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Temperature Sensitive Gels as Size Selective Absorbants

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ABSTRACT

We have used crosslinked polymer gels as extraction solvents for aqueous solutions. The gels swell to many times their dry weight by absorbing water and low molecular weight solutes, but excluding proteins and other high molecular weight solutes. The swollen gel is removed by filtration. When it is slightly warmed, it collapses, releasing most of the absorbed material. This sudden change of swelling with temperature occurs because the gel is near a critical point. After the gel is separated from the desorbed water by filtration, it is cooled and then can be reused.

INTRODUCTION

A wide variety of separation techniques are applied in the chemical industry. However, when dealing with dilute aqueous solutions of organic or biological materials, such as proteins, the existing technology is expensive and limited to small scale use.

We have overcome this by synthesizing crosslinked polymer gels which can be used as extractions solvents. The process relies on two facts: first, that these gels can absorb many times their weight in water, excluding high molecular weight solutes, such as proteins; and second, that the gels swelling characteristics are a violent function of temperature, so they can be easily regenerated and reused.

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A simplified diagram of our new process is seen in Fig. 1. Small gel beads are added to a solution of macromolecules. These beads swell, absorbing many times their weight in solvent, but excluding solute. The raffinate, now a more concentrated solution, is separated from the swollen gel by filtration. The swollen gel is now regenerated by a slight increase in temperature, which collapses the gel, releasing the absorbed solvent. This collapsed gel, after being separated from the extract, is ready to be used again.

Similar processes with gels which are not reused or with materials whose regeneration costs are prohibitive, like silica gel, have been periodically suggested (Flodin et al. (1), 1960; Jacobson and Branton, 1977 (2); Anderson et al., 1979 (3); Vartak et al., 1983 (4)). Gels whose swelling varies abruptly with temperature have also been described (Ilavsky et al., 1982 (5); Hirokawa and Tanaka, 1984 (6)). Our process combines these features.

This paper discusses the various aspects involved in this new separation technique. After describing the gel synthesis, we will focus our attention on the two major points upon which this process relies: the gels' swelling and their selectivity.

EXPERIMENTAL

Gel synthesis. We have synthesized two different gels, the first being a copolymer of N,N-diethylacrylamide and sodium methacrylate, and the second, poly(N-isopropylacrylamide). The copolymer of N,N-diethylacrylamide and sodium methacrylate was prepared from 100cm^3 of a mixture which contained 8cm^3 of the monomer N,N-diethylacrylamide, 0.40g of the crosslinking agent N,N'-methylenebisacrylamide, 1.94cm^3 of a 0.96M solution of sodium methacrylate, 0.02g of ammonium persulfate and 0.02g of sodium metabisulfite. The poly(N-isopropylacrylamide) was obtained by adding 8g of the monomer N-isopropylacrylamide, 0.100g of the crosslinking agent N,N'-methylenebisacrylamide, 0.005g of ammonium

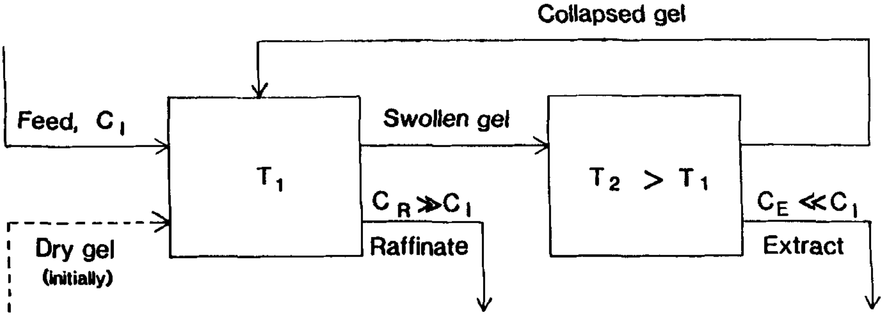

Fig. 1. Diagram of a temperature-sensitive gel extraction process.

persulfate and 0.005g of sodium metabisulfite in enough water to make $100cm^3$ of solution. Both synthesis were carried out in oxygen-free atmosphere, and further details are given elsewhere (Freitas and Cussler, 1986 (7); Ilavsky et al., 1982 (5)). After preparation, the gels were cut into 1mm pieces and dried in a vacuum oven.

Swelling experiments. We are interested in answering, basically two questions about swelling: 1) How much can the gels swell in aqueous solution or, in other words, how many times can they absorb their weight in water? 2) How much is the change in swelling at different temperatures?

In order to answer the first question, we placed dry gel in a known volume of water at a given temperature. We separated the swollen gel from the solution using a stainless steel screen attached to a rod. The swollen gel was then weighed.

In order to answer the second question, we placed a dry sample of gel with known weight (0.2 - 1.0g) in a $250cm^3$ graduated cylinder, adding aqueous solution at pH = 7.5, sealing, immersing the cylinder in a bath, and varying the temperature of the bath in a range that covered temperatures from 8°C to 80°C for the N,N-diethylacrylamide/sodium methacrylate gel, and from 8°C to 36°C for the N-isopropylacrylamide. The volume of the gel swollen to equilibrium was read at each temperature with a cathetometer.

Separation experiments. Gel separation experiments used the following solutes: vitamin B-12 (Sigma), polystyrene latex (Polysciences), polyethylene glycols with different molecular weights (Aldrich), polyethylene oxide (Polysciences), blue dextran (Sigma), ovalbumin (Sigma), gelatin (G-7, Fisher), sodium pentachlorophenolate prepared by mixing stoichiometric amounts of sodium hydroxide (Fisher) and pentachlorophenol (Sigma), and a solution of monoclonal antibodies in normal growth media.

The general procedure was similar to the one used to study gel swelling. Dry gel with known weight was put in a solution with known concentration in a graduated cylinder. The gel-solution mixture was stirred for 30 minutes on a wrist action shaker or by nitrogen sparging. The gel, now swollen, was separated from the raffinate using the steel screen, and both gel and raffinate were weighed. The gel was then collapsed by warming, and the extract was separated. The weights of the collapsed gel and of the extract were measured, as well as the concentrations of both the raffinate and extract.

The methods used for the analysis of the solutions were spectrophotometry using a Perkin-Elmer model 139 (vitamin B-12, blue dextran and sodium pentachlorophenolate), refractometry using a Brice-Phoenix differential refractometer (polyethylene glycols, polyethylene oxide and ovalbumin), evaporation to dryness (polystyrene latices and gelatin), and enzyme linked immunosorbant assay (monoclonal antibody). Details are given elsewhere (Gehrke, 1986 (8); Freitas, 1986 (9)).

Poly(N-isopropylacrylamide) gels with different amounts of crosslinking were synthesized and, following the same procedure

TABLE I

Degree of swelling, $X^{(a)}$, at 25 °C (aqueous solution, pH = 7.5)

Gel	Dry gel weight, g	Swollen gell weight, g	X
N,N-diethylacrylamide/ sodium methacrylate	0.581	30.056	51.7
	0.947	49.246	52.0
	1.243	65.719	52.9
Poly(N-isopropylacrylamide)	0.234	7.122	30.4
	0.728	22.323	30.7
	1.502	44.761	29.8

(a) $x = \dfrac{\text{mass of swollen gel}}{\text{mass of dry gel}}$

described above, they were used to concentrate solutions of vitamin B-12 and polyethylene glycol 3,400.

RESULTS AND DISCUSSION

Gel swelling. The results in Table I show that at 25°C, the copolymer of N,N-diethylacrylamide and sodium methacrylate absorbs water to approximately fifty times its dry weight while the poly(N-isopropylacrylamide) gel absorbs to about thirty times its dry weight. Moreover, the degree of swelling is independent of the initial mass of gel.

Figures 2 and 3 show the variation of gel volume with temperature for the poly(N-isopropylacrylamide) and for the copolymer of N, N-diethylacrylamide and sodium methacrylate, respectively. In both figures, V is the volume of the swollen gel, and Vo is the volume of the dry gel. Both gels shrink as temperature increases. The poly(N-isopropylacrylamide) gel collapses by a factor of about ten, from 25°C to 35°C, half of this collapse taking place within a 0.2°C range or, between 33.2°C and 33.4°C (cf. Fig. 2). The copolymer of N,N-diethylacrylamide and sodium methacrylate also shows a dramatic change in swelling with temperature, but at a lower rate than the isopropyl-based gel (cf. Fig. 3). We have not observed the discontinuity in swelling, reported by others, for this copolymer (Ilavsky et al., 1982 (5)).

The fact that these gels collapse with increasing temperature suggests that they behave as polymers with lower critical solution temperature (Malcolm and Rowlinson, 1957 (10); Dieu, 1954 (11)). Linear poly(N,N-diethylacrylamide) and linear poly(N-isopropyl-

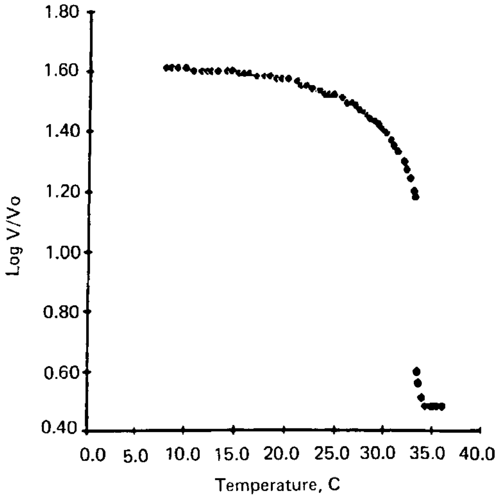

Fig. 2. Swelling of Poly (N-isopropylacrylamide) gel.

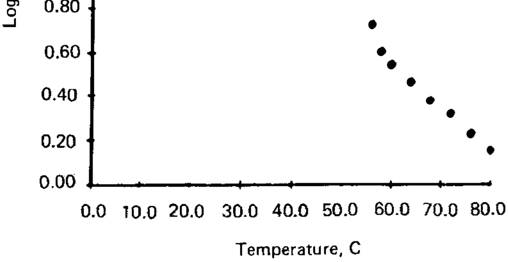

Fig. 3. Swelling of copolymer N,N-diethylacrylamice/sodium methacrylate gel.

acrylamide), readily soluble in water at low temperature, separate from solution at 29-30°C and 31°C, respectively (Ulbrich and Kopecek, 1979 (12); Heskins and Guillet, 1968 (13)). Such behavior indicates a high temperature dependence of the polymer-solvent interaction parameter χ, increasing with temperature. We believe that our systems behave in an analogous way, i.e., that χ increases with temperature.

Gel selectivity. Table II summarizes the results obtained from the extraction experiments. These results are expressed as an efficiency of gel extraction, η, which represents the degree to which a solute is excluded from the gel as water is absorbed. Thus, an efficiency of 100% means that the gel absorbs no solute: the solute is completely excluded from the gel.

The low separation efficiency obtained for urea and the high separation efficiency obtained for the blue dextran are consistent with the hypothesis that we are dealing with a size-selective separation process. The gel can be imagined to be a swollen mesh through which small solutes can freely move, while large solutes are excluded. Further evidence for this picture is given in Figures. 4 and 5. Figure 4 shows that, for a gel with a fixed amount of crosslinking, the separation efficiency gradually increases with solute molecular weight.

TABLE II

Selectivity of extractions using temperature sensitive gels.

		Gel Efficiencies, $\eta^{(a)}$	
Solute	Molecular Weight	Poly (N-iso) propylacrylamide	Copolymer of N,N-diethylacrylamide and sodium methacrylate
Urea	60	2	3
Sodium pentachlorophenolate	267	18	51
Vitamin B-12	1,355	32	15
Ovalbumin	45,000	97	84
Polyethylene oxide	600,000	96	89
Gelatin		98	97
Blue dextran	2,000,000	97	99
Polystyrene latex$^{(b)}$		95	96
Polyethylene glycol	400	10	5
	3,400	30	19
	8,000	56	25
	18,500	80	61
Monoclona antibody	160,000	88	-

(a) $\eta = 100 \times \dfrac{\text{measured concentration change}}{\text{that expected from gel volume change}}$

(b) This latex had a diameter of 0.06 μm

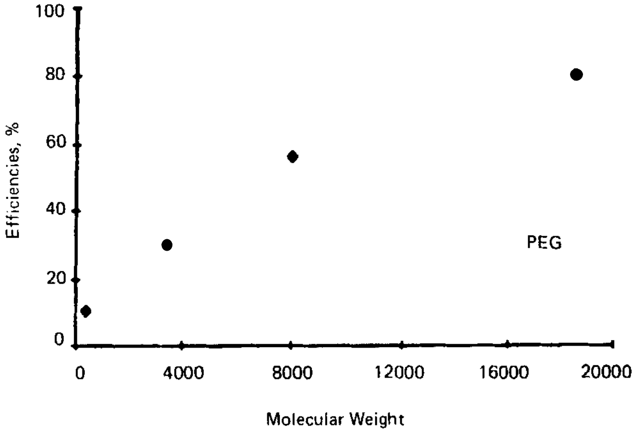

Fig. 4. Separation efficiency as a function of molecular weight.

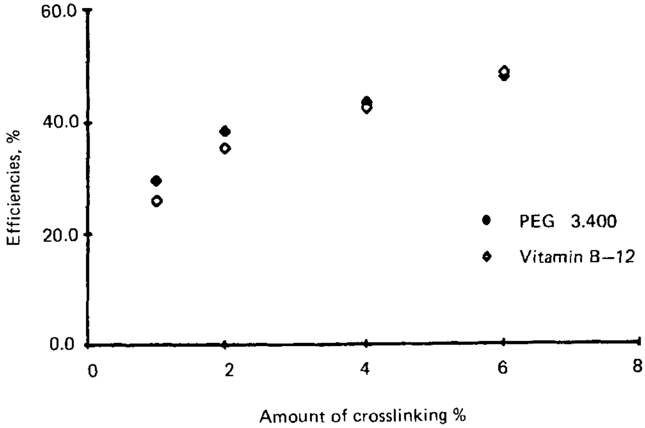

Fig. 5. Separation efficiency as a function of amount of crosslinking.

Figure 5 shows that, for a fixed solute molecular weight, the separation efficiency gradually increases with amount of crosslinking. In the first case, the size of the mesh is kept constant while the solute size increases, so more and more is excluded. In the second case, the solute size is kept constant while the mesh size decreases, so more and more solute is excluded.

We believe that large solutes like polyethylene oxide are completely excluded by the gels. The fact that the results obtained for separation efficiencies are, in some cases, much lower than the 100% expected for complete exclusion, can be attributed to the entrainment of small amounts of raffinate between the gel particles. A more complete discussion of this problem is given elsewhere (Freitas and Cussler, 1986 (7)).

If the gel is a polyelectrolyte, separations are also based on electrostatic charge. This is indicated by the results for sodium pentachlorophenolate shown in Table II. The separation efficiency for this salt is much higher when using the ionic copolymer of N,N-diethylacrylamide and sodium methacrylate (51%), than when using the non-ionic Poly(N-isopropylacrylamide) (18%).

CONCLUSION

We have developed crosslinked polymer gels that can be used as extraction solvents. These gels absorb small solutes and exclude large ones. Their selectivity, which is primarily based on size, can be improved by changing the number of crosslinks in the network. Because the gels are close to a lower consolute point, they can be easily regenerated by a slight increase in temperature.

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