

The mystery of clustering in macromolecular media

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ABSTRACT

Clustering occurs in most polar media such as water-soluble macromolecules. The true origin of clustering has been elusive despite a great deal of research effort. This paper uses the simplest water-soluble polymer, poly(ethylene oxide), dissolved in deuterated water to investigate the cause of clustering. The small-angle neutron scattering technique is used to separate out solvation effects from clustering effects and back out the various interaction parameters. It is found that clustering is related to attractive inter-chain interactions between hydrophobic groups which create physical crosslinks thereby causing clustering.

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1. Introduction

Clustering is pervasive in soft media. It has been observed in water-soluble synthetic polymers and in biological macromolecular systems such as DNA and proteins. Clusters form often in polar media. Clustering, however, is oftentimes an undesired phenomenon which prevents global dissolution and homogeneous mixing. The true cause of clustering is not understood.

Some effects are known to cause clustering. The incorporation of solvent-phobic end-groups was shown to cause clustering in polymer solutions [1]. The simplest water-soluble synthetic polymer, poly(ethylene oxide) comprises monomers that contain hydrophobic ethylene groups $-\text{CH}_2\text{CH}_2-$ and hydrophilic oxygen groups $-\text{O}-$. Poly(ethylene oxide) chains with methoxy end groups ($\text{CH}_3\text{O}-$) show clustering when dissolved in water. Moreover, poly(ethylene oxide) chains with hydroxy end groups ($\text{HO}-$) show clustering when dissolved in benzene. A form of clustering is caused by the solvent-phobic nature of these end groups. For example, the hydrophobic methoxy group will not achieve equilibrium until it “sticks” to an ethylene group on the polymer chain in PEO/water solutions [1]. This form of clustering occurs even for long chains that contain thousands of monomers (and two end groups). Actually, anionic polymerization uses stable initiator and terminator groups that are mostly hydrophobic. Chain end clustering prevails in synthetic polymer solutions but another possible cause of clustering is discussed in this paper.

Clustering appears as a low angle signal in the various small-angle scattering methods such as small-angle neutron scattering (SANS) or small-angle X-ray scattering (SAXS). It also appears as a “slow mode” in dynamic light scattering (DLS). It can be observed by optical microscopy when cluster sizes are of micron size. Clustering is also detected by rheology since cluster formation tends to increase the fluid viscosity.

The clustering of poly(ethylene oxide) solutions in water was investigated by DLS [2,3]. Both a slow mode (due to clustering) and a fast mode (due to polymer chain solvation) were observed. Filtering of the polymer solution made clustering disappear. Clustering, however, reappeared after a couple of days of equilibration. This suggests that filtering can break the physical crosslinks required to form clusters. But these physical crosslinks reform over time.

The purpose of the investigations reported here is to discuss a cause of clustering which may be prevalent.

2. Small-angle neutron scattering

The small-angle neutron scattering (SANS) technique is well suited to investigate the clustering phenomenon. Clustering shows up as a low- Q feature where Q is the scattering variable. SANS data are also characterized by a high- Q solvation feature which is due to polymer-solvent interactions. These two characteristic features (clustering and solvation) have been observed in synthetic as well as biopolymers in solutions.

Fig. 1 shows SANS spectra from an uncharged synthetic polymer, poly(ethylene oxide) (PEO), from a synthetic polyelectrolyte

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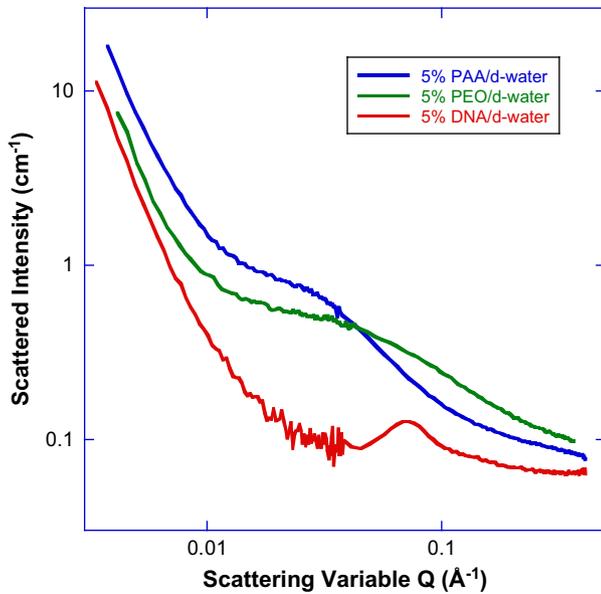


Fig. 1. SANS data from 5% poly(acrylic acid), 5% poly(ethylene oxide) and from 5% salmon DNA in deuterated water. A low-Q clustering feature and a high-Q solvation feature are observed.

poly(acrylic acid) (PAA) and from a charged biological macromolecule (DNA) in deuterated water (d-water). Deuterated solvent is used in order to enhance the neutron contrast and therefore the sensitivity of the SANS technique. In all of these cases, a strong low-Q clustering feature is observed. The high-Q solvation feature shows up as a smooth Lorentzian type behavior for the PEO solution or as a polyelectrolyte peak for the other two cases involving charged macromolecules. In the PAA case, the strong low-Q clustering feature and the high-Q polyelectrolyte peak have merged. Note that the SANS measurement window shown in Fig. 1 covers the tail end of the clustering feature only. Only the low-Q Porod region is observed. No low-Q Guinier region can be observed for such huge (micron size) clusters.

Note that like all scattering methods, SANS consists in measurements in reciprocal (i.e., Fourier transform) space and cannot therefore produce sample images as from microscopy. Models are used, instead, to interpret the data.

The SANS technique is used to investigate clustering in PEO/d-water solutions in the upcoming sections.

3. Sans from poly(ethylene oxide)/d-water

A series of SANS measurements were performed from PEO/d-water solutions. The PEO molecular weights were $M_w = 100\,000$ g/mol and $M_n = 96\,000$ g/mol corresponding to a polydispersity index of $M_w/M_n = 1.04$. A set of seven samples was prepared. These correspond to PEO volume fractions of 0.5%, 1%, 2%, 3%, 4%, 5%, and 10%. The measured temperatures were 10 °C, 30 °C, 50 °C, 70 °C, and 90 °C. Fig. 2 shows representative data from the 5% PEO sample. The low-Q clustering feature and the high-Q solvation features are clearly observed.

In order to separate out the low-Q clustering feature from the high-Q solvation feature for the PEO/d-water SANS data, a simple empirical model is used. The SANS scattering intensity is represented by:

$$I(Q) = \frac{A}{Q^n} + \frac{C}{1 + (Q\xi)^m} + B. \quad (1)$$

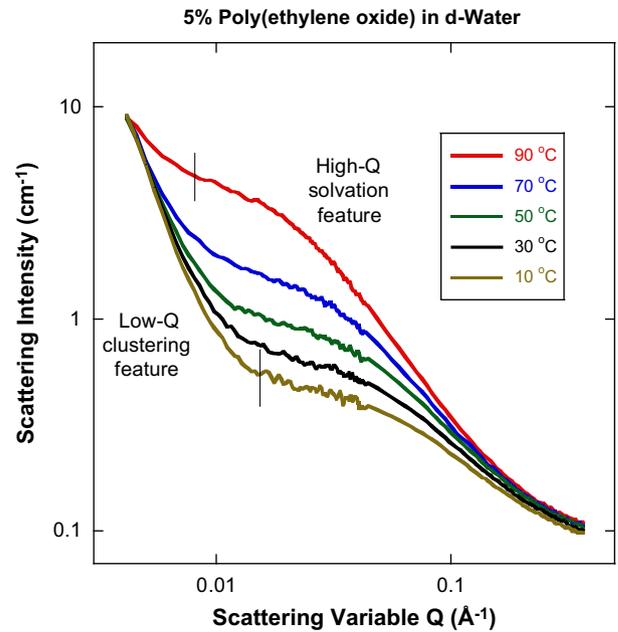


Fig. 2. SANS from 5% poly(ethylene oxide) in d-water for various temperatures. The low-Q clustering feature and the high-Q solvation feature can be clearly observed.

The first term describes Porod scattering from clusters and the second term describes scattering from solvated polymer chains. This second term characterizes the polymer/solvent interactions and therefore the thermodynamics of mixing. The two multiplicative factors A and C , the incoherent background B and the two Porod exponents n and m are used as fitting parameters. The final parameter ξ is a correlation length along the polymer chains and represents the chain entanglement length in semidilute polymer solutions.

Fig. 3 compares the low-Q clustering intensity A/Q^n and the high-Q solvation intensity C for the 5% PEO/d-water sample in the

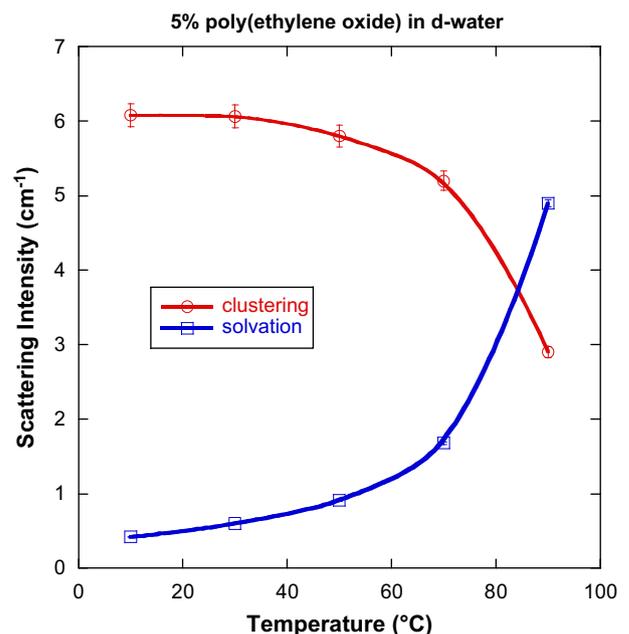


Fig. 3. Variation of the clustering intensity A/Q^n and the solvation intensity C with increasing temperature. A low-Q value of 0.004 \AA^{-1} is used for the clustering intensity. Smooth curves have been included as a visual guide. Statistical error bars are smaller than the symbols on the bottom curve. These correspond to one standard deviation and were obtained from fitting.

measured temperature range. Note that since the PEO/d-water solution tends to demix upon heating, the “solvation” intensity C could have been called “non-solvation” intensity in this case. The term “solvation” is kept for the purpose of generalization. Clustering is seen to decrease while solvation increases with temperature. These two trends are opposite pointing to different driving forces for these two phenomena. Solvation is driven by polymer solvent interactions. The cause for clustering is being investigated in this paper.

Increase of the solvation intensity with temperature characterizes a lower critical solution temperature (LCST) phase behavior in which phase separation occurs upon heating. Composition fluctuations increase when the phase boundary is approached leading to an increase in the scattering intensity (fitting parameter C). A plot of $1/C$ vs $1/T$ (where T is the absolute temperature) is characterized by a linear trend. Extrapolation to $1/C = 0$ (solvation intensity “blows up”) yields an estimate for the so-called spinodal temperature (98 °C for the 5% PEO/d-water sample). Note that some other polymers in solution phase separate upon cooling and are characterized by an upper critical solution (UCST) instead.

The clustering intensity A/Q^n decreases with temperature. Plot of its inverse Q^n/A vs $1/T$ does not show a linear trend. The major clue to remember for now is that solvation and clustering vary in opposite trends.

4. The random phase approximation

In order to perform a more detailed analysis of SANS data from the PEO/d-water series, the random phase approximation (RPA) model is used. This is a mean field approach that works best for polymer blend mixtures (without solvent) and is used here for a polymer solution in order to obtain approximate “molecular” parameters.

The two-component RPA equations are summarized here [4]. The scattering intensity (cross section $d\Sigma(Q)/d\Omega$) for the PEO/d-water polymer solution is given by:

$$\frac{(\rho_P - \rho_S)^2}{\frac{d\Sigma(Q)}{d\Omega}} = \frac{1}{S_{PP}^0(Q)} + \frac{1}{S_{SS}^0} - \frac{2\chi_{PS}}{\nu_0} \quad (2)$$

ρ_P and ρ_S are the neutron scattering length densities, $S_{PP}^0(Q)$ and S_{SS}^0 are the non-interacting scattering factors and χ_{PS} is the Flory–Huggins interaction parameter for the polymer (component P) and solvent (component S). ν_0 is a reference volume estimated as $\nu_0 = \sqrt{\nu_P \nu_S}$ in terms of the monomer volume ν_P and solvent molecule volume ν_S . Since our interest is in phase boundaries and not on conformational changes, the thermodynamic limit ($Q=0$) is considered in what follows. This two-component RPA model is used to fit the PEO/d-water data by setting:

$$\frac{d\Sigma(Q=0)}{d\Omega} \equiv C. \quad (3)$$

Where C is the solvation intensity obtained through fits to the empirical model. The RPA form factors are related to the degree of polymerization n_P , and polymer volume fraction ϕ_P as:

$$\begin{aligned} S_{PP}^0(Q=0) &= n_P \nu_P \phi_P \\ S_{SS}^0 &= \nu_S (1 - \phi_P). \end{aligned} \quad (4)$$

The following sample information is used:

$$\begin{aligned} n_P &= 2273 \\ \nu_P &= 6.47 \times 10^{-23} \text{ cm}^3 \\ \rho_P &= 6.39 \times 10^{-7} \text{ \AA}^{-2} \\ \nu_S &= 3.03 \times 10^{-23} \text{ cm}^3 \\ \rho_S &= 6.35 \times 10^{-6} \text{ \AA}^{-2} \end{aligned} \quad (5)$$

Nonlinear least squares fits were performed on the (ϕ_P, C) SANS data for each temperature. This produced a Flory–Huggins interaction parameter for each temperature. Linear fits yielded to following temperature dependence:

$$\chi_{PS} = 1.10 - \frac{132}{T}. \quad (6)$$

Here T is absolute temperature. Fits are improved when a composition-dependent Flory–Huggins interaction parameter is considered. The negative sign points to an LCST phase behavior as expected. The PEO/d-water solution phase separates at high temperatures. This approach explains the high- Q solvation part of the SANS data.

5. The ternary RPA

In order to understand the low- Q clustering part, we consider the PEO monomer to be an alternating copolymer of an ethylene ($-\text{CH}_2\text{CH}_2-$) block and an oxygen ($-\text{O}-$) block and use the RPA model for regularly alternating block copolymers in solution. This is a ternary system containing the oxygen blocks (component 1), the ethylene blocks (component 2) and d-water (component 3). The ternary RPA equations [5–7] are summarized here.

In the thermodynamic ($Q=0$) limit, the scattering cross section (previously referred to as solvation intensity C) is given by:

$$\frac{d\Sigma}{d\Omega} \equiv C = \Delta\rho_1^2 S_{11} + \Delta\rho_2^2 S_{22} + 2\Delta\rho_1 \Delta\rho_2 S_{12}. \quad (7)$$

The relevant contrast factors are:

$$\begin{aligned} \Delta\rho_1^2 &= (\rho_1 - \rho_3)^2 \\ \Delta\rho_2^2 &= (\rho_2 - \rho_3)^2 \end{aligned} \quad (8)$$

The partial structure factors for the fully interacting mixture are given by:

$$\begin{aligned} S_{11} &= \frac{S_{11}^0 (1 + \nu_{21} S_{12}^0 + \nu_{22} S_{22}^0) - S_{12}^0 (\nu_{21} S_{11}^0 + \nu_{22} S_{21}^0)}{(1 + \nu_{11} S_{11}^0 + \nu_{12} S_{21}^0)(1 + \nu_{21} S_{12}^0 + \nu_{22} S_{22}^0) - (\nu_{11} S_{12}^0 + \nu_{12} S_{22}^0)(\nu_{21} S_{11}^0 + \nu_{22} S_{21}^0)} \\ S_{22} &= \frac{S_{22}^0 (1 + \nu_{12} S_{21}^0 + \nu_{11} S_{11}^0) - S_{21}^0 (\nu_{12} S_{22}^0 + \nu_{11} S_{12}^0)}{(1 + \nu_{11} S_{11}^0 + \nu_{12} S_{21}^0)(1 + \nu_{21} S_{12}^0 + \nu_{22} S_{22}^0) - (\nu_{11} S_{12}^0 + \nu_{12} S_{22}^0)(\nu_{21} S_{11}^0 + \nu_{22} S_{21}^0)} \\ S_{12} &= \frac{-S_{11}^0 (\nu_{11} S_{12}^0 + \nu_{12} S_{22}^0) + S_{12}^0 (1 + \nu_{11} S_{11}^0 + \nu_{12} S_{21}^0)}{(1 + \nu_{11} S_{11}^0 + \nu_{12} S_{21}^0)(1 + \nu_{21} S_{12}^0 + \nu_{22} S_{22}^0) - (\nu_{11} S_{12}^0 + \nu_{12} S_{22}^0)(\nu_{21} S_{11}^0 + \nu_{22} S_{21}^0)} \end{aligned} \quad (9)$$

Excluded volume factors are defined in terms of the three Flory–Huggins interaction parameters (χ_{12} , χ_{13} , and χ_{23}) as:

$$\begin{aligned} \nu_{11} &= \frac{1}{S_{33}^0} - 2\frac{\chi_{13}}{\nu_0} \\ \nu_{22} &= \frac{1}{S_{33}^0} - 2\frac{\chi_{23}}{\nu_0} \\ \nu_{12} &= \frac{1}{S_{33}^0} + \frac{\chi_{12}}{\nu_0} - \frac{\chi_{13}}{\nu_0} - \frac{\chi_{23}}{\nu_0} \end{aligned} \quad (10)$$

The reference volume ν_0 is expressed in each case as the square root of the product of the relevant volumes. The non-interacting scattering factors for this alternating copolymer solution are given by:

$$\begin{aligned} S_{11}^0 &= n_1 \phi_1 \nu_1 \\ S_{22}^0 &= n_2 \phi_2 \nu_2 \\ S_{12}^0 &= \sqrt{n_1 \phi_1 \nu_1 n_2 \phi_2 \nu_2} \\ S_{33}^0 &= \phi_3 \nu_3 \end{aligned} \quad (11)$$

The volume fractions are related by $\phi_1 + \phi_2 + \phi_3 = 1$. The polymer volume fraction is $\phi_P = \phi_1 + \phi_2$. The individual volume fractions are expressed as $\phi_1 = \phi_P n_1 v_1 / (n_1 v_1 + n_2 v_2)$ and $\phi_2 = \phi_P - \phi_1$. The following sample information is used:

$$\begin{aligned} n_1 &= 2273 \\ v_1 &= 2.35 \times 10^{-23} \text{ cm}^3 \\ \rho_1 &= 2.47 \times 10^{-6} \text{ \AA}^{-2} \\ n_2 &= 2273 \\ v_2 &= 4.12 \times 10^{-23} \text{ cm}^3 \\ \rho_2 &= -4.04 \times 10^{-7} \text{ \AA}^{-2} \\ v_3 &= 3.03 \times 10^{-23} \text{ cm}^3 \\ \rho_3 &= 6.35 \times 10^{-6} \text{ \AA}^{-2} \end{aligned} \quad (12)$$

Nonlinear least squares fits are performed using the ternary RPA model. The same SANS data files containing two columns (ϕ_P , C) for each temperature are used to back out the three Flory–Huggins interaction parameters χ_{12} , χ_{13} , and χ_2 for that temperature. In order to improve the fits, composition-dependent Flory–Huggins interaction parameters are considered. Linear best fit results of the temperature dependence are given by:

$$\begin{aligned} \chi_{12} &= \left(-0.46 + \frac{27}{T}\right) + \left(-7.14 + \frac{3014}{T}\right)\phi_P \\ \chi_{13} &= \left(0.59 - \frac{31}{T}\right) + \left(-3.51 - \frac{1477}{T}\right)\phi_P \\ \chi_{23} &= \left(0.54 - \frac{50}{T}\right) + \left(11.25 - \frac{1425}{T}\right)\phi_P \end{aligned} \quad (13)$$

These results are summarized in Fig. 4 which contains the significant results of this paper.

6. Results and discussion

Fig. 4 shows that two of the Flory Huggins interaction parameters, χ_{13} (oxygen/d-water) and χ_{23} (ethylene/d-water) characterize an LCST phase behavior (phase separation upon heating) while the third one χ_{12} (oxygen/ethylene) characterizes a UCST phase behavior (phase separation upon cooling). The oxygen and ethylene groups, however, cannot phase separate since they form the PEO monomer (are covalently bounded). This produces a “frustrated” system where the ethylene group is forced to remain next to the backbone oxygen while it “prefers” to be close to another ethylene group. Ethylene groups remain dissolved but use any opportunity

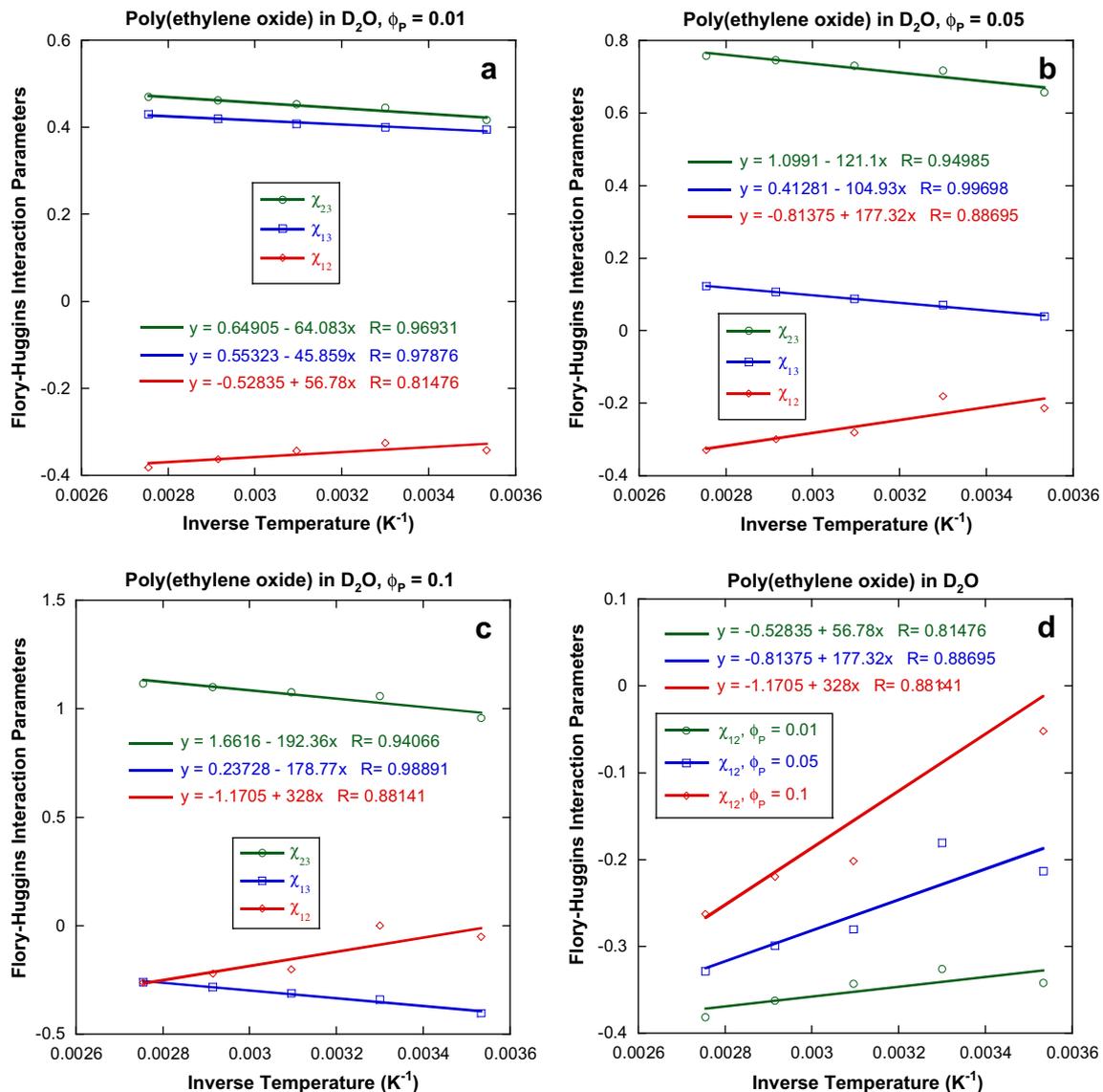


Fig. 4. Variation of the Flory–Huggins interaction parameters between the three components: χ_{12} (oxygen/ethylene), χ_{13} (oxygen/d-water) and χ_{23} (ethylene/d-water). Case (a) corresponds to a PEO volume fraction of $\phi_P = 0.01$, case (b) corresponds to $\phi_P = 0.05$ and (c) case (c) corresponds to $\phi_P = 0.1$. Case (d) summarizes χ_{12} for increasing PEO fraction.

to stick to other ethylene groups on adjacent chains each time they get close enough. This produces physical crosslinks that form large clusters. Chain entanglements in semidilute and concentrated solutions produce favorable sites for close proximity of ethylene groups. The clustering process is kinetically driven.

Fig. 4a and b, and c represents the three Flory Huggins interaction parameters for the 1%, 5% and 10% PEO volume fractions respectively. The ethylene/d-water parameter χ_{23} is the highest in all cases; this is due to the hydrophobic nature of ethylene. The oxygen/d-water parameter χ_{13} is seen to weaken as the PEO volume fraction increases. Actually χ_{13} and χ_{12} become comparable in magnitude for the 10% PEO fraction. However, χ_{12} remains characteristic of a UCST phase behavior throughout for all PEO fractions. Fig. 4d shows that χ_{12} increases with increasing PEO fraction thereby increasing the clustering driving force. It is clear that the behavior of χ_{12} can explain the origin of clustering. Just like clustering, χ_{12} decreases with increasing temperature but increases with increasing PEO fraction. Note that at the same time, χ_{23} increases with increasing PEO fraction which means that ethylene groups become more hydrophobic and tend to stick more to other ethylene groups.

Fig. 5 shows a schematic representation of clustering sites.

PEO dissolves in d-ethanol (deuterated ethanol) as well. The PEO/d-ethanol system is crystalline at low temperatures but yields dissolved polymers in solution at high temperatures. The PEO/d-ethanol polymer solution is known to obey a UCST phase behavior (phase separates upon cooling) [8]. Clustering, however, does not exist in this system. Using the same approach, a ternary system is formed of oxygen/ethylene (components 1 and 2) and d-ethanol (component 3). It is reasonable to assume that the two Flory–Huggins interaction parameters χ_{13} and χ_{23} follow a UCST phase behavior (just like PEO/d-ethanol). In the previous section, it was concluded that χ_{12} also follows a UCST phase behavior. The fact that all three Flory–Huggins interaction parameters follow a UCST phase behavior removes any need for cluster formation (ethylene groups are no longer solvent-phobic).

The origin of clustering discussed in this paper may be the answer to the clustering mystery that has been elusive. These results also give some insight into the nature of polar interactions. A similar idea was put forward in the so-called “Stockmayer fluid” [9] model in which a contribution to the interaction potential was included to represent dipolar interactions. The Stockmayer fluid forms clusters due to dipolar interactions.

The approach described here could be generalized to more complex systems containing a larger number of chemical groups. The multi-component RPA model [10] could describe macromolecules formed of $(n-1)$ groups in a solvent (n th component). This formalism is tractable involving the inversion of $(n-1)^*(n-1)$ matrices. A set of at least $n^*(n-1)/2$ samples have to be measured in order to back out the $n^*(n-1)/2$ Flory–Huggins interaction parameters. Since the RPA approach applies to homogeneous mixtures only, measurements have to be made in the mixed single-phase region.

In summary, clustering in PEO/d-water solutions is due to ethylene groups sticking together due to hydrophobic interactions. Physical closeness of such groups in semidilute and concentrated solutions enhances clustering. There is no clustering in dilute solutions. A recent investigation showed that clustering does not take place in athermal solutions as well [11]. In an athermal

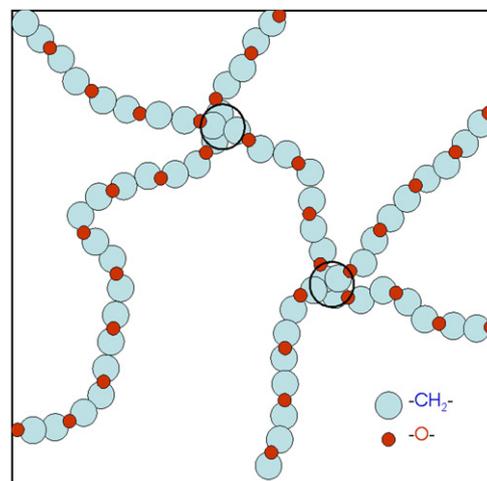


Fig. 5. Schematic representation of dissolved PEO chains showing two clustering sites.

solution, monomer–monomer, monomer–solvent and solvent–solvent interactions are equivalent. Therefore, all chi parameters vary similarly and all phase diagrams are equivalent (either all UCST or all LCST). Just like in the case of PEO/d-ethanol solution, such an athermal system would not form clusters.

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