DEVELOPMENT OF EXTENSIONAL RHEOMETER USING PARALLEL DISK RING

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ABSTRACT

We developed an extensional rheometer to measure the planar elongational viscosity of low-viscous fluids. The rheometer uses two parallel disk rings to create a cylindrical film of the sample fluid, which is subjected to a planar elongational deformation. The position and thickness of the sample and the forces acting on the rings were measured during elongation. Elongation rate and elongation stress were evaluated from the experimental results. From these results, the planar elongational viscosity was calculated and it shows reasonable results.

BACKGROUND

Elongational viscosity affects formability in molding processes such as film molding and blow molding[1]. Therefore, understanding the rheology of polymeric materials is essential for improving the functionality and manufacturing efficiency of end products. Rotational rheometers are used to measure the rheology of complex fluids, including polymeric fluids. However, the rheological properties obtained in shear flow cannot be applied to extensional flow due to the uncertainty of the constitutive equations in complex fluids. Therefore, to accurately understand the flow field used in polymer forming, it is necessary to conduct rheological measurements in extensional flow. RFX (Rheometric Scientific) and CaBER (Thermo Scientific HAAKE) were the only available extensional rheometers capable of handling highly fluidized fluids and measuring uniaxial elongation viscosity. While both instruments are no longer available for sale, they still provide valuable data on the rheological properties of materials under elongation deformation. This study proposes a method for measuring the properties of planar elongational flow that uses parallel disk rings as a simple and direct extensional rheometer for highly flowing fluids.

EXPERIMENTAL APPARATUS AND TEST FLUIDS

Two-disc rings were used in the experiment. They have an inner diameter of 30 mm and an outer diameter of 40 mm. The ring was made of ABS resin and fabricated by a 3D printer.

CTAB/NaSal surfactant solution was used in the experiment, consisting of a viscoelastic fluid CTAB solution (0.10 mol/l) and NaSal (0.30 mol/l).

Fig. 1 shows a schematic diagram of the elongation force measurement. The upper disc ring is attached to the balance and the lower disc ring to the moving stage. A load cell (UL-2GR, rated capacity 19.61 mN, Minebea) is placed under the right end of the balance. **Fig 2** shows a schematic diagram of film thickness measurement. A sample is filled between two parallel disk-shaped rings to form a cylindrical film. A film thickness measuring instrument (CL-P015, standard measuring range ±1.3 mm, manufactured by Keyence) is set up to measure the thickness of this film.

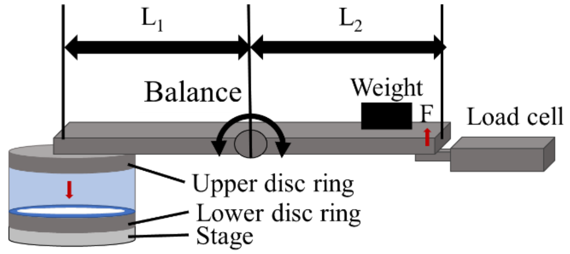

Figure 1: Schematic diagram of elongation force measurement

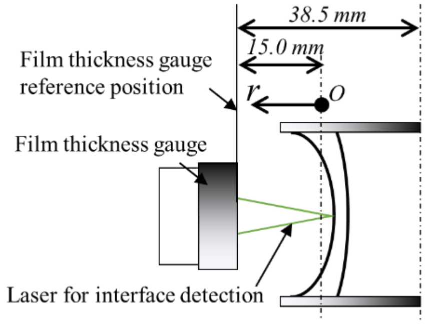

Figure 2: Schematic diagram of film thickness measurement

EXPERIMENTAL METHODS

As shown in **Fig. 1**, the test fluid is filled between the two disk rings at the left end of the balance; the initial gap between the two disk rings is 2.0 mm. The balance is balanced by placing a weight on the right arm of the balance. A cylindrical film is formed between the two rings by manually adjusting the balance and the stage up and down until the film thickness enters the measurement range. Subsequently, the film thickness is measured to ensure that it falls within the desired range, and the measurement process is halted upon confirmation. The measurement of film thickness and elongation force resumes concurrently, and the stage is incrementally lowered by approximately 1.00 mm every 10 seconds. The experiments were carried out at four distinct stage movement speeds:0.25, 0.50, 0.75 and 1.00 mm/s. Prior to stage movement, the balance in **Fig. 1** is tilted clockwise and a downward force (negative) is applied to the load cell. As the stage is subsequently lowered, an upward (positive) force acts on the load cell.

EXPERIMENTAL RESULTS

Fig. 3 shows the measurement results of elongation force F and film thickness. The stage was moved 9 times with a stage movement speed of 0.25 mm/s and a stage movement distance of 1.00 mm. Relaxation is observed when the stage is stopped. When the stage stops moving, the change in film thickness becomes small. The peak value of the elongation force and the film thickness both decrease with each repetition of the movement.

The elongation force, denoted as Fs, can be determined by calculating the difference between the force acting on the stage before movement and the force acting at the peak elongation. As shown in **Fig. 2**, the film thickness sensor measures the distance r between the position of the film interface and the reference position. To determine the film thickness and outer diameter, the method involves measuring the position of the interface between the sample and the air (i.e., top surface of the film) relative to a reference point using a thickness gauge. Specifically, the film thickness is obtained by calculating the difference in position between the interface and the reference point, while the outer diameter is obtained from the position of the thickness sensor and the film interface. When calculating the cross-sectional area of the sample, the film thickness $\Delta \mathrm{r}$ is the average of the film thickness $\Delta \mathrm{r}_1$ at the beginning of the stage movement and the film thickness $\Delta \mathrm{r}_2$ at the point where the movement stopped. The sample cross-sectional area A is calculated using Eq. 1. The elongation speed $\dot{\varepsilon}$ is obtained from Eq. 2. Let $\Delta \mathrm{r}$ be the film thickness at a certain point during stage movement.

Fig. 4 shows $\Delta \mathrm{r}/\Delta \mathrm{r}_1$ as a function of time. To evaluate the elongation rate, we compared the experimental results with Eq. 2 and performed a curve fitting process. By fitting the experimental data to Eq. 2, we determined the constant in the equation as the elongation rate.

$$A = 2\pi * r_o * \Delta r \tag{1}$$

$$\frac{\Delta r}{\Delta r_1} = e^{-\dot{\varepsilon} t} \tag{2}$$

The elongational viscosity was determined by analyzing the data on film thickness and elongation force obtained during the first stage movement. The planar elongational viscosity was found to be in the range of 200 to 700 Pa·s, while the shear viscosity of the sample was approximately 200 Pa·s. Although CTAB/NaSal is a non-Newtonian fluid and therefore cannot be directly compared, the planar extensional viscosity measured here falls within a reasonable range of values reported in the literature. To further validate the proposed rheometer, additional measurements using different samples and molar concentration ratios are recommended.

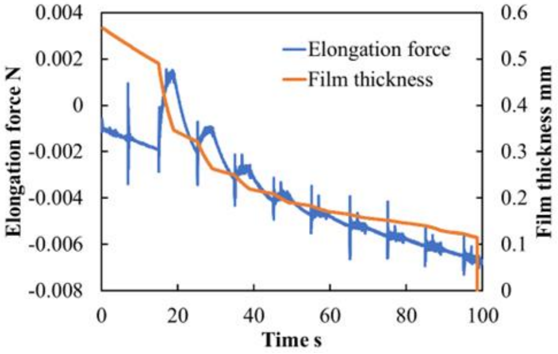

Figure 3: Measurement results of elongation force and film thickness

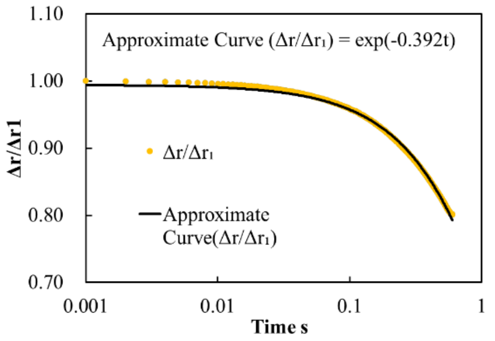

Figure 4: Determination of elongation rate

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