NOTES

Direct Measurement of the Thrust Response Time in a Modified Weissenberg Rheogoniometer

In shearing a non-Newtonian fluid and measuring the generated normal thrust $F(t)$, a degree of uncertainty might arise as to whether or not the monitored response is a true normal thrust measurement of the testing fluid and proportional to $N_1(t)$, the primary normal stress difference. Unless the response time τ for the thrust-measuring system is much smaller than the time interval during which $F(t)$ changes appreciably, the interpretation of the experimental results becomes obscure.

For a Newtonian liquid, $\tau = 6\pi\eta R/k\theta^3$, where η = viscosity, R = gap radius, θ = gap angle, k = combined spring and apparatus stiffness, and τ = time taken to attain 63.2% of equilibrium displacement following a step function change in $F(t)$. The theoretical analysis of the normal force measuring system with a non-Newtonian fluid in the gap is of interest, but the analysis requires the knowledge of the fluid constitutive equation which might not be readily available. Therefore, an experimental approach seems more desirable.

The shortcoming of the normal thrust measuring system in the Weissenberg rheogoniometer (WRG) was initially expressed by Huppler et al.[1] and later by Sakai et al.[2] The need for a stiff normal thrust system was first recognized by Mills[3] who replaced the soft spring servomechanism of the commercial WRG with a stiff piezoelectric crystal system. Mills measured τ directly by adding and removing up to 100-g weights on a platform under the cone when a 4° cone was filled with a 10^6-poise viscosity fluid. Meissner[4] also used a stiffer force-measuring system and, a stiffer apparatus frame, and, by shearing a molten polyethylene, showed directly that 2° and 4° gap angles gave erroneous results for $N_1(t)$. Crawley[5] and Chang[6] have reported similar undesirable artifacts attributed to gap angle smallness and spring softness, respectively.

Our Weissenberg rheogoniometer is modified like Meissner's, and the improved temperature control system[7] uses still more room which adds to the burden of placing a platform under the cone and adding large weights to the platform. Previously, Hansen and Nazem[8] used a steel rod under the cone instead of a platform and obtained the response time of the thrust-measuring system using loads of up to 2 kg. However, the steel rod would have interfered with the rotation of the cone which limited the response time measurements to the condition of the stationary cone. In the present research, we have circumvented this difficulty by adding a system of fixed electromagnets which attract a rotating plate (fixed to the cone shaft and hereafter referred to as the force plate) when energized. Our electromagnetic system has an additional advantage in that it can conveniently apply large loads of up to 10 kg on the cone assembly of the WRG and in a symmetrical fashion.

APPARATUS

Our electromagnetic system is made of 14 electromagnetic pole pieces, planted firmly on a base plate, and a circular force plate with a radius of 3.8 cm. The poles are placed in a circle 3.2 cm away from the center of the base plate with 0.1 cm distance between each neighboring poles. Each pole is wound with 300 turns of no. 24 copper wire of 0.7 Ω total resistance on a soft iron core. Figure 1 represents views from the top and side of the magnetic system, without the force plate, along with a drawing for the core of the pole. The position of the magnetic system in relation to other components of the normal force measurement system is shown schematically in Figure 2. The lower platen shaft A passes through a clearance hole (2 cm radius) in the center of the base plate B. The force plate C is firmly attached to the lower platen shaft A (radius 0.5

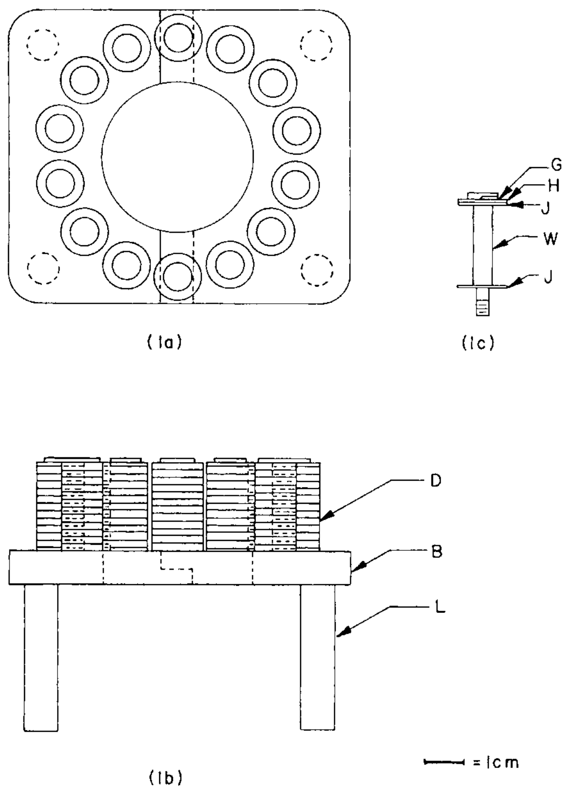

Fig. 1. Views from the top (1a), the side (1b) of the base plate B and the poles D of the electromagnetic system, and a drawing for the core of the pole (1c): G = milled slot for entrance leads; H = brass retaining washer; J = Teflon insulating washer; W = soft iron core; L = legs and the mechanical ground.

cm). The lower assembly made of the base plate B, and the poles D are firmly attached to the frame of the WRG and considered to be the mechanical ground.

To design the magnetic system, we used the equation[9]

$$f = SV\mu/4a^2r^2 \tag{1}$$

where f is the magnetic force/pole pair which is a function of gap permeability μ, surface area of each core S, applied voltage per pole pair V, average resistance r of the wire per turn, and the gap distance a between the poles and the force plate. We chose 0.05 cm for a, and r was 0.00237 Ω/turn.

Upon application of a certain voltage, a magnetic force is generated, attracting the force plate C toward the poles D. Therefore, the lower platen shaft A will impose a force on the normal thrust cantilever spring E, causing spring deflection from the null equilibrium position. Using a linear variable differential transformer FF, the deflection of the spring E is monitored and the rise time of the normal force measuring system obtained. Similarly, the fall time of the measuring system is also determined by reversing the above procedure. With no liquid in the cone–plate gap, we found that the rise time for the low pass filter (Fig. 2) was 0.0015 sec, the rise time of the LVDT signal conditioner was 0.001 sec, and the rise time of the thrust spring was 0.0018 sec without the damping diode Q and 0.01 sec with the damping diode.

RESULTS AND DISCUSSION

Results of τ measurements using the electromagnetic system are given in Table I. Typical oscilloscope plots of spring deflection versus time used to determine τ are given in Figures 3 and 4, corresponding to the conditions that the gap volume was filled either with air or with a molten

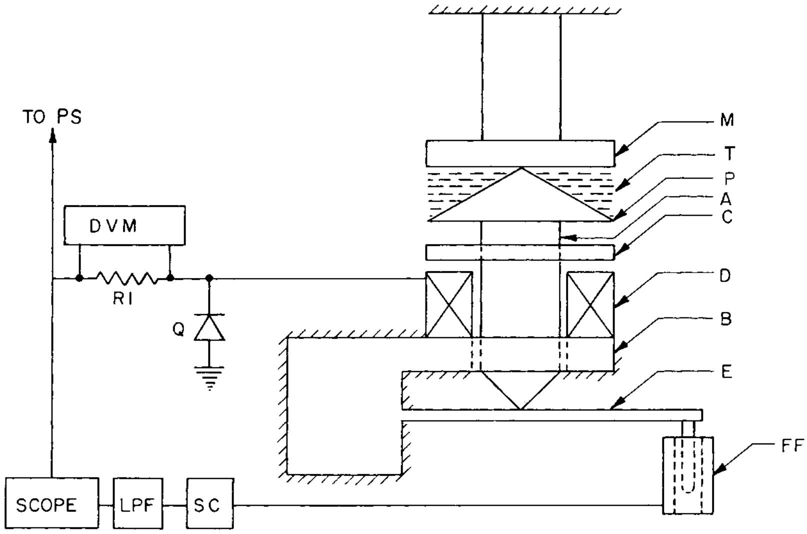

Fig. 2. Electromagnetic apparatus and the normal thrust-measuring system: M = WRG upper platen; T = test fluid; P = WRG lower platen; A = cone drive shaft; C = force plate; D = magnetic poles; B = base plate; E = cantilever spring; FF = linear variable differential transformer; Q = damping diode; SC = LVDT signal conditioner; LPF = low pass filter (500 Hz, 5 pole chebyshev 0.5 db); SCOPE = oscilloscope; R1 = 1 Ω current sense resistor; DVM = digital voltmeter; PS = power supply.

polyethylene (zero shear rate viscosity = 5 × 10^5 poises at 150°C). Columns 7 and 8 of Table I represent the measured rise and fall times, defined as the times required to attain 63.2% of the equilibrium values after application and removal of a load.

A correlation between values of the input voltage to the circuit and applied magnetic load on

TABLE I
Response Time of the Normal Thrust-Measuring System[a]

Experiment no.	Load, g	Rotation speed, radian/sec	In gap	Gap angle, degrees	Shear strain, shear units	Time to reach 63.2% of equilibrium, sec	
						Rise	Fall
1	927	0	air	8.046	0	0.032	—
2	927	0.7	air	8.046	0	0.030	0.010
3	1,624	0	air	8.046	0	0.028	—
4	1,624	0.7	air	8.046	0	0.028	0.012
5	427	0	LDPE	8.046	0	—	0.012
6	1,624	0	LDPE	8.046	0	0.032	0.014
7	1,624	0	LDPE	1.920	0	1.60	—
8	1,624	0.7	LDPE	8.046	19.0	0.036	—
9	1,624	0.7	LDPE	8.046	22.5	—	0.014
10	1,624	0.7	LDPE	8.046	85.0	0.036	—
11	1,624	0.7	LDPE	8.046	88.5	—	0.012
12	1,624	0.7	LDPE	8.046	128.0	0.034	—
13	1,624	0.7	LDPE	8.046	131.5	—	0.014
14	1,624	0.7	LDPE	8.046	193.0	0.036	—
15	1,624	0.7	LDPE	8.046	196.5	—	0.016
16	1,624	0.7	LDPE	8.046	239.0	0.036	—
17	1,624	0.7	LDPE	8.046	242.5	—	0.016
18	1,624	0.7	LDPE	8.046	18.5	0.034	—

[a] Gap radius = 1.2 cm, spring constant = 10 kg/1 μm.

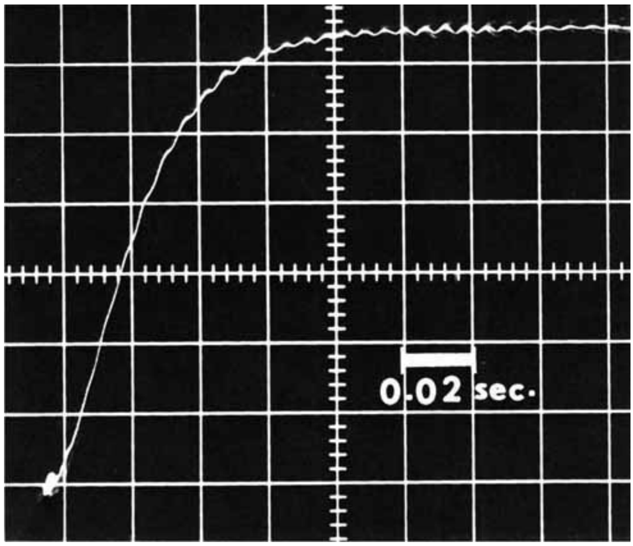

Fig. 3. Response of the normal force-measuring system to a sudden magnetic load application, experiment 3: applied load = 1,624 g; air in gap; no rotation; vertical sensitivity = 0.5v/division; horizontal sensitivity = 0.02 sec/division; time to attain 63.2% of equilibrium value = 0.028 sec.

the force plate was established by recording the deflection of the thrust spring for different applied voltages and for different weights placed on the cone. By changing the input voltage to the circuit, the influence of the magnetic load on the response time of the thrust measuring system was determined. Column 2 of Table I represents the loads in grams. Comparing the rise times of experiments 2 and 4, the response time of the apparatus was found to be independent of the applied load, within experimental error. Column 3 indicates whether the cone was rotating or kept stationary. The excellent agreement between the rise times of experiments 3 and 4 testifies that the point of contact of the thrust spring E and cone drive shaft A does not change due to the rotation of the cone. Hence, cone rotation (without molten polyethylene in the cone–plate gap) does not effect the response time of the thrust measuring system.

Columns 4 and 5 of Table I contain information which illustrates the effect of radial flow on the response time of the thrust system. Comparing the rise time of experiment 3 (air in the gap) with the rise time of experiment 6 (gap filled with molten polyethylene at 150°C), one concludes that the molten polyethylene influences the measured response time, but not appreciably more than the experimental error encountered in our measurements. However, if the gap angle is reduced from 8.046 degrees to 1.92 degrees as in experiments 6 and 7, respectively, the response time of the thrust system due to the slow and controlling nature of the radial flow in the gap significantly increases. Therefore, in agreement with Meissner,[4] the use of a nominal 2-degree cone with a gap radius of 1.2 cm and normal force spring constant of 10 kg/μm is not suitable for measuring the normal thrust transients when shearing the above polyethylene at 150°C. Hence, our electromagnetic system can provide guidance in choosing a proper cone angle for transient experiments.

Column 6 of Table I shows the shearing strain in the sample when a load was imposed on the shearing specimen or removed from the sample by the electromagnetic system. Comparing the rise times of experiments 8, 10, 12, 14, 16, and 18, we conclude that the shearing of the molten polyethylene at 150°C does not have an appreciable effect on the rise time measurement. However, those experiments give a slightly different rise time than that of experiment 6. This small difference can be accounted for by the poor resolution of the oscilloscope trace photograph for these experiments. We have reached the same conclusion about the fall time of experiments 9, 11, 13, 15, and 17 and their comparison with the fall time of experiment 6. Comparing the fall time with the rise time for each experiment in Table I, the fall time is significantly less because of the added series resistance from the diode Q in the resistance–inductance circuit (with elements Q and D) when diode Q is conducting during turn-off.

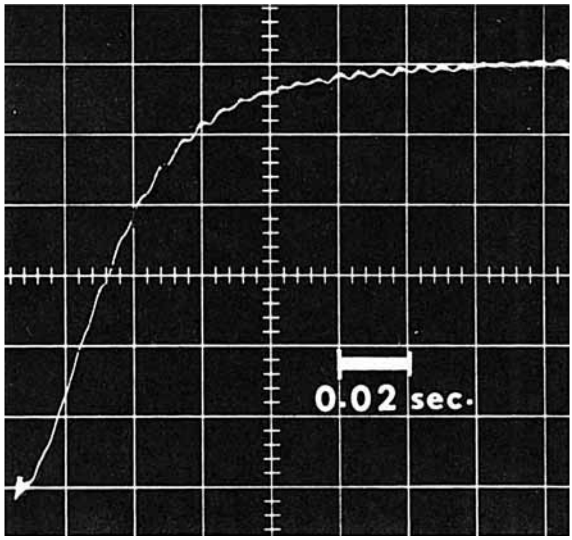

Fig. 4. Response of the normal force-measuring system to a sudden magnetic load application, experiment 6: applied load = 1,624 g; molten LDPE in cone–plate gap; no rotation; vertical sensitivity = 0.5v/division; horizontal sensitivity = 0.02 sec/division; time to attain 63.2% of equilibrium value = 0.032 sec.

The response time measurement of the thrust-measuring system using the magnetic loading system is sound if the plate is the mechanical ground, and thus the cone–plate separation is equal to the deflection of the thrust cantilever spring at the point of load application. To accomplish this in practicality, the upper structure of our rheogoniometer was greatly stiffened, similar to Meissner's,[4] with load-carrying members symmetrically placed about the plate. This modification increased the vertical stiffness of our apparatus by a factor of 10 in comparison to the commercial Weissenberg rheogoniometer.

In a cone–plate rheogoniometer where the upper platen assembly is not adequately stiff in comparison to the thrust-measuring system, the response time measurement (using the magnetic loading system) might not represent the actual response time of the normal force measuring system. In this case, discrepancy arises due to the opposite axial movements of the upper platen upon the magnetic load application and the development of the normal stress in a shear experiment, respectively. As the vertical stiffness of the upper-platen assembly decreases, one expects an increase in the response time of the thrust-measuring system. Therefore, a high axial stiffness of the upper-platen assembly in a cone–plate apparatus is essential (which is generally assumed) to obtain a sound value of the response time for the normal thrust measuring system using the magnetic loading system.

We expect that the above magnetic loading system will be useful and of practical convenience in future measurements of $N_1(t)$ for polymer melts. If one selects, for example, an 8° gap, initial response time measurements can be made with a given melt; if this response is appreciably faster than the rise in $F(t)$ subsequently measured on the same sample, one can have confidence in the relation $N_1(t) = 2F(t)/\pi R^2$ to evaluate $N_1(t)$, without the need to use other gap angles.

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