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Structure and Interaction of Poly(ethylene glycol) in Aqueous Solutions. Small-Angle Neutron Scattering Data

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Summary: Behavior of low molecular mass poly(ethylene glycol) (PEG) polymer, i.e. molar masses $M_n = 400$ and 1000, in heavy water is studied by small-angle neutron scattering (SANS). Some part of the polymer molecules in concentrated solutions is found to form aggregates with size exceeding 30 nm. The form-factor of Gaussian coil is used to describe low concentrated PEG solutions. Virial coefficients are obtained from approximation of experimental SANS data for PEG solutions with concentration higher than 3% where the interparticle interaction effect is well observed.

Keywords: interacting Gaussian coil; magnetic fluids; poly(ethylene glycol) (PEG) solutions; small-angle neutron scattering; virial coefficient

Introduction

Poly(ethylene glycol), $H\text{-}(O\text{-}CH_2\text{-}CH_2)_n\text{-}OH$, (PEG) is widely used polymer in various applications (e.g. food, medicine, pharmaceutics etc.), in particular due to its high biocompatibility. Thus, nanoparticles coated with PEG in living organisms are not immediately degraded by immune system,[1] so the introduction of PEG in the structure of nanoparticles and complexes may increase significantly the circulation time of such particles in organisms. The reason for this is related to the fact that the particle surface coated with PEG shows enhanced resistance against protein adsorption, see e.g..[2] An example of such application of PEG with low molar masses is the increase of the lifetime of magnetic nanoparticles from water-based ferrofluids or magnetic fluids (liquid dispersions of magnetic nanoparticles) in organisms.[3–5] Some increase in biocompatibility is observed even at simple addition of PEG into magnetic fluids, i.e. without the direct covalent bonding between PEG and magnetic particles.

The goal of the current study is to investigate the behavior (structure and interaction characteristics) of PEG molecules in water, which gives some basic knowledge useful for further structural analysis of the complex PEG-comprising systems. For this purpose the solutions of PEG of low molecular weights, viz $M_n = 400$ and 1000, in deuterated water (D_2O) are studied by small-angle neutron scattering (SANS). We continue our previous study,[6] where SANS was applied for the structure characterization of diluted aqueous solutions of PEG with different molecular weights in a range of $M_n = 400$–20000. Here, the additional SANS analysis of the structure-factor effect in concentrated PEG solutions is carried out. The measurements are performed at the physiological temperature of 37 °C taking into account a specific interest to using PEG in biocompatible ferrofluids. The general task is also related

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with the interaction characteristics between surfactant/polymer molecules used in the stabilization of magnetic fluids,[7,8] which is important for understanding the synthesis procedure of highly stable magnetic fluids with controllable properties.

Materials and Methods

PEG with molar masses $M_n = 400$ and 1000 (PEG 400 and PEG 1000 correspondingly) was purchased from Sigma-Aldrich. It was dissolved in pure D_2O (D-content 99.9%) with the mass fractions within an interval of 0.5–10% and 0.6–20.5% for $M_n = 400$ and 1000, respectively. D_2O was used to achieve a sufficient scattering contrast between PEG and the liquid carrier, as well as for reduction of the incoherent neutron scattering background from hydrogen. SANS experiments were performed at the SANS-1 instrument of the Neutron Facility at the GKSS Research Centre, Geesthacht, Germany. Measurements were done at the temperature of 37 °C. The 5 mm and 1 mm thick quartz cells were used for solutions of PEG with $M_n = 400$ and 1000, respectively. In all cases as a buffer pure D_2O was used. The differential cross-section per sample volume (hereafter referred to as scattered intensity) was obtained as a function of the scattering vector module, $q = (4\pi/\lambda)\sin(\theta/2)$, where λ is the incident neutron wavelength and θ is the scattering angle. To obtain the scattered intensity in the absolute scale (cm^{-1}) the standard calibration[9] using the scattering from 1-mm water sample was made after the corrections on the background, buffer (D_2O) and empty cell scattering.

Results and Discussion

The experimental SANS data for PEG 400 and PEG 1000 are given in Figure 1. As it was previously shown,[6] for low (less than 3%) polymer concentrations the scattering curves are approximated well by the form-factor of polymer coils (intramolecular correlations) only. For higher PEG concentrations the structure-factor effect (interparticle interaction) should be taken into account.

Some upturn of the scattering at low q-values ($q < 0.2\,nm^{-1}$) is observed (Figure 1). This fact is actively discussed in the literature on polymer solutions[10–12] and related to some kind of clustering of polymer chains. It should be noted that only the tail end of the signal from clusters is detected in the experimental SANS curves. It gives the lower estimates of the aggregate size at the level of 30 nm. The signal from the clusters is quite distinguishable for PEG

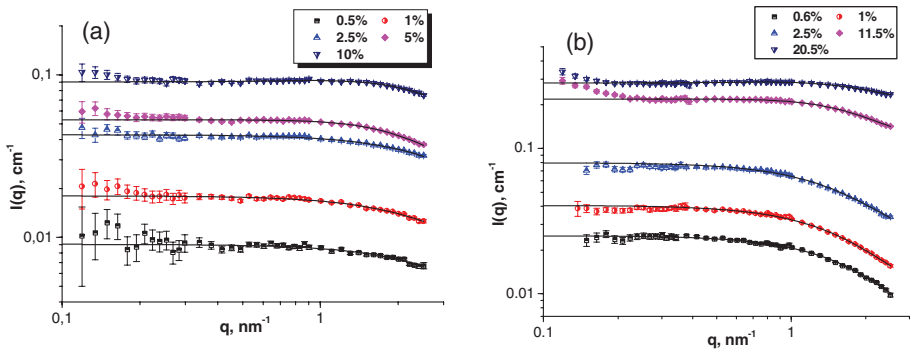

Figure 1.
SANS data (dots) as a function of concentration of PEG dissolved in D_2O, M_n is 400 (a) and 1000 (b). Solid lines show fits in accordance with the Debye formula (1) for non-interacting Gaussian coils (concentration less than 3%) and for interacting Gaussian coils (2) (concentration 5% and higher).

Table 1.
Data parameters of PEG400 and PEG1000 solutions derived from SANS.

Mass fraction of PEG400	$I(0)$, cm^{-1}	R_g, nm	A	Mass fraction of PEG1000	$I(0)$, cm^{-1}	R_g, nm	A
0.005	0.007(3)	0.5(1)	–	0.006	0.024(1)	0.80(4)	–
0.01	0.012(2)	0.58(6)	–	0.01	0.036(1)	0.91(2)	–
0.025	0.033(3)	0.48(3)	–	0.025	0.067(1)	0.92(1)	–
0.05	0.076(3)	0.82(4)	0.037(1)	0.115	0.297(1)	1.04(1)	0.156(1)
0.1	0.137(5)	0.77(2)	0.081(2)	0.205	0.265(2)	1.03(1)	0.162(2)

concentrations starting from 5% and higher. This is consistent with the data for the aqueous solution of PEG with molecular mass M_n =100000 when the clusters were formed at the volume fraction of 4% PEG in D_2O.[13] The specific features of the scattering are revealed also for higher q-values ($q > 0.2\ nm^{-1}$). The further analysis considers this region.

For low (< 3%) PEG concentrations the Debye formula for the scattering from non-interacting Gaussian coils works well. This is demonstrated in Figure 1, where for the diluted PEG solutions the fits are based on the corresponding expression:[14]

$$I(q) = 2I(0)[e^{-x} - (1-x)]/x^2 + B, \qquad (1)$$
$$x = (qR_g)^2.$$

Here, $I(0)$ is the forward scattered intensity, R_g is the gyration radius and B is the residual background. These three parameters, i.e. $I(0)$, R_g and B, were varied in the fitting procedure.

For higher (> 3%) PEG concentrations equation (1) does not result in good fits, and scattered intensity is treated in terms of the random phase approximation:[14]

$$I(q) = I(0)\left[P(q) - (A/I(0))P(q)^2\right] + B, \qquad (2)$$

where $P(q)$ is Debye form-factor of the Gaussian coil as defined by equation (1) and A is a single virial interaction term, which describes the effective monomer-monomer interaction. One can see in Figure 1 that the equation (2) fits well the experimental curves with the varied parameters $I(0)$, R_g, A, B, besides the initial parts of the curves related with the aggregate formation. The resulting parameters of the fits are collected in Table 1.

As a first approximation, the non-interacting PEG molecules can be considered as ideal chains with the radius of gyration $R_g^2 \approx Na^2/6$, where N (9 and 22 for PEG 400 and PEG 1000, respectively) is the number of links in the freely jointed chain and a (~0.35 nm) is the link length. It gives $R_g \approx 0.43$ nm (PEG 400) and $R_g \approx 0.67$ nm (PEG 1000), which are comparable with the experimental values (Table 1) obtained for the lowest polymer concentrations in the solutions.

So, the concentrated solutions of PEG show that non-aggregated molecules independently of their mass behave like Gaussian coils despite the presence of some kind of aggregates. This is in agreement with our previous conclusion for diluted solutions.[6] We suppose that the approximation (2) taking the interaction effect into account explains reasonably the deviation from the Debye form-factor. It is an alternative way to the approach[15] considering the packing of all polymer molecules into somewhat flat aggregates in solutions.

Conclusion

Our study confirms the Gaussian coil type structure of PEG in solutions for the polymer molecular mass range of 400–1000. For low concentrations (<3%) SANS data for aqueous solutions of PEG are described well by the Debye formula for the scattering from non-interacting Gaussian coils, while for high concentrations (>3%) one can use the model of interacting Gaussian coils. Such interaction in concentrated PEG solutions can be characterized by some analogue of the virial coefficient.

Along with this, the polymer aggregates with size larger than 30 nm are observed in concentrated solutions.

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