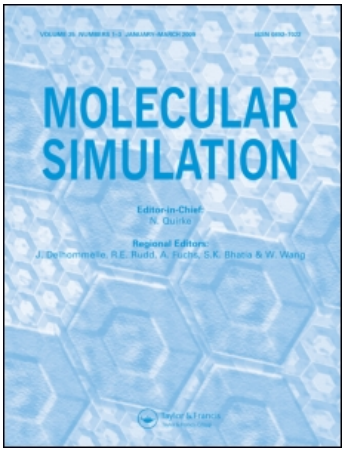

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MOLECULAR DYNAMICS STUDY OF WATER IN HYDROGELS

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Molecular dynamics simulations are performed for aqueous solutions of polymers: Poly (vinyl alcohol) (PVA), Poly (vinyl methylether) (PVME), and Poly (N-isopropyl acrylamide) (PNiPAM). The distributions and dynamics of hydrogen-bonds, the translational diffusion of water, and the orientational relaxation of water are analyzed to investigate the properties of water which is highly influenced by the surrounding polymer chains. The water molecules around the polymer chains are highly hindered by the chains.

KEY WORDS: Polymer, water, hydrogel, molecular dynamics, simulation.

1 INTRODUCTION

The hydrogels, which are made of hydrophilic polymer and water, are used for various functional materials. The hydrogels which have the lower critical solution temperature (LCST) swell at low temperature and are transformed into condensed state by the volume phase transition at high temperature. Interaction between water and polymers plays an essential role in this transition. Water molecules in the hydrogels have different character from pure water since those are constrained by polymers. It is very interesting to study the character of water molecules coexisting with hydrophilic polymers, because it has relation to the folding of proteins and various biological phenomena.

Water has characteristic physico-chemical properties due to hydrogen-bonding networks. These days, the physico-chemical properties of water are elucidated by many molecular simulation studies using molecular dynamics (MD) or Monte Carlo (MC) method, and it is revealed that hydrogen-bonds play a significant role in both static and dynamic properties of water [1].

Water molecules are highly influenced in the presence of polymer chains. Maeda *et al.* [2] evaluated the number of hydrogen-bond defects caused by monomer unit of polymers by measuring the relative intensities of collective bands of the Raman spectroscopy. The numbers of defects of water in hydrophilic polymer solutions are greater than those in hydrophobic polymer solutions. Terada *et al.* [3] evaluated the dependence of the number of defects on the molecular weights and the degrees of cross-links. They found that the numbers of defects increase with the molecular

weights and the degrees of cross-links. They argued that the number of defects increases when the size of the cluster of *interstitial* water surrounded by polymer networks decreases below a critical size and the orientation of water molecules are restricted.

Poly (vinyl alcohol) (PVA) is soluble in water at high temperature but is insoluble at low temperature. On the other hand, Poly (vinyl methylether) (PVME) and Poly (N-isopropyl acrylamide) (PNiPAM) are soluble in water at low temperature but are not soluble and phase separations are observed at high temperature because PVME and PNiPAM have LCST. The difference in solubility seems to arise from a difference in the interaction between water and polymers. Ohta *et al.* [4] examined the mobility of water molecules in the PNiPAM solution around the volume phase transition temperature, by measuring the spin-spin relaxation time T_2 by NMR. In the pure water, T_2 increases linearly with temperature. In the PNiPAM solution, though T_2 increases with temperature in most the temperature range, it decreases uncontinuously at the phase transition temperature, where the mobility of water molecules is significantly suppressed. It is thought that the volume phase transition phenomena has a close relation to the change of the entropy of water caused by the hydrophobic hydration.

In this study, we performed MD simulations for the aqueous solutions of PVA, PVME, and PNiPAM to elucidate their solubilities in water. We examined the distribution and dynamics of hydrogen-bonds, and the translational and orientational relaxations of water, which are expected to be highly influenced by the surrounding polymers. The temperature dependences of these properties are also examined.

2 SIMULATION DETAILS

2.1 *Model and Potential Functions*

PVA, PVME, and PNiPAM are modeled as shown in Figure 1. The degrees of polymerization, x, are 21 for PVA and PVME, and 11 for PNiPAM. The united atom approximation is applied for $-CH_3$, $-CH_2-$, and $-CH-$ groups. The AMBER/OPLS [5] force field was used for the polymers, and the SPC/E [6] for water. The potential energy of the system is described as

$$V=\sum k_\theta(\theta-\theta_0)^2+\sum k_\phi[1+\cos(n\phi-\delta)]+\sum_{i,j}\left(\frac{A_{ij}}{r_{ij}^{12}}-\frac{C_{ij}}{r_{ij}^{6}}\right)+\sum_{i,j}\frac{q_iq_j}{4\pi\epsilon_0 r_{ij}} \quad (1)$$

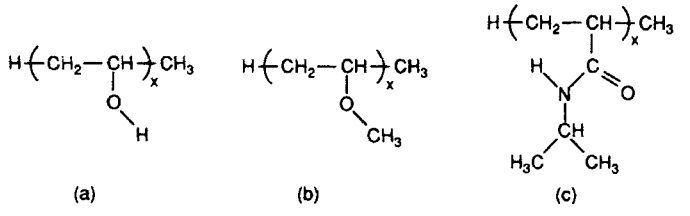


Figure 1 Models of (a) Poly (vinyl alcohol) (PVA), (b) Poly (vinyl methylether) (PVME), and (c) Poly (N-isopropyl acrylamide) (PNiPAM). The degrees of polymerization, x, are 21 for PVA and PVME, and 11 for PNiPAM.

where θ and ϕ are the bond and dihedral angles in polymers, respectively, k_θ and k_ϕ are the force constants, θ_0 is the equilibrium bond angle, n is the multiplicity factor, δ is the phase shift, r_{ij} is the distance between atom i and j, A_{ij} and C_{ij} are coefficients arising from the Lennard-Jones interaction parameters, q_i is the charge of atom i, and ϵ_0 is the dielectric constant in vacuum. Only the Lennard-Jones and Coulomb terms are included for SPC/E water.

2.2 *MD Simulation*

Using the modified self-avoiding random walk, a polymer chain and 215 water molecules were confined in a unit cell under the periodic boundary condition at the density of 1.0 g/cm^3. In this method, a chain is built up site by site with fixed bond lengths and bond angles and with randomly generated dihedral angles. A new site is either accepted or rejected by the Monte Carlo method similar to the Metropolis scheme. The degrees of polymerization are 21 for PVA and PVME, and 11 for PNiPAM. The end-to-end distances of the chains are approximately the same order as the unit cell lengths. The chains can interact with the image chains. Though the chain lengths are not so long, we think these models are enough to study the interaction between water and polymers in hydrogels.

The tacticity of all the main chains is atactic; the fraction of meso diads is 0.5. Water contents are approximately 75 wt % for all the systems. After the steepest-descent energy minimization, MD simulations were performed under the constant NPT ensemble using Nosé-Andersen method [7,8]. Under the pressure of 0.1 MPa, the simulations were performed at five temperatures: 200, 250, 300, 350, and 400 K. The bond lengths are constrained to the equilibrium lengths by the SHAKE algorithm. The bond angles, H—O—H of water and —C—O—H of PVA, are also constrained to the equilibrium angles. The short-range Lennard-Jones terms of the potentials were cut off at 9 Å, and the long-range correction terms are added. The Long-range Coulombic interactions were handled by the Ewald sum method. The equations of motion were solved using the Verlet algorithm with a time step of 0.5 fs. After the systems were equilibrated, a trajectory of 40 ps for each system was sampled for analyses. The simulations for pure water (216 molecules in a unit cell) were also performed by the same method.

A detailed description of the potential functions, generation of initial structures, and the MD simulations are given elsewhere. [9] Calculations were performed on CRAY Y-MP2E supercomputer using the molecular simulation program PAMPS which we coded.

3 RESULTS AND DISCUSSION

3.1 *Densities*

Figures 2 shows the temperature dependences of the densities calculated for the aqueous solutions and pure water. The calculated values for pure water agree well with the experimental values [10]. For the aqueous solutions of polymers, the densities are higher than those of pure water, especially at the low temperature,

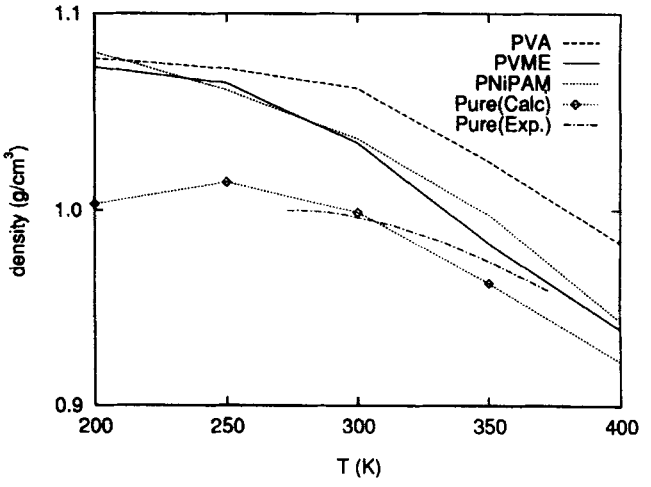


Figure 2 Temperature dependence of the densities calculated for the aqueous solutions and pure water. Experimental values for pure water are also plotted.

where the 3 kinds of polymers show approximately the same density. At the high temperature, the densities of PVME and PNiPAM are smaller than those of PVA and are close to those of pure water.

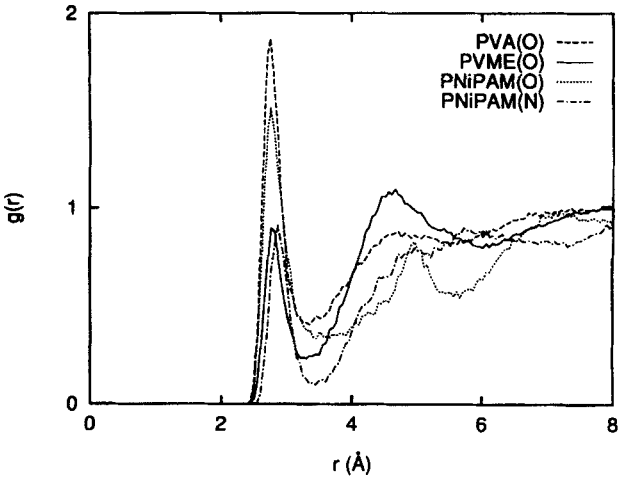
3.2 Radial Distribution Function and Coordination Number

Figure 3 shows the polymer-water radial distribution functions $g(r)$ at 300 K. The distribution of oxygen atoms around the functional groups of the polymers are shown in the figure. With increasing the temperature, the heights of the peaks become lower and the positions of the peaks shift slightly toward the long distance of r. Figure 3a shows $g(r)$ for water oxygen around the hydrophilic atoms of the polymers at 300 K. The heights of the first peaks follow the order of PVA(O) > PNiPAM(O) > PVME(O) $\simeq$ PNiPAM(N). PVA is the most hydrophilic among the three polymers. Figure 3b shows $g(r)$ for water around the hydrophobic atoms of polymers at 300 K. Large peaks are found in $g(r)$ around the $-CH_3$ groups, which are extended into water. This implies that the structuralization of water is promoted.

Regarding the region in the first peaks of $g(r)$ as the first hydration shell, we calculated the coordination number

$$n_{cd} = 4\pi\rho \int_0^{r_{cd}} g(r) r^2 \, dr \tag{2}$$

where ρ is the number density of water and r_{cd} is the radius of first hydration shell. Since the temperature dependence of r_{cd} is very small, we used an fixed r_{cd} value averaged over five temperatures for the calculations of n_{cd} at five temperatures. The coordination number as listed in Table 1 is approximately 2 for O(PVA), and 1 for O(PVME) and N(PNiPAM). An intermediate value of these two numbers is observed for O(PNiPAM). The coordination numbers decrease at higher temperature.



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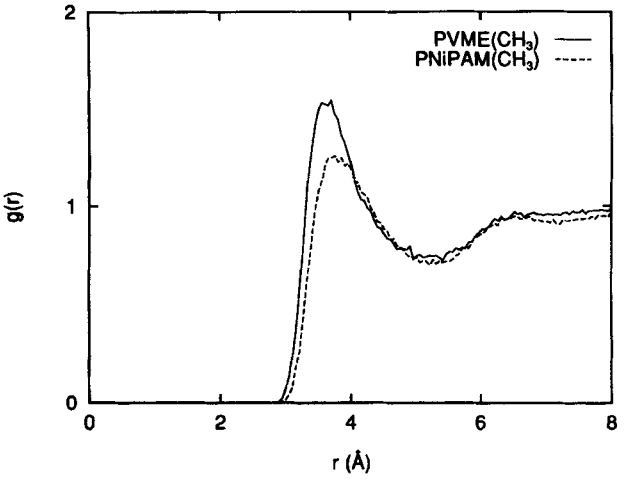


b

Figure 3 Water-Polymer radial distribution functions $g(r)$ at 300 K. (a) O(water)—O(polymer) and O(water)—N(polymer). (b) O(water)—CH_3(polymer).

3.3 Classification of Water Molecules

We classified the water molecules into three categories: (1) those around hydrophilic groups, (2) those around hydrophobic groups, and (3) bulk region (outside the region 1 and 2). Table 2 lists the classification of atoms and the radii of the regions around the atoms. The radii are determined so as to cover the first peaks of $g(r)$. water molecules are classified by the coordinates of oxygen atoms. The other classification method based on the mass center of water could lead to approximately the

Table 1 Coordination number of water around polymers.

			coordination number				
Polymer	*Atom*	r_{cd}(Å)	200 *K*	250 *K*	300 *K*	350 *K*	400 *K*
PVA	O	3.30	2.06	2.09	2.21	2.20	2.12
PVME	O	3.30	0.98	1.15	1.05	0.88	0.77
PNiPAM	O	3.30	1.96	1.96	1.80	1.74	1.56
PNiPAM	N	3.40	1.03	0.94	0.98	0.95	0.77

Table 2 Hydrophilic and hydrophobic regions in the solutions. The value in the parenthesis is the radius of the region from the center atom (in a unit of Å). Each area covers the first peak of the radial distribution function.

Polymer	*Hydrophilic*	*Hydrophobic*
PVA	O(3.30)	CH(4.10)
	H(2.45)	CH_2(4.50)
PVME	O(3.30)	CH(4.10)
		CH_2(4.50)
		CH_3(4.50)
PNiPAM	C(4.40)	CH(4.50)
	O(3.30)	CH_2(4.50)
	N(3.40)	CH_3(4.50)
	H(2.60)	

same results as present study. The regions which belong to both the region 1 and 2 are incorporated in the region 1. The bulk region (region 3) is defined as the region which is excluded from both the region 1 and 2.

Table 3 lists the average number of water molecules contained in each region. The number of molecules increases with temperature in the region 3. The number in the region 1 and 2 decreases with temperature except for that in the region 1 of PVA solution, where the number is independent of temperature. The water molecules in the PVME and PNiPAM solutions are extracted from the hydration shell into the bulk region at high temperature. On the contrary, the water molecules around —OH groups in the PVA solutions remain in the hydration shell even at high temperature.

The water molecules diffuse from one region to another with the passage of time. The residence rate, $P_{res}(t)$, is defined as the probability that the water molecule which existed in one region at time 0 has successively stayed in the same region at time t. Figure 4a and 4b show $P_{res}(t)$ for region 1 and 2, respectively, at 300 K. PNiPAM has large hydrophilic region and PVA has a high polarity. In the region 1 of these two polymers, the residence rates do not decay for a long period. This is because the hydrogen-bonds between water and the polymer bind the water molecules to the region for long time. In the region 1 of PVME, $P_{res}(t)$ decreases much faster than that of the other polymers since it has less polarity and smaller hydrophilic regions. In the region 2,

Table 3 Number of water molecules in each region. The regions 1, 2, and 3 denote the hydrophilic, hydrophobic, and bulk regions, respectively.

T(K)	number of molecules		
	Region 1	Region 2	Region 3
	PVA solution		
200	40.5	35.3	139.3
250	38.5	33.4	143.1
300	40.3	32.1	142.6
350	40.7	29.9	144.5
400	39.5	24.8	150.6
Average	39.9	31.1	144.0
	PVME solution		
200	19.6	112.6	82.8
250	21.6	109.0	84.4
300	20.3	98.0	96.7
350	17.0	85.5	112.4
400	15.0	80.4	119.6
Average	18.7	97.1	99.2
	PNiPAM solution		
200	32.0	85.5	97.4
250	31.9	83.6	99.5
300	29.6	76.6	108.9
350	28.2	71.5	115.3
400	27.4	64.2	123.4
Average	29.8	76.3	108.9

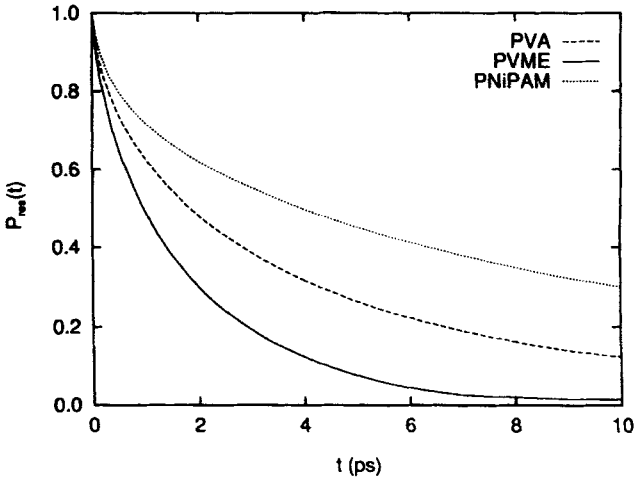
$P_{res}(t)$ decreases in shorter time than that in the region 1 because the hydrophobic groups form no hydrogen-bonds with water and the volume of the region itself is small.

3.4 *Number of Hydrogen-Bonds*

The hydrogen-bonds are defined by the distances and angles as follows [11]

$$\begin{aligned} R_{OO} &\leqslant 3.60\text{Å} \\ R_{OH} &\leqslant 2.45\text{Å} \\ \phi &\leqslant 30^\circ \end{aligned} \tag{3}$$

where R_{OO} is the distance between O ... O of two molecules, R_{OH} is that between O ... H, and ϕ is the angle of H—O ... O. The hydrophilic groups of polymers also form the hydrogen-bonds to water. The hydrogen-bonds are defined also for —OH(PVA) and > NH(PNiPAM) in the same manner. We assume that the groups —O—(PVME) and C = O(PNiPAM) also form the hydrogen-bonds with the hydrogen atoms of water. The distribution of hydrogen-bond number per a atom, $P_{HB}(n)$, where n is the number of hydrogen bonds, and the average hydrogen-bond number, $\langle n_{HB} \rangle$, are calculated from 800 configurations for each system.



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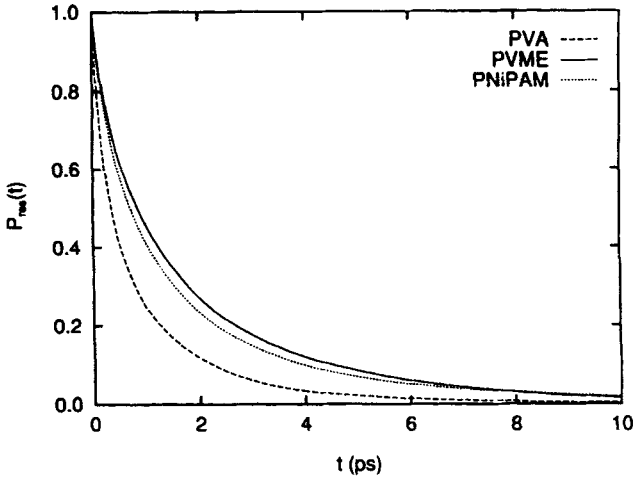

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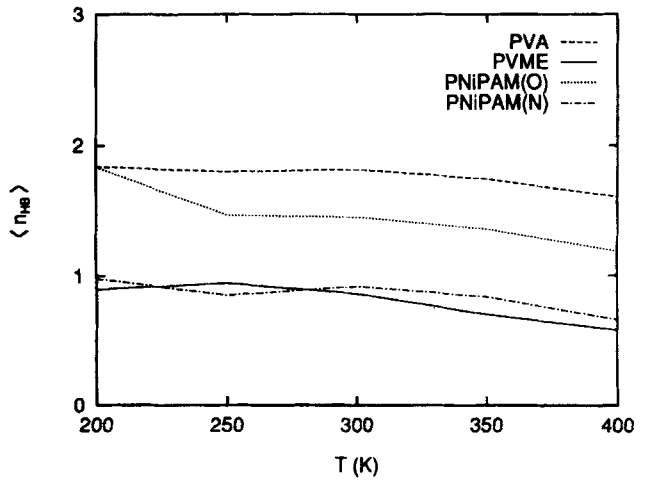
Figure 4 Residence rated $P_{res}(t)$ of water (a) around hydrophilic groups and (b) around hydrophobic groups of polymers at 300 K.

Figure 5a shows $\langle n_{HB} \rangle$ for the polar groups of polymers bonded to water molecules. The —OH group of PVA forms hydrogen-bonds with 1.8 water molecules, and the —O— group of PVME and the > NH group of PNiPAM with 0.9 water molecules. The C=O group of PNiPAM forms those with the water molecules of intermediate number. These values are slightly smaller than the coordination numbers of each system. The values of $\langle n_{HB} \rangle$ decrease with temperature since the hydrogen-bonds are broken by the molecular motion at high temperature. Figure 5b shows $\langle n_{HB} \rangle$ between two functional groups of polymers. PVA forms the polymer-polymer hydrogen-bonds and the



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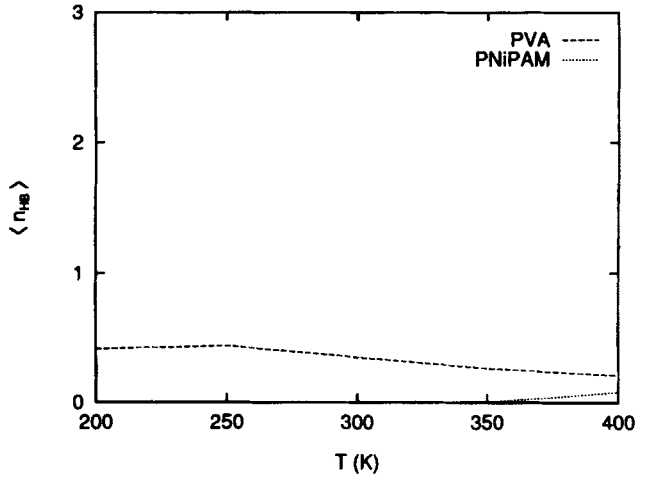


b

Figure 5 Hydrogen-bond number of the hydrophilic groups of polymers. (a) Polymer-water hydrogen-bonds. (b) Polymer-polymer hydrogen-bonds.

number decreases with temperature. No polymer-polymer hydrogen-bonds are observed for PVME and only the small number for PNiPAM.

Figure 6 shows $P_{HB}(n=0)$ for the functional groups of polymers. The value is interpreted as the probability that the groups form no hydrogen-bonds. For the groups —O— and >NH of PVME and PNiPAM, $P_{HB}(0)$ increases at high temperature; naked polar groups increase with temperature. On the other hand, $P_{HB}(0)$ for the —OH group of PVA is very small even at high temperature.

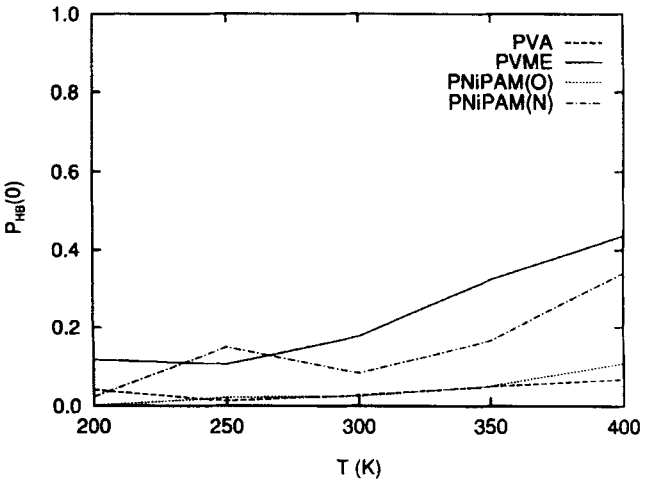
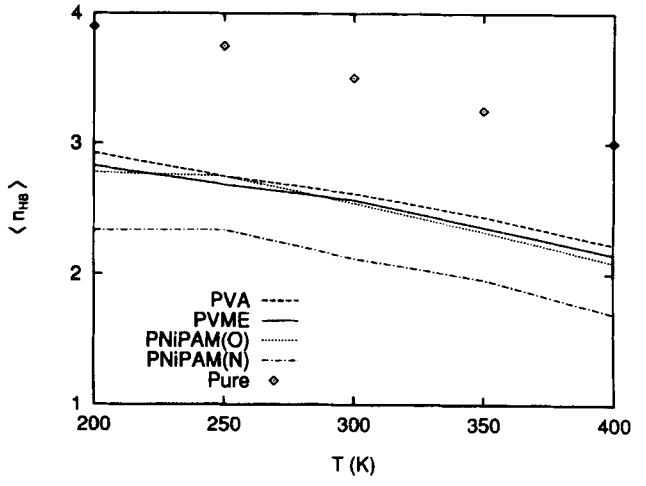


Figure 6 Temperature dependence of non-hydrogen-bonded fraction, $P_{HB}(n=0)$, for the hydrophilic groups of polymers.

Figure 7 shows $\langle n_{HB} \rangle$ of water-water hydrogen-bonds according to the three regions. The figures a, b, and c are the results for the regions 1, 2, and 3, respectively. The results for pure water are also plotted in the figures. In the region 3, the numbers of hydrogen-bonds are equal to those in pure water. In the region 1, $\langle n_{HB} \rangle$ of water-water hydrogen-bonds are smaller by approximately 1 than those in pure water since water molecules form hydrogen-bonds with the polymers. Around the > NH groups of PNiPAM, the values are smaller by 1.5. In the region 2, the number of water molecules around one water molecules is smaller than that in pure water by the presence of the polymer chains. Though this leads to smaller $\langle n_{HB} \rangle$ values, the degree of the decrease is very small. Therefore, the hydrogen-bonds are promoted so as to compensate for the small number of water molecules. The values of $\langle n_{HB} \rangle$ decrease with temperature. The temperature dependences are less sharper around the hydrophilic groups than those in pure water, and much sharper around the hydrophobic groups.

Figure 8 shows the total number of hydrogen-bonds per water molecule in region 1, including the water-polymer hydrogen-bonds. For the system of the aqueous PVA solution, the total numbers of hydrogen-bonds are approximately equal to those in pure water. For the system of aqueous PVME and PNiPAM solutions, the numbers are slightly small. The number of hydrogen-bond defects are completely compensated by the water-polymer hydrogen-bonds for PVA but not for PVME and PNiPAM.

PVME and PNiPAM are soluble in water at low temperature but undergo phase separation at high temperature. One of the reason for this is that at high temperature the destruction of polymer-water hydrogen-bonds makes polymers hydrophobic and the structuralization of water are promoted around the polymers by the hydrophobic hydration. Although the polymer-water hydrogen-bonds for PVA also decrease at high temperature, the effect to lower hydrophilicity is small since few naked polar groups exist. The decrease of the polymer-polymer hydrogen-bonds seems to accelerate the hydration of polymers. This agrees to the fact that PVA is soluble in hot water.



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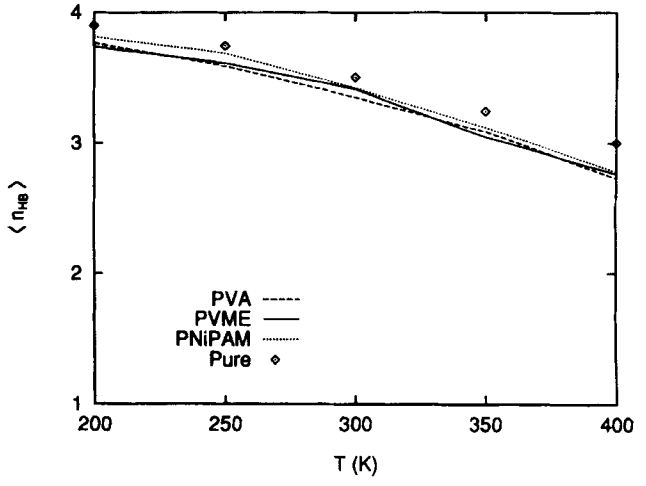

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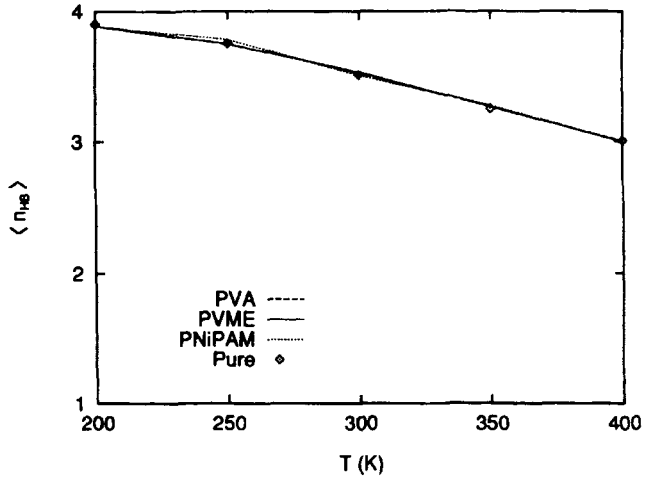
Figure 7

3.5 *Dynamics of Hydrogen-Bonds*

To obtain the information related to the life-time of hydrogen-bonds, we calculated the hydrogen-bonds autocorrelation functions

$$C_H(t) = \frac{\langle \sum_i h_i(t+t_0) \cdot h_i(t_0) \rangle}{\langle \sum_i h_i^2(t_0) \rangle} \tag{4}$$

where $h_i(t)$ is defined for an atom pair i as



c

Figure 7 Number of water-water hydrogen-bonds per water molecule (a) in the region 1, (b) in the region 2, and (c) in the region 3. The numbers in pure water are also plotted by diamonds.

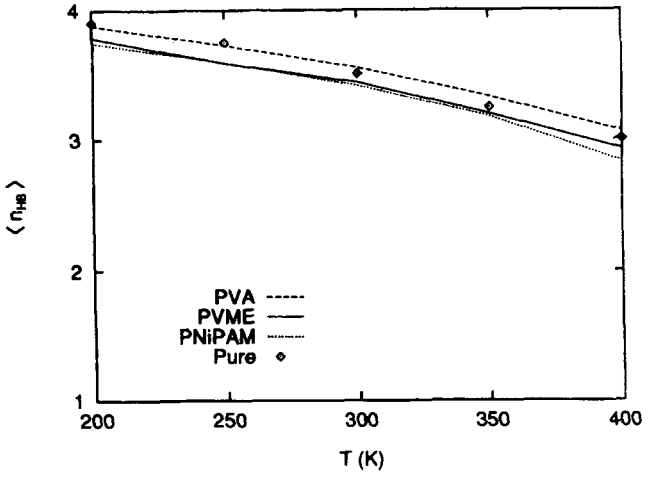


Figure 8 Number of hydrogen-bonds per water molecule including the water-water and water-polymer hydrogen-bonds.

$$h_i(t) = \begin{cases} 1 & \text{(bonded)} \\ 0 & \text{(nonbonded)} \end{cases} \tag{5}$$

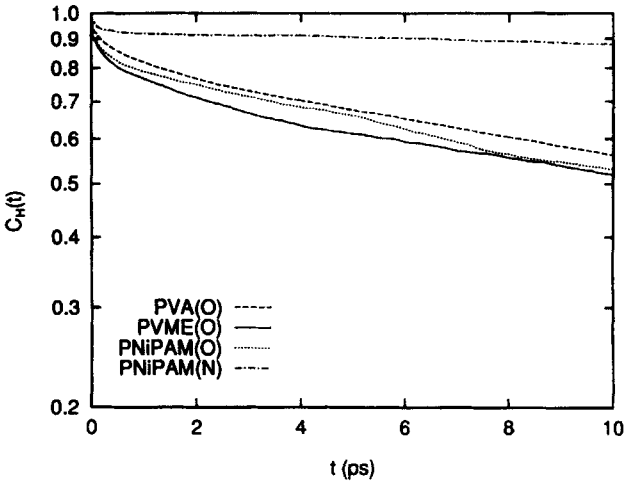
The sums are taken for the atom pairs which had already formed hydrogen-bonds at time t_0, and are averaged over all the time origins t_0.

Figures 9a shows $C_H(t)$ for the polymer-water hydrogen-bonds at 300 K. The decays of $C_H(t)$ are similar for oxygen atoms of PVA, PVME, and PNiPAM. The decay is anomalously slow for nitrogen atoms of PNiPAM. Figure 9b shows $C_H(t)$ for the

water-water hydrogen-bonds around PNiPAM according to the three regions at 300 K. The decay of $C_H(t)$ in the region 3 is the same as that for pure water but that in the region 1 and 2 is slower.

3.6 *Dynamics of Water*

The diffusion coefficient and the orientational relaxation time were calculated to examine the influence of polymer chains on the dynamics of water molecules. The diffusion



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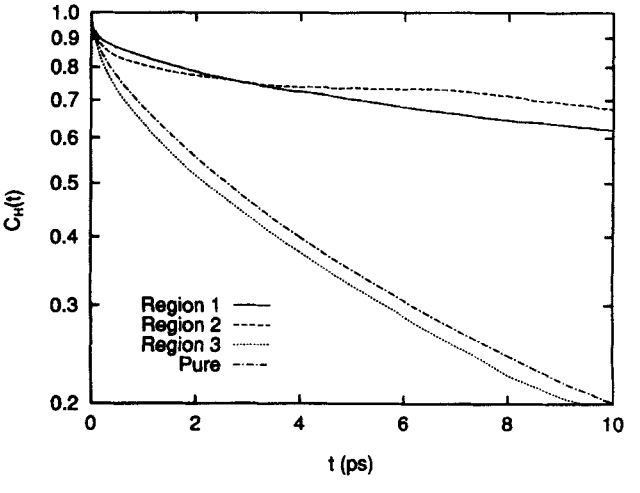


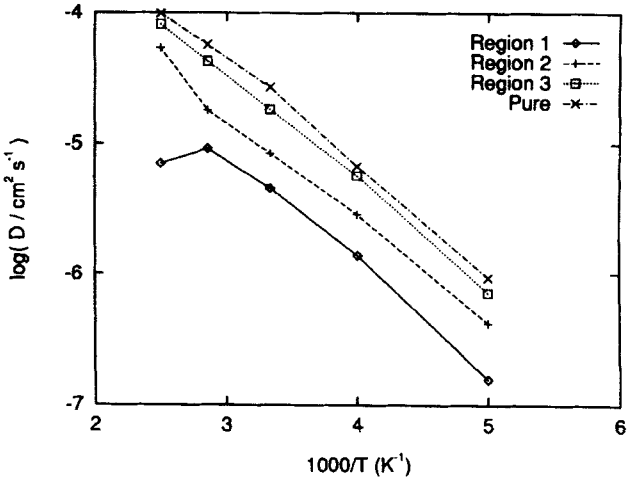
b

Figure 9 Semi-logarithmic plots of hydrogen-bond autocorrelation functions $C_H(t)$ (a) of water-polymer hydrogen-bonds and (b) of water-water hydrogen-bonds at 300 K.

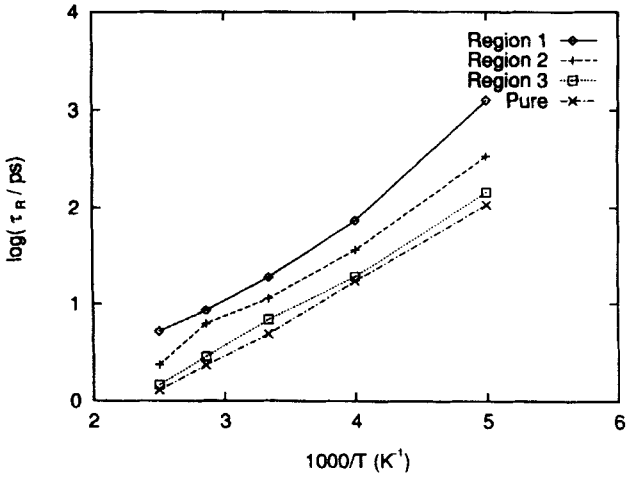
coefficient D was calculated from the mean-square displacement (MSD). The orientational relaxation time τ_R was calculated from the orientational autocorrelation function

$$C_R(t) = \frac{\langle \mu(t) \cdot \mu(0) \rangle}{\langle \mu(0) \cdot \mu(0) \rangle} \tag{6}$$

where $\mu(t)$ is the dipole vector of a water molecule. At the time region shorter than 0.1 ps, rapid relaxation which is caused by the libration of the molecule is observed in



a



b

Figure 10 Arrhenius plots of (a) diffusion coefficients D and (b) orientational relaxation time τ_R of water in the aqueous PNiPAM solution.

$C_R(t)$. At the time regions longer than 0.5 ps, the single exponential decay is observed. The orientational relaxation time τ_R was calculated by fitting the decay of $C_R(t)$ to the exponential function

$$C_R(t) = A \exp\left(-\frac{t}{\tau_R}\right) \tag{7}$$

Figure 10a and 10b show the Arrhenius plots of D and τ_R, respectively, for water in the aqueous PNiPAM solution. The plots are linear in all the regions. The diffusion coefficient and relaxation time in the region 3 are almost the same as in pure water. In the region 1 and 2, the motions of water molecules are highly suppressed by the presence of polymer chains. The motions are suppressed more highly in the region 1 than in the region 2. The same tendency is observed for the aqueous PVME solution. For the aqueous PVA solution, however, no marked difference is observed between the value in the hydrophilic region and that in the hydrophobic region.

The value of τ_R becomes large around the hydrophobic groups because the structuralization of water is promoted in the region 2. The value of τ_R also becomes large around the hydrophilic groups because the motion of water molecules is constrained by the water-polymer hydrogen-bonds. An uncontinuous change is expected in the temperature dependence of τ_R around the phase transition temperature. In this study, however, it could not be observed. Further studies should be carried out to elucidate the phenomena.

4 CONCLUSION

MD simulations are performed for the aqueous solutions of PVA, PVME, and PNiPAM. The distributions and dynamics of hydrogen-bonds, the translational diffusion of water, and the orientational relaxation of water are analyzed. The water molecules around the polymer chains are highly hindered by the chains. The orientational relaxation time τ_R of water becomes long because of the hydrogen-bonds between water and polymers around the hydrophilic groups and because of the structuralization of water around the hydrophobic groups.

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