

Thermodynamics of swelling of poly (N-isopropylacrylamide-co-N-tertiarybutylacrylamide-co-acrylamide) hydrogels

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Abstract : In the present study, the swelling properties of poly (NIPAM-co-NTBA-co-AAm) hydrogels have been discussed. The enthalpy change of mixing ΔH_{mix} , entropy change of mixing ΔS_{mix} , free energy change of mixing ΔG_{mix} were determined for swelling of hydrogels at 25°C. ΔH_{mix} and ΔS_{mix} were found to be decreased with increasing the crosslinking ratio. The value of ΔG_{mix} and ΔG_{ela} are found to be increased with increasing the crosslinking ratio followed by decrease in swelling percentage. The Overall results indicate that negative free energy supports more swelling percentage. At all temperatures the equilibrium swelling percentage of the hydrogels are found to be increased with decreasing the crosslinking ratio.

(Keywords : NIPAM, swelling percentage, thermodynamic properties)

Introduction

Poly N-isopropylacrylamide (PNIPAM) based thermoresponsive have found a wide range of applications in controlled drug delivery systems, artificial implants, dialysis membrane, burn dressings and cardiovascular devices.¹⁻³ Since, all of these applications depend on the swelling properties of the hydrogels, the fundamental understanding of swelling behavior of the hydrogels with water is important.⁴ In addition the thermodynamic parameters affecting the swelling properties also describes give a detailed insight to diffusion mechanism for the water absorption process.^{5, 6} The hydrogels with high swelling capacities are usually more

advantageous in increasing the permeability and biocompatibility.

Flory and Rehner kept the foot print for subsequent development and given basic thermodynamic framework for analyzing the swelling of hydrogel.⁷ Their theory considered four additional contributions in the Gibbs free energy: the (1) entropy of mixing between the hydrogel polymers and the solvent molecules,⁸ (2) an enthalpy term due to binding of solvent molecules with the polymers, (3) the elastic energy term due to the configurational entropy change of the crosslinked polymer chains,⁹ and (4) for polyelectrolyte hydrogels, an ionic osmotic pressure term. Tanaka and co-workers reported two different models for the swelling of hydrogel, one based on the electrostatic energy in the hydrogel¹⁰ and another based on modification of the Flory and Rehner theory¹¹.

The purpose of the present study is to elucidate the thermodynamic analysis to water in hydrogels to gain better insights related to Poly (NIPAM-co-NTBA-co-AAm) hydrogels applications in various fields. In light of this the swelling of poly (NIPAM-co-NTBA-co-AAm) hydrogels were studied using Flory–Rehner theory. Also, the thermodynamics of swelling of hydrogels were discussed. This study is a novelty for NIPAM based literature because it is the first time that the above mentioned polymer have been used to investigate the thermodynamics of swelling behaviour of the hydrogels.

2. Experimental

2.1 Materials

NIPAM, NTBA and AAm monomer was purchased from TCI, USA. The other chemicals N,N-methylene-bisacrylamide (MBA), Ammonium persulfate (APS) and N,N,N,N-tetra-methylene-diamine (TEMED) from Central Drug House Ltd. Co., India were used as cross-linking agent, initiator and accelerator, respectively. 1,4-Dioxane was also obtained from Central Drug House Ltd. Co., India. All other reagents were of AR grade and double distilled water was used for swelling and deswelling studies.

2.2 Hydrogel Preparation

NIPAM, NTBA, and AAm random copolymers with different compositions were prepared by free radical polymerization¹². In the copolymerization process NIPAM, NTBA and

AAm were dissolved in a mixture of doubly distilled water and 1, 4-dioxane (1:2 vol). After dissolution crosslinking agent MBA and initiator APS (1 mole % in terms of monomer) was added consequently and stirred for dissolution. After few minutes the accelerator TEMED (0.25 ml solution (0.3 ml in 1.5 ml water)) was mixed. After completion of the reaction (24 hours) the hydrogel was removed washed 8-10 times with distilled water followed by SOXHLET extraction for 10-12 cycles with 1-4 dioxane to remove the unreacted monomer, linear homopolymer and physically entrapped chemicals within the gel. After washing the prepared gels were dried at room temperature for 2-4 days. Subsequently they were dried in vacuum oven for 48 hrs at about 80 °C until constant weight.

The compositions for the production of poly (NIPAM-co-NTBA-co-AAm) copolymers are summarized in the following Table 1:

Table 1:
The different proportions of monomers and reagents in copolymer composition

NIPAM/NTBA/ AAm (Molar ratio)	MBA (moles) $\times 10^{-8}$	APS (moles) $\times 10^{-4}$	TEMED (20 vol %)	Nomenclature
25/37.5/37.5	0.03	1.85	0.25	NTA1
25/37.5/37.5	0.06	1.85	0.25	NTA2
25/37.5/37.5	0.12	1.85	0.25	NTA3
25/37.5/37.5	0.15	1.85	0.25	NTA4
25/37.5/37.5	0.20	1.85	0.25	NTA5

2.3 Characterizations

2.3.1 Swelling and deswelling behaviour

Swelling measurement was carried out in constant temperature water bath and the swelling percentages were calculated by using following equation (1),

$$\%Swelling = \frac{m_t - m_d}{m_d} \times 100 \quad (1)$$

Where m_d is the dry weight of hydrogel and m_t is

the weight of swollen hydrogel at different time intervals.

3. Results and Discussion

3.1 Thermodynamics of swelling

Flory and Rehner credibly deduced the swelling of polymeric networks through their mathematical model⁷. According to which equilibrium swelling of hydrogel can be calculated by balancing the mixing and elastic contributions

to the osmotic pressure¹³. The free energy change can be given as sum of free energy of mixing and the elastic free energy can be expressed as follows,

$$\Delta G = \Delta G_{mix} + \Delta G_{el} \quad (2)$$

The increase in configurational entropy (ΔS_M^*) representing the total entropy change due to mixing (ΔS_M^*) is given by;

$$\Delta S_M^* = -k_B(n_1 \ln f_1 + n_2 \ln \phi) \quad (3)$$

Where k_B is the Boltzmann constant, f_1 and ϕ represents the volume fraction of the solvent.

In addition to the entropy of mixing, the mixing of the solvent with the polymer also causes a change in the enthalpy, which can be expressed as

$$\Delta H_M = K_b T \chi n_1 \phi \quad (4)$$

where χ is a Flory-Huggins polymer-solvent interaction parameter. $\chi > 0$ signifies the mixing as endothermic and $\chi < 0$ as exothermic. Generally, polymer solvent mixing belongs to $\chi > 0$. We note here that no pressure effect was taken into account in the derivation of the above expression for enthalpy change. Inside hydrogels, the pressure is usually much higher than the ambient pressure.

$$\Delta G_M = \Delta H_M - T \Delta S_M^* = kT \times [n_1 \times \ln f_1 + n_2 \ln \phi + \chi n_1 \phi] \quad (5)$$

Due to absence of free polymer molecules in the network structure, n_2 is equal to zero, then

$$n_2 \ln \phi = 0$$

Therefore, the free energy of solvent-polymer network mixing will be given;

$$\Delta G_M = kT \times [n_1 \ln f_1 + \chi n_1 \phi] \quad (6)$$

The derivative of ΔG_M to n_1 is

$$\frac{\partial \Delta G_M}{\partial n_1} = kT [\ln(1 - \phi) + \phi + \chi \phi^2] \quad (7)$$

The change in elastic free energy ΔG_{el} of polymer is related to the expansion of the polymer

network, is equal with $-T \Delta S_{el}$ representing the entropy change in network configuration. Flory and Rehner^{7,9,14} derived the following expression for the elasticity arises from the polymer configurational entropy change during stretching;

$$\Delta S_{el} = -\frac{k_b v_e}{2} (a_x^2 + a_y^2 + a_z^2 - 3 - \ln(a_x a_y a_z)) \quad (8)$$

where a_x , a_y and a_z are the stretching ratios in the direction of X, Y and Z represented by the subscript and V_e represents the effective number of crosslinked units that excludes the two free ends of a polymer chain. V_e is related to the actual cross-linking units v and the number of molecules n_2 through

$$v_e = v - 2n_2 = v \left(1 - \frac{2n_2}{v}\right) = v \left(1 - 2\frac{M_c}{M}\right) \quad (9)$$

where M_c and M are the molecular weight of a crosslinked segment and that of the polymer molecules before crosslinking, respectively.

$$\Delta G_{el} = -\frac{k_b v_e T}{2} (3a_s^2 - 3 - \ln a_s^3) \quad (10)$$

The derivative of ΔG_{el} to n_1 is

$$\frac{\partial \Delta G_{el}}{\partial n_1} = \frac{\partial \Delta G_{el}}{\partial a_s} \times \frac{\partial a_s}{\partial n_1} \quad (11)$$

where a_s is the ratio of the chain extension in one-direction after isotropic swelling which can be related to the solvent contribution to the total volume of the system computed by incorporation the molar volume of the solvent,

$$a_s^3 = \frac{V}{V_0} = \frac{v_0 + n_1 v_1}{v_0} = \frac{1}{\phi}$$

where $v_1 = V/N_A$ is the volume of a solvent molecules, N_A is Avogadro no. Hence,

$$\Delta G_{el} = -\frac{k_b v_e T}{2} \left(3 \left(\frac{V}{V_0} \right)^{\frac{2}{3}} - 3 - \ln \left(\frac{V}{V_0} \right) \right) \quad (12)$$

Then,

$$\frac{\partial \Delta G_{el}}{\partial n_1} = k_b v_e T \frac{V}{V_0} \left[\phi^{1/3} - \frac{\phi}{2} \right] \quad (13)$$

Combining Eqs (6) and (12), the total change in the Gibbs free energy for isotropic swelling is

$$\Delta G = RT[(n_1 \ln f_1) + \chi n_1 \phi] + \left[\frac{RT n_e}{2} \left(3 \left(\frac{V}{V_0} \right)^{2/3} - 3 - \ln \left(\frac{V}{V_0} \right) \right) \right] \quad (14)$$

where $n_e = v_e / N_A$ and $R (= k_B N_A)$ the universal gas constant, v_1 is molar volume of the solvent.

To evaluate the above parameters, five hydrogel samples, with varying crosslinking ratio were allowed to swell in distilled water at 25°C and their mass measurement has been done at different time intervals till attainment of equilibrium swelling.

Table 2

Thermodynamic parameters of hydrogels with varying crosslinking ratio

Samples	ΔS_{mix}	ΔH_{mix}	ΔG_{mix}	$\Delta G_{\text{elastic}}$	Total free energy ($\Delta G_{\text{mix}} + \Delta G_{\text{el}}$)
NTA 1	0.316343	47.75506	-46.5151	0.045307	-46.4698
NTA 2	0.28708	43.35225	-42.1975	0.051267	-42.1462
NTA 3	0.191899	29.04272	-28.1432	0.145544	-27.9976
NTA 4	0.180824	27.27807	-26.6076	0.514524	-26.0931
NTA 5	0.17632	26.08816	-26.4552	1.382454	-25.0727

The results of ΔH_{mix} , ΔS_{mix} and ΔG_{mix} are displayed in Table 1. It is seen that the signs of total free energy ($\Delta G_{\text{mix}} + \Delta G_{\text{el}}$) are negative for all the hydrogels. Since polymer–solvent systems possessing the LCST are characterized by negative values of total free energy ($\Delta G_{\text{mix}} + \Delta G_{\text{el}}$), the results indicate that all the NTA hydrogels studied in the present work have LCST's. Moreover, the values of ΔH_{mix} and ΔS_{mix} decrease and ΔG_{mix} increase with increasing amount of crosslinker MBA indicating that the thermoresponsive properties of the hydrogels increase with increasing crosslinking ratio¹⁴. The value of ΔG_{mix} and ΔG_{ela} are found to be increased with increasing the crosslinking ratio followed by decrease in swelling percentage. Overall results indicate that negative free energy supports more swelling percentage.

3.2 Effect of temperature on swelling

In the present case, the effect of temperature on the water uptake of hydrogel samples were studied in the temperature range 5–60°C in distilled water (Table 2). The results thus obtained clearly suggest that the increase in the temperature causes decrease in the equilibrium swelling, which showed their thermoresponsive behaviour. Also, increasing the temperature causes decrease in ΔG_{mix} and increase in ΔG_{ela} . The increase in ΔG_{ela} may be attributed to hydrophobic interaction showing their thermoresponsive behaviour. At all temperatures the equilibrium swelling percentage of the hydrogels are found to be increased with decreasing the crosslinking ratio.

Table -3
Equilibrium swelling percentage of hydrogels at 5, 10, 15, 25, 40, 50 and 60°C

Temperature (°C)	Equilibrium Swelling percentage				
	NTA1	NTA2	NTA3	NTA4	NTA5
5	2700	2100	1000	600	450
10	2200	1800	900	500	325
15	1600	1500	850	400	270
25	1300	1100	600	350	240
40	120	90	70	60	50
50	80	70	50	40	36

3.9 Conclusions

In this study, poly (NIPAM-co-NTBA-co-AAm) hydrogels were successfully synthesized varying the relative amount of the MBA as a crosslinker. The results, from the swelling experiments showed that the swelling percentages were found to be increased with

increasing in crosslinking agent as well as lowering the temperature. This study may represent the first step towards a full understanding of the correlation between swelling and thermodynamic properties

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