

Stoichiometry of Poly(ethylene glycol) in Water and Benzene by Excess Volume

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SYNOPSIS

In this work, we studied the excess volume of solutions of low molecular weight poly(ethylene glycol)s (200, 400, and 600) in water and in benzene. We noted that there is a higher contraction of the volume for water solutions in all compositions. Solutions of these polymers in benzene also undergo a volume contraction. However, the magnitude of this effect is lower for benzene solution than for water. Moreover, the stoichiometry of the system at the composition corresponding to the maximum volume contraction is different in each case: one water molecule per two oxyethylene (EO) units, and one benzene molecule per four EO units. The results are compared with the mixing enthalpy measured by Lakanpal et al.²⁹ As reported, they observed that while the system PEG/water is exothermic in all compositions, the system PEG/benzene is endothermic, which shows that although in both solvents there is volume contraction, the driving forces for these dissolutions are different. © 1997 John Wiley & Sons, Inc.

INTRODUCTION

Poly(ethylene glycol) (PEG) belongs to a class of polyethers with the following unique property: complete miscibility in water over both a wide range of temperature and molecular weights. This property has been explained by the fact that the structure of the H-bonds in water is not changed significantly by the introduction of the PEG macromolecules.¹⁻³ Blandemer et al.⁴ suggested that the PEG chains can be accommodated within the hexagonal water structure because the distance between alternate oxygen atoms of PEG in a suitable conformation is equal the next nearest neighbor distance (≈ 0.47 nm) of the water oxygen atoms.⁴ In the same sense, other authors suggested that a third of the water molecules, at the lattice points, should be substituted by the ether oxygen atoms of the PEG. In this case, each ether oxygen would be connected to a water molecule

by one hydrogen bond with the ethylene groups oriented toward the cavities of the crystal lattice.⁵

The solubility in water of this class of polymers is particularly important in several technological applications, including in pharmacy and biology.⁶⁻⁹ For these reasons, there are various works, using different techniques, looking for evidence to explain the stoichiometry, mechanism, conformation, and driving forces for the dissolution of PEG by water or organic solvents. However, these subjects are still controversial. While Molyneux¹⁰ suggested that in the high dilution region, there is an interaction of two moles of water per base mole of PEG, with both molecules of water being hydrogen bonded to an oxygen of the oxyethylene (EO) group, Graham et al.¹¹⁻¹³ showed that the polymer exists as a trihydrate, stable even at high levels of dilution for molar mass greater than a critical value of 1500 when the polymer adopts a helical conformation, also observed in the crystalline state.^{2,14-17} More recently, Bieze et al.¹⁸ established that the total number of water molecules that can be packed around each EO group is approximately six, although only two potential acceptor sites are available on each atom to form hydrogen bonds to water molecules. Moreover, ca-

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lorimetric measurements indicate that the average primary hydration number is actually closer to one.¹⁹ The presence of hydrate layers on the PEG macromolecules has also been reported earlier; in this case, it has been suggested that the first layer is being formed by one mole of water bonded to the ether atom of the PEG with the second layer exhibiting a diffuse structure.⁹ Otherwise, from viscosity measurements²⁰ and determination of diffusion coefficients,²¹ a random coil conformation for the PEG molecules in water was proposed. In addition, from volumetric properties, Lepori and Mollico²² indicated that the most realistic picture of the PEG molecules in aqueous solution is an "expanded" random coil of hydrated polymers, probably with helical segments.

It has also been demonstrated that whatever the structure and conformation of PEG molecules in aqueous solutions was, PEG molecules in chloroform, methylene chloride,¹⁵ and other organic solvents³ exist primarily as random coils. Moreover, in aqueous solutions, the structure is very complex and depends on the molecular weight and concentration.

The partial molar volume of solutes in infinitely dilute solutions (V^0) is one thermodynamic property which reflects solute-solvent interactions. In a nonideal solution, it is expected that the partial molar volume of the solute (V^0) should be reduced compared with pure solute (V^*). The magnitude of the volume change of mixing defines the excess volume (V^{Ex}) and represents the difference between the measured volume (V) of the nonideal solution from the combined partial volumes ($\sum V_i^*$) of the two components before mixing.

In this work, we studied the diagrams of V^{Ex} versus concentration for low molecular weight poly(ethylene glycols) (200, 300, 400, and 600) in water (a solvent which could produce a partially structured solution) and in benzene (a solvent where, in principle, PEG exists in a random coil structure). These low molecular weight polymers have been chosen since they present a less ordered structure in aqueous solutions,²³ and the relative importance of the conformation of the polymer chains in both these different solvents should be similar. In this study, we measure the excess volume of the solutions, in both solvents, and in several concentrations and analyzed its magnitude for PEG with different molecular weights.

EXPERIMENTAL

The poly(ethylene glycol)s (PEG) were purchased from Sigma (200 and 400), Merck (300),

Table I Number Average Molecular Weights of the PEGs

PEG	M_n (g mol ⁻¹)
200	229 ± 10
300	292 ± 9
400	405 ± 17
600	585 ± 34

and Riedel de Haen (600). These numbers specified the nominal number average molecular weights in g mol⁻¹. These polymers are known to be very hygroscopic and must be carefully dried by adding 4 Å molecular sieves to the liquid polymer. We stored the dry polymer under vacuum in a desiccator. The drying process can be evaluated by infrared spectroscopy, following the intensity of the band at 3500 cm⁻¹ to constant intensity. The water content should also be evaluated, using a method described elsewhere,²⁴ to be lower than 0.1% in mass.

Number average molecular weights of these polymers were determined by vapor pressure osmometry using a Kanauer instrument with an universal probe and benzil as a standard.²⁵ These values are shown in Table I.

Benzene was purified using the procedure recommended by Perrin and Armarego.²⁶

Solutions of PEG in water (distilled through a Vigraux column) and benzene (Merck) were prepared in a volumetric flask under exhaustive magnetic stirring for 2 h in order to get very homogeneous solutions.

The excess volume for each PEG solution was obtained from density determinations by a gravimetric method. The PEG solutions were equilibrated at 25°C for 1 h before measurements. The density of each solution was measured by picnometry using a bottle calibrated with water with a volume of 40.4610 ± 0.0009 cm³. All of the measurements were performed at 25°C, and the temperature was controlled within a limit of ±0.5°C. The gravimetry determinations was done using a Fisher Scientific A-250 analytical balance. The data shown in this work are the average values that resulted from three independent determinations for each solution.

RESULTS AND DISCUSSION

Excess volumes can be determined from the density values using the following definitions: for a

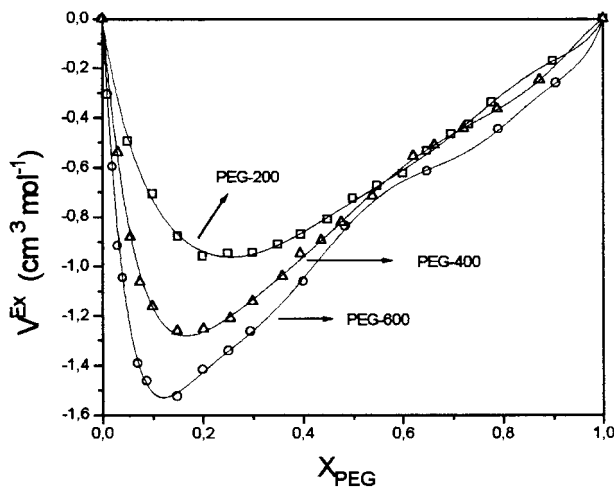


Figure 1 V^{Ex} diagrams for PEG/water mixtures at 25°C, for PEG 200, 400, and 600.

binary solution of PEG and a solvent, the excess volume V^{Ex} of the solution is expressed by the following equation:²⁷

$$V^{\text{Ex}} = \frac{V - V^*}{n} = X_{\text{PEG}} (\bar{V}_{\text{PEG}} - \bar{V}_{\text{PEG}}^*) + X_s (\bar{V}_s - \bar{V}_s^*) \quad (1)$$

where \bar{V}_{PEG}^* , \bar{V}_s^* , \bar{V}_{PEG} , and \bar{V}_s are the molar volumes of PEG and solvent for ideal (*) ($V^* = n_{\text{PEG}}\bar{V}_{\text{PEG}}^* + n_s\bar{V}_s^*$) and nonideal solutions, respectively; X_{PEG} and X_s are the molar fractions; * denotes pure components; $n = (n_{\text{PEG}} + n_s)$ is the total number of moles of the solution; and V , the volume in the composition (X_{PEG}, X_s), can be obtained from the relationship, as follows.

$$V = \frac{(n_{\text{PEG}}M_{\text{PEG}} + n_sM_s)}{\rho} \quad (2)$$

where ρ is the solution density, which is, in this work, determined by gravimetry.

Using these equations and the density values determined by gravimetry, we could determine the excess volume for all the solutions.

Excess Volume for PEG/Water Mixtures

Diagrams of V^{Ex} versus composition for PEG/water mixtures at 25°C are shown in Figure 1. This figure shows that all the solutions present negative V^{Ex} (volume contraction) for all compositions, and that the magnitude of this effect increases

with the PEG molecular weight, at least in the range studied here. We could also note that the curves present a minimum, which represents the maximum volume contraction (MVC) of the solution. As indicated earlier, the magnitude of the mixing volume change reflects the strength of molecular solute/solvent interaction. This result should reveal some details for the organization of the components in the solution, which signifies, in this case, the structure for which both PEG and water molecules exist in a more compacted lattice. Therefore, it is interesting to analyze the MVC for the PEG with different molecular weights.

It is noteworthy that the stoichiometric number of water molecules for each EO unit at the MVC points, from Figure 1, is independent of the PEG molecular weights and corresponds to one water molecule per two EO units. Khrakoz²⁸ stated that the formation of one mole of stable hydrogen bonds with the solute should result in the loss of $\frac{1}{2}$ mole of hydrogen bonds in the solvent and that the formation of each hydrogen bond between the polar group and water should be accompanied by a decrease of the partial molar volume of $\sim 2\text{--}2.5 \text{ cm}^3 \text{ mol}^{-1}$. Moreover, they have also stated that there is a good correlation between the volumetric stoichiometry of the H-bonding and the chemical structure of the polar groups. Particularly, in the case of cyclic and linear ethers and ethylene glycols, there is one H-bonding per oxygen atom and a corresponding decrease of the partial molar volume in the range of -1.2 to $-1.5 \text{ cm}^3 \text{ mol}^{-1}$, which corresponds to the effect of formation of one hydrogen bond with water.

For the purpose of comparing the MVC points for PEG with different molecular weights, we have determined the molar volume of water at the MVC point (see Fig. 1). This can be done by using the slope method, in which the MVC point is the minimum of the curve. The line tangent to the curve, in this point, is parallel to the abscissa, and $V_{\text{H}_2\text{O}}$ (MVC) could be obtained from the value of V^{Ex} , which has been calculated from the projection of the tangent to the ordinate axis (for $X_{\text{PEG}} \rightarrow 0$). Dependence of $V_{\text{H}_2\text{O}}$ (MVC) on PEG molecular weight is shown in Figure 2.

The $V_{\text{H}_2\text{O}}$ (MVC) values for those polymers are shown in Table II. In this table, the percentage of the molar volume contraction of water in relation to the pure water $V_{\text{H}_2\text{O}}^*$ is also indicated. From Table II, it is observed that $V_{\text{H}_2\text{O}}$ (MVC) decreases with an increase in the PEG molecular weight. This result is evidence that the system becomes

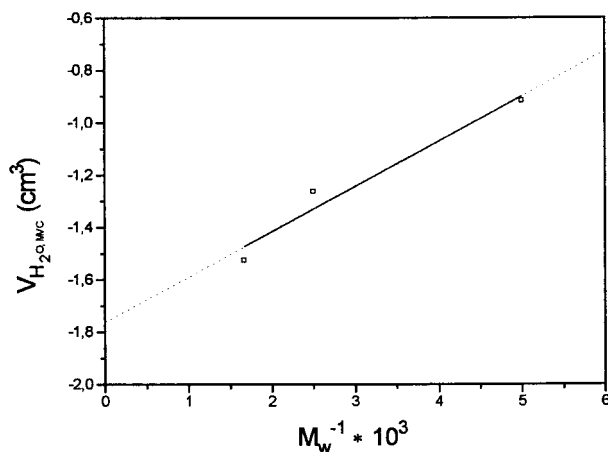


Figure 2 Dependence of $V_{\text{H}_2\text{O}}(\text{MVC})$ on PEG molecular weight.

more ordered for higher PEG molecular weights, as observed in other studies. Values obtained for these PEG/water systems should be compared with the system ethanol/water.²⁷ In this system, the water molar volume at the MVC point is $V_{\text{H}_2\text{O}}(\text{MVC}) = 16.9 \text{ cm}^3 \text{ mol}^{-1}$, which corresponds to a contraction of 6.2% compared with pure water.

Excess Volumes for PEG/Benzene Mixtures

This study was performed to compare the volumetric properties of PEG/water and PEG/benzene mixtures. As indicated earlier, benzene has been chosen to verify if the presence of a random coil structure of these PEG produces any significant influence on V^{Ex} in relation to the PEG/water system. Plots of V^{Ex} versus PEG composition

Table II Water Molar Volumes and Percentage of Contraction (In Relation to Pure Water $\bar{V}_{\text{H}_2\text{O}}^{\text{H}_2\text{O}}$ $18.0 \text{ cm}^3 \text{ mol}^{-1}$ at 25°C) at the MVC Point

PEG (g mol^{-1})	$\bar{V}_{\text{H}_2\text{O}, \text{MVC}}$	$(\bar{V}_{\text{H}_2\text{O}, \text{MVC}}/\bar{V}_{\text{H}_2\text{O}}^{\text{H}_2\text{O}})$ (%) ^a
229 ± 10	17.0	5.5
405 ± 17	16.8	6.9
585 ± 34	16.5	8.3
Ethanol ^a	16.9	6.2
∞^b	16.3 ^a	9.4 ^a

^a From Levine.²⁷

^b This value was determined from the extrapolation shown in Figure 2.

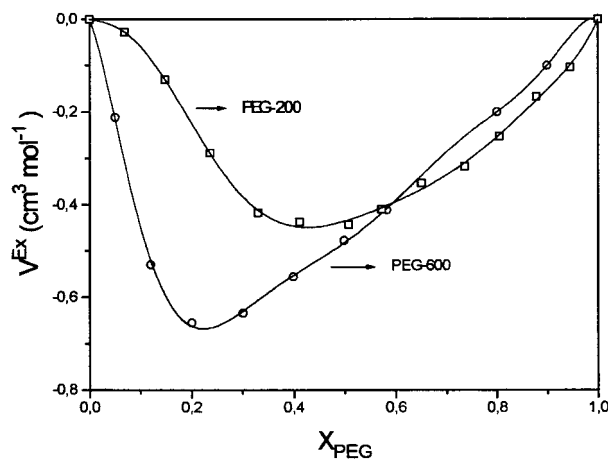


Figure 3 V^{Ex} diagrams for PEG/benzene mixtures at 25°C , for PEG 200 and 600.

(for 200 and 600), at 25°C , are shown in Figure 3. This figure shows a volume contraction for PEG/benzene system over the whole composition range in a similar way to that which was obtained for PEG/water mixtures. However, the magnitude of the contraction at the MVC point is approximately two times smaller than for PEG/water system. Otherwise, we have also noted that the stoichiometry of PEG/benzene mixture at the MVC point is one benzene molecule per four EO units. Moreover, if we compare the molar volume of pure benzene and the molar volume of benzene in PEG solution at the MVC point, we verify that they have almost the same value.

As discussed earlier, Hey and Illet¹⁹ demonstrated using Raman spectroscopy that the $\frac{7}{2}$ helical form of PEG-8000 chains is largely retained in aqueous solution and this conformation becomes less common on raising the temperature. However, England et al.²³ pointed out that the structure of PEG chains in water is dependent on the molar weight; and only for high molar weights, they are mainly present as a helix, with the hydrocarbon groups in the interior of the helix. Otherwise, for low molar weights (such as the polymers used in our work), hydrocarbon interactions control solution behaviour, and an “expanded” random coil of the hydrated polymer should explain the volumetric data.

From our results using low molecular weight polymers, we could conclude that the higher magnitude of the volume contraction of these polymers in water reflects the higher structural order of these mixtures compared with PEG/benzene systems. However, from these volumetric data, we have no evidence for the presence of helical segments of the polymer

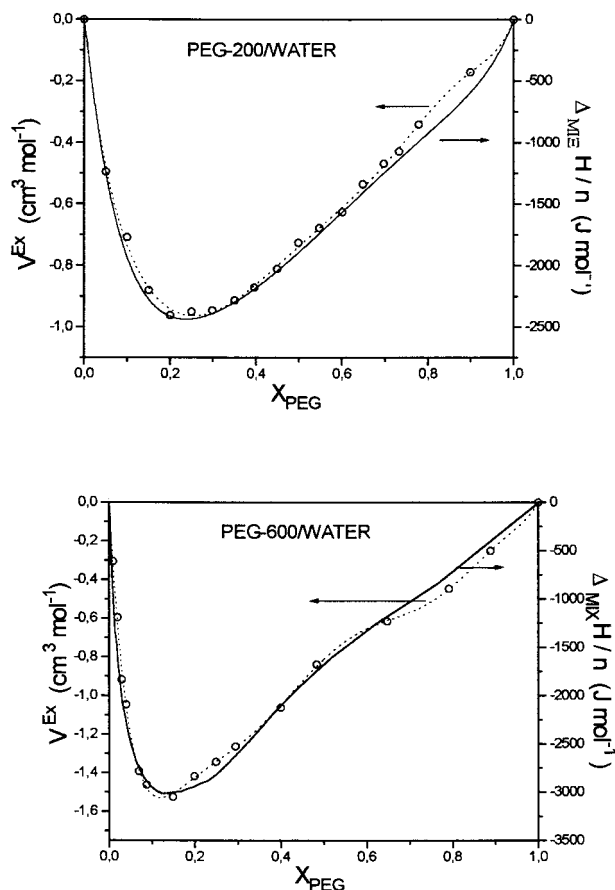


Figure 4 Superposition of V^{Ex} and $\Delta_{\text{mix}}H/n$ versus X_{PEG} diagrams for PEG/water mixtures at 25°C, for PEG 200 and 600.

chains in water. The stoichiometry of the mixtures at the MVC point of all PEG/water systems suggest the possibility of different conformation of the chains for different solution compositions.

Moreover, if the hydrogen bondings and the presence of the remaining helix structure of the polymer chains are the only driving forces responsible by the volume contraction of the PEG/water mixtures, we should expect an expansion of the volume for the PEG/organic solvent systems. However, many experiments have demonstrated that the conformation of PEG chains in water are quite different from that in organic solvents and that in organic solvents, like chloroform, chloromethane, benzene, and others, there is no evidence for the presence of helical segments.²

Excess Volume and Enthalpy of These Solutions

Lakanpal et al.^{29–31} measured the enthalpy of mixing ($\Delta_{\text{mix}}H/n$) for some PEG/benzene and PEG/water systems.

The enthalpy of mixing, for a nonideal solution, can be defined as follows:

$$(\Delta_{\text{mix}}H/n) = X_{\text{PEG}}(H_{\text{PEG}} - H_{\text{PEG}}^*) + X_{\text{solvent}}(H_{\text{solvent}} + H_{\text{solvent}}^*) \quad (3)$$

Using their experimental data, we have constructed plots comparing the excess volume and enthalpy of mixing for the same polymers in water (Fig. 4) and benzene (Fig. 5) for each composition (molar fraction). These plots reveal interesting and complete superposition for both diagrams for PEG 200 and PEG 600 in water, and the MVC point is observed in the same molar fraction as the point of minimum in the enthalpy plot.

We also note that while the process of PEG dissolution in water is simultaneously exothermic and contractile, the process in benzene is contractile but endothermic for all compositions. Moreover, the curves for the excess volume and mixing enthalpy for PEG/benzene system are not symmetrical, and the maximum point in the enthalpy curve does not fit with the MVC point in the excess volume curve. Therefore, we conclude that the driving forces for these two dissolution processes are different.

As shown in Figure 5, the mixing enthalpy of the PEG/benzene solution is positive in all compositions. Considering that these polymers are soluble in benzene in all proportions, we conclude that this spontaneous process is controlled by entropy, or in other words, is controlled by the disruption of the ordered helix of the polymer chains, as reported earlier. Therefore, the explanation that the driving force for the dissolution of PEG in benzene

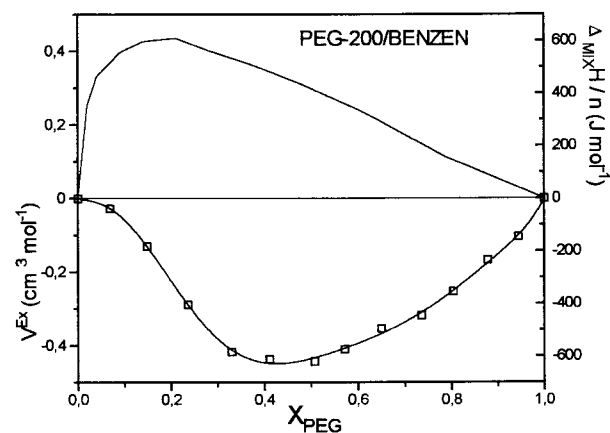


Figure 5 Superposition of V^{Ex} and $\Delta_{\text{mix}}H/n$ versus X_{PEG} diagrams for PEG-200/benzene mixtures at 25°C.

should present a weak charge transfer complex seems not to be very reasonable.

On the other hand, the process of PEG dissolution in water is exothermic, and, consequently, the driving force controlling this process should be defined by the balance between entropic factors resulting in the presence of a partially ordered structure, if some helix segments remain in the solution, and the enthalpy of the process (formation and disruption of hydrogen bondings).

CONCLUSIONS

Dissolution of PEG with several different molecular weights in water produces a significant contraction of the solution volume. The magnitude of the excess volume is dependent on the composition. The composition for which we observed the maximum volume contraction is independent of the molecular weight, in the range used in this work, and involves one water molecule per oxyethylene unit. This stoichiometry ratio is also coincident with the most exothermic mixing enthalpy. These results can be explained assuming that the PEG chains remain partially organized in the aqueous solution. On the other hand, the helical structure of the PEG chains in benzene solution is destroyed, and the volume contraction is less significative. Moreover, we obtained that, independent of the molecular weight, there is a defined stoichiometry of one benzene molecule per four EO units as the composition for which we obtain the maximum volume contraction.

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