Dispersion Polymerization of *N*-Vinylformamide in Polar Media. Preparation of Monodisperse Hydrophilic Polymer Particles

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ABSTRACT: Dispersion polymerization of *N*-vinylformamide (NVF) in polar media has been performed using poly(2-ethyl-2-oxazoline) as stabilizer. The polymerization in methanol gave micron-size monodisperse particles of highly hydrophilic polymers. Particle size increased as the stabilizer concentration decreased. Effects of the monomer concentration and the solvent composition upon the particle size and size distribution have been examined. The polymerization in the presence of a divinyl compound afforded crosslinking polymer particles. In using a hydrophilic poly(2-methyl-2-oxazoline) macromonomer bearing polymerizable styryl group instead of poly(2-ethyl-2-oxazoline), monodisperse polymer particles in the sub-micron range were obtained. The macromonomer acted as a stabilizer as well as a comonomer. The substituent of the macromonomer affected the particle size.

KEY WORDS   *N*-Vinylformamide / Dispersion Polymerization / Poly(2-ethyl-2-oxazoline) / Poly(2-oxazoline) Macromonomer /

Monodisperse polymer particles in the micron range have much potential for novel functional beads in technical and biomedical fields. Several methodologies for preparation of such particles are known.[1,2] Among them, dispersion polymerization in polar media has been often used because of the varsatility and simplicity of process. So far, the dispersion polymerizations of hydrophobic monomers such as styrene (St) and methyl methacrylate (MMA) have been extensively investigated and the particle size can be controlled by changing polymerization parameters.[3-8]

Poly(vinylamine) (PVAm) is a polyamine possessing primary amino group directly linked to the backbone. PVAm is industrially employed as chelating and agglomerating agents and in laboratories often used as a prepolymer for preparation of functional

polymers. The first synthesis of PVAm has been achieved by polymerization of *N*-vinylphthalimide followed by treatment with hydrazine.[9] Recently, highly pure PVAm has been prepared with development of precursor synthesis; radical polymerization of *N*-vinylformamide (NVF) followed by acidic or basic hydrolysis afforded PVAm.[10,11] So far, polymerizability of NVF and functionalization of polymers based on NVF have not been reported. Very recently, we have succeeded in preparation of monodisperse PNVF particles by dispersion polymerization in methanol.[12] Among hydrophilic polymers examined for the stabilizer of the dispersion polymerization, poly(2-ethyl-2-oxazoline) (PEtOZO) and styryl-type poly(2-methyl-2-oxazoline) macromonomer **1a** were found to be effective as a stabilizer for preparation of monodisperse PNVF particles. The

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present paper describes comprehensive results of the dispersion polymerization of NVF in polar media using PEtOZO and poly(2-alkyl-2-oxazoline) macromonomers **1a—c** as stabilizer.
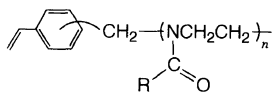
1a: R = Me, $M_w = 4800$
1b: R = Et, $M_w = 3500$
1c: R = iso-Pr, $M_w = 4200$

EXPERIMENTAL

Materials

NVF was supplied from Mitsubishi Kasei Co., Tokyo and purified by distillation. PEtOZO was purchased from Polyscience Co. Poly(2-alkyl-2-oxazoline) macromonomers were prepared according to the literature.[13] Other reagents and solvents were commercial products and purified in a usual manner.

Dispersion Polymerization of NVF

The polymerization was performed as follows; a mixture of NVF, stabilizer, and 2,2-azobis(2,4-dimethylvaleronitrile) in a solvent were heated at 56°C for 24 h under argon with shaking (150 shakings per. min). After removal of coagulum from the stable dispersion by filtration, the resulting particles were separated by centrifugation.

Measurements

Scanning electron micrographic (SEM) analysis was carried out on a Hitachi H-8010 electron microscope. Gel permeation chromatographic (GPC) analysis was performed by using a Toso SC8010 apparatus with a refractive-index (RI) detector under the following conditions: Gelpack GL-A130 column and chloroform eluent at a flow rate of 1.0 ml min^{-1}.

RESULTS AND DISCUSSION

Effect of Stabilizer Concentration on Particle Size

PEtOZO was reported to be an effective stabilizer for the preparation of micron-size monodisperse PSt or PMMA particles by dispersion polymerizations in polar media.[8,14,15] At first, the dispersion polymerization of NVF in methanol was performed by using PEtOZO as a stabilizer. In most cases, stable dispersion was obtained and the yield of the resulting particles was quantitative. The particles were analyzed by scanning electron micrograph (SEM).

The effect of PEtOZO concentration on the particle size and size distribution is shown in Figure 1. When the concentration was higher than 10 wt% for NVF, relatively monodisperse particles in micron range were obtained. The particle size decreased with increasing the stabilizer concentration, indicating that the stabilizer of higher concentration stabilized the particles more efficiently to produce smaller monodisperse polymer particles. In the concentration of 5 wt%, stable dispersion was not obtained and the size distribution became broader $(D_n = 1.51 \mu m,\ D_w/D_n = 1.22)$ (not shown in Figure 1), suggesting that monodisperse particles are not obtained in the NVF concentration of less than 5 wt%.
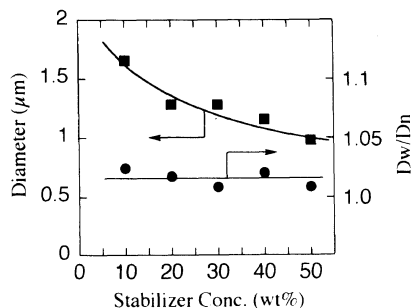

Figure 1. Effect of the concentration of PEtOZO on the size and size distribution of the particles prepared by using 10 wt% of NVF for the total in methanol.

Effect of Monomer Concentration

In case of dispersion polymerizations, the monomer concentration often affects the size and size distribution of the resulting particles since the monomer is a part of the initial solvent system. It was reported that the particle size increased as the monomer concentration increased and the size distribution becomes broader at high monomer concentration in the dispersion polymerization of hydrophobic monomers such as styrene and MMA in polar media.[7,8] This is due to the decrease of hydrophilicity of the solvent with increasing the concentration of the hydrophobic monomer.

Figure 2 shows the effect of NVF concentration on the size and size distribution of the particles. It is to be noted that relatively monodisperse particles of almost the same diameter were obtained between 10 wt% and 30 wt% of NVF concentration, which behavior was different from that of the dispersion polymerization of hydrophobic monomers in polar media.[7,8] This is probably because the hydrophilicity of NVF is similar to that of methanol, and hence, during the polymerization the hydrophilicity of the initial reaction system hardly changes in the range of the monomer concentrations examined.

Effect of Solvent

Control of the particle size and size distribution is readily achieved by changing the solvent composition in the dispersion polymerization of styrene.[3–7] In order to examine the solvent effect on the particle size, the polymerization was performed in various hydrophilic solvents, *i.e.*, ethanol, DMF, N-methylpyrrolidone, and ethylene glycol, and so on. In these solvents, polydisperse particles were obtained or no particle formation was observed.

Then, the dispersion polymerization in a mixed solvent containing methanol was investigated. The polymerization results in a mixed solvent between methanol and ethanol are shown in Figure 3. In all cases, a stable dispersion was obtained quantitatively. As the content of ethanol increased, the particle diameter decreased. Monodisperse particles were obtained by the polymerization in 25 and 50 wt% ethanol. In the mixed solvent containing 75 wt% ethanol, the size distribution became broader. The polymerization in methanol/N-methylpyrrolidone (70 : 30 wt%) gave monodisperse particles and their average size was smaller than that obtained by the polymerization in methanol ($D_n = 1.1$, $D_w/D_n = 1.01$). The polymerization in a mixture of methanol and DMF did not afford monodisperse particles.

Dispersion Polymerization in the Presence of Crosslinking Monomer

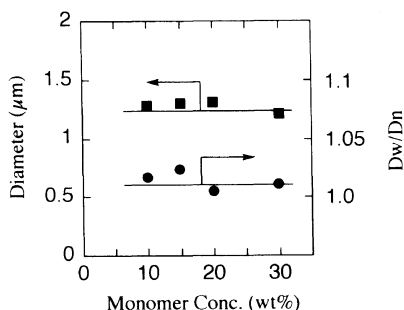Hydrogels possess high water-absorbability

Figure 2. Effect of the concentration of NVF for the total on the size and size distribution of the particles prepared by using 20 wt% of PEtOZO for NVF in methanol.
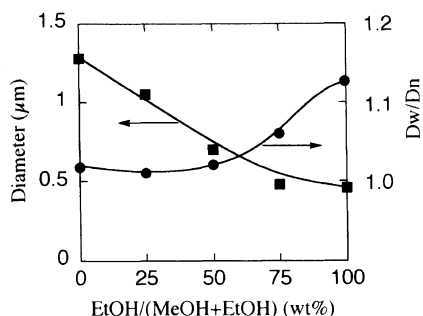

Figure 3. Effect of the solvent composition on the size and size distribution of the particles prepared by using 10 wt% of NVF for the total and 20 wt% of PEtOZO for NVF.

Table I. Dispersion polymerization of NVF in the presence of crosslinking monomer[a]

Entry	Crosslinking monomer[b]	Concn[c]	Yield	D_n[d]	D_w/D_n[d]
		wt%	%	μm	
1	MBAAm	0.5	95	0.62	1.05
2	MBAAm	1	98	0.51	1.02
3	MBAAm	3	98	0.57	1.03
4	MBAAm	5	98	0.72	1.05
5	EGDMA	0.5	96	1.37	1.02
6	EGDMA	1	92	1.38	1.02
7	EGDMA	3	92	1.34	1.04
8	DVB	1	100	0.94	1.12
9	DVB	3	92	0.48	1.29
10	—	—	95	1.28	1.02

[a] Dispersion polymerization of NVF with 10 wt% for the total amount using PEtOZO of 20 wt% for NVF in methanol.
[b] MBAAm, *N,N'*-methylenebisacrylamide; EDGMA, ethylene glycol dimethacrylate; DVB, divinylbenzene.
[c] Based on NVF.
[d] Determined by SEM.

and -preservability and are industrically utilized for various purposes. Recently, hydrogel microsphere containing mainly highly hydrophilic polymer was synthesized by a precipitation polymerization of acrylamide in the presence of *N,N'*-methylenebisacrylamide (MBAAm) and methacrylic acid.[16,17] This hydrogel microsphere has large surface area and is expected to broaden the applications of hydrogels.

The dispersion polymerization of NVF in the presence of crosslinking monomers was performed to produce novel hydrogel microsphere. The crosslinking monomers used were divinyl compounds; MBAAm, ethylene glycol dimethacrylate (EGDMA), and divinylbenzene (DVB). Polymerization results are shown in Table I. In all cases examined, the hydrogel microsphere was obtained quantitatively. The copolymerization of NVF with MBAAm and EGDMA afforded relatively monodisperse particles (entries 1—7). The diameter of the particles obtained by MBAAm was much smaller that without a crosslinking monomer (entries 1—4 and 10). On the other hand, the polymerization of NVF in the presence of EGDMA produced larger particles compar-

able with the polymerization without a crosslinking monomer (entries 5—7 and 10). In case of the polymerization using MBAAm or EGDMA, the effect of the concentration of the divinyl compound was small; the particle size was almost the same in the range of the concentration examined. Monodisperse hydrogel microsphere was not obtained by the polymerization in the presence of DVB (entries 8 and 9). This may be due to the difference of radical polymerizability between NVF and the crosslinking monomers.

Particle Growth

In order to investigate the mechanism of monodisperse PNVF particle formation in the present dispersion polymerization, instantaneous yield and size of the particles were measured by using 20 wt% of PEtOZO. Figure 4 shows time–polymer yield curve. The polymer yield gradually increased and after 8 h the yield was beyond 80%. The polymerization rate was larger than that of conventional solution polymerizations. In case of the dispersion polymerization of styrene in an aqueous ethanol solution or the dispersion polymerization of MMA in an aqueous
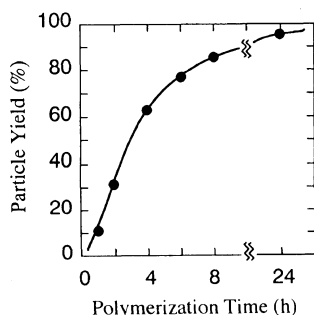
Figure 4. Time–particle yield curve in the dispersion polymerization using 10 wt% of NVF for the total and 20 wt% of PEtOZO for NVF in methanol.
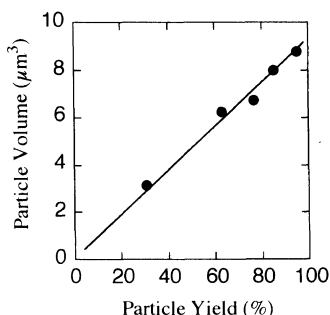

Figure 6. Effect of the substituent and concentration of macromonomer 1 in the dispersion copolymerization using 10 wt% of NVF for the total in methanol.

Figure 5. Relationships between particle yield and volume in the dispersion polymerization using 10 wt% of NVF for the total and 20 wt% of PEtOZO for NVF in methanol.

methanol solution, the polymerization was highly accelerated in the initial stage.[8,15] This would be due to the gel effect. On the other hand, such a behavior was not observed in the present polymerization.

The volume of the resulting particles increased linearly with the particle yield in the present system (Figure 5), indicating that the nucleation takes place at an early stage of the dispersion polymerization, followed by growth of the nuclei without formation of new particles to afford monodisperse polymer particles. This behavior was also observed in the dispersion polymerization of styrene or MMA in polar media.[3,18] Therefore, the formation mechanism for monodisperse PNVF particles is the same as that for hydrophobic polymer particles in the dispersion polymerization.
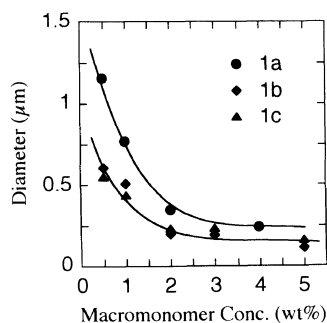
Dispersion Copolymerization with Poly(2-oxazoline) Macromonomer

Recently we have reported preparation of monodisperse polymer particles in micron range by a dispersion copolymerization of MMA or styrene with hydrophilic poly(2-oxazoline) macromonomer.[18–20] The macromonomer acted as a stabilizer as well as a comonomer, and hence, the stabilizer chains were chemically fixed on the particle size. Therefore, the concentration of the macromonomer, necessary for the preparation of monodisperse particles, was much lower than that of a homopolymer-type stabilizer. In this study, hydrophilic poly(2-alkyl-2-oxazoline) macromonomers 1a—c bearing a polymerizable styryl group were employed as a stabilizer of the dispersion polymerization.

Figure 6 shows effects of substituent of poly(2-oxazoline) in 1 and the concentration of 1 upon the particle size. As the concentration of 1 increased, the particle diameter decreased. When the same concentration of the macromonomer was used, the size of the particles prepared by using 1a was larger than that by 1b or 1c, and the diameter of the particles by 1b was almost the same as that by 1c. In the range of 1a concentration from 0.5 to 2 wt%, monodisperse particles ($D_w/D_n = 1.01$—1.03) were obtained. As shown in Figure 1, more than 10 wt% of homopolymer-type stabilizer is necessary for the preparation of such

particles. On the other hand, a very small concentration is enough to produce monodisperse PNVF particles in the present dispersion copolymerization system. These data indicate that the macromonomer acted as a very efficient stabilizer. However, the dispersion copolymerization using **1b** or **1c** gave polydisperse particles $(D_w/D_n = 1.05$—1.20) in the sub-micron range. A poly(2-alkyl-2-oxazoline) is well known to become hydrophilic or hydrophobic by changing the alkyl group.[21] Among the macromonomers used in this study, **1a** is more hydrophilic than **1b** and **1c**. These data imply that a higher hydrophilic macromonomer stabilizes polymer particles more effectively to produce particles with narrower dispersity. A similar phenomenon is observed in the dispersion copolymerization of MMA with poly(2-oxazoline) macromonomer **1**.[18]

CONCLUSION

The dispersion polymerization of NVF in polar media using PEtOZO as stabilizer produced highly hydrophilic polymer particles in the micron range with narrow size distribution. Particle size was controlled by changing polymerization parameters, the concentration of stabilizer and the solvent composition. The dispersion copolymerization with poly(2-methyl-2-oxazoline) macromonomer also monodisperse particles. The concentration necessary for the preparation of such particles was much lower than that by using PEtOZO stabilizer.

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