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Tunable LCST behavior of poly(N-isopropylacrylamide/ionic liquid) copolymers

Kamiya JAIN,[a] Raman VEDARAJAN,[a] Masaki WATANABE,[b] Masaki ISHIKIRIYAMA[b] and Noriyoshi MATSUMI[a]

Poly(*N*-isopropylacrylamide), PNIPAM is a thermoresponsive polymer widely known for its lower critical solution temperature (LCST) phenomenon at 32 °C in aqueous solutions. Precise tuning of the LCST of PNIPAM to a broader temperature range offers larger window of applications especially in the field of biotechnology and nanotechnology. A series of free radical random copolymerizations between *N*-isopropylacrylamide (NIPAM) with various imidazolium based ionic liquids (ILs) were conducted. IL structures were varied in terms of their alkyl chain length at N-3 (or N-1) position of imidazolium ring and counter anion. LCST behavior for aqueous solution of copolymers was investigated by UV-VIS transmission measurements. The results confirm that introduction of IL in the PNIPAM offers wide range of LCST behavior with a synergism between the hydrophobic part of ionic liquid and basic strength of counter anion, plausibly by varying hydrogen bonding abilities of the copolymer.

Introduction

Thermo-responsive or thermo-sensitive polymers are an important class of stimuli-responsive (like temperature, pH, light and electric field) polymers[1,2] which show discontinuous changes in their physical properties with changes in temperature. These polymers possess inherent ability to show abrupt transitions in their conformations with change in temperature. These polymers can be classified on the basis of their solubility. The increase of polymer solubility with raise in temperature is a kind of thermo-responsive polymers and are known to exhibit upper critical solution temperature (UCST).[3] On the contrary, the polymers showing decrease in solubility with raising temperature are known to exhibit well known phenomenon called lower critical solution temperature (LCST).[4] Generally, LCST is addressed in terms of its cloud point (T_{cp}) or phase separation temperature i.e. temperature at which the solution suddenly becomes milky is referred as T_{cp}. Any reduction in temperature from T_{cp} will tend to make the solution clear owing to the formation of a single phase. These types of polymers have received a greater importance in recent years as they have wide range of applications in drug-delivery[5], bio-engineering[6], sensors[7,8], thermal affinity separation[9] etc.

One of the best known thermo-responsive polymer is poly(*N*-isopropylacrylamide) PNIPAM having a structure as shown in Figure 1. The repeating unit has both hydrophobic and hydrophilic moieties, and therefore, the aqueous polymer solution undergoes transitions between water soluble state and insoluble state depending on their different higher ordered structure under different temperature. PNIPAM has been intensively investigated as it possesses a sharp cloud point range from 31 °C to 33 °C in water (irrespective of polymer concentration).[4,10] Fujishige et al. studied the conformational changes of aqueous PNIPAM solution with change in temperature.[11] They reported that aqueous solution of PNIPAM undergoes coil to globule transition on heating. Below LCST, PNIPAM chains exist as coils due to hydrogen bonding of amide groups with water. But above LCST, it is considered that plausibly hydrogen bonding is weakened as the kinetic energies of the molecules become larger than the energy of hydrogen bonding between water and molecules. Thus, hydrophobic interactions between the hydrophobic backbone and iso-propyl groups become dominant[12] and causes change in polymer conformation from linear and flexible PNIPAM chains to the collapsed globules due to intra or intermolecular aggregation of hydrophobic moieties. Interactions that lead to attraction between polymer-water and polymer-polymer are the dominant factors for the determination of LCST behavior. Structural factors that enhance the polymer-water interactions result in increase in LCST. On the contrary, increment in

[a.] *School of Materials Science, Japan Advanced Institute of Science and Technology, 1-1 Asahidai, Nomi, Ishikawa – 923 1292, Japan*
[b.] *Toyota Motors Corporation, Japan*

†Corresponding Author

Professor Noriyoshi Matsumi
Tel: +81-761-51-1600 Email: matsumi@jaist.ac.jp
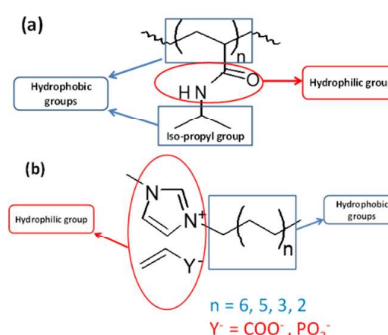
Figure 1. Chemical structures of (a) PNIPAM and (b) IL.

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the polymer-polymer interactions decreases the value of LCST. Precisely tuning the LCST of PNIPAM to a broader temperature range offers larger window of applications.

LCST phenomena of the polymers can be modulated by variety of techniques. One of the most interesting method is preparation of thermo-responsive polymers by copolymerization with hydrophilic and hydrophobic comonomers.[13-16] Addition of salts[17] and/or surfactants[18] to the polymer solution was also found to be an effective method to control LCST behavior. Maeda *et al.* reported the synthesis of random copolymers of *N*-isopropylacrylamide (NIPAM) and *N*, *N*-diethylacrylamide (DEA) and their thermo-responsive behavior.[19] McCormick *et al.* showed that di- and tri- block copolymers of NIPAM and *N*, *N*-dimethylacrylamide (DMA) are capable of reversibly forming micelles with changes in temperature.[20] More recently, Tenhu *et al.* have prepared di-block copolymers of polymerized ionic liquids (PIL) and PNIPAM.[21] Further, they studied the effect of PNIPAM block length on the properties of PIL and effect of cationic structure of ionic liquid on the thermal properties of PNIPAM in aqueous dispersions. Many studies have been conducted for the tuning of LCST pattern in PNIPAM-co-PIL systems. But, scarcely any systematic investigation has been performed to understand the effect of IL on LCST of PNIPAM by varying the degree of hydrophobicity of cation or polymerizing anion of IL with NIPAM.

Hence, in our current study, the LCST behavior of PNIPAM has been systematically tailored to obtain copolymers showing T_{cp} below and above 32 °C in aqueous solutions. This has been demonstrated by the random copolymerizations of NIPAM with different *N*, *N di*-substituted imidazolium based ionic liquids via free radical polymerization and their LCST behavior was confirmed by UV-Vis transmittance measurements.

Experimental

Materials and Instruments

Acrylic acid (Tokyo Chemical Industry Co. Ltd.). *N*-isopropylacrylamide (NIPAM, Tokyo Chemical Industry Co. Ltd.), 1-bromotetradecane (Tokyo Chemical Industry Co. Ltd.), vinyl phosphonic acid (Wako Co. Ltd.), 1-methylimidazole (Wako Co. Ltd.), 2,2'-Azobis(2-methylpropionitrile) (AIBN, Wako Co. Ltd.), dehydrated tetrahydrofuran (THF, Wako Co. Ltd.), acetonitrile

(Wako Co. Ltd.) and diethyl ether (Wako Co. Ltd.). All chemicals were used as received without any further purification.

400 MHz Nuclear Magnetic Resonance (NMR) spectrometer (Ultrashield™ Plus Bruker, Z101355) was employed to characterize ionic liquid and polymer structures. Polymer molecular weight was determined using Gel Permeation Chromatography (GPC, Shodex Asahipak GF-7M HQ) in methanol containing 0.05 M LiCl and polyethylene glycol was used for calibration as standards. Cloud point measurements were performed using UV-Vis spectrometer (JASCO V-630) equipped with a temperature controller system (Eyela NCB–1200).

Ionic liquids Synthesis

A series of 1-alkyl-3-methylimidazolium bromide (as precursor to acrylate (Ac) and vinylphosphonate (VP) salts) ILs (Scheme 1) were synthesized as reported in literature.[22]
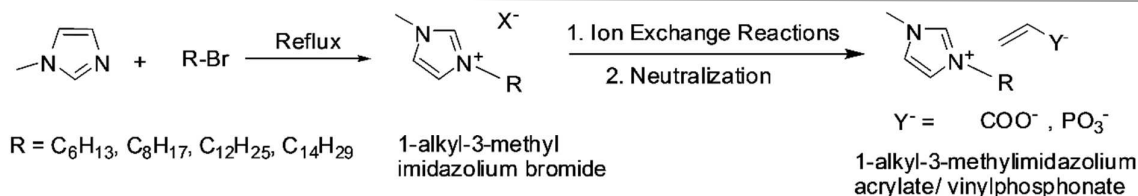
1-methyl-3-tetradecylimidazolium acrylate (TDMImAc) / vinyl phosphonate (TDMImVP): Bromide anions of IL were exchanged with hydroxide by passing an aqueous IL solution through a column filled with anion exchange resin (Amberlite IRN- 78, Sigma Aldrich Co. Ltd.). This aqueous hydroxide solution was neutralized with equimolar acrylic acid or vinylphosphonic acid.[23] Thereafter, ionic liquid was dried in vacuum at 60 °C for 24 h. The obtained ILs were characterized with ^{1}H NMR (Bruker spectrometer 400 MHz) as shown in Figure 2 (a), 2 (b).

TDMImAc: ^{1}H NMR (400 MHz, DMSO-d$_6$): δ = 9.35 (s, 1H, NC(*H*)N), 7.71-7.80 (d, 2H, NC(*H*)C(*H*)N), 5.85-5.97 (m, 1H, *H*-CH=CH-COO$^-$), 5.62-5.71 (d, 1H, H-C*H*=CH-COO$^-$), 5.11-5.18 (d, 1H, H-CH=C*H*-COO$^-$), 4.16 (t, 2H, N-C*H$_2$*), 3.84 (s, 3H, N-C*H$_3$*), 1.76 (m, 2H, C*H$_2$*),1.22 (br. s, 22H, N-CH$_2$- CH$_2$- (-C*H$_2$*-)$_{11}$-), 0.87 (t, 3H, C*H$_3$*)
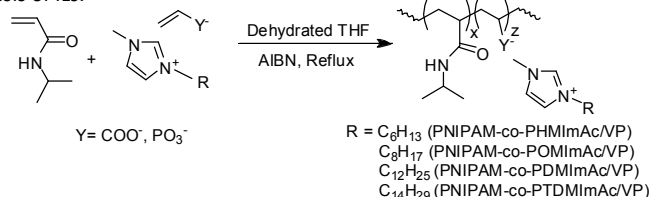
TDMImVP: ^{1}H NMR (400 MHz, DMSO-d$_6$): δ = 9.35 (s, 1H, NC(*H*)N), 7.71-7.80 (d, 2H, NC(*H*)C(*H*)N), 5.92-6.05 (m, 1H, *H*-CH=CH-PO$_3^-$), 5.45-5.58 (m, 1H, H-C*H*=CH- PO$_3^-$), 5.23-5.45 (m, 1H, H-CH=C*H*- PO$_3^-$), 4.16 (t, 2H, N-C*H$_2$*), 3.85 (s, 3H, N-C*H$_3$*), 1.78 (m, 2H, C*H$_2$*),1.24 (br. s, 22H, N-CH$_2$- CH$_2$- (-C*H$_2$*-)$_{11}$-), 0.87 (t, 3H, C*H$_3$*)

Polymerization

NIPAM (13 mmol) was polymerized using AIBN as an initiator (1 mol % or 5 mol %) in THF for 12 h at 65 °C. After polymerization, solvent

Scheme 1. Synthesis of ILs.

Scheme 2. Synthesis of Random copolymers of NIPAM and Ionic Liquids via Free Radical copolymerization.
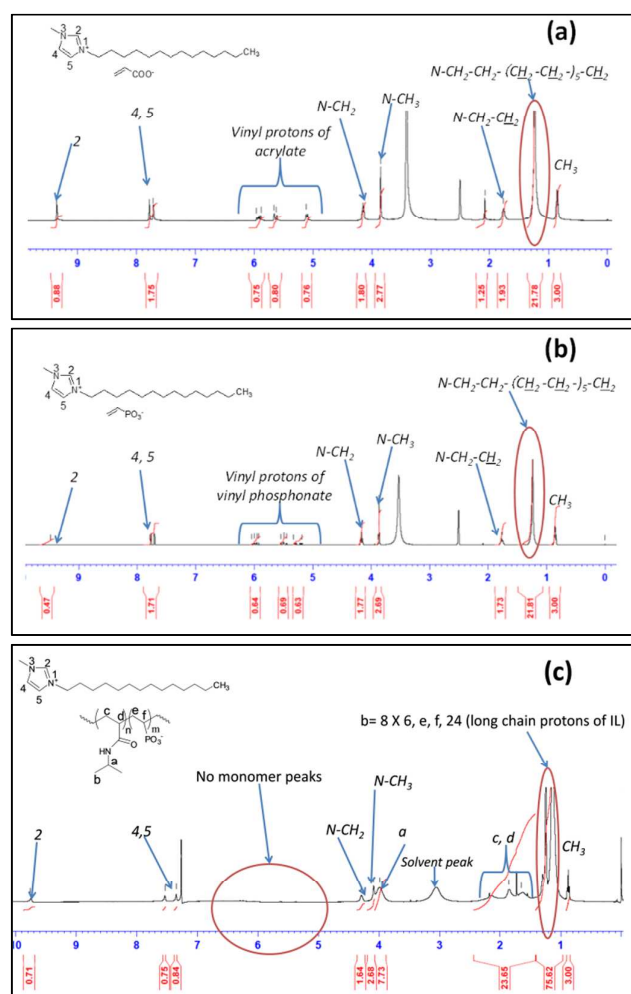
Figure 2. ¹H-NMR spectra of ionic liquids and random copolymer (a) 1-tetradecyl-3-methylimidazolium acrylate (TDMImAc) (b) 1-tetradecyl-3-methylimidazolium vinylphosphonate (TDMImVP) (c) PNIPAM-co-PTDMImVP (5mol% AIBN).

was removed and polymer was precipitated in cold diethyl ether. Polymers were dried under vacuum for 5 h at 50 °C.

Random copolymerization of each ionic liquid with NIPAM was performed by free radical polymerization as shown in Scheme 2. As a typical procedure, NIPAM (13 mmol), ionic liquid (1.3 mmol) and AIBN (1 mol % or 5 mol %) were added under N_2 in 35 mL ground neck test tube equipped with a magnetic stirrer. Thereafter, dehydrated THF (5 mL) was added in the reaction mixture and placed in a preheated oil bath maintained at 65 °C for 12 h. Then the reaction mixture was quenched by cooling under liquid nitrogen. Copolymers were purified by reprecipitating in cold diethyl ether. Then, solvent was removed by decantation and the polymers were dried under vacuum for 5 h at 50 °C. All Polymerizations were carried out under nitrogen atmosphere.

Polymer Characterization

Polymer structures were characterized by analysing ¹H NMR (400 MHz) in CDCl₃. The cloud point measurements were performed with aqueous polymer solution (5 mg/mL) using a UV-Vis spectrometer

equipped with a temperature controller system. The UV-Vis transmission properties of the solutions were studied in the temperature range of 20 to 60 °C to determine the precise cloud point temperature.

A series of copolymers were synthesized via free-radical copolymerization between NIPAM with a variety of ionic liquids. The amount of radical initiator (AIBN) was varied as 1 mol % and 5 mol %. The polymerization results are summarized in Table 1. It was observed that conversion rate for polymerization was predominantly around 90 %. However, it was found that the conversion rate at 1 mol % of AIBN was invariably lower than 5 mol %. Copolymers were characterized by ¹H NMR operated at 400 MHz. It was found that when ionic liquid polymerized with NIPAM, vinyl protons of IL and NIPAM disappeared from olefin region. Amount of NIPAM units incorporated in the copolymers were calculated from ¹H NMR by considering per unit incorporation of IL as indicated by 'a' in Figure 2 (c).

PNIPAM-co-PTDMImVP_5mol%AIBN: ¹H NMR (400 MHz, CDCl₃):
δ = 9.98 (s, 1H, H-2), 7.62 (d, 1H, H-4), 7.35 (d, 1H, H-5), 4.32 (t, 2H, N-CH_2), 4.12(s, 3H, N-CH_3), 4.0 (br, 7H, H-a), 1.51-2.38 (m, 23H, N-CH_2-CH_2, H-c, H-d), 1.08-1.35 (m, 76H, H-b, H-e, H-f, N-CH_2- CH_2- (-CH_2-)₅), 0.87 (t, 3H)

Typical number average molecular weight (M_n) of two polymers namely PNIPAM-co-DMImAc_5mol%AIBN and PNIPAM-co-DMImVP_5mol%AIBN were determined using GPC and found to be 6200 g/mol and 2800 g/mol respectively. Difference between M_n of two polymers can be due to different interactions of different anions (acrylate and vinylphosphonate) with propagating radicals.

Lower critical solution temperature measurements

Cloud point temperature of PNIPAM depends on hydrogen bonding with water. Therefore, it was expected that the chemical incorporation of ionic liquid in PNIPAM chain could modify hydrogen bonding and consequently regulate the cloud point temperature. The lower critical solution temperature (LCST) transition behavior of polymer solutions was studied through UV-Vis measurements under various temperatures and will be discussed in the subsequent section.

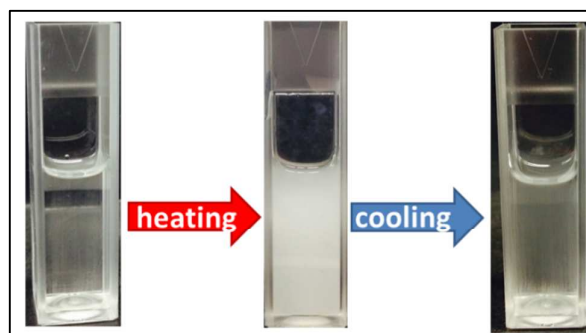The cloud point of the solution was determined by

Figure 3. Image of the phase separation of copolymers before and after the LCST.

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Table 1 List of the random copolymers prepared under different incorporation ratio (calculated by ^{1}H NMR) and their LCST behavior at 563 nm (50 % Transmittance).

Chain length	AIBN	PNIPAM-*co*-PIL_Ac			PNIPAM-*co*-PIL_VP		
		Yield (%)[a]	NIPAM : IL[b]	T_{cp}	Yield (%)[a]	NIPAM : IL[b]	T_{cp}
14	1	44.6	-	-	43.6	-	-
	5	88.7	08:01	24.6	95.3	08:01	25.5
12	1	87.8	08:01	28.0	98.0	08:01	33.0
	5	92.6	09:01	28.2	99.5	08:01	32.0
8	1	97.8	08:01	50.0	94.7	07:01	40.0
	5	98.9	10:01	50.0	n.d.[d]	07:01	38.5
6	1	88.4	09:01	54.0[c]	96.8	07:01	44.0
	5	93.9	08:01	56.0[c]	98.9	08:01	45.0
PNIPAM					[a] [(Experimental yield x 100)/ theoretical yield] [b] Incorporation Ratio of NIPAM and IL (calculated by ^{1}H NMR spectroscopy) [c] After the addition of chaotropic agent (0.5 M KBr salt) [d] not determined		
0	1	93.3	-	31.5			
	5	98.7	-	31.0			

studying the UV-Vis transmittance at 563 nm and a fall in transmittance to 50 % of the initial was noted as the T_{cp} of the polymer. Figures 4-5 demonstrate the LCST behavior of random copolymers of NIPAM and IL and Figure 3 shows their reversible nature.

Results and discussion

Several parameters can influence the LCST behavior of these copolymers: 1) effect of hydrophobicity induced by cation structure in IL and, 2) effect of counter anion in IL. The influences of such parameters on LCST behavior will be discussed in the subsequent sections.

Effect of Concentration of Initiator (AIBN)

The LCST behavior of random copolymers obtained with varied AIBN amount were found to be nearly similar (Figure 4, 5).

This is evident from almost similar incorporation ratio of IL and NIPAM in the random copolymer, as confirmed by NMR measurements. As no significant differences were observed with change in concentration of initiator, subsequent discussions will be carried out for copolymers prepared with 5 mol% AIBN as initiator unless mentioned.

Effect of Cation (Hydrophobicity)

Figure 4a, 4b show the LCST behavior of random copolymers prepared by structurally varying the length of alkyl chain in the cationic part of IL, while the counter anion (acrylate) was maintained same. The hydrophobicity of the copolymer was varied with respect to the alkyl-chain attached to N-1 (or sometimes N-3) of imidazolium ring of the IL. The hydrophobicity increased with increasing alkyl chain length. The LCST behavior of all copolymers are summarized in Table 1. It was found that
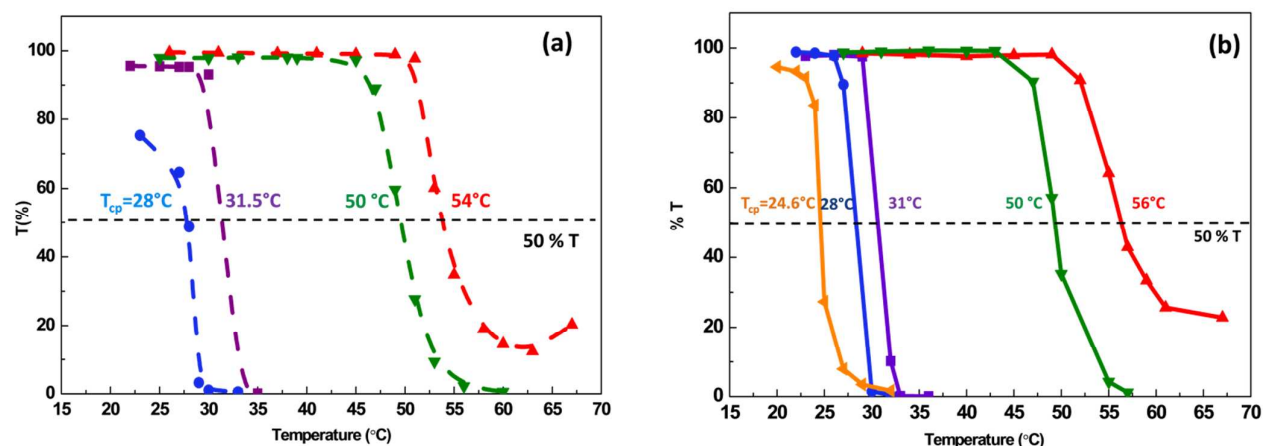

Figure 4. LCST behavior of random copolymers of NIPAM and acrylate-based IL using (a) 1 mol% AIBN for PNIPAM-co-PDMImAc (---, ●), PNIPAM (---, ■), PNIPAM-co-PHMImAc + 1.1 M KBr (---, ▲), PNIPAM-co-POMImAc (---, ▼) and (b) 5 mol% AIBN for PNIPAM-co-PTDMImAc (—, ◄),PNIPAM-co-PDMImAc (—, ●), PNIPAM (—, ■), PNIPAM-co-PHMImAc + 0.5 M KBr (—, ▲), PNIPAM-co-POMImAc (—, ▼).
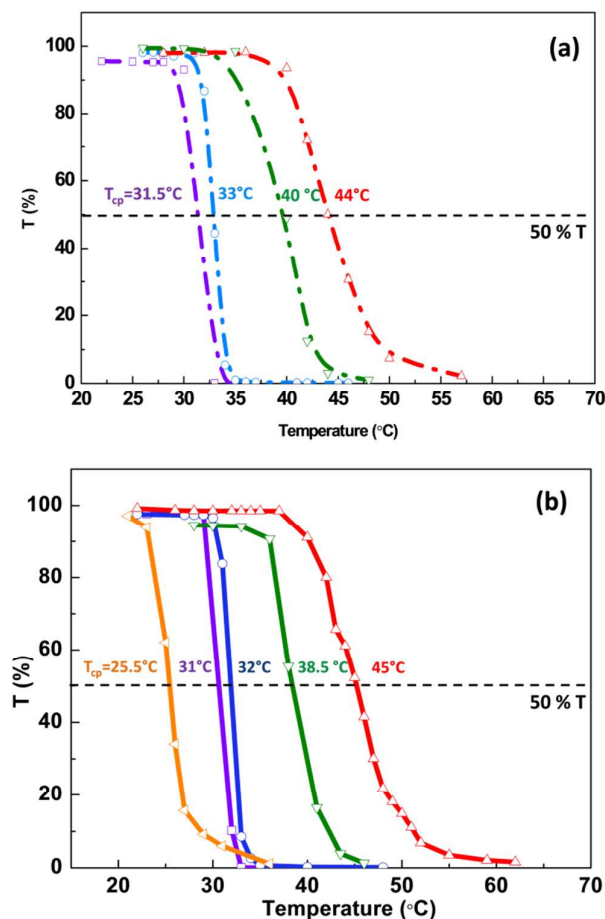
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Figure 5. LCST behavior of random copolymers of NIPAM and vinyl phosphonate-based IL using with (a) 1 mol% AIBN during polymerization. PNIPAM-co-PDMImVP (---, ○), PNIPAM (---, □), PNIPAM-co-PHMImVP (---, △), PNIPAM-co-POMImVP (---, ▽) (b) 5 mol% polymerization. PNIPAM-co-PTDMImVP (—, ◁), PNIPAM-co-PDMImVP (—, ○), PNIPAM (—, □), PNIPAM-co-PHMImVP (—, △), PNIPAM-co-POMImVP (—, ▽).

changing the kind of ionic liquid in the copolymer provides a broad range of LCST distribution both below and above the characteristic T_{cp} of PNIPAM (31 °C). For instance, it was observed that the LCST transitions of PNIPAM-co-PTDMImAc (25 °C) and PNIPAM-co-PDMImAc (28 °C) were observed to be lower than PNIPAM (31 °C). On the other hand, LCST of PNIPAM-co-POMImAc (50 °C) and PNIPAM-co-PHMImAc (> 90 °C) were higher than PNIPAM. Introducing hydrophobic molecules/moieties in water tend to minimize their surface energy by forming aggregates (hydrophobic effect[24]). Hence larger hydrophobic moiety offers greater interference with the hydrogen bonding. Moreover, increase in the surface tension between polymer/water interfaces leads to lower LCST. LCST temperature of the acrylate based copolymers was found to be increasing in the order of alkyl chain length on IL unit tetradecyl < dodecyl < octyl. The copolymer containing hexyl chain had a high T_{cp} above 90 °C. Similar trends (Figure 5a, 5b) were observed for other copolymers (having vinyl phosphonate as anion)

with their corresponding cloud point temperatures in the order of alkyl chain length on IL unit tetradecyl < dodecyl < octyl< hexyl.

These observations (Figure 4, 5) clearly indicated the effect of hydrophobicity induced by the alkyl-chain of ILs. The results can be envisaged in terms of interference of hydrophobic interaction with the hydrogen bonding of main polymer chain between two separate moieties: 1) hydrogen bonding between PNIPAM chains and water and, 2) hydrogen bonding of acrylate anion with water molecules.

Effect of Chaotropic Agent

Chaotropic agents are salts or particularly anions which lower the T_{cp} of polymer solution when added in excess amount.[17] Hexyl group containing acrylate copolymer PNIPAM-co-PHMImAc showed specific behavior in LCST. T_{cp} of this copolymer was found to be higher than 90 °C (beyond the experimental range of measurement) which led us to investigate the effect of excess of chaotropic agent. It is widely known that the excess of chaotropic agents assist disruption of macromolecular intra/intermolecular interaction networks.[17] The LCST behavior of PNIPAM-co-PHMImAc was observed at 56 °C through the addition of chaotropic agent solution (KBr, 0.5 M). The effect of chaotropic agent concentration on LCST value has been shown in Figure 6. Hence, more precise modulation of LCST was achieved through the addition of chaotropic agents.

Effect of Counter Anion

It was observed that LCST behavior varied by changing the kinds of anion, namely, acrylate and vinyl phosphonate. Figure 5a represents the results of LCST behavior of random copolymers having vinyl phosphonate as an anion at 1 mol % of AIBN. It was observed that all the vinyl phosphonate based copolymers show higher cloud point temperature than PNIPAM except of PNIPAM-co-PTDMImVP. On the other hand, quite complex behavior was observed for the acrylate based copolymers (Figure 4a). Tetradecyl and dodecyl- containing acrylate based copolymers show relatively lower T_{cp} than corresponding vinyl phosphonate based copolymers. On the contrary, octyl- and hexyl- containing acrylate based copolymers show higher T_{cp} than corresponding vinyl phosphonate
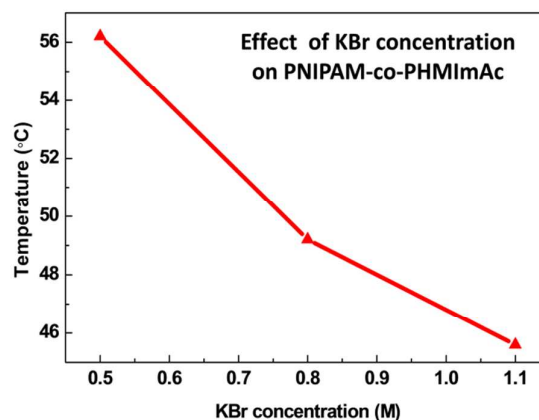

Figure 6. Effect of salt concentration on LCST behavior of PNIPAM-co-PHMImAc.
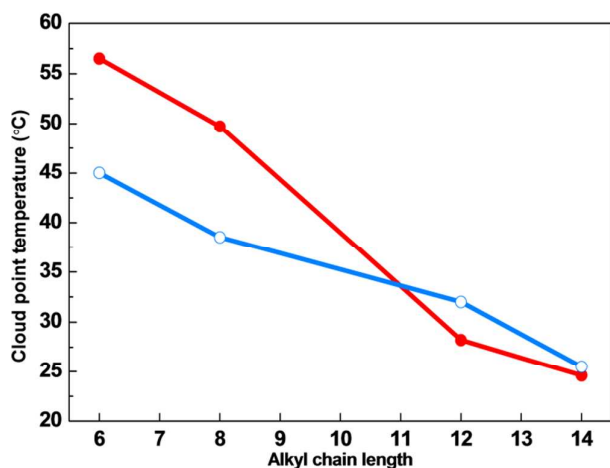
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Figure 7. Synergistic correlation between hydrophobicity with counter anion structure on the LCST behavior of acrylate (—, ●) and vinyl phosphonate based random copolymers (—, ○).

based copolymers as shown in Figure 7. The obtained results can be understood on the basis of two competitive effects *i.e.* primary and secondary effects. The primary effects originate from the widely known acid-base theory *i.e.* stronger base possess higher tendency to form hydrogen bonding and vice versa. While secondary effects accompany hydrophobic interactions between the ions originated from the bulkier substituent which results in weaker hydrogen bonding. In the case of tetradecyl and dodecyl- containing acrylate based copolymers, secondary effects dominate owing to the presence of bulky alkyl chain. Interestingly, the secondary effects were less effective in the case of corresponding vinyl phosphonate based copolymers. These observations can be attributed to the better dimensional flexibility for hydrogen bonding due to greater charge distribution sphere of vinyl phosphonate than acrylate. That is, more flexible hydrogen bonding is possible for vinyl phosphonate under different conformations of cation. Beyond C_{10}-alkyl chain length the anionic effect becomes less dominant and exhibited converging behaviour irrespective of anion type.

On the other hand, octyl- and hexyl- containing acrylate based copolymers show higher T_{cp} than vinyl phosphonate based corresponding copolymers. These results can be comprehended in the terms of dominant primary effects. Obviously, reduction in the length of alkyl chain suppresses the secondary effects and offers greater interaction of the chemical entities with the surroundings. Moreover, it is known that acrylic acid (pK_a = 4.52) is a weaker acid compared to vinyl phosphonic acid (pK_a = 2.74)[25] and consequently acrylate (strong conjugate base) offers stronger hydrogen bonding and higher T_{cp}. Furthermore, octyl- and hexyl- containing acrylate based copolymers offer lower steric shielding effect and facilitates stronger hydrogen bonding, respectively than corresponding vinyl phosphonate based copolymers.

Conclusions

PNIPAM and its random copolymer with various kinds of IL were synthesized and their LCST behavior was systematically elucidated. It was found that LCST behavior of the synthesized random copolymers was greatly affected by varying the kind of IL in terms of their hydrophobicity and structure of counter anion. It was found that both of these factors synergistically affected the LCST behavior of these random copolymers. This study contributes toward the profound understanding of the LCST behavior of NIPAM-IL based random copolymers and will be useful for custom designed thermo-sensitive materials.

References

1 R. Liu, M. Fraylich, B. R. Saunders, *Colloid Polym. Sci.*, 2009, **287**, 627–643.
2 A. S. Hoffman, *Artif. Organs*, 1995, **19**, 458–467.
3 M. Koyama, T. Hirano, K. Ohno, Y. Katsumoto, *J. Phys. Chem. B,* 2008, **112**, 10854–10860.
4 M. Heskins, J. E. Guillet, *J. Macromol. Sci.: Part A-Chem.*, 1968, **2**, 1441-1455.
5 G. Fundueanu, M. Constantin, P. Ascenzi, *Int. J. Pharm.,* 2009, **379**, 9–17.
6 P. S. Stayton, T. Shimoboji, C. Long, A. Chilkoti, G. H. Chen, J. M. Harris, *Nature,* 1995, **378**, 472–474.
7 H. Akiyama, N. Tamaoki, *Macromolecules,* 2007, **40**, 5129–5132.
8 T. Hoare, R. Pelton, *Macromolecules,* 2007, **40**, 670–678.
9 A. Kondo, T. Kaneko, K. Higashitani, *Biotechnol. Bioeng.,* 1994, **44**, 1–6.
10 H. G. Schild, D.A. Tirrel, *J. Phys. Chem.*, 1990, **94**, 4352–4356
11 S. Fujishige, K. Kubota, I. Ando, *J. Phys. Chem.,* 1989, **93**, 3311–3313.
12 C. Wu, S. Zhou, *Macromolecules,* 1995, **28**, 8381-8387.
13 H. Feil, Y. H. Bae, J. Feijen, S.W. Kim, *Macromolecules,* 1992, **25**, 5528–5530.
14 C. S. Brazel, N. A. Peppas, *Macromolecules,* 1995, **28**, 8016–8020.
15 S. Zhou, B. Chu B, *J. Phys. Chem. B,* 1998, **102**, 1364–1371.
16 M. D. Determan, J. P. Cox, S. Seifert, P. Thiyagarajan, S. K. Mallapragada, *Polymer*, 2005, **46**, 6933–6946.
17 K. V. Durme, H. Rahier, B. V. Mele, *Macromolecules,* 2005, **38**, 10155-10163.
18 W. McPhee, K. C. Tam, R. Pelton, *J. Colloid Interface Sci.,* 1993, **156**, 24-30.
19 Y. Maeda, M. Yamabe, *Polymer,* 2009, **50**, 519–523.
20 A. J. Convertine, B. S. Lokitz, Y. Vasileva, L. J. Myrick, C. W. Scales, A. B. Lowe, C. L. McCormick, *Macromolecules,* 2006, **39**, 1724–1730**.**
21 E. Karjalainen, N. Chenna, P. Laurinmaki, S. J. Butcher, H. Tenhu, *Polym. Chem.,* 2013, **4**, 1014-1024.
22 S. V. Dzyuba, R. A. Bartsch, *J. Heterocyclic Chem.,* 2001, **38**, 265-268.
23 F. Fukaya, A. Sugimot, H. Ohno, *BioMacromolecules,* 2006, **7**, 3295-3297.
24 N. T. Southall, K. A. Dill, A. D. J. Haymet, *J. Phys. Chem. B,* 2002, **106**, 521-533.
25 B. Bingöl, W. H. Meyer, G. Wegner G, *Polym. Preprints,* 2007, **48**, 144-145.

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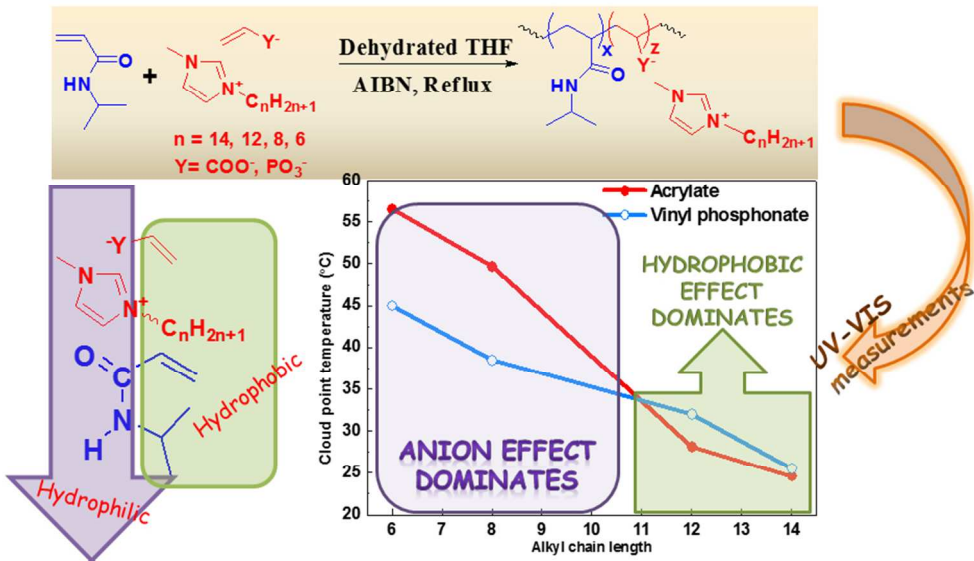
Tunable LCST of PNIPAM-IL Copolymers
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