Control of the temperature responsiveness of poly(N-isopropylacrylamide-co-2-hydroxyethyl methacrylate) copolymer using ultrasonic irradiation

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ABSTRACT

Poly(N-isopropylacrylamide-co-2-hydroxyethyl methacrylate) (poly(NIPAM-co-HEMA)) is a temperature-responsive copolymer that is expected to be applicable as an advanced functional polymeric material in various fields. In this study, a novel method was developed to control the responsive temperature of poly(NIPAM-co-HEMA) using an ultrasonic polymerization technique. Initially, the behavior of the reaction was investigated using NIPAM and HEMA monomers under ultrasonic irradiation. A high ultrasonic power was found to produce a high reaction rate and low number average molecular weight of the copolymer. The polydispersity of the synthesized copolymer was approximately 1.5 for all ultrasonic powers examined. In the early stage of the reaction, the molar fraction of NIPAM in the copolymer was lower than the initial molar fraction of the monomers. It was concluded that ultrasonic irradiation affected the initiation reaction and polymer degradation, but did not affect the propagation reaction. Furthermore, the effect of the ultrasonic irradiation conditions on the temperature responsiveness of the copolymer was investigated. The lower critical solution temperature (LCST) of the copolymer was found to increase with increasing ultrasonic irradiation time. In addition, in the early stages of the reaction, the measured values of the LCST were higher than the estimated values using copolymer composition. This can be attributed to some parts of the copolymer chain possessing a higher NIPAM fraction than the overall fraction due to different reactivities of the monomers and terminated radicals. This hypothesis was indirectly verified by the synthesis of a block copolymer from the PNIPAM homopolymer and HEMA monomer.

1. Introduction

Poly(N-isopropylacrylamide-co-2-hydroxyethyl methacrylate) (poly(NIPAM-co-HEMA)) is a temperature-responsive copolymer consisting of poly(N-isopropylacrylamide) (PNIPAM) and poly(2-hydroxyethyl methacrylate) (PHEMA). The phase transition of PNIPAM in water is caused by the hydration and dehydration changes of the PNIPAM polymer chains, PNIPAM exhibits temperature responsiveness with a lower critical solution temperature (LCST) [1,2]. At lower temperature than LCST, the NIPAM polymer chains hydrate to form expanded structures in water. At higher temperature than LCST, on the other hand, the polymer chains dehydrate due to the activation of the molecular motion of water. PHEMA possesses a relatively high mechanical strength and biocompatibility [3], so that the combination of PNIPAM and PHEMA produces a copolymer that exhibits both of these properties. This copolymer is expected to be an advanced functional material that can be applied in sensors [4], drug delivery systems [5], cell separation systems [6], and actuators [7]. Because the molecular weights and their compositions of the copolymers affect the physical and chemical properties, it is desirable to develop a method that allows the control of both factors.

Ultrasonic polymerization is a potential method that could allow control of the polymer properties [8,9]. When ultrasound is irradiated to a liquid, microscale bubbles are formed [10]. The subsequent collapse of bubbles causes a local high-temperature and high-pressure field [11], in addition to a high shear field [12]. When ultrasound is applied to a solution containing a monomer, the polymerization reaction proceeds by generating radicals at a local high temperature [13-16], while polymer degradation proceeds simultaneously due to the high shear field [17,18], thereby imparting a degree of control over the process. To
date, various polymers have been synthesized using this method, including polystyrene [14,19,20], poly(methyl methacrylate) [13,15,21], poly(2-hydroxyethyl methacrylate) [22], and poly(N-isopropylacrylamide) [23,24]. Various copolymers also has been synthesized, including poly(styrene-co-n-butyl methacrylate) [25], poly(styrene-co-methyl methacrylate) [25], and poly(N-isopropylacrylamide-co-2-hydroxyethyl methacrylate) [26].

Most of the previous studies focused on the synthesis of the polymer and the conversion to polymer. However, the polydispersity is one of the important factors that affect the properties of the polymer. The effect of ultrasonic irradiation on polydispersity has been reported [14]. We demonstrated that the PHEMA homopolymer, which possesses a low polydispersity (i.e., a narrow molecular weight distribution), is able to be obtained via polymerization reaction by regulating the ultrasonic irradiation conditions [22]. We also demonstrated that the poly(NIPAM-co-HEMA) copolymer possesses a low polydispersity in addition to sharp temperature responsiveness compared to that of the copolymer obtained using the conventional method with a chemical initiator [26]. In our previous studies, we did not evaluate the copolymer composition, which affects the temperature responsiveness of the copolymer. To the best of our knowledge, no study has focused on the control of the temperature responsiveness of poly(NIPAM-co-HEMA) copolymer.

In this study, we herein report the development of a novel method to control the responsive temperature of the temperature-responsive poly (NIPAM-co-HEMA) copolymer prepared using ultrasonic polymerization. First, the formation of the copolymer from the NIPAM and HEMA monomers under ultrasonic irradiation is investigated, and subsequently, the temperature responsiveness of the copolymer is investigated using the LCST. The relationship between the copolymer composition and LCST is also investigated, and we demonstrate the dependence of the LCST on the initial molar fraction of the monomer and on ultrasonic irradiation conditions.

2. Materials and methods

NIPAM (Wako Pure Chemical Co., Japan) and HEMA (Wako Pure Chemical Co., Japan) were used as monomers. Ethanol (Wako Pure Chemical Co., Japan) and water were used as mixed solvents. Pure water was obtained using a water purification system (Purelite, Organo Co., Japan). In this study, no chemical initiator was used for the main radical polymerization experiment. However, to synthesize the PNIPAM homopolymer as a starting material for the block copolymer experiment, ammonium persulfate (APS) (Wako Pure Chemical Co. Japan) was used as the chemical initiator, and $N, N', N''-\text{tetramethylethlenediamine}$ (TEMED) (Wako Pure Chemical Co. Japan) was used as an accelerator. $N, N$-dimethylformamide (Wako Pure Chemical Co. Japan) was used as the eluent for analysis by a gel permeation chromatography (GPC). LiBr (Sigma-Aldrich Co., USA) was used as an additive for the eluent. Polystyrene standards (GL Science Inc., Japan) were used to calibrate molecular weights. Poly(N-isopropylacrylamide) (Polymer Source Inc., Canada) and poly(2-hydroxyethyl methacrylate) (Wako Pure Chemical Co., Japan) were used to calibrate polymer concentrations. Perdeuterated methanol (Methanol-d$_{4}$, Wako Pure Chemical Co., Japan) was used as the solvent for $^1$H NMR analysis. All reagents were used as received without further purification.

The experimental apparatus used for copolymer synthesis was the same as that used in our previous study [22,26]. More specifically, the apparatus consisted of a horn-type ultrasonic generator with a solid probe diameter of 13 mm (VC 750, Sonics and Materials Inc, USA) with an ultrasonic frequency of 20 kHz, in addition to a glass vessel with an inner diameter of 55 mm and a height of 100 mm, a syringe for sampling the solution, an inlet and outlet for nitrogen gas, and a condenser. The reaction vessel was immersed in a temperature-controlled water bath using a water circulator (CLH301, Yamato Science Co., Ltd., Japan). The probe of the ultrasonic generator was immersed at 30 mm depth below the free surface of the solution.

A mixture of ethanol and water was used as the solvent, and the volume of the reaction solution was 100 cm$^3$. The desired concentration of monomers was dissolved in the solvent, and the solution was poured into the glass reactor. During the reaction, nitrogen gas continued to be bubbled through the reaction solution to remove oxygen. To prevent the solution from evaporating, the condenser was used to send back the trapped solvent. The reaction was initiated by ultrasonic irradiation of the reaction solution. The temperature of the solution was regulated at 303 K during the ultrasonic irradiation by balancing the heat generation by ultrasonic irradiation and heat emission to the temperature regulated water bath. The ultrasonic power per solution volume was measured using calorimetry [27,28]. The ethanol volume fraction in the mixed solvent was 60 vol%, and the total monomer concentration in the solution was 0.4 mol/dm$^3$.

At defined time intervals, samples of the reaction solution were taken from the reactor to monitor the progress of the reaction. Specifically, the conversion to copolymer, the number average molecular weight, and the polydispersity of the copolymer were measured by a GPC system (W2695, Waters Co., USA) equipped with a GPC linear column and a refractive index (RI) detector. The temperatures of the column and the detector were both set to 313 K. The eluent was $N,N$-dimethylformamide containing 0.01 mol/dm$^3$ LiBr, and its flow rate was 0.5 cm$^3$/min.

The synthesized copolymer was dried in a vacuum oven (AVO-310, AS ONE Co., Japan). A portion of the dried polymer was then dissolved in deuterated methanol, and the composition of the copolymer was analyzed by $^1$H NMR spectroscopy (AV400, Bruker Co., USA). Fig. 1 shows a typical NMR spectrum of poly(NIPAM-co-HEMA) synthesized using ultrasonic irradiation. The peaks at 1.2 ppm 4.0 ppm are ascribed to the methyl (CH$_3$) and methine (CH) protons of the NIPAM segment, respectively. The peak at 2.0 ppm is related to the methyl (CH$_3$) protons of the HEMA segment, and the peaks at 3.8 ppm and 4.1 ppm are related to the methylene (CH$_2$) protons of the HEMA segment. The peaks between 1.0 ppm and 2.1 ppm are also attributed to the methylene and methine protons of the main chain of the copolymer. The peaks at 5.6 ppm and 6.2 ppm are attributed to the methyldiene ($=\text{CH}_2$) and methine ($=\text{CH}$) protons of the NIPAM and HEMA monomers. The peaks at 3.3 ppm and 4.8 ppm are from the deuterated methanol solvent. The molar fraction of the NIPAM unit was estimated using the integrated value of the resonance signals assigned to the NIPAM and HEMA units in the copolymer, and those of the residual NIPAM and HEMA monomers. The experimental error on the molar fraction in the copolymer was within 3%.

![Fig. 1. Typical NMR spectrum of the poly(NIPAM-co-HEMA) synthesized using ultrasonic irradiation. NIPAM:HEMA = 7:3.](image-url)
Another portion of the dried copolymer was redissolved in water at a concentration of 1.0 wt%. To evaluate the responsive temperature of the copolymer, the transmittance of the aqueous polymer solution was measured using an ultraviolet-visible spectrophotometer (V-570, JASCO Co., Japan) at a wavelength of 600 nm. The temperature of the solution was increased at specific temperature intervals. Near the LCST of the copolymer, the temperature interval was 1 K. At each temperature, the solution was kept for 5 min before measurement to approach the equilibrium state. It is confirmed that there was no hysteresis between heating and cooling processes. The temperature at a transmittance of 0.5 was defined as the LCST of the copolymer. The LCST was determined by the linear interpolation of the obtained data, and the experimental error on LCST was within 1 K.

Fig. 2 shows the relationship between the molar fraction of NIPAM in copolymer and LCST of copolymer. The square plots denote the results for the copolymer synthesized using a chemical initiator [29], and the circle plots denote the results for the copolymer synthesized using ultrasonic irradiation without any chemical initiator [26]. The copolymers synthesized using ultrasound were obtained when the reaction was completed. As shown in the figure, the higher the molar fraction of NIPAM, the higher the LCST is. Since NIPAM is more hydrophilic than HEMA, the hydrophilicity was higher for the copolymer with higher molar fraction of NIPAM [30]. The higher hydrophilicity results in the higher extent of hydration of polymer chain, so that the temperature of hydration-dehydration transition, i.e., LCST, is higher. The relationship between the LCST and molar fraction of NIPAM of the copolymer was linear. Accordingly, the following equation can be obtained:

$$T_{LCST} = 51.1x_{NIPAM} - 16.2$$  \hspace{1cm} (1)

where $T_{LCST}$ is the temperature at the LCST, and $x_{NIPAM}$ is the molar fraction of the NIPAM unit. Using the measured value of the molar fraction of NIPAM (as determined by $^1$H NMR spectroscopy), the LCST can be estimated using Eq. (1). This LCST was compared with the measured LCST obtained using a UV-spectrophotometer.

As a verification experiment, the block copolymer was synthesized under ultrasonic irradiation using the PNIPAM homopolymer and HEMA monomer as starting materials. In this experiment, the PNIPAM homopolymer with relatively high molecular weight was synthesized using a chemical initiator and an accelerator. An aqueous solution (100 cm$^3$ containing 0.4 mol/dm$^3$ of the PNIPAM monomer was prepared, and TEMED (0.24 cm$^3$) was then added. Subsequently, an aliquot (1 cm$^3$) of a 0.1 mol/dm$^3$ APS aqueous solution was poured into the solution to initiate polymerization reaction, conducted at 293 K over 120 min for complete polymerization. The obtained PNIPAM homopolymer was then mixed with the HEMA monomer, and the ultrasonic irradiation was used to synthesize the block copolymer of PNIPAM and PHEMA. The concentration of the PNIPAM homopolymer was 0.14 mol/dm$^3$, and the concentration of the HEMA monomer was 0.06 mol/dm$^3$, providing a total monomer base concentration of 0.2 mol/dm$^3$ and a NIPAM:HEMA molar ratio of 7:3. A mixture of ethanol and water was used as the solvent, wherein the volume fraction of ethanol was 60 vol%. The reaction was performed at 303 K and initiated using an ultrasonic power of 300 W/dm$^3$. When polymer degradation occurs under ultrasonic irradiation, a polymer radical is generated. This polymer radical acts as an initiator for radical polymerization, resulting in the addition of the HEMA monomer to the terminal of the PNIPAM polymer radical to generate a block copolymer. Samples of the solution were withdrawn, and the temperature-dependent transmittance for the block copolymer aqueous solution was measured.

3. Results and discussion

Fig. 3 shows the reaction behavior at various ultrasonic powers for the initial molar ratio NIPAM:HEMA of 7:3; the conversion to copolymer, number average molecular weight, polydispersity, and molar fraction of NIPAM in the copolymer. As shown in Fig. 3(a), the conversion to the copolymer increased with ultrasonic irradiation time. From this result, it is found that the polymerization reaction was initiated by a radical species generated by ultrasonic irradiation, without the requirement for a chemical initiator. In addition, the higher polymerization rate at a higher ultrasonic power can be attributed to the large number of radical species generated at higher ultrasonic powers.

As shown in Fig. 3(b), the number average molecular weight was high in the early stage of the reaction and then decreased with a longer ultrasonic irradiation time. From this result, it is found that the degradation of copolymer occurred due to the cavitation-induced high shear stress. When the ultrasonic power was higher, the number average molecular weight of the copolymer was lower. This result can be attributed to the decomposition of the generated copolymer due to the higher shear stress caused by the ultrasonic cavitation.

As shown in Fig. 3(c), the polydispersity of the molecular weight was almost 1.5. For an ideal radical polymerization, the minimum polydispersity for radical polymerization is 1.5 for termination by combination and 2.0 for termination by disproportionation [31]. At ultrasonic power of 150 W/dm$^3$, in the early stage of the reaction, the polydispersity decreased with time due to the slow polymer degradation rate. Therefore, these results indicate that ultrasonic irradiation allows to synthesize the copolymers with low polydispersities.

As can be seen in Fig. 3(d), the molar fraction of NIPAM in the copolymer was lower than the initial monomer fraction in the early stage and gradually approached the initial molar fraction (denoted by the dashed line) in the latter stage. According to the homopolymer synthesis, the reactivity of NIPAM is higher than that of HEMA [26]. Using the Fineman-Ross method to the experimental data in Fig. 3, the reactivity ratio of HEMA was much higher than that of NIPAM. Considering these two results, the rate of propagation of the NIPAM-terminated radical with the HEMA monomer is significantly faster than that of the HEMA-terminated radical with the NIPAM monomer. This can also be attributed to the reactivity of the NIPAM-terminated radical (i.e., secondary radical), which is higher than that of the HEMA-terminated radical (i.e., tertiary radical). In other words, the stability of the HEMA-terminated radical is higher than that of the NIPAM-terminated radical. In the early stage of the reaction, the fraction of the HEMA-terminated radical becomes higher in the early stage of the reaction. Then, the HEMA-terminated radical consumes more HEMA monomer, so that the larger amount of HEMA monomer was consumed. Overall, this resulted in the more rapid consumption of the HEMA monomer compared to the NIPAM monomer.

Fig. 4 shows the relationship between the conversion to copolymer and molar fraction of NIPAM in the copolymer, which was plotted using...
the data presented in Fig. 3(a) and (d). As shown in the figure, for all ultrasonic powers, the molar fraction of NIPAM was similar at the same level of the conversion, i.e., the data for all conditions lie on the same curve. This result suggests that ultrasonic irradiation does not affect the chain propagation reaction during polymerization. This finding agrees with those in the earlier works such as polystyrene [14] and PMMA [13,15]. Therefore, ultrasonic irradiation affects only the initiation step of the polymerization reaction and degradation of the polymer chain.

Fig. 3. Time variation in (a) the conversion to copolymer, (b) number average molecular weight, (c) polydispersity, and (d) molar fraction of NIPAM for various ultrasonic powers.

Fig. 4. Relationship between the conversion to polymer and molar fraction of NIPAM.

the data presented in Fig. 3(a) and (d). As shown in the figure, for all ultrasonic powers, the molar fraction of NIPAM was similar at the same level of the conversion, i.e., the data for all conditions lie on the same curve. This result suggests that ultrasonic irradiation does not affect the chain propagation reaction during polymerization. This finding agrees with those in the earlier works such as polystyrene [14] and PMMA [13,15]. Therefore, ultrasonic irradiation affects only the initiation step of the polymerization reaction and degradation of the polymer chain.

Fig. 5 shows the transmittance change as a function of temperature for the aqueous solution containing the copolymer synthesized at various ultrasonic irradiation times (at 300 W/dm$^3$) for initial NIPAM:HEMA molar ratios of 5:5, 7:3, and 9:1. In all cases, lower temperatures produced a transmittance of 1. Beyond a specific temperature for each system, the transmittance decreased sharply, reaching 0 at higher temperatures for all ultrasonic irradiation times. These results suggest that the synthesized polymer exhibits temperature responsiveness under all conditions examined herein. As shown in Fig. 5(a), for the case where the NIPAM:HEMA molar ratio was 5:5, a longer ultrasonic irradiation time resulted in a higher temperature for the transmittance change, i.e., a higher LCST. Based on the results presented in Fig. 3(d), the lower molar fraction of NIPAM in the early stage, compared to the initial molar fraction of NIPAM. Since NIPAM is more hydrophilic than HEMA, the copolymer with the lower molar fraction of NIPAM has lower hydrophilicity, that is, the temperature of hydration-dehydration transition is lower. For NIPAM:HEMA molar ratios of 7:3 and 9:1 (Fig. 5(b) and 5(c)), although the absolute values of the LCST were different from the case where the NIPAM:HEMA molar ratio of 5:5, the trend throughout the overall ultrasonic irradiation time was the same, i.e., the longer ultrasonic irradiation time resulted in a higher LCST.

To investigate the LCSTs of the prepared copolymers, each LCST value was estimated from the copolymer molar fraction of NIPAM using Eq. (1), which is the linear relationship between the LCST of the copolymer and the molar fraction of NIPAM, and was compared with the measured value. Fig. 6 shows the LCST values at various ultrasonic irradiation times for different initial monomer fractions of NIPAM. The solid plots denote the measured values based on the temperature-dependent transmittance (Fig. 5), while the open plots denote the estimated values from the molar fraction of NIPAM in copolymer (Fig. 3(d)) using Eq. (1). Note that the estimated values of the LCST for the molar fraction of NIPAM smaller than 0.5 was obtained by the extrapolation. At any initial monomer molar fraction of NIPAM, in the early stage of the reaction, the measured value was higher than the estimated value. As shown in Fig. 2, the polymer with a higher molar fraction of NIPAM exhibited a higher LCST, and this may be due to some portions of the polymer chain containing a higher NIPAM fraction than the overall fraction. This could be attributed to the differences in reactivities between the monomers and terminated radicals. In all cases, as the
ultrasonic irradiation time increased, the measured value of the LCST approached the estimated value. This can be attributed to the degradation of the synthesized polymer proceeding over time, resulting in the sequence of the monomer unit approaching a random value in a later stage of the reaction. In addition, in the case of a higher initial molar fraction of NIPAM, the measured value of the LCST was reached faster than in the case of a lower initial molar fraction. This was due to the reactivity of the NIPAM monomer being higher than that of HEMA. Note that the difference between measure and estimated LCST was smaller at NIPAM:HEMA = 9:1. This is because the influence of HEMA is smaller due to the smaller molar fraction of HEMA. Moreover, the reaction rate at NIPAM:HEMA = 9:1 is faster, and the difference between measured and estimated LCST becomes smaller as the reaction proceed.

There are two possible hypotheses for the difference in LCST between the measured values and estimated values, namely composition distribution and sequence distribution, as outlined in Fig. 7. The first hypothesis can be considered as follows. As shown in Fig. 3(d), the copolymer generated in the early stage of the reaction had a lower molar fraction of NIPAM than the initial monomer molar fraction. This result implies that the molar fraction of the unreacted NIPAM monomer is higher than the initial monomer molar fraction and the copolymer generated in the later stage contains a higher molar fraction of NIPAM. In the final stage, the generated copolymer possessed a distribution of the molar fraction of NIPAM. In this case, the responsive temperature could be affected by the polymer containing a lower monomer fraction of NIPAM, thereby lowering the LCST compared to that associated with the average molar fraction of NIPAM.

The second hypothesis is as follows. In the early stage of the reaction, the differences in the reactivity between the terminated radicals resulted in the HEMA monomer being preferentially elongated at the polymer

| NIPAM:HEMA | 9:1 | 7:3 | 5:5 |
|------------|-----|-----|-----|
| measured   | ▲   | ■   | ▲   |
| estimated  | ▼   | □   | ▼   |

Fig. 5. Temperature-dependent transmittances for the aqueous solution containing the copolymer synthesized at various ultrasonic irradiation times, for initial NIPAM:HEMA molar ratios of (a) 5:5, (b) 7:3, and (c) 9:1.

Fig. 6. LCST values at various ultrasonic irradiation times for different initial molar fraction of NIPAM.
radical terminal. In this case, the synthesized polymer possesses the distribution of the monomer sequence. The HEMA sequence at one end of the polymer terminal does not contribute to the temperature responsiveness of the polymer, thereby indicating that only a part of the polymer chain contributes to the temperature responsiveness. Therefore, the apparent molar fraction of NIPAM capable of producing temperature responsiveness was higher than the actual molar fraction. As the reaction proceeds, because both polymerization and polymer degradation occur simultaneously, the monomer sequence becomes random. Thus, the LCST of the synthesized copolymer approaches the estimated value.

To verify the first hypothesis, copolymers with different molar fractions of NIPAM were mixed, and the temperature-dependent transmittance of the mixed copolymer aqueous solution was compared with that of the single copolymer aqueous solution. If the temperature-dependent transmittance of the mixed copolymer is the same as that of the copolymer possessing the average molar fraction of NIPAM, the LCST should be determined by the average molar fraction of NIPAM. However, if the temperature-dependent transmittance of the mixed copolymers is the same as that of the copolymer with a lower molar fraction of NIPAM, the temperature responsiveness, LCST, will be determined by the component having the lower molar fraction of NIPAM.

Thus, equivalent mixtures of the copolymers synthesized at initial NIPAM:HEMA molar ratios of 3:7 and 7:3 were prepared by dissolution in water. In this case, the average molar fraction of the copolymer mixture was 5:5. Similarly, equivalent mixtures of the polymers synthesized at initial NIPAM:HEMA molar ratios of 5:5 and 9:1 were prepared by dissolution in water to obtain an average molar ratio of 7:3.

Fig. 7. Illustration of the possible compositions and sequences of copolymer. (a) Composition distribution and (b) sequence distribution.

Fig. 8. Temperature-dependent transmittances of aqueous copolymer solutions (wherein the copolymers were synthesized using various monomer ratios) and mixtures of copolymers (ultrasonic irradiation time = 480 min).
7:3 was not consistent with that of the single copolymer with a molar ratio of 7:3. These results therefore indicate that when the solution contains copolymers with various molar fractions of the NIPAM unit, the copolymer with a lower molar fraction of the NIPAM unit dominates the temperature responsiveness. Thus, the first hypothesis based on the composition distribution of the synthesized polymer does not account for the measured LCSTs being higher than the estimated values.

To verify the second hypothesis, the block copolymer was synthesized under ultrasonic irradiation using the PNIPAM homopolymer and HEMA monomer as the starting materials. In this experiment, the PNIPAM homopolymer was synthesized using a chemical initiator and an accelerator. When the polymer got decomposed under ultrasonic irradiation, a polymer radical was generated. This polymer radical acted as an initiator so that the HEMA monomer was added to the terminal of the PNIPAM polymer radical to generate a block copolymer of PNIPAM and PHEMA. As the reaction proceeded, the composition of the HEMA unit in the copolymer increased, decreasing the composition of NIPAM, thereby resulting in a decrease in the LCST of the copolymer.

Fig. 9 shows the temperature-dependent transmittances of the aqueous copolymer solution, wherein the copolymer was synthesized from the PNIPAM homopolymer and HEMA monomer as the starting materials. As expected, the LCST decreased with increasing ultrasonic irradiation time. This result suggests that block copolymers of PNIPAM and PHEMA were generated.

Table 1 shows the molar fraction of NIPAM and LCST for the copolymer obtained from PNIPAM polymer and HEMA monomer. For example, the molar fraction of NIPAM at 240 min was 0.786, higher than 0.7. The estimated LCST from the molar fraction of NIPAM was 24.0 °C, which was higher than the measured LCST of 12.1 °C. This is because the starting material of this experiment was chemically synthesized PNI

Table 1  Molar fraction of NIPAM and LCST for the copolymer obtained from PNIPAM polymer and HEMA monomer.

| Time [min] | Molar fraction of NIPAM [-] | Measured LCST (°C) | Estimated LCST (°C) |
|-----------|-----------------------------|--------------------|---------------------|
| 5         | 0.993                       | 32.5               | 34.5                |
| 10        | 0.978                       | 30.2               | 33.8                |
| 60        | 0.907                       | 18.7               | 30.2                |
| 240       | 0.786                       | 12.1               | 24.0                |

...was investigated. It was found that the lower critical solution temperature (LCST) of the copolymer increased with an increasing ultrasonic irradiation time. In the early stages of the reaction, the measured values of the LCST were higher than the estimated values. This difference was attributed to some portions of the copolymer chain possessing a higher NIPAM fraction than the overall fraction due to the differences in reactivity of the monomers and terminated radicals. This hypothesis was indirectly investigated by the synthesis of the block copolymer of PNI

4. Conclusions

In this study, the effects of experimental conditions such as ultrasonic power, ultrasonic irradiation time, and molar fraction of monomer were investigated to control the responsive temperature of the temperature-responsive copolymer poly(NIPAM-co-HEMA). Initially, the polymerization reaction of NIPAM and HEMA under ultrasonic irradiation was investigated. It was found that at higher ultrasonic powers, the rate of polymerization was faster, and the number average molecular weight of the copolymer was lower. It was also found that the polydispersity of the molecular weight was approximately 1.5 for all the condition examined; thus, by varying the ultrasonic irradiation condition, the molecular weight and its distribution could be controlled while maintaining a low polydispersity. In addition, it was found that the molar fraction of NIPAM in the copolymer generated in the early stage of the reaction was lower than the initial molar fraction of this monomer. These results indicated that ultrasonic irradiation affected the initiation reaction and degradation of the polymer, but did not affect the propagation reaction for the synthesis of poly(NIPAM-co-HEMA). This finding agrees with those in the earlier works such as polystyrene and PMMA.

To evaluate the temperature responsiveness of each obtained copolymer, the optical transmittance of a copolymer aqueous solution...
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