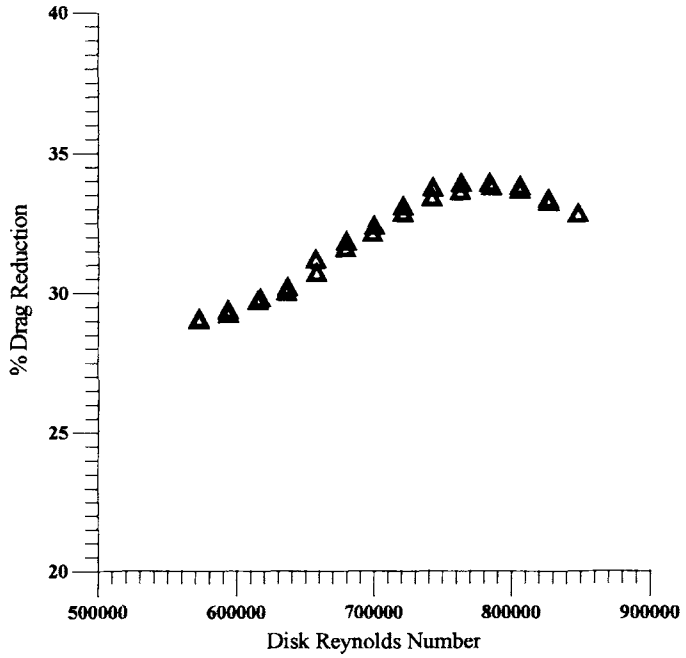

Figure 5 Reynolds Number sweep of a 20 ppmw PAM (American Cyanamid 900N) in deionized H_2O. Data acquired *via SWEEP* program.

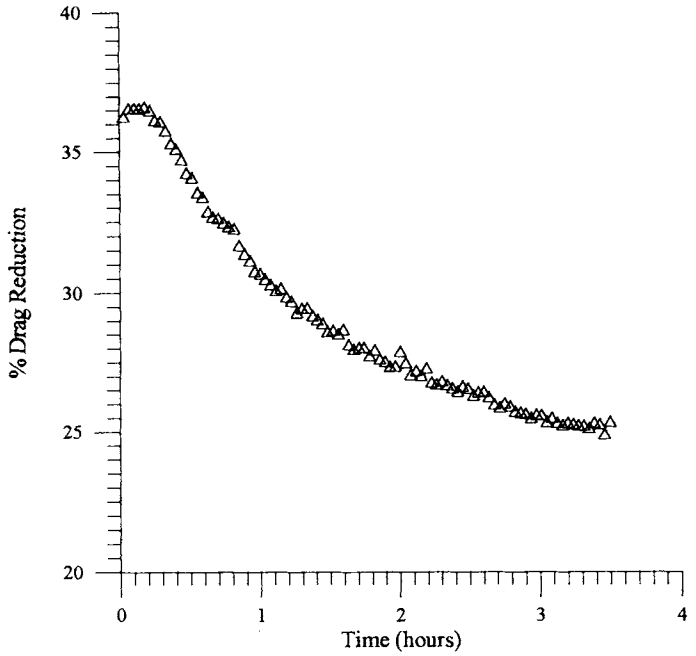

Figure 6 Time dependence of %DR for 25 ppmw PAM (American Cyanamid 900N) in deionized H_2O. Disk N_{RE} is 900,000.

To achieve the highest possible precision of measurement, a fourth program, *DELTA*, has been developed to operate only at fixed Reynolds numbers. The disk is filled with solvent, then a calibration run is made at two Reynolds numbers corresponding to disk speeds of 800 and 1000 rpms [see Figs. 7(a and b)]. An aliquot of the concentrated polymer solution is then added to the reservoir through the entry port in the lid and measurements are again taken at the two Reynolds numbers. At each Reynolds number, the values for *%DR*, the disk friction factor, shaft torque, and so on, are calculated and stored. Low-speed disk rotation is done prior to measurement to insure good polymer-solvent mixing. Appropriate delay constants are included in the software to insure good solution mixing at low speeds and that steady-state torque is reached at high speeds. The advantage to this technique, especially with polymer solutions, is that the time required for an experiment is less than 5 min which minimizes the effect of any polymer degradation.

CALIBRATION

Since *%DR* is a difference measurement between solvent and solution, the solvent torque measurement must be recorded prior to an actual solution experimental run—much the same way a solvent "blank" is run before most solution optical measurements. In this case, two such "blanks" are run: one for the mechanical torque of the instrument and one for the solvent. The torque measurements for these systems (usually 60–80 data points over the range of N_{Re} are fit to a 6^{th} degree polynomial using a least squares fitting algorithm. The coefficients from this fit are stored in a configuration file that is loaded by the software prior to each run. A unique file is created for each solvent system.

Once the configuration file is created, the solution DR measurements may be taken. At run time, the software loads the current solvent configuration file. When a solution's measurement is taken, the mechanical and solvent torque are estimated by using the calibration polynomials and *%DR* is evaluated using eq. (5). The advantage of separating the mechanical torque from the solvent torque is twofold: (1) the evaluation *%DR* is more "correct" by eq. (5) than eq. (4), and (2) mechanical maintenance or shaft realignment can be done without recalibrating for each solvent system. When routine checks indicate a deviation from the initial mechanical fit, typically the load bearing has worn. Replacement of this bearing and a recalibration run of the mechanical torque is all that is needed. These new mechanical values can now be added to the existing configuration file for each solvent without recalibrating for each solvent.

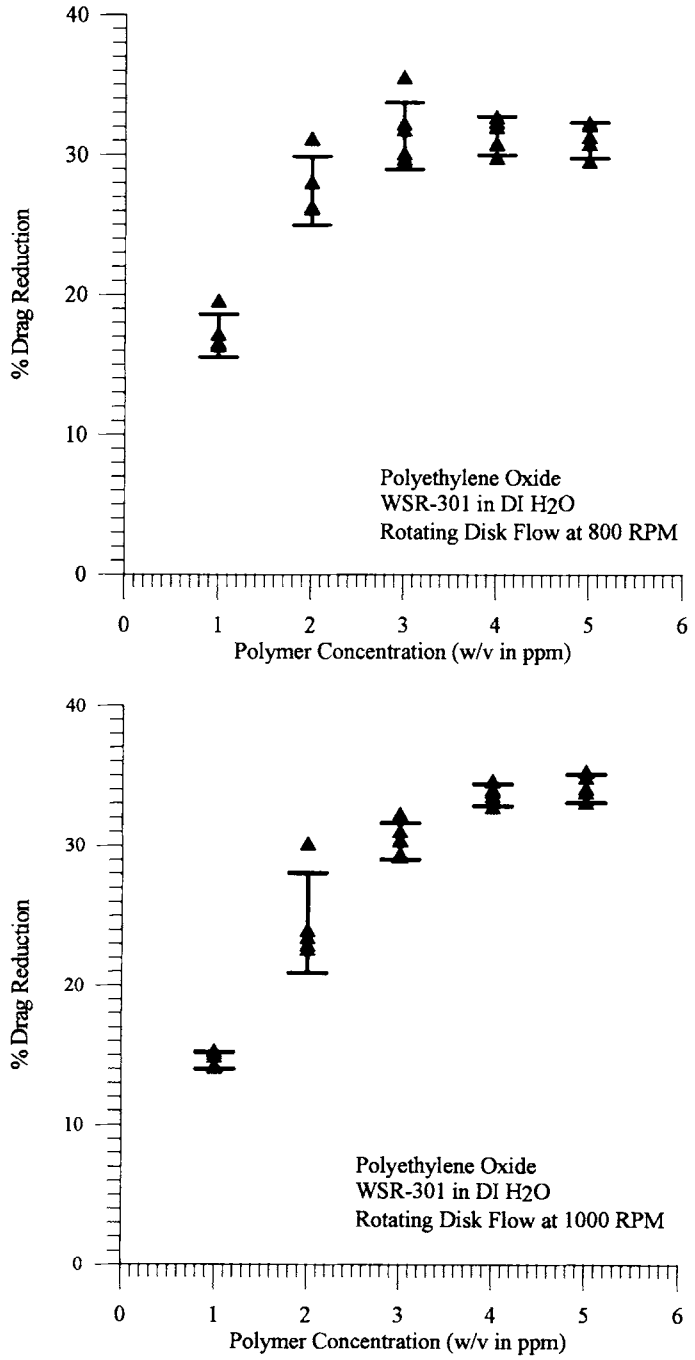

Figure 7 (a and b) Concentration dependence of %DR of various concentrations of poly(ethylene oxide) in deionized H_2O. PEO sample is Union Carbide WSR-N-60K. Molecular weights from size exclusion chromatography measurements are 2.5×10^6 g/mol for weight average and 900,000 g/mol for number average.[7] Scale bars indicate 95% confidence interval. All data acquired using the *DELTA* program.

Time Dependence

Many polymer systems, especially polymers with hetero-atoms in the backbone are susceptible to time-dependent changes in DR. Polyethylene oxide (PEO) is especially sensitive to time-dependent reduction of DR. Polyacrylamide (PAM) also shows a time-dependent reduction in DR (Fig. 6). This

reduction is usually attributed to fluid shear forces which lower the polymer molecular weight. Prior to detailed analysis of a polymer sample, a time-dependent study is done using the *DEGRAD* program. The parameters for the *SWEEP* may be altered to increase or decrease the number of Reynolds Number conditions sampled and/or the number of samples taken at each N_{Re}. The average time for a sweep from 500,000 to 900,000 N_{Re} incrementing by 20,000 is approximately 15 min; therefore, the polymer in question must maintain a reasonably stable signal over the duration of the sweep. PAM has proven acceptable for using the *SWEEP* analysis, while PEO is too shear sensitive and experiences degradation during this time period.

INSTRUMENT MAINTENANCE AND DURABILITY

Once the torque transducer has been calibrated, the system provides a quick and accurate means of characterizing the DR profile of a polymer solution. DR behavior has been accurately recorded in solutions as dilute as 5×10^{-7} g/mL. The greatest amount of error introduced into a system typically comes from the cumlative error in measuring the concentration at such extreme dilution.

Various solvent systems, such as sea water, urea solutions, and concentrated salt solutions, have been analyzed with no adverse effects to the disk components. Once calibrated, only periodic checks with the solvent need to be run to insure reproducibility. Periodic checks are also made of the mechanical torque experienced by the instrument. Any effects of wear in the bushing at the bottom of the tank can be overcome by small adjustments made to the stop position on the motor support column (see Fig. 1).

Experimentally, the mechanical torque measured was found to be less than 5×10^4 dyne-cm, even in excess of 1,000 rpm. Contrast this with water, which has torque of approximately 2×10^6 dyne-cm at 1,000 rpm. For this reason, it is usually ignored in *%DR* calculations. Visually, the system is remarkably stable with the disk surface appearing almost motionless at high-disk speeds.

CONCLUSIONS

At the time of this writing, two such disk systems are operating at the University of Southern Mississippi Department of Polymer Science. Experimentation with these two devices has proven them to be effective, dependable instruments for characterization of various water-soluble polymer and copolymer systems. The disk systems can measure solution *%DR* with a precision of ±0.5% in the disk N_{Re} range of 450,000 to 1,000,000.

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