**Supplementary Information**

# Drag force of polyethyleneglycol in flows of polymer solutions measured by a scanning probe microscope

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## SI1. Physical properties of glycerol and PEG solutions

The glycerol (FUJIFILM Wako Pure Chem. Corp.) and polyethyleneglycol (PEG, FUJIFILM Wako Pure Chem. Corp.) solutions were prepared in a wide range of concentrations for the drag force measurements. The concentration of each solution, viscosities, and densities are summarized in Table SI1.

**Table SI1.** Physical properties of (a) glycerol, (b) PEG10k, (c) PEG20k and (d) PEG35k solution.

(a)

| Glycerol Concentration [wt%] | Viscosity [$\times 10^{-3}$ Pa·s] | Density [kg/m$^3$] |
|---|---|---|
| 5 | 1.15 | 1013 |
| 6 | 1.24 | 1016 |
| 8 | 1.32 | 1021 |
| 10 | 1.4 | 1026 |
| 15 | 1.59 | 1039 |
| 22 | 1.88 | 1058 |
| 35 | 2.41 | 1093 |

(b)

| PEG10k Concentration [wt%] | Viscosity [$\times 10^{-3}$ Pa·s] | Density [kg/m$^3$] |
|---|---|---|
| 0.75 | 1.13 | 1002 |
| 1.0 | 1.20 | 1004 |
| 1.25 | 1.30 | 1008 |
| 1.5 | 1.37 | 1009 |
| 2.0 | 1.53 | 1013 |
| 3.0 | 1.81 | 1025 |
| 5.0 | 2.46 | 1046 |

(c)

| PEG20k Concentration [wt%] | Viscosity [$\times 10^{-3}$ Pa·s] | Density [kg/m$^3$] |
|---|---|---|
| 0.5 | 1.13 | 1001 |
| 0.75 | 1.23 | 1002 |
| 1.0 | 1.32 | 1003 |
| 1.25 | 1.39 | 1003 |
| 1.5 | 1.59 | 1003 |
| 2.0 | 1.83 | 1005 |
| 3.0 | 2.41 | 1008 |

(d)

| PEG35k Concentration [wt%] | Viscosity [$\times 10^{-3}$ Pa·s] | Density [kg/m$^3$] |
|---|---|---|
| 0.25 | 1.12 | 1001 |
| 0.35 | 1.21 | 1001 |
| 0.50 | 1.31 | 1001 |
| 0.75 | 1.37 | 1003 |
| 1.0 | 1.55 | 1003 |
| 1.5 | 1.86 | 1008 |
| 2.0 | 2.47 | 1010 |

Zero-shear specific viscosity, $\eta_{sp}$ [-], which is defined with the zero-shear viscosity $\eta_0$ [Pa·s] and the solution viscosity $\eta_s$ [Pa·s], as $\eta_{sp} = (\eta_0 - \eta_s)/\eta_s$, of PEG solutions, was used to find the overlap concentration, $c^*$ [g/ml], and entanglement concentration, $c_e$ [g/ml]. $\eta_{sp}$ of PEG solutions. $\eta_{sp}$ obtained in the present study reasonably follows the scaling index suggested in the previous studies as shown in Fig. SI1 [1, 2]. $c^*$ and $c_e$ are shown in each figure.

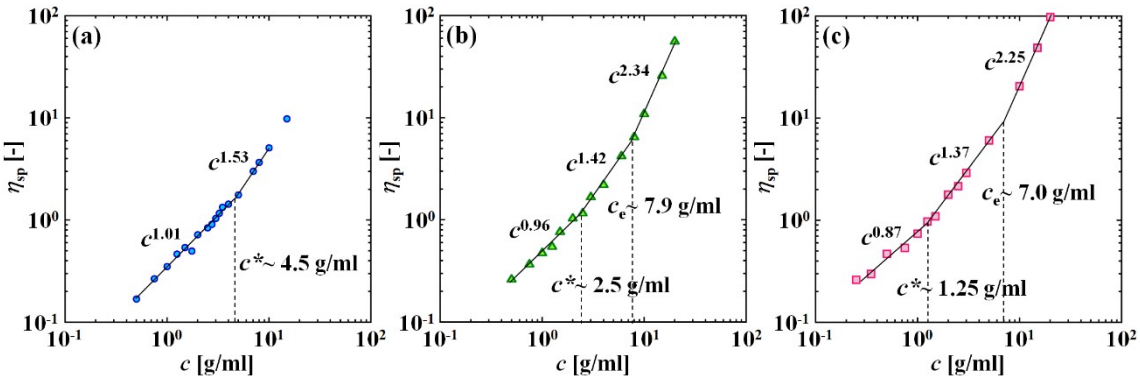


**Fig. SI1** $\eta_{sp}$ of (a) PEG10k, (b) PEG20k and (c) PEG35k solutions.

## SI2. Example of the measurement data

An example of the experimental data detected by the SPM through the oscilloscope. The oscilloscope did not detect any force when the sample solution was at rest. However, when the sample solution flowed through the channel, the oscilloscope detected a drag force as shown in Fig. SI2.

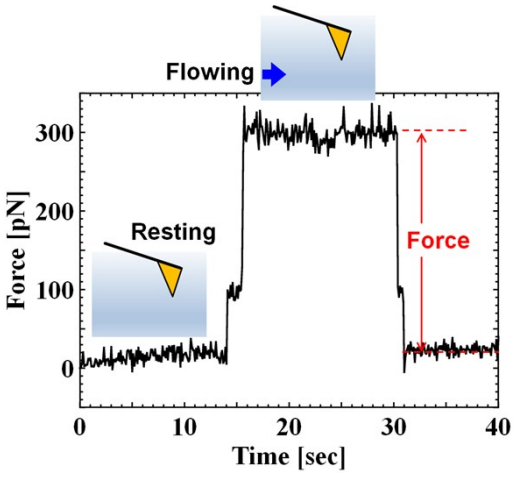


**Fig. SI2** The force detected by the cantilever in the flow of glycerol 22wt% solution at the flow rate of 4mL/min.

## SI3. Evaluation of the experiments

The $C_d$ values of the naked cantilever probe measured in the PEG10k and PEG35k solutions are shown in Fig. SI3, which are also a function of *Re*. $C_d$–*Re* is independent of the solution around the naked cantilever, verifying the validity of the measurements.

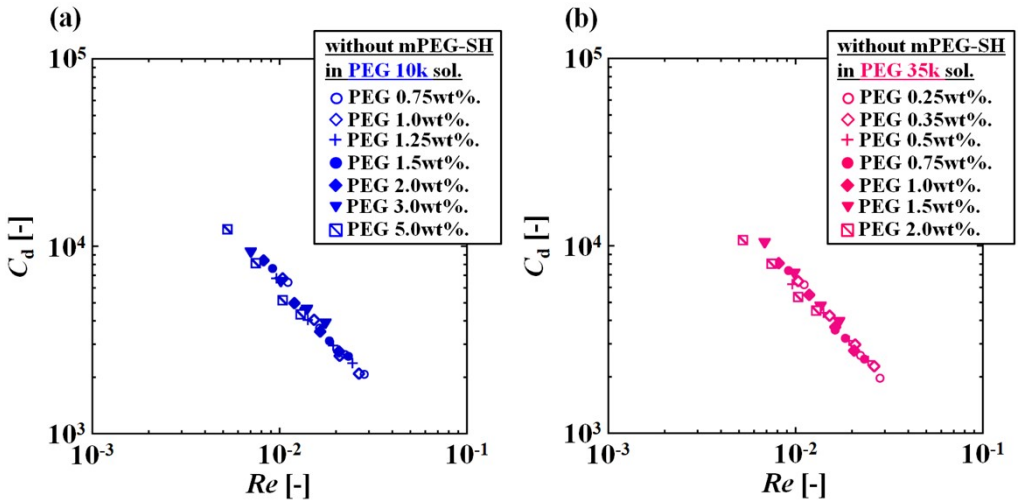


**Fig. SI3** $C_d$-*Re* plot for the naked cantilever probe in (a) PEG10k and (b) PEG35k solutions.

## SI4. Parameters and examples of calculated values to obtain Δ*F* by Eq. (5)

Here we summarize several important parameters and calculated values to obtain Δ*F* by Eq. (5). Dimensions of the cantilever and calculated values based on the dimensions are summarized in Table SI2. The grafting distance, Δ*l*, was calculated based on data obtained from previous studies, which is summarized in Table SI3. Table SI4 summarized the velocities *V* [mm/s] of glycerol solution at each flow rate as examples. Table SI5 summarized the averaged values of $f_{single}$ [pN] of each PEG in glycerol solutions at each flow rate as examples.

**Table SI2.** Dimensions of the cantilever.

| $\cos\alpha$ | $\cos\theta$ | *L* [nm] |
|---|---|---|
| 0.754 | 0.966 | 100 |

**Table SI3.** The grafting distance, Δ*l*, of mPEG-SH of each molecular weight.

| mPEG-SH | Δ*l* [nm] |
|---|---|
| 10k | 2.5 |
| 20k | 3.9 |
| 40k | 4.9 |

**Table SI4.** The velocity, $V$ [mm/s], of each glycerol solution at each flow rate. The position measured the velocity was the height of 1.4 mm, at the test position in the flow channel.

| Flow rates [mL/min] | 5 wt% | 10 wt% | 15 wt% | 22 wt% | 35 wt% |
|---|---|---|---|---|---|
| 2.0 | 1.69 | 1.69 | 1.69 | 1.68 | 1.68 |
| 3.0 | 2.50 | 2.48 | 2.46 | 2.43 | 2.39 |
| 4.0 | 3.41 | 3.39 | 3.38 | 3.36 | 3.32 |
| 5.0 | 4.33 | 4.29 | 4.26 | 4.22 | 4.14 |

**Table SI5.** The averaged values of $f_{single}$ [pN] of mPEG-SH (a) 10k, (b) 20k and (c) 40k in glycerol solution at each concentration at each flow rate.

(a)

| Flow rates [mL/min] | 5 wt% | 10 wt% | 15 wt% | 22 wt% | 35 wt% |
|---|---|---|---|---|---|
| 2.0 | 0.108 | 0.132 | 0.149 | 0.176 | 0.226 |
| 3.0 | 0.160 | 0.194 | 0.218 | 0.255 | 0.321 |
| 4.0 | 0.218 | 0.265 | 0.299 | 0.352 | 0.446 |
| 5.0 | 0.277 | 0.336 | 0.377 | 0.442 | 0.557 |

(b)

| Flow rates [mL/min] | 5 wt% | 10 wt% | 15 wt% | 22 wt% | 35 wt% |
|---|---|---|---|---|---|
| 2.0 | 0.165 | 0.202 | 0.228 | 0.269 | 0.345 |
| 3.0 | 0.244 | 0.295 | 0.332 | 0.388 | 0.487 |
| 4.0 | 0.333 | 0.404 | 0.454 | 0.533 | 0.675 |
| 5.0 | 0.421 | 0.509 | 0.571 | 0.668 | 0.838 |

(c)

| Flow rates [mL/min] | 5 wt% | 10 wt% | 15 wt% | 22 wt% | 35 wt% |
|---|---|---|---|---|---|
| 2.0 | 0.235 | 0.287 | 0.324 | 0.382 | 0.489 |
| 3.0 | 0.347 | 0.419 | 0.470 | 0.551 | 0.688 |
| 4.0 | 0.472 | 0.574 | 0.641 | 0.754 | 0.957 |
| 5.0 | 0.598 | 0.720 | 0.809 | 0.947 | 1.194 |

**References**

[1] W. E. Krause, E. G. Bellomo and R. H. Colby, Biomacromolecules, 2001, 2, 65.

[2] R. Hidema, T. Oka, Y. Komoda and H. Suzuki, Phys. Fluids, 2019, 31, 072005.