Rheological characterization of poly(ethylene oxide) aqueous solution under dynamic helical squeeze flow

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(Received July 8, 2012; final revision received October 29, 2012; accepted November 1, 2012)

Oscillatory shear flow has been widely used to investigate the flow properties of a wide range of complex fluids. The flow is useful because experimental platform is already fixed and its analysis has sound theoretical background. However it is too simple compared to the complex flows encountered in industry. Accordingly, the rheological response of complex fluids needs to be investigated in more complicated flow field. There were several reports on the superimposed flows in which oscillatory flow was applied either parallel or perpendicular to the steady shear flow. In this paper, we propose dynamic helical squeeze flow (DHSQ) which superimposes oscillatory shear and oscillatory squeeze between parallel plates. The nonlinear response in DHSQ was studied by comparing DHSQ with oscillatory shear (OS) and with oscillatory squeeze (OSQ) in terms of stress shape and Lissajous plot. In DHSQ, both stress curve and Lissajous plot of shear and normal stresses showed nonsymmetric characteristics unlike shear stress in large amplitude oscillatory shear (LAOS). The normal stress in DHSQ was more distorted than that of OSQ. The shear stress in DHSQ showed the onset of nonlinearity at lower strain amplitude than that of oscillatory shear flow (OS). It is due to the coupling of shear and squeeze flows, and the effect was more pronounced in the shear stress than in the normal stress.

Keywords: dynamic helical squeeze flow (DHSQ), nonsymmetric stress, normal stress, shear stress

1. Introduction

Small amplitude oscillatory shear (SAOS) test has become the canonical method for probing the linear viscoelastic properties of complex fluids due to its sound theoretical background and usefulness (Hyun et al., 2011). Large amplitude oscillatory shear (LAOS) measurement is also useful in material characterization under large deformation. Under LAOS, the stress signal becomes non-sinusoidal wave due to the existence of high order harmonics. The nonlinear stress can be effectively used to understand the difference between the complex fluids. Various methods have been developed and used to characterize the nonlinear stress signals in LAOS. Stress analysis, i.e. stress curve and Lissajous plot, is a simple method to characterize the nonlinear stress responses as a function of time. The Fourier-transform (FT) analysis is a sensitive method that focuses on the higher harmonics to characterize the nonlinearity (Wilhelm et al., 1998; Hyun and Kim, 2011). The stress decomposition (SD) method enables us to decompose stress signals into elastic and viscous components even in nonlinear regime (Cho et al., 2005; Yu et al., 2009). In spite of the usefulness of LAOS, it is restricted to the simple shear flow.

Oscillatory squeeze flow (OSQ) is more complicated than the simple shear flow, but is still controllable and well-defined. Under dynamic squeeze flow, the complex fluid is repeatedly compressed and extended. For this reason, the OSQ is nonhomogeneous and transient flow and suffers from being adopted as a convenient method to measure the rheological properties. In spite of the disadvantages, OSQ has received considerable attention as a useful tool to characterize the complex fluids (Phan-Thien, 2000; Phan-Thien et al., 2000; Walberer and McHugh, 2001; Jiang et al., 2003; Debault and Thomas, 2004; See and Nguyen, 2004; Engmann et al., 2005; Bell et al., 2006; Kim et al., 2012). The oscillatory squeeze rheometry has been used to evaluate a wide class of complex fluids and biological materials. Phan-Thien (1980) provided a theoretical basis for characterizing viscoelastic fluids under oscillatory squeeze flow. In experiments, the linear viscoelasticity of complex fluids was investigated under small amplitude oscillatory squeeze flow (Field et al., 1996; See and Nguyen, 2004). In the nonlinear regime, the oscillatory squeeze flow was also analyzed in terms of the closed loop of [stress vs. strain] with a biological material (Phan-Thien et al., 2000) and dental composite resin (Jiang et al., 2003). The linear viscoelasticity of hard sphere suspension was also studied in the oscillatory shear, oscillatory squeeze, and lubricated squeeze flow (Walberer and McHugh, 2001). A numerical inves-

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tigation for oscillatory squeeze flow was carried out by finite element method and simple model simulation (Phan-Thien, 2000; Debbaut and Thomas, 2004). Kim et al. (2012) predicted non-symmetric responses of normal stresses in oscillatory squeeze flow using constitutive equations and provided a platform for the analysis of non-symmetric stress signals in OSQ.

The rheological measurements mentioned above, e.g. shear and squeeze flow, afford a useful information on complex fluids, but they are not enough in the sense that the flow fields are still too simple compared to real processes. To get over this problem, superposition of oscillatory flow onto steady shear flow has been developed to probe the microstructural characteristics. The first investigation under superimposed flow field was carried out by Osaki et al. (1965), using parallel superposition which imposes steady and oscillatory shear flow in the same direction. Orthogonal superposition of oscillatory motion to the perpendicular direction into the steady shear flow was also used (Simmons, 1966). Similar measurements were carried out with diverse complex fluids including polymer solutions, wormlike micellar solutions, branched polydisperse polymer melts, entangled DNA, soft glassy materials and non-aqueous layered silicate suspensions (Vermant et al., 1997, 1998; Walker et al., 2000; Mewis et al., 2001; Anderson et al., 2006; Somma et al., 2007; Boukany and Wang, 2009; Mobuchon et al., 2009; Ovarlez et al., 2010). Previous researches on the superimposed flows are summarized in Table 1.

Table 1. Previous studies on superimposed flows.

<table>
<thead>
<tr>
<th>The type of flow</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>Steady shear + Oscillatory shear</td>
<td>Anderson et al. (2006), Bernstein (1972), Booj et al. (1966, 1968), Boukany et al. (2009), De Cleyn et al. (1987), Dinser et al. (2007), Laufer et al. (1975), MacDonald et al. (1973), Osaki et al. (1965), Powell et al. (1975), Simmons (1968), Somma et al. (2007), Tanner (1968), Tanner et al. (1967), Tirtaatmadja et al. (1997), Vermant et al. (1998), Vlastos et al. (1997), Walker et al. (2000), Yamamoto (1971)</td>
</tr>
<tr>
<td>Steady shear + Oscillatory shear + Oscillatory squeeze</td>
<td>Mobuchon et al. (2009)</td>
</tr>
<tr>
<td>Oscillatory shear + Oscillatory squeeze</td>
<td>Ovarlez et al. (2010)</td>
</tr>
<tr>
<td>Oscillatory shear + Oscillatory squeeze</td>
<td>This study</td>
</tr>
</tbody>
</table>

The schematic diagram of the modified fixture for dynamic helical squeeze flow is shown in Fig. 1. The DHSQ is operated by the modified fixture which superimposes the oscillatory squeeze on the oscillatory shear. This modified fixture can be used to impose not only DHSQ but also OSQ mode (Kim et al., 2008; Kim and Ahn, 2012). Here RMS800 (Rheometrics Mechanical Spectrometer 800, TA Instruments) is used as the mechanical platform. A servo motor which was mounted on RMS800 performs oscillatory rotational motion over a wide range of frequencies and strain amplitudes. When the motor is operated, the ball screw transfers rotational movement to vertical or helical motion. For the oscillatory squeeze (OSQ) and dynamic helical squeeze (DHSQ) flow mode, the top plate is stationary, while the bottom plate is subjected to vertical movement for OSQ, and to linear response and structural anisotropy of complex fluids under the superimposed dynamic flow fields. The objective of this study is to introduce an instrument which allows the characterization of viscoelastic fluids under DHSQ and to provide a platform for the analysis of experimental data. In addition, we investigate the superposition effect induced by the complex flow field in DHSQ. Thereby it is expected that the instrument bridges the gap between conventional rheometry and more complicated and practical real processes. The paper is organized as follows. We first introduce a new setup for dynamic helical squeeze flow (DHSQ). Next, we will explain theoretical background for DHSQ and propose an analysis method to deal with the asymmetric stress signals. Finally, we will show specific features of viscoelastic fluids under the dynamic helical squeeze flow (DHSQ) in terms of stress curve and Lissajous plot.

2. Experiments

2.1. Dynamic helical squeeze flow (DHSQ)

The schematic diagram of the modified fixture for dynamic helical squeeze flow is shown in Fig. 1. The DHSQ is operated by the modified fixture which superimposes the oscillatory squeeze on the oscillatory shear. This modified fixture can be used to impose not only DHSQ but also OSQ mode (Kim et al., 2008; Kim and Ahn, 2012). Here RMS800 (Rheometrics Mechanical Spectrometer 800, TA Instruments) is used as the mechanical platform. A servo motor which was mounted on RMS800 performs oscillatory rotational motion over a wide range of frequencies and strain amplitudes. When the motor is operated, the ball screw transfers rotational movement to vertical or helical motion. For the oscillatory squeeze (OSQ) and dynamic helical squeeze (DHSQ) flow mode, the top plate is stationary, while the bottom plate is subjected to vertical movement for OSQ, and to
helical motion for DHSQ. Parallel-plate geometry was used for all measurements (diameter: upper plate 40 mm and lower plate 50 mm) and the initial gap height between the plates was 1.5 mm. To prevent flowing out of the domain between the parallel plates, high viscosity sample (2,150 Pa·s) was used. To obtain the raw stress signals, a 16bit ADC card (PCI-6052E; National Instruments) with a sampling rate up to 333 kHz was used. This ADC card was plugged into a laptop computer installed with laboratory-written LabView (National Instruments) software. The stresses developed during the test were measured by a transducer connected to the upper fixture, and recorded by an on-line computer. All measurements were taken at room temperature.

2.2. Sample preparation
Poly(ethylene oxide) (PEO, Sigma-Aldrich) aqueous solution was selected as a viscoelastic fluid. The molecular weight (Mn) and density were \(4 \times 10^6\) g/mol and 1.13 g/cm\(^3\), respectively. For PEO aqueous solution, distilled water and PEO (4 wt\%) were rotated in a sealed glass bottle by a mechanical milling machine at 60 rpm for 7 days at room temperature. The concentration of PEO aqueous solution was higher than the overlap concentration \(c^*\), where \(n = 3M_n/4N_A\pi R_g^3\) (Dasgupta et al., 2002). The linear viscoelastic properties were measured by a controlled strain type rheometer (RMS, TA instruments). PEO solution displayed strain thinning behavior in which complex viscosity decreased with power-law dependence at high frequencies. The strain thinning behavior is commonly observed in polymer solutions and melts, and originates from chain orientation or alignment of microstructures along the flow direction.

3. Theoretical Background
It is easy to define true strain rate in simple shear flow which has uniform flow field in whole domain. Thus the material function of the flow can be clearly defined without any difficulty in simple shear flow. On the other hand, the sample experiences non-homogeneous strain and stress in the whole domain under DHSQ. For this reason, the true strain rate in DHSQ cannot be clearly defined without constitutive equation because there exist both shear and compressive flows. This non-uniformity makes it difficult to define the material functions. In this study, we define the strain as in Eq. (1) and (2), which may well be regarded as engineering strain. This approach has also been used in previous researches (Vermant et al., 1997; Ovarlez et al., 2010).

When the material is subjected to DHSQ, two strains need to be defined. The two engineering strains are operated at the same frequency:

\[
\gamma_\theta = \gamma_0 \sin \omega t,
\]

\[
\gamma_z = \gamma_0 \sin \omega t
\]

where \(\omega\) is the applied frequency, \(\gamma_\theta\) and \(\gamma_z\) are the strain amplitudes of angular and vertical direction, respectively. The strain amplitudes in angular and axial displacement are defined respectively by

\[
\gamma_\theta = \frac{R \theta}{H_0},
\]

\[
\gamma_z = \frac{\alpha}{H_0},
\]

where \(R\) is the radius of the plate, \(\theta\) is the angular displacement, \(H_0\) is the initial gap between the plates, and \(\alpha\) is the deformation amplitude in vertical direction. The gap height \(H\) in Eq. (3) and (4) varies as a function of time; however we assumed it as constant even under large deformation. The inclined angle \(\alpha\) determines the ratio of \(\gamma_z\) and \(\gamma_\theta\) (see in Fig. 1). In this study, we fix the inclined angle \(\alpha\) at 60°. With this angle, the strain restraint was set as 0.11 for \(\gamma_z\) and 0.06 for \(\gamma_\theta\) to prevent overload on the transducer.

It is not easy to define material properties for DHSQ with large deformation. The theoretical analysis in DHSQ leads to considerable complexity even with constitutive models, and no robust theory for DHSQ has yet been worked out. For this reason, we define the storage and loss moduli as the area formed by the loop in the plot of [stress vs. strain rate] and by the loop in the plot of [stress vs. strain], respectively. The apparent moduli are defined as
follows in terms of circular integration.

\[ G' = \frac{1}{\pi(\gamma_0)^2} \left\{ \sigma_{\gamma} d(\gamma/\omega) \right\}, \quad G'' = \frac{1}{\pi(\gamma_0)^2} \left\{ \sigma_{\gamma} d\gamma_{\gamma} \right\} \]

(5)

\[ E' = \frac{2H_{0}^{2}}{3R} \frac{1}{\pi(\gamma_0)^2} \left\{ \sigma_{\gamma} d(\gamma/\omega) \right\}, \quad E'' = \frac{2H_{0}^{2}}{3R} \frac{1}{\pi(\gamma_0)^2} \left\{ \sigma_{\gamma} d\gamma_{\gamma} \right\} \]

(6)

where \( \sigma_{\gamma} \) and \( \sigma_{\gamma} \) are the shear and normal stresses, and \( 2H_{0}/3R \) is a geometric factor. Although \( \mathbb{H}_{\mathbb{H}_{0}} \) under large deformation as mentioned already, we set it as a constant to define the material function. Linear trapezoidal rule was used to calculate the area of the loop using MATLAB software (MathWorks, Inc.).

4. Results and Discussion

4.1. Strain sweep test

To separate linear or nonlinear region, strain sweep test was carried out for PEO solution under DHSQ flow. Fig. 2(a) shows the storage and loss modulus obtained from the normal stress of DHSQ using Eq. (6). At small strain amplitude, the storage and loss moduli were constant irrespective of strain amplitude. At larger strain amplitude, the moduli decreased over critical strain amplitude which was defined as the onset point when the moduli start to decrease or increase. Fig. 2(b) shows the storage and loss moduli calculated from the shear stress of DHSQ as a function of strain amplitude using Eq. (5). The storage and loss moduli were constant regardless of the strain amplitude in the linear region. However, in the nonlinear region, the modulus also showed strain thinning behavior similar to DHSQ flow. The moduli from normal and shear stresses under DHSQ showed strain thinning behavior as in OS for polymer solutions, polymer melts, and so on. The strain thinning leads to the reduction of modulus as the strain amplitude increases.

4.2. Normal stress and Lissajous plot

The viscoelastic moduli \( (E' \text{ and } E'') \) of DHSQ were similar to those of OSQ in linear regime (Kim and Ahn, 2012). They look rarely affected by the superposition of two flows. The linear viscoelasticity is not enough to explain the dynamics of complex fluids. The storage and the loss moduli lose their physical significance when the stress is no longer sinusoidal at large deformation. For this reason, we apply diverse methods to investigate the nonlinear response in DHSQ. The stress analysis, i.e. stress curve and Lissajous plot of [stress vs. strain] or [stress vs. strain rate], is a useful method to investigate the nonlinear response with higher harmonics at large deformation. This method was used to analyze the nonlinear response in the LAOS flow for a long time because it is simple and intuitive. In the linear regime, the stress waveform is sinusoidal regardless of strain amplitude, but becomes non-sinusoidal in the nonlinear regime. The stress waveform provides visual information on the structural changes of the material during the deformation. The Lissajous plot is a closed loop in which the periodic stress response is plotted against strain or strain rate. The Lissajous loop maintains an elliptic shape in linear regime, but becomes non-elliptic in nonlinear regime. Under the LAOS flow, the stress curve and Lissajous plot showed various shape reflecting the structural changes of the complex fluids such as polymer solutions, polymer melts, suspension, biological materials, surfactants, emulsion, and so on (Hyun et al., 2011).

We carefully compared the normal stress in DHSQ with that in OSQ, and investigated the nonlinear and nonsymmetric responses in the nonlinear regime. Fig. 3 shows the normal stress of DHSQ and OSQ at strain amplitudes 0.0007, 0.07 and 0.11 and at frequency 2 rad/s. At low strain amplitude 0.0007, the normal stress was sinusoidal and symmetric in both DHSQ and OSQ, and the stress...
magnitude of DHSQ was smaller than that of OSQ. At large strain amplitude, however, the stress magnitude of DHSQ was larger than that of OSQ on the contrary to the results at low strain amplitude 0.0007, and the normal stress became nonsymmetric both in magnitude and shape (over the axis \( \sigma_{zz} = 0 \)). The nonsymmetric normal stress may be considered as a result of the microstructural difference when the viscoelastic fluid is compressed and extended. This nonsymmetric response was also reported in the studies with both experiment and simulation of oscillatory squeeze flow (Phan-Thien, 2000; Phan-Thien et al., 2000; Debbaut and Thomas, 2004; Kim et al., 2012). The normal stress exhibited forward-tilted shape which was also observed in OS (Hyun et al., 2011). Even though the moduli (\( E' \) and \( E'' \)) showed similar behavior in both DHSQ and OSQ (Kim and Ahn, 2012), there was a difference in the stress curve analysis. The normal stress curve in DHSQ was more distorted than that in OSQ. In addition, the normal stress showed nonsymmetry in stress magnitude (maximum and minimum) even at the same strain amplitude. This result means that the normal stress in DHSQ is affected by the coupling of oscillatory shear flow and oscillatory squeeze flow which act perpendicular to each other. The effect of combined flow became more pronounced at large strain amplitude. From the stress waveform analysis, we could confirm that the superimposed flow can enhance nonlinear characteristics of complex fluids by the flow-induced orientation.

The Lissajous plot of [stress vs. strain] in DHSQ was compared with that of OSQ to investigate the viscous contribution in Fig. 4. At strain amplitude 0.0007, the Lissajous plot of [stress vs. strain] showed an ellipsoidal loop indicating linear viscoelasticity. However, the loop became distorted and nonsymmetric with increasing strain amplitude. This nonsymmetry is a unique feature of normal stress at large deformation. The Lissajous plot was symmetric when the deformation was small; this symmetric loop implies the same response during compression and extension. On the other hand, the Lissajous loop could not maintain symmetry at large deformation; nonsymmetric Lissajous loop means different response when the fluid is compressed and extended. Furthermore, the Lissajous plot showed difference in stress magnitude at maximum and minimum relative to the axis \( \sigma_{zz} = 0 \). The difference became more pronounced as the strain amplitude increased. Although the nonsymmetric characteristics was observed in both DHSQ and OSQ, the Lissajous plot of DHSQ was more distorted than that of OSQ due to the superposition effect.

Fig. 5 shows the Lissajous plot of [stress vs. strain rate] at different strain amplitudes. At low strain amplitude 0.0007, the Lissajous plot of DHSQ and OSQ showed symmetric ellipsoidal loop which means linear viscoelasticity. As the strain amplitude increased, the Lissajous loop of [stress vs. strain rate] became nonsymmetric.
meaning the nonlinear regime. At high strain amplitude, the Lissajous plot was more distorted in DHSQ than in OSQ due to the coupling effect.

4.3. Shear stress and Lissajous plot

In this section, we analyze the shear stress induced by angular deformation in DHSQ and discuss the nonlinear characteristics. The storage modulus $G'$ showed strong nonlinear behavior at lower strain amplitude in DHSQ than in OS (critical strain amplitude: DHSQ=0.02, OS=1) (Kim and Ahn, 2012). The shear stress underwent more dramatic changes compared with the normal stress in previous section. Fig. 6 shows the shear stress of DHSQ and OS at strain amplitudes 0.02, 0.03 and 0.06 and at frequency 2 rad/s. In both DHSQ and OS measurements, the shear stress was weaker than the normal stress due to low intensity of the stress signal. Nevertheless, the shear stress showed a periodical response and a dramatic change even at small strain amplitude. At strain amplitude $\gamma_{0}=0.02$, the shear stress showed sinusoidal waveform in both DHSQ and OS. The stress signal maintained sinusoidal shape under OS even at large strain amplitudes. On the other hand, the shear stress in DHSQ became distorted as the strain amplitude increased. The stress in OS maintained symmetry relative to the axis $\sigma_{z}=0$ even at large strain amplitudes, while the stress in DHSQ showed non-symmetry at smaller strain amplitudes. This nonsymmetric characteristic was also observed in previous studies.

The nonsymmetry of the first normal stress difference was reported as due to the presence of even harmonics (Nam et al., 2010). As shown in Fig. 6(a), the shear stress of DHSQ was first distorted in negative region (compression), and then became distorted in positive region too at larger deformation. At the same strain amplitude, the shear stress in DHSQ showed stronger nonlinearity than that in OS. From this stress analysis, we can confirm that the shear stress of DHSQ is strongly affected by the oscillatory squeeze flow imposed on the perpendicular direction of oscillatory shear flow.

We also plotted the Lissajous loop of [stress vs. strain] to investigate the viscous contribution of shear stress in DHSQ and compared the closed loop of DHSQ with that of OS. Fig. 7 shows the Lissajous loop of [stress vs. strain] at strain amplitudes 0.02, 0.03 and 0.06 and at frequency 2 rad/s. At strain amplitude 0.02, the closed loop showed elliptic shape in both DHSQ and OS which indicates linear viscoelasticity. As the strain amplitude increased, the closed loop of DHSQ did not remain elliptic any more, while the loop of OS maintained elliptic shape within the region we could measure. The distorted loop implies that the stress signal has higher harmonic contributions meaning the nonlinear behavior. In DHSQ, the nonlinear characteristic was observed at smaller strain amplitude than OS. The Lissajous loop of DHSQ became more nonsymmetric as the strain amplitude increased.

The Lissajous loop of [stress vs. strain rate] was also
Rheological characterization of poly(ethylene oxide) aqueous solution under dynamic helical squeeze flow

plotted to show the elastic contribution of shear stress in DHSQ, and the closed loops of DHSQ and OS were compared. Fig. 8 shows the Lissajous loop of [shear stress vs. strain rate] at strain amplitudes 0.02, 0.03, 0.06. The Lissajous loop of DHSQ and OS showed totally different shape as the strain amplitude increased. The Lissajous plot in OS maintained round loop regardless of the strain amplitudes. However, the loop of DHSQ shows strong nonlinear and nonsymmetric behavior compared with that of OS at the same strain amplitude. The loop of DHSQ underwent dramatic change as the strain amplitude increased in view of graphical presentation. The onset of nonsymmetric response in DHSQ was first observed in the negative region for the axis \( \sigma_z = 0 \) (compression). This nonlinear and nonsymmetric loop results from the coupling effect of oscillatory shear flow and oscillatory squeeze flow that act perpendicular to each other. This can be confirmed by the comparison of DHSQ and OS at the same strain amplitude. For example, the loop of OS showed elliptic shape meaning the linear regime even at strain amplitude 0.06, while the loop of DHSQ showed strong nonlinear and nonsymmetric response even at lower strain amplitude.

At strain amplitude \( \gamma_0 = 0.06 \), the area of the loop was very small compared with that at \( \gamma_0 = 0.02 \). The area of the loop of [stress vs. strain rate] corresponds to the mechanical energy storage, and normally decreases with strain amplitude, where mechanical energy storage

\[
\int_0^{\gamma_0} \sigma_z(\dot{\gamma}_0) \, d\gamma_0.
\]

It means that the energy storage decreased significantly due to the dynamic squeeze flow superimposed into the dynamic shear flow at strain amplitude 0.06. Previous literatures demonstrated that the moduli of superposition flow were lower than the ones with no superposition (Vermant et al., 1997; 1998; Somma et al., 2007). From these results, it was proved that the shear stress was significantly affected by the superposition effect of DHSQ.

5. Conclusions

The nonlinear and nonsymmetric responses of materials under dynamic helical squeeze flow (DHSQ) were investigated for the first time. In this flow, the oscillatory squeeze flow was applied perpendicular to the oscillatory shear flow. The first focus was on the nonlinear and nonsymmetric normal stresses in DHSQ. As the strain amplitude increased, the normal stress of DHSQ was more distorted than that of OSQ. This result implies that the normal stress in DHSQ was significantly affected by the coupling of oscillatory shear flow and oscillatory squeeze flow. Under large deformation, the normal stress of both
DHSQ and OS showed nonsymmetric characteristics in magnitude and shape. The Lissajous plot showed nonsymmetric behavior, which means different response when the sample is compressed or extended.

The second focus was on the nonlinear and nonsymmetric shear stress in DHSQ. There was a significant difference between DHSQ and OS in terms of stress analysis. The shear stress of OS maintained sinusoidal waveform indicating linear response even at largest strain amplitude we could investigate, while that of DHSQ became non-sinusoidal and nonsymmetric at much lower strain amplitude. The onset of nonlinear response was first observed in compression region. The Lissajous plot of shear stress vs. strain or shear stress vs. strain rate showed distorted loop at large deformation under DHSQ, while the loop of OS maintained elliptic shape. In summary, we have investigated the nonlinear and nonsymmetric response of polymer solution under DHSQ. It is concluded that the rheological behavior under dynamic helical squeeze flow provides useful information for the materials in more complicated flow-induced environment compared with a simple flow.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant (No. 20100026139) funded by the Korea government (MEST).

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Rheological characterization of poly(ethylene oxide) aqueous solution under dynamic helical squeeze flow


