Dynamics of Flexible High-Molecular-Weight Polymers in Dilute Solution under Circular Couette Flow

Yoshisuke Tsunashima

Chain dynamics of poly(α-methylstyrene) of high molecular weight in benzene, a good solvent, in dilute solution was investigated by dynamic light scattering under Couette flow. At the shear gradient above 2.8-4.5 s⁻¹, the internal modes of motions were exclusively suppressed and only the center-of-mass translational diffusion motion of the chain was detected. Whereas, in the intermediate shear region, the decay rate for the internal mode was constant, and that of the diffusion mode increased with increasing the shear rate. The obtained universal ratio \( \Omega/D_{g0} q^2 \) was located close to the theoretical curve predicted for the flexible chains with the microscopic description of chain dynamics in \( \Theta \) state. This quantitative agreement between theory and experiments means that the coupled kinetic equations for chain segments and solvent in the same dynamic level is indispensable for describing rigorously chain dynamics in dilute solution.

Keywords: Dynamic light scattering/ Shear flow/ Diffusion/ Internal motions/ Dynamic coupling

In the quiescent, i.e., thermodynamically equilibrium state, dynamics of flexible linear polymers in dilute solution has not been understood fundamentally because the well-qualified experimental results disagreed quantitatively with the hydrodynamic descriptions of the polymer chain so far proposed theoretically. The reasons may be assigned to the following assumptions which have been made heretofore in the theoretical descriptions of chain dynamics in the quiescent state (the so-called macroscopic description of chain dynamics): (i) the polymer segments waggle in continuous viscous fluid (where the solvent motions are smeared and neglected) in accordance with a diffusion-type equation of the segment configurational distribution and (ii) the hydrodynamic disturbance of the fluid velocity caused by different polymer segments is described approximately by the Oseen tensor. This tensor was derived as a solution of the Stokes equation which neglects the nonlinear inertia term \((u \cdot \nabla) u\) of the Navier-Stokes (NS) general equation of motion,

\[
\frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\nabla p/\rho + \nu \Delta u, \tag{1}
\]

with \( u \) the fluid velocity. However, the inertia term disappears essentially in the Couette flow. The Couette flow is thus a rigorous solution of the NS general equation of motion, as well as the Stokes equation. Therefore, if experiments were made under the Couette flow, not in the quiescent state, the results will give us new understanding to solve the disagreements between experimental facts and theoretical predictions. In this paper, we apply the dynamic light scattering (DLS) to the dilute solutions of high molecular-weight polymer sample in a good solvent in circular Couette flow and discuss the adequacy of the microscopic description proposed for chain dynamics in dilute solution.

A monodispersed poly(α-methylstyrene) (PMS) fraction of \( M_w = 6.85 \times 10^6 \) was dissolved in benzene and the dilute solutions of different polymer mass concentration \( c \) \((c=2.0-8.1 \times 10^{-4} \text{ g cm}^{-3})\) were prepared by filtering through a 0.2 µm pore-size filter. The solution was set in...
the 2mm-gap between the concentrically rotating rotor and the stator (glass cylinders) which stood perpendicularly. In the gap, the one-dimensional shear flow with a constant low-shear gradient $\gamma$ was induced by the eddy current.\(^2\) The single-frequency Ar-ion laser light of 3W was plunged perpendicularly to the rotor and, at given $\gamma$ of $0=4.5s^{-1}$, the intensity time correlation function $A(t)$ of the $I'$ component of the scattered light from the sample solution at the angle $\theta=75.6^\circ$ was measured at $27^\circ C$ by homodyne method through a laboratory-made software correlator. The measured $A(t)$ was analyzed with the histogram method to obtain the decay rate $\Gamma_i$ of the chain modes of motions $i$.

At all $c$ examined, $A(t)$ curves were composed of two decay modes (slow and fast modes) at $\gamma$ except the highest shear gradient $\gamma_{\text{max}}$ of one slow mode. The slow mode with decay rate $\Gamma_1$ was the translational diffusion which represents the center-of-mass motion of the polymer chain, where the diffusion coefficient was $D_1 = (\Gamma_1\gamma^2)$ with $q$ the scattering vector. The fast mode with decay rate $\Gamma_2$ was the intramolecular motions. The observation of slow mode alone at $\gamma_{\text{max}}$ means that the intrachain motions are suppressed with the increase of the shear field. The $\gamma$ and $c$ dependence of $D_i$ below $\gamma_{\text{max}}$ shows that, at fixed $c$, the $D_i$ increases with $\gamma$, as is the case for polystyrene-latex in aqueous solution\(^3\) and for PMS of $M=2.71\times10^6$ in benzene.\(^1\) However, with decreasing $c$, the $D_i$ changes from a descending to an ascending incline at higher $\gamma$. The double extrapolation to $\gamma, c \to 0$ gives the equilibrium value at infinite dilution $D_i(0,0)$. On the other hand, $\Gamma_i/q^2$ for internal motions at each $c$ was constant independent of $\gamma$. Thus, the increasing decay rate with $\gamma$ for translational mode and the $\gamma$-independent decay rate for internal modes indicate that, in shear field, the chain moves with a constant characteristic intramolecular frequency, though the translational motion is made faster by shear flow.

The first cumulant $\Omega$, which represents all the motions the chain performs, was combined with the $\gamma$ dependence of the translational motion and then the universal ratio $\Omega/D_i\gamma^2$ at the infinite extrapolations to $c \to 0$ and $\gamma \to \gamma_{\text{solvent}}$ was estimated to be 1.9 at $qR_\theta=3.03$. Here $D_i$ is the translational diffusion coefficient at infinite dilution and $R_\theta$ is the radius of gyration of the chain. The obtained universal value is shown by a filled triangle ( □ ) in Figure 1, where data for polystyrene and polysoprene in $\Theta$ state ( □ ) and the theoretical lines 1 and 2 calculated by the microscopic description of chain dynamics for $\Theta$ and good solvents\(^1\) respectively are also given. The present data point is located near the line 1 and the feature is coincident with our recent one ( □ ) obtained at low shear gradient for PMS of $M_w=2.71\times10^6$ in benzene.\(^4\) It is very suggestive that data obtained in Couette flow in good solvent ( □ , □ ) are close to the data in $\Theta$ state ( □ ) and are distinguished clearly from the data in good solvent in the quiescent state\(^4\) ( □ ) which is located between lines 1 and 2. The microscopic description of polymer chain dynamics\(^1\) is composed of the coupled kinetic model equations for polymer and solvent, where the segment velocity $\mathbf{c}(\mathbf{r}, t)$ at the chain contour position $\mathbf{r}$ and the solvent velocity $\mathbf{u}(\mathbf{r}, t)$ at the fluid position $\mathbf{r}$ are expressed in the same dynamic level:

\[
\partial \mathbf{c}(\mathbf{r}, t) / \partial t = -\mathbf{c}(\mathbf{r}, t) \cdot \mathbf{u}(\mathbf{r}, t) + \mathbf{f}(\mathbf{r}, t) \quad (\text{polymer})
\]

\[
\partial \mathbf{u}(\mathbf{r}, t) / \partial t = \eta \nabla \cdot \mathbf{u}(\mathbf{r}, t) - \| \nabla H \| \nabla \mathbf{c}(\mathbf{r}, t) + \mathbf{f}(\mathbf{r}, t) \quad (\text{solvent})
\]

with the incompressibility condition $\nabla \cdot \mathbf{u} = 0$. $\mathbf{H}$ is the chain potential and $\mathbf{f}$ is the random force. In conclusion, the present result in Couette flow, which realizes an ideal fluid state in the hydrodynamic sense, can be explained by the microscopic view in $\Theta$ state, not in good solvents, and supports the necessity of the microscopic description in chain dynamics in dilute solution.\(^5\) The slight disagreement between data and the theoretical line 1 suggests further works in theoretical treatments in $\Theta$ state.

References


![Figure 1. The $\Omega/D_i\gamma^2$ vs. $qR_\theta^2$ plots for flexible polymers in dilute solution.](image-url)