

ON SWELLING CHARACTERISTICS AND MECHANISM OF TEMPERATURE SENSITIVE HYDROGELS*

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ABSTRACT

A series of N-substituted acrylamide monomers and the temperature sensitive hydrogels of their copolymer with N, N'-methylene-bis-acrylamide (Bis) have been synthesized. The effects of monomer structures, composition of the initial monomer mixture, polymerization temperature, the extent of ionization of the network and the presence of acid, base, salt or organic compound on the formation and the swelling characteristics of the temperature sensitive hydrogels have been systematically studied. The mechanism of the temperature sensitive phase transformation of the hydrogels was also investigated.

INTRODUCTION

Several gels while swelling in water or water solution are known to undergo a discontinuous volume change upon changes in temperature. It means that at certain critical temperature range an almost infinitesimal change in temperature brings about a finite change in hydrogel volume. These gels are called temperature sensitive hydrogels. These phenomena have been interpreted as a phase transition in gels, and the temperature which the phase transition takes place is called the phase transition temperature of the hydrogel.

Since Tanaka et al.^[1] discovered the sensitive phase transition of aged polyacrylamide (PAAm) hydrogels swollen in acetone-water mixture in 1978, other ionic and nonionic crosslinked polymer hydrogels such as poly(N,N-diethylacrylamide) hydrogels, poly(N-isopropylacrylamide) hydrogels and poly(methyl vinyl ether) temperature sensitive hydrogels have also been found by other researchers^[2-6].

In early period, it was considered that the ionization of the network was the crucial factor that caused the sensitive phase transition of the hydrogels. But later, nonionic poly(N-isopropylacrylamide) hydrogel was also found to show a sharp change of swelling in water at 33 °C in 1984^[2,3]. Although temperature sensitive phenomena have been experimentally observed among the above-mentioned nonionic hydrogels, the mechanism of these phenomena seems obscure. In the meantime, several physical interpretations were proposed on the basis of a variety of theories of polymer solution thermodynamics. However, the exact nature between structure and sensitivity is still unknown in these hydrogels. In spite of that, temperature sensitive hydrogels have been widely used in chemical, mechanical, biological and medical fields.

In this paper, the effects of various factors on the sensitive swelling properties

of hydrogels will be reported and the mechanism of nonionic temperature sensitive hydrogels will be discussed.

EXPERIMENTAL

1. Sample preparation

The monomers, N-ethylacrylamide (NEA) and N, N-dimethylacrylamide (NDMA), were synthesized from the reaction of acryloyl chloride with ethylamine hydrochloride and dimethylamine hydrochloride respectively. The monomers, N, N-dimethylacrylamide (NDEA), N-n-propylacrylamide (NNPA), N-isopropylacrylamide (NIPA) and piperidylacrylamide (PRA) were synthesized from the reaction of acryloyl chloride with diethylamine, n-propylamine, isopropylamine and hexahydropyridine respectively. The hydrogels were prepared by polymerizing NIPA or other N-substituted acrylamide monomers with N,N'-methylene-bisacrylamide (Bis) in water solution. Redox initiators, ammonium persulfate and sodium metabisulfite or N,N'-tetramethylethylenediamine (TEMED) were used. A series of hydrogels of different monomers with different total monomer content and crosslinking agent content were prepared. The polymerization procedures were as follows. All components except sodium metabisulfite or TEMED were dissolved in water. This solution was flushed with nitrogen for three minutes. Then sodium metabisulfite or TEMED was added; the solution was stirred and placed in a 1 cm diameter test tubes. The solution was again flushed with nitrogen for three minutes, then the test tube was sealed. The reactants polymerized for 12 hours at a certain temperature; thereafter the gels were removed from the test tubes, cut into 1 mm³ particles, washed thoroughly with deionized water and dried in a vacuum oven.

2. Swelling characteristics

To measure the swelling ratio of the hydrogels, various known amounts (~1.0g) of dry gels were swollen in deionized water or in other solutions at different temperatures. The equilibrium degree of swelling (R) was characterized by the following expression:

$$R = w_2 / w_1$$

w_1 , w_2 are weights of the swollen hydrogel and the dry gel respectively.

3. Measurement of phase transition temperature (PTT)

The PTTs of the hydrogels (listed in Table 1) were determined according to the positions of the endothermic peaks on the DSC diagrams measured by Du Pont Instruments-990 Thermal Analyzer. It could be also measured by observing the temperature at which the hydrogel was changed into turbid from transparent when heated slowly (1 ~ 2 °C /10 min). The PTT was also the temperature at which the swelling ratio of the hydrogel undergoes a dramatic change.

RESULTS AND DISCUSSION

1. The equilibrium swelling characteristics and their influential factors of temperature sensitive hydrogels

(1) The effect of monomer structure

In order to investigate the effect of monomer structure, a series of hydrogels of different N-substituted acrylamide monomers were prepared and their equilibrium

degrees of swelling (R) and PTT were measured. The PTT and R of every hydrogel at various temperatures are listed in Table 1.

All the hydrogels mentioned in Table 1 were prepared by copolymerizing the corresponding monomers with Bis in water solutions at 5 °C.

The monomer concentrations in the original solutions were all 0.8 mol/l, and the concentration of Bis in each case was 1.5 mol Bis/100 mol monomer. All the hydrogels in Table 1 except PNDMA undergo discontinuous volume changes upon change in temperature, but the temperatures at which the phase transition taken place and the extents of phase transition are different from one another. Since the hydrogel of the copolymer of acrylamide and Bis is not a temperature sensitive hydrogel, the presence of the N-substituted group and the number and structure of the substituted groups are the important factors upon the equilibrium swelling characteristics of the hydrogels.

Table 1 Dependence of swelling characteristics on monomeric structures

Hydrogels	Swelling ratio (R)							PTT
	5 °C	15 °C	25 °C	35 °C	50 °C	60 °C	70 °C	
P (NEA)	/	/	24.28	20.58	15.50	11.84	7.99	59 °C
P (NNPA)	14.32	14.19	1.58	1.50	1.50	1.44	/	23 °C
P (NIPA)	/	16.50	15.60	5.13	1.69	1.56	/	33 °C
P (NDMA)	/	/	30.90	30.83	28.38	26.30	24.61	/
P (NDEA)	/	13.90	12.72	3.61	1.36	1.35	/	30 °C
P (PRA)	17.37	13.23	8.13	5.07	3.77	3.10	/	17 °C

(2) The effect of the crosslinking agent concentration

Usually, the concentrations of NIPA or other monomers and Bis in original solutions are designated as T and C , where T is the percentage ratio of the total weight of comonomers (involve NIPA and Bis) to the volume of the solution, while C is the percentage ratio of the weight of Bis to the total weight of the comonomers.

Fig 1 and Fig 2 describe the relationship between the temperature and the swelling ratio of PNIPA hydrogels and ionized PNDEA hydrogels respectively at various crosslinking agent concentrations.

The $PTTs$ of PNIPA hydrogels at various crosslinking agent concentrations are all around 33 °C and those of 3.5% sodium acrylate ionized PNDEA hydrogels are all around 40 °C. It seems that the concentration of the crosslinking agent does not effect the PTT of the hydrogel but it does influence the extent of the phase transition, especially the R of the hydrogel below phase transition temperature. The higher the concentration of the crosslinking agent the smaller is the swelling ratio of the hydrogel below PTT .

(3) The effect of polymerization temperature

Fig 3 shows the swelling characteristics of PNIPA hydrogels copolymerized at -10 °C and 20 °C. It seems that the copolymerization temperature does not effect the PTT of the hydrogel but the hydrogel prepared at -10 °C has a lower R below the phase transition temperature.

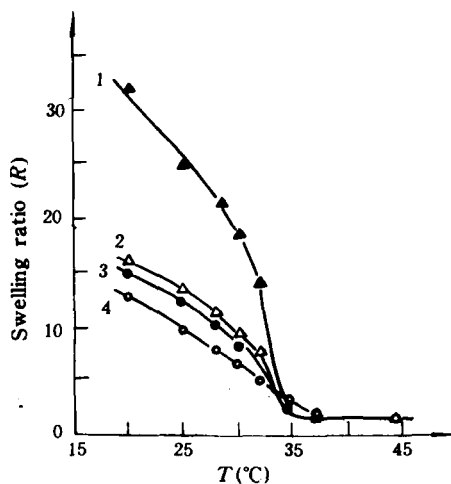


Fig. 1 The effect of crosslinking agent concentration to the swelling ratio of the PNIPA hydrogels.
1. $C=1\%$, 2. $C=2\%$, 3. $C=4\%$, 4. $C=8\%$

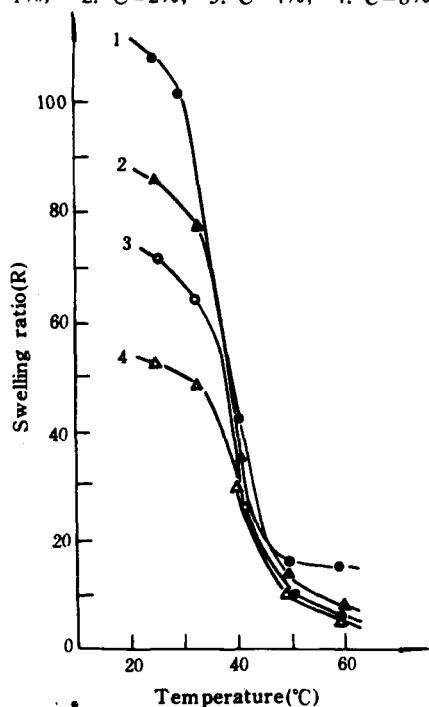


Fig.2 The swelling characteristics of ionized PNDEA hydrogels at various crosslinking agent concentrations (1) 1%, (2) 2%, (3) 3.5%, (4) 4.5%.
The content of sodium acrylate is 3.5% gm/gm total monomer

(4) The effect of total monomers concentration

Fig.4 describes the effect of total monomers concentration to the swelling characteristics of PNIPA hydrogels. PNIPA hydrogels were prepared with different total monomers concentrations but the concentrations of the crosslinking agent were all 2.4%. It seems that the concentration of the total monomers does not influence the PTT but does effect the swelling ratio of the hydrogels. When the temperature is below PTT , the higher the concentration of the total monomers, the smaller the swelling ratio.

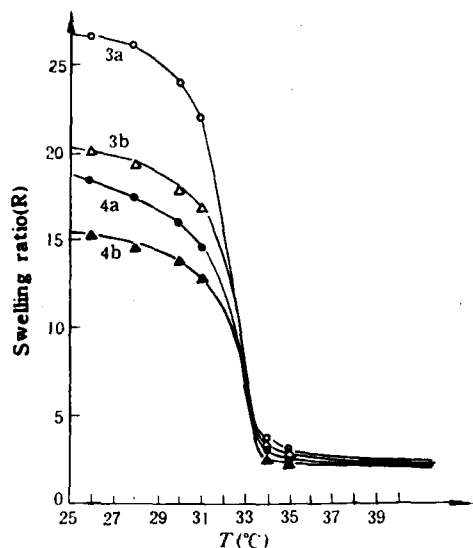


Fig. 3 The effect of polymerization temperature to the swelling characteristics of the hydrogels

3a: $T=6\%$, $C=2.4\%$ 4a: $T=8\%$, $C=2.4\%$
 $T_p=20^\circ\text{C}$ $T_p=20^\circ\text{C}$

3b: $T=6\%$, $C=2.4\%$ 4b: $T=8\%$, $C=2.4\%$
 $T_p=-10^\circ\text{C}$ $T_p=-10^\circ\text{C}$

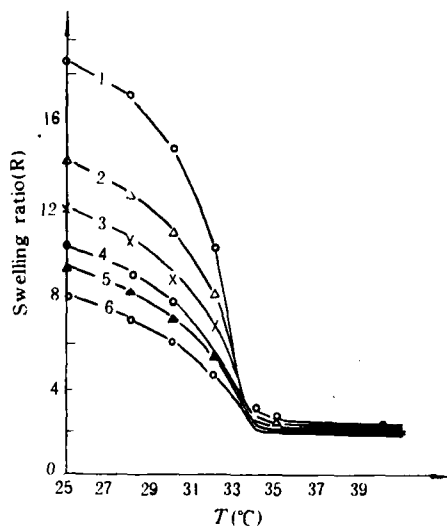


Fig. 4 The effect of total monomers concentration to the swelling characteristics of the hydrogel

1. $T=8\%$; 2. $T=10\%$; 3. $T=12\%$;

4. $T=14\%$; 5. $T=16\%$; 6. $T=20\%$

(5) The effect of the extents of ionization

Fig 5 shows the swelling characteristics of the ionized PNDEA hydrogels with different contents of sodium acrylate. The PTT and the R of the hydrogel are all raised while the content of the sodium acrylate unit in the copolymer is increased.

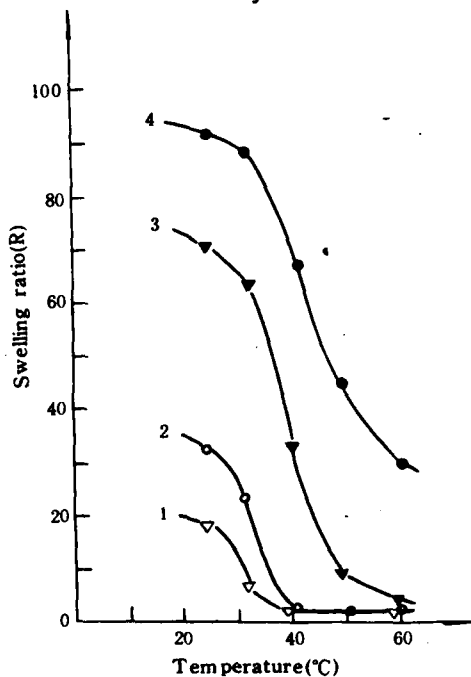


Fig. 5 The effect of the extent of ionization to the swelling characteristics of the hydrogel-The content of sodium acrylate
 (1) 0; (2) 0.7%; (3) 3.5%; (4) 5.3%

However, when the content of sodium acrylate unit in the copolymer is greater than 30%, the copolymer hydrogel is no longer a temperature sensitive hydrogel. Table 2 gives the experimental results.

Table 2 The relationship between extents of ionization and the *PTT* of the hydrogel

Content of sodium acrylate g/g total monomer	0%	3.5%	10%	20%	30%	50%	75%	100%
PTT	30 °C	40 °C	65 °C	85 °C	98 °C	no phase transition		

(6) The effect of inorganic acids, bases and salts

Inorganic acids, bases and salts are known to influence considerably the swelling characteristics of hydrophilic polymers^[7, 8]. Some salts (such as perchlorates, thiocyanates, iodides, etc.) have a salting-in effect on polymers; others, such as sulphates and halides, have a salting out effect. The effect of a salt, acid or base on the swelling of the network is the result of a number of effects such as electrostatic effect, effect of ions on the structure of water and on the association of hydrophobic parts of the network and the last but not the least the possibility of complex formation between the ion and the network's group. In order to obtain the preliminary information about the influence of some inorganic acids, bases and salts on the swelling of nonionic temperature sensitive hydrogels and to search for the reason of the water swelling of the nonionic hydrogel below *PTT*, the equilibrium degrees of swelling of PNIPA hydrogels in 0.1 *M* solutions of several acids, bases and salts at various temperatures were determined. The experimental results are listed in Table 3. From these data the following observations can be drawn:

Table 3 The effect of acids, bases and salts to the swelling characteristics of the PNIPA hydrogels *

R 0.1 <i>M</i> Solution	Temperature						
	26 °C	28 °C	30 °C	32 °C	34 °C	36 °C	40 °C
Pure water	17.73	12.74	11.32	9.18	2.02	1.86	1.84
HCl	15.25	12.20	11.43	8.89	1.69	1.69	1.61
NaCl	15.78	11.33	9.24	5.64	1.69	1.67	1.62
KCl	16.81	12.33	9.84	6.22	1.68	1.62	1.60
LiCl	16.39	12.35	10.45	7.31	1.65	1.69	1.52
KBr	16.42	14.24	12.57	10.38	3.87	1.58	1.61
NaBr	16.59	14.26	12.54	10.29	3.63	1.62	1.60
KI	18.30	16.24	13.21	11.66	7.23	1.83	1.77
NaI	18.80	15.74	13.27	9.97	6.70	1.82	1.76
NaOH	13.12	9.52	5.82	2.94	1.68	1.62	1.55
NaHCO ₃	14.84	10.41	7.04	3.54	1.53	1.57	1.54
Na ₂ CO ₃	8.83	3.93	2.57	2.33	1.69	1.68	1.68
Na ₂ SO ₄	9.13	4.20	2.43	2.23	1.63	1.56	1.55
K ₂ HPO ₄	7.99	3.46	2.40	2.07	1.56	1.53	1.46

*: Polymerization condition: $T_p=20$ °C, $T=8\%$, $C=2.5\%$

a. Inorganic acids, bases and salts do not influence the swelling characteristics of the hydrogel above the phase transition temperature.

b. Br^- and I^- raise the PTT and increase the R of the hydrogel, other ions decline the PTT and decrease the R when the temperature is below PTT .

c. The influence of the bivalent ions is considerably higher than that of the monovalent ions. With the same valent ion, especially the monovalent anion, the PTT of the hydrogel is lowered, as the radius of the ion is increased.

Buchanan et al.^[9] studied the effect of various salts to the swelling characteristics of the ionized polysodium acrylate hydrogel. They found that the important influential factors were the ion strength of the solution and the valency of the cation. They considered that the electrostatic effect might be the main reason that the gel absorbs water. In the case of nonionic temperature sensitive hydrogel, whether the ion strength is still an important factor to the swelling characteristics of the hydrogel or not, the swelling characteristics of the PNIPA hydrogel in acid, base and various salts with the same ion strength were measured. The results in Table 4 show that the electrostatic effect is not the main reason that the nonionic hydrogel absorbs water in the lower temperature.

Table 4 The effect of acids, bases and salts solutions with the same ion strength to the swelling characteristics of the PNIPA hydrogels *

R Temperature $I=0.3^{**}$							
	25 °C	28 °C	30 °C	32 °C	33 °C	34 °C	40 °C
Pure water	20.22	17.08	15.82	12.00	7.32	5.40	1.73
HCl	16.67	14.00	12.73	8.69	6.23	5.16	2.79
NaCl	12.04	6.29	2.30	2.06	1.86	1.77	1.58
NaOH	5.34	1.60	1.58	1.44	1.40	1.39	1.41
MgSO_4	12.45	7.70	5.85	5.44	3.26	3.11	2.02
$\text{Al}_2(\text{SO}_4)_3$	13.84	10.87	8.15	5.23	3.21	3.05	2.07
Na_3PO_4	10.51	5.88	3.06	2.74	1.96	2.04	1.70
KCl	11.15	9.80	2.55	1.86	1.65	1.72	1.69
KBr	17.28	14.26	10.75	8.48	3.25	3.09	1.97
AlCl_3	18.92	16.04	10.99	9.12	3.09	2.94	2.01
CaCl_2	17.23	13.22	12.52	8.37	3.72	3.25	1.90
Na_2SO_4	6.51	3.53	1.93	1.85	1.60	1.60	1.49
KI	20.79	17.19	15.97	16.26	13.34	11.51	2.08

* Polymerization condition: $T_p=20^\circ\text{C}$, $T=10\%$, $C=1.25\%$

** Ion strength $I=1/2 \sum C_i Z_i^2=0.3$ (gmequivalent $\times$ charge²)

(7) The effect of organic substances

The effects of several organic substances to the swelling characteristics of nonionic PNIPA temperature sensitive hydrogel are listed in Table 5.

Table 5 The effect of organic substances to the swelling characteristics of PNIPA hydrogel*

R Medium	Temperature	25℃	28℃	30℃	32℃	33℃	34℃	40℃
Acetone (4%) - water		16.70	13.95	12.86	10.39	8.29	1.82	1.84
Acetone (20%) - water		8.84	4.37	2.74	2.19	2.07	2.14	1.74
Ethanol (4%) - water		17.37	13.66	12.56	11.30	5.99	2.16	1.79
Ethanol (20%) - water		13.74	4.64	1.60	1.55	1.54	1.55	1.57
Pure water		17.98	12.74	11.32	9.18	8.49	2.02	1.84

* Polymerization condition: $T_p=20\text{ }^{\circ}\text{C}$, $T=8\%$, $C=2.5\%$

2. The swelling and deswelling kinetic characteristics of temperature sensitive hydrogel

The motion of highpolymer is time dependent, for the same reason the sensitive behavior of the hydrogel is also time dependent. Because the *PTT* of PNIPA is 33℃, the swelling and deswelling kinetics of PNIPA hydrogel at 25℃ and 35℃ in the deionized water were measured. The results are in Fig. 6, 7 and 8.

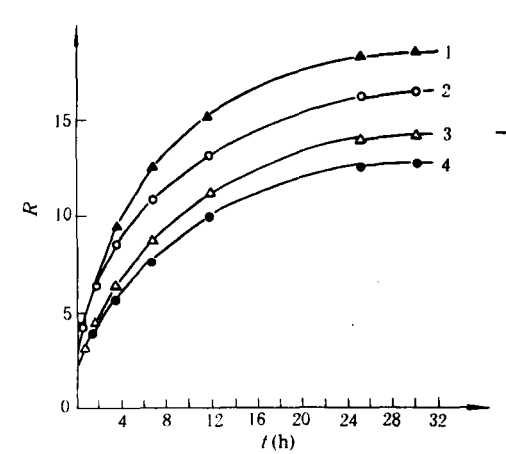


Fig. 6 The swelling kinetic curves of collapsed hydrogels at 25℃

1. $T=9\%$, $C=1\%$; 2. $T=8\%$, $C=2.4\%$;
3. $T=10\%$, $C=2.4\%$; 4. $T=9\%$, $C=2\%$

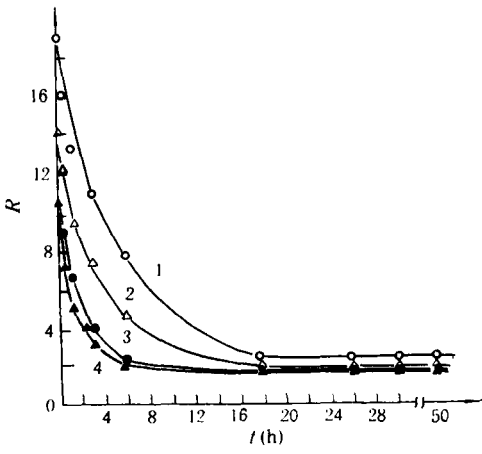


Fig.7 The deswell-time curves of hydrogels made with different total monomers concentration at 25℃

1. $T=8\%$, $C=2.4\%$; 2. $T=10\%$, $C=2.4\%$;
3. $T=12\%$, $C=2.4\%$; 4. $T=14\%$, $C=2.4\%$

The *T* and *C* of the hydrogel have no significant influence upon the velocity of swelling, they only effect the equilibrium swelling ratio of the hydrogel. However as the *T* and *C* of the hydrogel are raised, the time required to establish the deswelling equilibrium of the hydrogel is shortened.

3. The approach of the mechanism of the nonionic temperature sensitive hydrogel

The DSC diagrams of dry PNIPA gel and swollen PNIPA hydrogel are shown in Fig.9, there is no endothermic peak around 33℃ (*PTT*) for the dried

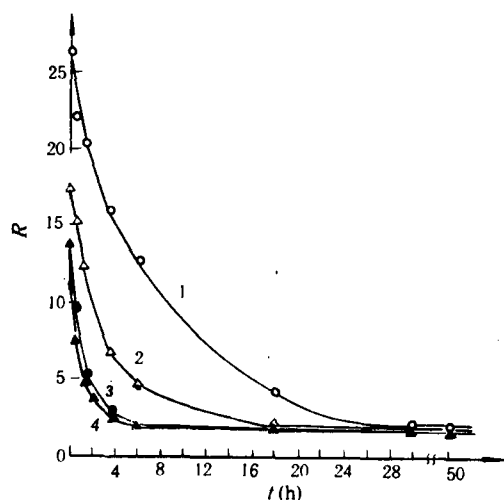


Fig.8 The deswell-time curves of the hydrogels made with different concentration of crosslinking agents at 35 °C

1. $T=9\%$, $C=1\%$; 2. $T=9\%$, $C=2\%$;
3. $T=9\%$, $C=3\%$; 4. $T=9\%$, $C=4\%$

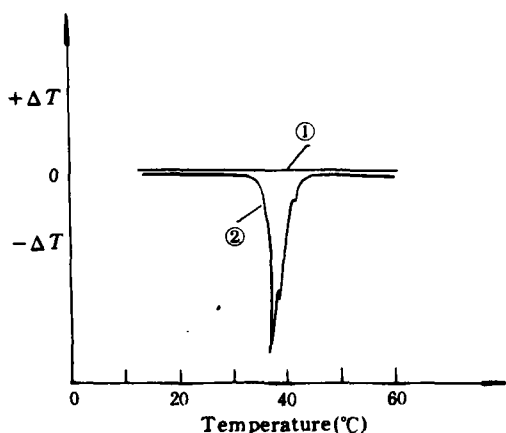


Fig.9 DSC of PNIPA hydrogels where ① is the dry gel, ② is the swollen hydrogel.

hydrogel. For the swollen hydrogel, an endothermic peak however, does exist around 33 °C. This endothermic peak represents the interaction between water and the polymer.

The solubility parameters of water, ethanol and acetone are as follows:

$\delta_{\text{H}_2\text{O}} = 47.9$, $\delta_{\text{acetone}} = 20.3$, $\delta_{\text{ethanol}} = 26$ ($\text{J}^{1/2}/\text{cm}^{3/2}$). The solubility parameters of PAAm, PMAAm and PNIPA are as follows: $\delta_{\text{PAAm}} = 19.4 \sim 29.4$, $\delta_{\text{PMAAm}} = 21.9$, $\delta_{\text{PNIPA}} = 21.9$ ($\text{J}^{1/2}/\text{cm}^{3/2}$).

The differences between the solubility parameter of water and the above mentioned polymers are very large. It is generally true that, in the absence of interactions, solution will not occur if $\delta_1 - \delta_2$ is large, but the converse is not always true, probably because specific interaction effects dominate. The very large equilibrium swelling ratio of PNIPA hydrogel below the *PTT* could only be explained by the presence of specific interaction between water and PNIPA. Besides, when the temperature is below *PTT*, the fact that the *R* of the hydrogel can be lowered by the addition of acetone or ethanol to water can only be interpreted by the existence of a specific interaction between water and PNIPA, otherwise the *R* should be raised by the addition of acetone or ethanol since the difference between δ_{acetone} and δ_{PNIPA} is much smaller. It has already been proved that electrostatic effect is not the main reason that the nonionic temperature sensitive hydrogel absorbs water in the lower temperature, therefore the specific interaction between water and the polymer network could only be the hydrogen bond between water and the group on the polymer network.

The strength of the hydrogen bond between the water molecule and the N or O atom on the network depends not only on the temperature but also on the nature of the substituted group on the N atom and the property of the swelling medium (water solution). As the volume of the substituted alkyl group on the N atom is larger or the number of substituted group increases, the strength of the

hydrogen bond formed is weakened and the phase transition temperature of the hydrogel is lowered as shown in Table 1. The formation of hydrogen between water and the group on the network becomes more difficult when the content of the organic substance in the water solution is raised, therefore in this case both R and PTT of the hydrogel are declined.

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