

Phase behavior of poly(*N*-isopropylacrylamide) in binary aqueous solutions

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Received 28 March 2002; received in revised form 15 July 2002; accepted 17 July 2002

Abstract

In this work, the phase behavior of linear poly(*N*-isopropylacrylamide) (PNIPA) in water–solvent mixtures was investigated. Several solvents, including low molecular weight alcohols, were selected and phase separation temperatures were determined through cloud point measurements. All the studied systems exhibited the cononsolvency effect, i.e. lower PNIPA compatibility within definite ranges of composition in water-rich mixtures. However, it was first detected that the coexistence of phase separation temperatures—a lower critical solution temperature (LCST) with an upper critical solution temperature (UCST)—at higher solvent concentrations in most systems, depend on the hydrophobic nature of the solvent. The change from a LCST to a UCST was correlated with the competition between polymer–water and polymer–solvent interactions mediated by compositional factors. The effects produced by the different solvents tested were qualitatively compared, considering aspects related to their particular molecular structures, such as the potential to form hydrogen bonds and the implications of the size and shape of non-polar groups for hydrophobic hydration. © 2002 Published by Elsevier Science Ltd.

Keywords: Hydrophobic hydration; Lower critical solution temperature; Thermoreversible hydrogel

1. Introduction

Poly(*N*-isopropylacrylamide) (PNIPA) exhibits a well-known lower critical solution temperature (LCST) in water [1], i.e. phase separation occurs on increasing temperature. Similarly, PNIPA gels undergo a considerably abrupt volume phase transition at around 32–34 °C in water [2, 3]. While theoretical aspects correlating the coil-to-globule transition of linear chains with the unusual discontinuity of volume transition in gels have been the subject of extensive discussions [4–6], the potential technological use of PNIPA gels associated with their particular structure and thermodynamic behavior has attracted the interest of many research groups. PNIPA gels and their derivatives have been tested for many different applications, including concentration of macromolecular solutions [7,8], column

packing materials for chromatography [9], drug delivery systems [10] and cell culture substrata [11].

It is generally believed that the LCST behavior of PNIPA in aqueous solutions is strongly related to the destabilization of hydrogen bonds between water molecules and amide groups with increasing temperature, probably induced by the presence of the hydrophobic isopropyl group and backbone [12–14]. Thermodynamically, the mixing process at low temperatures is favored by the formation of hydrogen bonds, which lead to a large negative enthalpy of mixing. However, despite the moderate gain in compositional entropy resulting from the mixing process, water molecules hydrogen-bonded to PNIPA chains acquire a very low orientational entropy [15]. Phase separation occurs with increasing temperature due to the more unfavorable entropy contribution to the free energy.

A variety of additives such as salts, surfactants, organic solutes and solvents have been reported to affect significantly the phase transition of PNIPA/water systems [16]. Particularly, the addition of solvents may promote a drastic change in the LCST, which has been demonstrated by

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swelling experiments with PNIPA gels [2,17–24] and cloud point or calorimetric measurements of linear PNIPA solutions [24–28]. Contrary to what might be expected, the addition of small amounts of a good solvent such as methanol to PNIPA–water solutions initially decreases transition temperature, and only a further addition of solvent promotes an increase in it, as reported by Schild and coworkers [25]. In a general manner, PNIPA solubility is reduced within a range of intermediate solvent concentrations in binary aqueous solutions, originating a curious phenomenon that has been termed ‘cononsolvency’. Schild and coworkers [25] suggested that ‘water–methanol complexes’ are preferred to PNIPA–water hydrogen bonds. They also found similar results using tetrahydrofuran and dioxane, and identified acetone, ethanol and dimethylsulfoxide as cononsolvents as well.

When similar experiments are carried out using PNIPA gel instead of linear PNIPA, the poor polymer solubility in the cononsolvent mixtures manifests itself as an abrupt decrease in its swelling degree, termed ‘reentrant phase transition’. Mukae and coworkers [21] studied the behavior of PNIPA gels in water–alcohol (C_1 – C_4) mixtures at a constant temperature and determined that the addition of a more hydrophobic alcohol promotes gel shrinkage at a lower alcohol concentration in the water-rich region. This effect was explained on the basis of a highly cooperative dehydration of water molecules from polymer gel network. Alternatively, Hirotsu [18] confirmed that the larger the carbon number of the alcohol added, the larger the shift of transition temperature. It was also reported that the addition of a small amount of alcohol to PNIPA–water solution drives the transition from the near critical to the distinctly first-order one, and that the discontinuity of volume at the critical temperature increases as the carbon number of alcohol increases.

Amiya and coworkers [19] demonstrated that the incorporation of ionic units into PNIPA gel network, by its copolymerization with sodium acrylate, decreases and even eliminates the reentrant phase transition in water–methanol mixtures, depending on the amount of sodium acrylate employed. It was suggested that a less hydrophobic gel stabilizes the hydrogen bonds between polymer and water molecules.

Among the cited authors, some have argued that the understanding of the molecular mechanism of both polymer–solvent interactions and structure formation among solvent molecules would be quite important to elucidate the observed phenomena.

In this paper, we report the investigation of the phase behavior of linear PNIPA in several water–cononsolvent systems. Solvents with comparable molecular structures were selected so as to determine the effects of individual chemical groups on the aspects of temperature–composition plots. The effects produced by the different solvents tested were qualitatively discussed and compared, considering aspects related to their particular molecular structures,

such as the potential to form hydrogen bonds and the implications of the size and shape of non-polar groups for hydrophobic hydration.

2. Experimental

N-Isopropylacrylamide (NIPA) (Eastman Kodak) was purified by ion removal with Dowex Macroporous resin (Sigma) in deionized water. The monomer was recovered by extraction with chloroform, evaporation of solvent and recrystallization in acetone/heptane mixture. Details of this procedure have been reported elsewhere [29]. All the other reagents and solvents were reagent grade and used as received from standard vendors.

PNIPA was obtained via free radical polymerization of NIPA (25.00 g) in water (225 ml), initiated by the redox pair ammonium persulfate (0.125 g) and sodium metabisulfite (0.125 g). The reaction was carried out under inert atmosphere (N_2) at $(8.0 \pm 0.2)^\circ C$ for 24 h. The polymer was obtained from solution by evaporation of water, at $80^\circ C$.

A Shimadzu TGA-50 was used for thermogravimetric analyses (TG). Samples were heated to $300^\circ C$ at $10^\circ C/min$ with a flow of 20 ml N_2/min . It was determined that the remaining water content in PNIPA was $\sim 9\%$.

Quasi-static laser light scattering was performed by using a Spectra Physics 127-35 He–Ne laser (632.8 nm and 35 mW), equipped with a 256-channel correlating board (Brookhaven Instruments BI-9000AT). PNIPA was dissolved in water in seven different concentrations from 5.1 to 35.6 g/l. The determined weight-average molecular weight was 1.2×10^5 g/mol.

For each system, several solvent–water solutions were prepared at the desired concentrations and PNIPA was dissolved at a concentration of 1.0 wt%. Each flask was sealed and put in a temperature controlled water bath or water/ethanol bath, till equilibrium was reached. The correspondent cloud point was visually recorded upon heating or cooling depending on whether the solution had a LCST or an upper critical solution temperature (UCST), respectively. Cloud points were measured within the range of -10 to $90^\circ C$, with a precision of 0.1 – $0.5^\circ C$.

Solvents for this study were selected according to the similarity of their molecular structures and their miscibility with water in the whole range of compositions. By using methanol, ethanol, 1-propanol and 2-propanol, it was possible to evaluate the influence of size and shape of hydrophobic groups on phase separation temperatures. 2-Propanol is also comparable with acetone and dimethylsulfoxide (DMSO), which have very similar structures. *N,N*-Dimethylformamide (DMF) was selected because it is also an aprotic solvent and has a proton acceptor group in between two methyl groups, similar to acetone and DMSO.

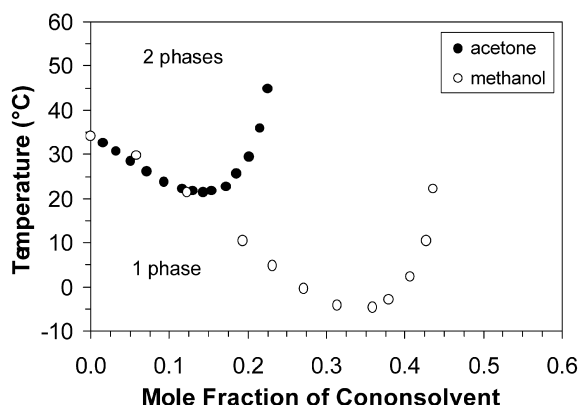


Fig. 1. Comparison between phase transition temperatures of PNIPA in water–methanol (open symbols) and water–acetone (filled symbols) solutions. Both systems exhibit only LCST behavior.

3. Results and discussion

3.1. Comparison between methanol and acetone: LCST systems

The transition temperatures (T_t) obtained for PNIPA–water systems containing methanol and acetone are shown in Fig. 1. It can be observed that the addition of methanol promotes a continuous decrease in T_t from 34 °C for PNIPA in pure water to around –5 °C for PNIPA in the aqueous solution with a mole fraction of methanol $x \cong 0.34$. These results are in good agreement with what was reported by Schild and coworkers [25], who found a minimum T_t of –7.5 °C at a volume fraction of methanol of 0.55, which is equivalent to $x \cong 0.35$. Likewise it can be observed in Fig. 1 that PNIPA–water–acetone system exhibits a minimum T_t at 21.3 °C for $x \cong 0.14$ of acetone. In both cases, additional amounts of cononsolvent increase T_t , so that the LCST disappears at higher concentrations ($x_{\text{acetone}} > 0.23$ and $x_{\text{methanol}} > 0.44$). Despite the similarities between both systems, the reduction promoted by acetone ceases at a lower mole fraction and it is less pronounced than in the case of methanol.

As suggested earlier [21], these results may be explained picturing a dehydration of polymer chains caused by the presence of solvent molecules with hydrophobic groups. To clearly understand this effect, it is necessary to analyze the fact that the so-called structure of liquid water, produced by an extensive network of hydrogen-bonded molecules, is certainly modified by changes in temperature or pressure, and by the addition of ionic or non-ionic solutes [30–32]. When a small amount of a low polarity organic solvent is added to water, these solute molecules are surrounded by cages of water molecules, this phenomenon being known as hydrophobic hydration. The shape of this hydration shell depends on the molecular structure of the solute and is stabilized by the hydrogen bonds formed among water molecules in a configuration different from that in pure water. The low polarity molecules are also called ‘structure-

makers’ due to their ability to increase relaxation time of ‘clusters’ of water molecules. Since solute–solvent interactions are poor, solute does not destroy water structure, but enhance its stability. Alcohols and ketones are examples of structure-makers, while compounds like glycerol, DMSO and amides are considered to be ‘structure-breakers’ because their favorable interactions with water decrease stability of the hydrogen-bonded water structure [32]. Nevertheless, the referred ‘structure promotion’ is limited to the capability of water to hydrate certain amounts of solute, beyond which the so-called hydrophobic interaction may be prevalent, ultimately leading to phase separation. A more hydrophobic solute demands a larger number of water molecules to hydrate it and is more likely to cause rupture of its hydration shell.

Therefore, the decrease in T_t observed upon addition of methanol or acetone, shown in Fig. 1, might result from the mobilization of water molecules (some of which would otherwise be surrounding PNIPA chains) to participate in hydration structure. Despite the widely accepted existence of hydrogen bonds between water molecules and PNIPA amide groups, a large number of water molecules are certainly involved in hydration structures of PNIPA isopropyl group and backbone. It is reasonable to assume that the hydrophobic hydration of small solvent molecules with only one or two methyl groups is preferable in entropy terms to the larger PNIPA segments. Furthermore, Schild and coworkers [25] showed that the enthalpy of the endothermic LCST transition, which is attributed to PNIPA–water hydrogen-bonding breakage [1], decreases with increasing non-aqueous solvent concentration, probably due to the reduction of either the number or the strength of PNIPA–water contacts. Since a lower enthalpy of mixing is involved, only a decrease in the entropy term $T\Delta S$, provided by a lower temperature, would favor PNIPA dissolution in water–solvent mixtures.

The fact that T_t increases with further addition of non-aqueous solvent can be explained in terms of the predominance of hydrophobic interaction at higher solvent concentrations. Once the hydration shells around solvent molecules are broken or, in other words, the amount of solvent is large enough to avoid its complete hydration, the free non-aqueous solvent molecules are allowed to interact with polymer chains. Both methanol and acetone are good solvents for PNIPA and, apart from hydrophobic hydration, their addition would be expected to increase PNIPA solubility or, in other words, to increase the LCST (as a matter of simplicity, T_t will be referred as either ‘LCST’ or ‘UCST’ to indicate the sense of the phase separation temperature). It is also consistent the fact that acetone system exhibits a minimum T_t at a lower mole fraction ($x = 0.14$) than methanol system (0.35) because acetone behaves as a more hydrophobic solvent than methanol and is probably able to overcome its hydration shell at a lower concentration.

An alternative model has been proposed by Zhang and

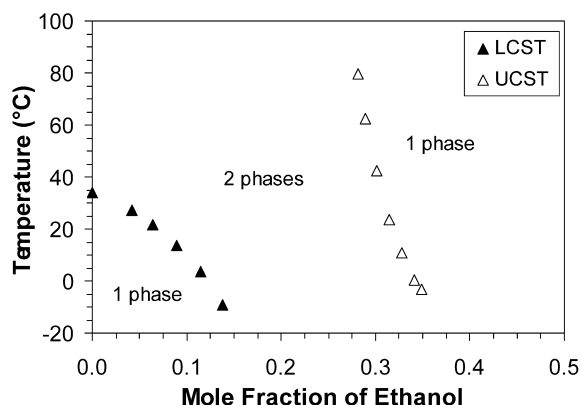


Fig. 2. Phase transition temperatures of PNIP in water–ethanol solutions. Filled symbols represent LCST behavior and open symbols represent UCST behavior.

Wu [33,34] to explain the reentrant coil-to-globule-to-coil transition of PNIP, well characterized in water–methanol system. It has been suggested that hydrogen bonds between 1 to 5 methanol molecules and hydrogen-bonded water pentagons play a major role in the formation of complexes that are ultimately non-solvents for PNIP. Additional experiments and calculations using molecular modeling would be required to evaluate if this hypothesis is also consistent for the acetone system studied here. Perhaps the steric hindrance impedes that five acetone molecules be hydrogen-bonded to the water pentagon. In this case, the critical acetone/water mole ratio for globule-to-coil transition would be lower than the 1:1 ratio suggested for methanol system, which might explain the fact that the mole fraction of acetone at minimum T_t ($x \cong 0.14$) is lower than that of methanol ($x \cong 0.34$).

Actually our data are in fine agreement with data obtained by Zhang and Wu [33,34]. It has been determined that in mixtures with mole fractions of methanol within the range from ~ 0.17 to ~ 0.40 , both the radius of gyration and the hydrodynamic radius of PNIP chains decrease more than 10 times from the values observed in pure water. This interval nearly coincides with the range of insolubility of PNIP in water–methanol mixtures, i.e. from 0.13 to 0.43 (Fig. 1) at 20 °C, which was the temperature selected for their experiments. An interesting observation is that, at the selected temperature (20 °C), PNIP is soluble in water–acetone mixtures independent of composition (Fig. 1), so that a change in the conformational state of chains would not be likely detected.

3.2. Simultaneous LCST and UCST

An interesting phenomenon not yet reported in any other paper occurs when ethanol and many other cosolvents are used. Fig. 2 shows the results obtained for PNIP–water–ethanol system. Similarly to the methanol system, a decrease in the LCST (filled symbols) occurs when small amounts of ethanol are added. However, instead of a further

increase in the LCST, a completely unexpected UCST (open symbols) behavior arises from addition of higher mole fractions of ethanol. So, for $x < 0.15$, phase separation occurs on increasing temperature; for $0.15 < x < 0.28$, PNIP is precipitated at any temperature; for $0.28 < x < 0.35$, phase separation occurs on decreasing temperature; and for $x > 0.35$, PNIP is soluble at any temperature. It is interesting that the consolvency effect is essentially the same as the one observed for methanol and acetone systems, i.e. PNIP solubility is lower at intermediate solvent concentrations. Nonetheless, the increase in PNIP solubility manifests itself in a different way because the system was turned into a UCST one.

It seems reasonable that this phenomenon has remained unknown thus far. It occurs within a very narrow range of compositions, so that it is unlikely to be discovered by chance. Moreover, most researchers have dealt with swelling experiments of PNIP gel [2,17–24], which means that experiments are usually performed by measuring the swelling degree of PNIP gel as a function of composition at a constant temperature. The decrease in PNIP compatibility with water–solvent mixtures (reentrant phase transition) has been detected, but the increase in PNIP compatibility at higher solvent concentrations has been perceived as a higher degree of swelling, not as a different transition temperature, thus masking the UCST behavior.

Nevertheless, an interesting experimental evidence that confirms this phenomenon was reported by Hirotsu and coworkers [23], even though the UCST phenomenon itself was not detected. It was determined that the microscopic patterns observed on PNIP gels that undergo reentrant phase transition when mixed with water–ethanol mixtures are different, depending on whether the gel was previously immersed in pure water or ethanol. If previously immersed in water, PNIP chains aggregate into fibers due to the stiffness provided by hydrogen bonds, while the gels previously immersed into ethanol exhibit a dot pattern characteristic of flexible chains that aggregate into spherical globules.

The appearance of a UCST region in PNIP–water–ethanol system indicates that the prevailing interactions between PNIP segments and ethanol molecules are non-specific, i.e. dipole–dipole interactions should predominate, even though hydrogen bonds may play a role. But, in water-rich mixtures, ethanol is not able to enhance polymer solubility because of the formation of hydration structures that isolate the two species. Once ethanol molecules are liberated from hydration shells, their interaction with PNIP is apparently preferable to PNIP–water hydrogen bonds, considering that the UCST behavior occurs at a low concentration of ethanol ($x \cong 0.28$). Another evidence for such assertion is provided by Mukae and coworkers [21], who found that the concentration of ethanol inside PNIP gels is higher than in the outside solution in equilibrium over the entire range of compositions.

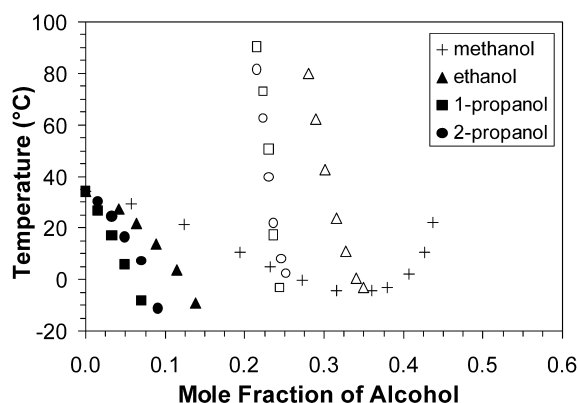


Fig. 3. Phase transition temperatures of PNIPA in several water–alcohol solutions. Filled symbols represent LCST behavior and open symbols represent UCST behavior.

3.3. Comparison among alcohols

Fig. 3 compares the results obtained for methanol, ethanol, 1-propanol and 2-propanol. The transition temperatures measured for PNIPA–water–alcohol systems are presented as a function of mole fraction of alcohol; filled symbols represent solvent concentrations that exhibit a LCST behavior, while open symbols indicate UCST behavior. Methanol is the only alcohol that does not exhibit a UCST behavior because its hydrophobic group is too small to compete with hydrogen bonds provided by hydroxyl group. In addition, while at $x = 0.05$ of methanol, the LCST is reduced by less than 4 °C, the same amount of 1-propanol promotes a decrease of nearly 30 °C. The fact that a more hydrophobic alcohol produces a larger decrease in LCST is related to what have already been discussed about the number of water molecules required to form the hydration shell. One 1-propanol molecule disturbs the system much more significantly than one methanol molecule considering the hydrophobic volumes that need to be accommodated in water structure. Besides, because a 1-propanol molecule is hydrated by more water molecules than an ethanol molecule, its hydration shell is destroyed by a lower mole fraction. As a result, the UCST region appears at a lower mole fraction of 1-propanol ($x \cong 0.21$) than of ethanol ($x \cong 0.28$). The same argument is valid when comparing ethanol and methanol systems: the mole fraction of methanol ($x \cong 0.35$), from which the LCST starts to increase, is higher than the mole fraction of ethanol from which the system is converted into a UCST.

A comparison between 1-propanol and 2-propanol shows that the former produces a larger LCST reduction at $x < 0.1$. The difference between these two compounds resides only in the molecular shape, which leads to an interesting discussion, again involving hydration shells. Spherical hydrophobic solutes are more miscible with water than their linear analogues because they permit the formation of a cage structure with less distortion of the normal angle between hydrogen bonds in water [35]. That is the reason

why *tert*-butanol is miscible with water in any proportion at room temperature, whereas the other butyl alcohols are only partially soluble in water [36]. Although both 1-propanol and 2-propanol are miscible with water in any proportion, each solvent demands a different hydration structure. Because the 1-propanol molecule is more linear, its hydration process probably leads to a more significant disturbance in water structure and promotes a more extensive dehydration of PNIPA segments. According to small-angle X-ray scattering studies, Hayashi and co-workers [35] determined that the concentration fluctuations in water-1-propanol solutions are much higher than in water-2-propanol solutions. This means that the hydration shell involving 1-propanol is less stable and it is more likely to mobilize a larger number of water molecules when compared with 2-propanol, thus promoting a larger decrease in the LCST.

Considerations about the hydrophobic character of alcohol molecules could also explain the slightly more negative slope of solubility curve for 1-propanol than for ethanol in the UCST region. In this concentration range, the molecules of a more hydrophobic alcohol are more likely to interact with PNIPA segments. We think that an additional mole fraction of 1-propanol could be almost completely used to improve polymer solubility while a small part of an equal addition of ethanol would be more easily hydrated and impeded to interact with PNIPA segments, the resulting decrease in transition temperature being smaller (Fig. 3).

An interesting fact observed is that acetone system does not exhibit a UCST behavior at higher mole fractions, while ethanol does. The LCST behavior in acetone system indicates that specific interactions predominate, in this case the hydrogen bonds between N–H groups of PNIPA segments and C=O groups of acetone molecules. On the contrary, the UCST behavior in ethanol system indicates that hydrophobic interactions among non-polar groups seem to predominate thermodynamically over hydrogen bonds between C=O of PNIPA and O–H of ethanol.

In the absence of specific quantitative thermodynamic data involving PNIPA in these binary mixtures, a qualitative discussion involving only water and solvent molecules might be useful. Acetone and 2-propanol have closer molecular weight and structure, but both are miscible with water in all proportions. A comparison between similar higher molecular weight ketones and alcohols shows that butanone is twice as soluble in water than the analogous 2-butanol at room temperature [36] and both compounds are considered to be structure-makers [32], which reveals that a ketone is less hydrophobic than its analogous alcohol. According to this simple line of reasoning, it is possible to conjecture that the more hydrophobic 2-propanol non-polar groups would contribute more significantly to the formation of non-specific interactions with PNIPA segments, thus forming a UCST more likely than acetone, as it is actually observed.

Nevertheless, the comparison between acetone and

ethanol is not so straightforward. Even though both acetone and ethanol dissolve exothermically in water at room temperature in the mole fraction range considered, endothermic mixing is observed with increasing temperature in both cases [32]. At the moment, we can at most speculate that the observed behavior is provided by a conjunction of factors involving the shape of solvent molecules, more specifically the relative positions of their hydrophobic and hydrophilic groups, and the access to amide groups in PNIPA segments susceptible to interact with either an OH or a C=O group.

3.4. DMSO system

It is interesting to compare DMSO with acetone (Fig. 4), given their very similar molecular structures, which contain the same hydrophobic groups but differ in the replacement of the carbonyl group with a sulfoxide one. The differences in size and electronic configuration between carbon and sulfur atoms result in a significantly higher dipole moment ($\mu = 3.96$) and boiling point (bp = 189 °C) for DMSO when compared with acetone ($\mu = 2.88$, bp = 56.5 °C) [37]. As noted in Fig. 4, DMSO system exhibits a UCST behavior, as opposed to acetone. This difference might be explained by the predominance of dipole–dipole interactions between DMSO and PNIPA segments, in detriment of specific interactions.

Interestingly, the UCST region occurs in a much higher mole fraction range ($0.6 < x < 0.85$) than in any other system. As mentioned earlier, DMSO is considered a structure-breaking solute. Therefore, even though DMSO interacts very well with PNIPA, as demonstrated by swelling experiments [2], the cononsolvency range is very wide due to its highly favorable interaction with water. Also, the addition of DMSO causes a lower decrease in the LCST than acetone because the latter, a structure-maker, promotes a more extensive dehydration of PNIPA segments (detail in Fig. 4).

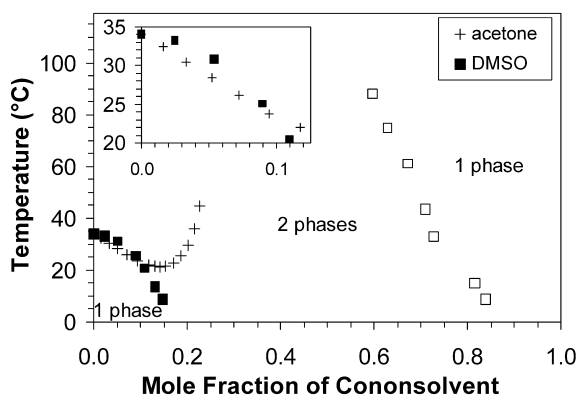


Fig. 4. Comparison between phase transition temperatures of PNIPA in water–DMSO and water–acetone solutions. Filled symbols represent LCST behavior and open symbols represent UCST behavior.

3.5. DMF system

Fig. 5 shows results obtained for PNIPA–water–DMF system. Similarly to DMSO, DMF is considered to be a structure-breaker and has high dipole moment and boiling point ($\mu = 3.82$, bp = 153 °C) [37]. Therefore, the reason for the existence of a UCST behavior at high mole fractions is probably the same as for DMSO system, i.e. the predominance of dipole–dipole contributions. However, among all solvents tested, DMF is the only one that promoted a slight increase in the LCST from 34 to 37 °C at low mole fractions ($x < 0.07$). A reasonable explanation for that is related to its amide group, which is able to form a stronger hydrogen bond with water due to the existence of resonance forms, as pointed out in earlier studies [38]. Assuming that low concentrations of DMF break water structure very efficiently, DMF molecules would be able to avoid its own hydrophobic hydration and even to favor hydration of PNIPA segments, thus increasing PNIPA compatibility with water. Actually, excluding the hydration effects, that would be the expected behavior when a good solvent for the polymer is added in the solution. The possibility to increase the LCST to 37 °C may be quite interesting for application of PNIPA gel in thermo-responsive drug delivery systems, but also demonstrates that precaution is required concerning the influence of proteins on PNIPA phase behavior. Nevertheless, the fact that, at DMF fractions higher than 0.07, the LCST decreases, as in the other systems, is quite intriguing. We cannot precisely explain the whole phenomenon at the moment, but it might be related to a change in the predominant DMF–water interactions with increasing DMF concentration.

Another interesting and peculiar fact is that, at $x = 0.267$, a LCST is detected, while, at $x = 0.283$, a UCST occurs, which means that DMF system exhibits the most obvious discontinuity from LCST to UCST behavior at a very well defined mole fraction ($x = 0.275 \pm 0.008$), as

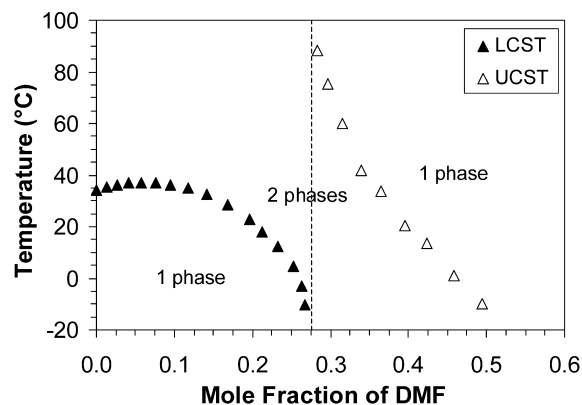


Fig. 5. Phase transition temperatures of PNIPA in water–DMF solutions. Filled symbols represent LCST behavior and open symbols represent UCST behavior. Vertical dotted line suggests the composition at which system is converted from LCST to UCST behavior.

observed in Fig. 5. At this concentration, the system undergoes a unique change in the arrangement of molecules, with hydrogen bonds being replaced with dipole–dipole interactions. At this moment, we cannot offer a reasonable explanation for the occurrence of this very narrow transition range only in DMF system. Theoretically, a precise critical mole fraction may exist for each solvent considered, although it is unlikely to be experimentally assessed because the transition temperatures to be determined would be out of the range within which solutions remain liquid.

4. Conclusion

The phase transition temperatures of linear PNIPA in binary aqueous solutions are highly dependent on the type of solvent and its concentration. Although the cononsolvency effect occurs upon addition of any of the tested solvents to PNIPA–water solutions, only methanol and acetone systems exhibit a single LCST behavior.

In the study of ethanol, 1-propanol, 2-propanol, DMSO and DMF systems, the coexistence of a LCST and a UCST at different solvent concentration ranges was disclosed. The cononsolvency phenomenon was qualitatively explained on the basis of the weakening of PNIPA–water interactions due to the preferential hydrophobic hydration of solvent molecules in water-rich region. The rupture of hydration shells with increasing solvent concentration allows solvent molecules to interact with PNIPA segments. Thus, the incidence of a UCST behavior results from the predominance of non-specific PNIPA–solvent interactions in opposition to what have been thought so far. The magnitude of the effects caused by the increasing solvent concentration was correlated with the molecular structure of solvent, according to the size and shape of its hydrophobic groups and the potential to hinder hydrophobic hydration. While 1-propanol promoted the largest decrease in the LCST in the water-rich region and induced the steepest UCST curve, DMF and DMSO systems demonstrated a less sharp dependence.

The observed phenomena are of major interest not only because of their unusual nature, but also because of their implications on the study of separation technologies involving these systems.

Acknowledgements

This work was supported by grants from CNPq, PADCT and FAPEMIG.

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