

Compressed Fluid Sedimentation Polymerization

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In this paper, we report the synthesis of uniform, spherical cross-linked polymer beads by sedimentation polymerization¹ in compressed fluid solvents. Supercritical fluid (SCF) solvents have provoked much interest recently in the area of polymer synthesis.² The prevention of environmental pollution is high on the global agenda, and the development of sustainable solvent alternatives such as SCFs is an important challenge both for academia and for industry.³ The unique physical properties associated with SCFs are (i) adjustment of density (and other physical properties) by changing temperature and pressure, (ii) low viscosity and high solute diffusivity, (iii) zero surface tension, and (iv) ease of solvent separation. The most widely used SCF is supercritical carbon dioxide (scCO₂).⁴ CO₂ is nontoxic and nonflammable and is widely available from a number of inexpensive, high-purity sources. We have reported the synthesis of cross-linked polymer microspheres,⁵ macroporous polymer monoliths,⁶ porous polymer beads,⁷ and emulsion-templated polymer materials,⁸ using either CO₂^{5,6} or mixtures of CO₂ and water.^{7,8} No organic solvents were involved in any of these processes.^{5–8} We have also investigated other compressed fluid solvents, such as 1,1,1,2-tetrafluoroethane (R134a), as solvents for dispersion polymerization at much lower pressures than are possible with CO₂.⁹ Like CO₂, R134a ($T_c = 101.1\text{ }^\circ\text{C}$, $P_c = 40.6\text{ bar}$) is nontoxic and nonflammable and has zero ozone depletion potential.¹⁰

Cross-linked polymer beads in the size range 50 nm–2 mm have been used for biomedical applications, as solid supports for combinatorial chemistry, as catalyst supports, and for chromatography.¹¹ Micron-sized beads are typically prepared by emulsion polymerization, dispersion polymerization, or suspension polymerization.¹² The particle size achieved by suspension polymerization¹³ is typically in the range 50–2000 μm , and the size distribution is usually quite broad (15–60%), although it is possible to form (smaller) monodisperse beads by the more sophisticated technique of “staged-templated suspension polymerization”.¹⁴ Larger polymer beads (diameters >250 μm) are often convenient because they are simple to handle, can be easily separated by filtration, and are useful in a range of applications. However, it is very difficult to prepare large beads with uniform size distributions by suspension polymerization.

The method of “sedimentation polymerization” was introduced by Ruckenstein and co-workers.¹ In this approach, droplets of an aqueous monomer solution are allowed to sediment through a heated oil medium contained in a vertical reactor. The droplets are partially polymerized during the sedimentation process and allowed to polymerize completely at the bottom of the reactor. The bead size can be adjusted by changing the

nozzle diameter or the injection rate, and beads in the size range 0.5–2.5 mm were obtained with relatively narrow size distributions (5–35%).¹

More recently, we have adapted this process to produce monodisperse, highly porous, emulsion-templated polymer¹⁵ and silica beads¹⁶ by the process of “O/W/O sedimentation polymerization”. All of these approaches share a common disadvantage: oil (e.g., mineral oil) is used as the sedimentation medium which becomes contaminated with monomer, and a large volume of organic waste is produced. This problem is even greater in our O/W/O route because additional oil is used as the internal phase to produce the templated porosity in the beads.^{15,16} Moreover, the separation of the beads from the sedimentation medium is difficult, and a considerable volume of organic solvent is required to wash the beads at the end of the process, particularly in the case of the emulsion-templated materials.^{15,16}

We report here the use of compressed fluid solvents (e.g., CO₂ and R134a) for sedimentation polymerization. In this new approach, the use of oil as the sedimentation medium is completely avoided, thus greatly reducing the quantity of organic waste in the process and allowing simple separation and isolation of the products (i.e., the sedimentation medium can be removed by simple depressurization).

First, we prepared polymer beads by conventional sedimentation polymerization using a mixture of light and heavy mineral oil as the sedimentation medium. The acrylamide (AM)/*N,N'*-methylenebis(acrylamide) (MBAM)/ammonium persulfate (APS) system first reported by Ruckenstein¹ was studied in these preliminary experiments. (Safety note: acrylamide is highly toxic and should only be handled in an appropriate fume cupboard.) The aqueous solution of monomer and initiator was injected into the oil medium ($T = 90\text{ }^\circ\text{C}$) using a high-performance liquid chromatography (HPLC) pump. The partially gelled droplets were allowed to polymerize for 3 h (60 $^\circ\text{C}$) at the bottom of the column after sedimentation had occurred. After filtering and washing, uniform spherical beads were obtained with a mean diameter of 1.93 mm and a standard deviation in bead diameter of 3.0% (Figure 1a). Vegetable oil, which is less expensive, was also used as the sedimentation medium, and similar products were obtained. However, in both cases a large volume of contaminated waste oil and organic solvent was produced per gram of polymer.

To carry out sedimentation polymerization using compressed fluids, a custom-built high-pressure sedimentation reactor was developed, as shown schematically in Figure 2. The main body of the apparatus consisted of a stainless steel sedimentation column and a collection vessel. The aqueous monomer solution was injected into the compressed fluid using an HPLC pump. The sedimentation column was equipped with view windows and a simple CCD system in order that the sedimentation process could be observed.

The density (and viscosity) of the sedimentation medium are important considerations since these parameters determine whether, and how fast, sedimentation will occur. For SCFs, the density can be adjusted by changing the pressure and/or the temperature. This is also true, albeit to a lesser extent, for compressed fluid

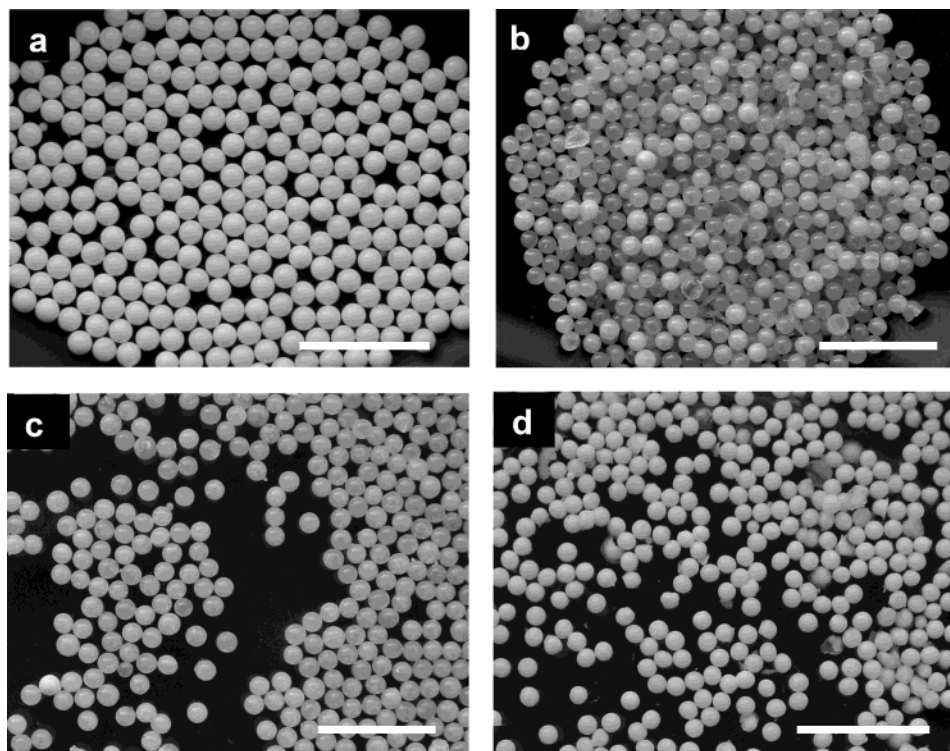


Figure 1. Optical images of cross-linked poly(acrylamide) beads prepared by sedimentation polymerization (scale bar = 10 mm in all images). (a) Beads prepared by sedimentation polymerization in mineral oil; average diameter = 1.93 mm; standard deviation in diameter = 3.0%. (b) Beads prepared by sedimentation polymerization in liquid R134a (entry 2); average diameter = 1.54 mm; standard deviation in diameter = 5.4%. (c) Beads prepared by sedimentation polymerization in a mixture of heptane and R134a (25% v/v heptane, entry 4); average diameter = 1.60 mm; standard deviation in diameter = 5.3%. (d) Beads prepared by sedimentation polymerization in a mixture of R134a and CO₂ (entry 9); average diameter = 1.45 mm; standard deviation in diameter = 3.5%.

solvents below the critical temperature. The density of the aqueous monomer solution was approximately 1.0 g/cm³. For CO₂, the highest density that can be achieved in the reaction temperature range 60–90 °C is approximately 0.8 g/cm³. This CO₂ density can only be achieved at rather high pressures (350–450 bar), which contributes to operating costs and energy consumption. Even under these high-pressure conditions, the aqueous monomer droplets were found to sediment far too rapidly through the CO₂ to form individual polymer beads (i.e., the residence time in the column was too short). This was because the viscosity of scCO₂ was very low and also because the density difference between the CO₂ phase and the aqueous phase was too great. In principle, the residence time for a given CO₂ density could be increased by using a longer sedimentation column (i.e., >600 mm), but this was not attempted in these preliminary experiments.

Liquid R134a was evaluated as the sedimentation medium because it is considerably denser at much lower operating pressures.^{9,10} At a polymerization temperature of 90 °C,¹ it was found that the injection nozzle became hot, even though the nozzle was water-cooled (Figure 2), presumably because of heat transport through the R134a vapor. As such, the monomer solution was observed to partially polymerize in the injection nozzle before injection, and only a small fraction of injected monomer solution was collected as beads (Table 1, entry 1).

By adding a quantity of *N,N,N,N*-tetramethylethylenediamine (TMEDA) to the R134a sedimentation medium as a redox co-initiator, it was possible to carry out the sedimentation polymerization at somewhat

lower temperatures (entries 2 and 3).¹⁵ An improved yield of spherical polymer beads was obtained under these conditions (Figure 1b), but there were still problems associated with partial polymerization in the injection nozzle due to the relatively high temperatures used in these reactions.

It was not possible to decrease the reaction temperature much below 80 °C because the density of liquid R134a at that temperature is close to 1.0 g/cm³ (i.e., the aqueous monomer droplets will no longer sink in the sedimentation medium). As such, it was necessary to reduce the density of the R134a sedimentation medium in order to reduce the reaction temperature. First, we mixed heptane (density at 25 °C = 0.68 g/cm³) with the R134a phase (entry 4). This led to an increased yield of spherical beads (Figure 1c) and gave rise to efficient and uniform droplet sedimentation, but this approach has the disadvantage of reintroducing an organic solvent into the process.

CO₂-expanded organic solvents have been used previously in chemical synthesis.¹⁷ We employed CO₂-expanded R134a for sedimentation polymerization, thus avoiding the use of any volatile organic solvents. R134a is much more polar than CO₂ (dipole moment = 2.1 D), and it has a significantly higher liquid density.^{9,10} Thus, the density and polarity of the CO₂–R134a mixtures can be adjusted over a wide range.¹⁸

The phase behavior of CO₂ and R134a was investigated using a 10 cm³ high-pressure view cell. Liquid R134a was found to be miscible with liquid CO₂ at room temperature, at least up to a volumetric ratio of 4:1 CO₂:R134a. The view cell was charged with a fixed volume of R134a (4.3 cm³) at room temperature and

Table 1. Experimental Conditions and Product Characterization for Poly(acrylamide) Beads Produced by Compressed Fluid Sedimentation Polymerization^a

	<i>T</i> (°C) ^b		TMEDA (cm ³)	R134a ^c (cm ³)	CO ₂ ^d (bar)	yield ^e (%)	bead diameter ^f		absolute density ^g (g/cm ³)
	upper	lower					diameter (mm)	s.d. (%)	
1	90	75	0	222		<40	1.34	6.0	1.33
2	90	83	8	200		~50	1.54	5.4	1.20
3	85	80	10	200		<50	1.69	8.0	1.19
4 ^h	85	80	10	152	<i>h</i>	~60	1.60	5.3	1.19
5 ⁱ	60	60	25	160	27 ⁱ	76	1.77	4.3	1.30
6	65	65	35	160	34	80	1.73	3.7	1.24
7	65	68	50	160	31	68	1.78	5.2	1.25
8	63	65	20	185	41	59	1.89	2.5	1.22
9	65	65	20	186	34	84	1.45	3.5	1.23
10	65	65	30	184	31	72	1.68	3.6	1.25

^a The concentration of the monomer solution was 31 wt % with AM:MBAM = 1:4.6 w/w. APS solution (0.25 cm³, 10% w/v) was added to 35 cm³ of the monomer solution. All injections were carried out using an HPLC pump at an injection rate of 0.6 cm³/min through a stainless steel nozzle with an internal bore diameter of 0.88 mm. ^b The sedimentation column and the collection vessel were heated independently to allow two different temperature zones (upper and lower, see Figure 2). ^c Volume of R134a as added from an Isco syringe pump (which was maintained at 10 bar and 4 °C). ^d CO₂ added at 55 °C, pressure value indicates the total pressure. ^e Isolated yield after sieving products through a 2 mm mesh sieve to remove any agglomerates. ^f Calculated by measuring > 100 bead diameters, s.d. = standard deviation. ^g Measured using helium pycnometry. ^h 50 cm³ heptane added to R134a. ⁱ CO₂ was added at 45 °C.

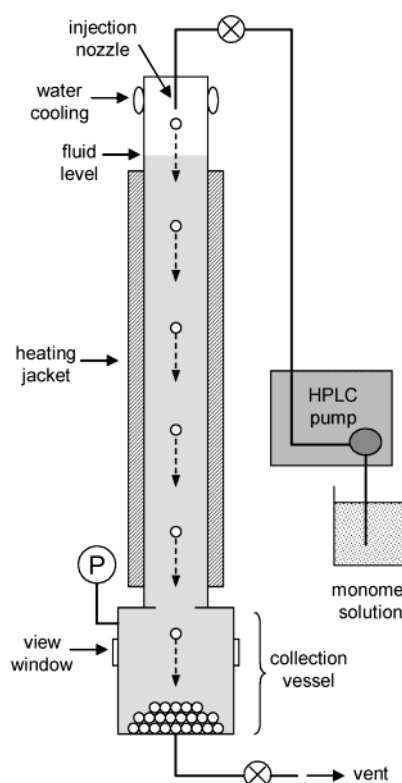


Figure 2. Schematic representation of high-pressure sedimentation polymerization reactor. Collection vessel was heated using heating cartridge inserts. The height of the sedimentation column was 600 mm, and the internal diameter was 25 mm. The total reactor volume including the collection vessel was 380 cm³.

then heated to 55 °C. Upon heating, the R134a liquid volume decreased to 3.3 cm³. CO₂ was then slowly added to the view cell, and the change in liquid volume was recorded as a function of the total pressure. Figure 3 shows the volumetric expansion ratio, $(V - V_0)/V_0$, as a function of the total pressure at 55 °C. The liquid volume increased quite sharply as the CO₂ was added, and it was found that the volume of the liquid could be doubled at a total pressure of around 60 bar. As such, it was possible to “fine-tune” the R134a density over a wide range by expansion with CO₂, without increasing the pressure very dramatically (i.e., the total pressure

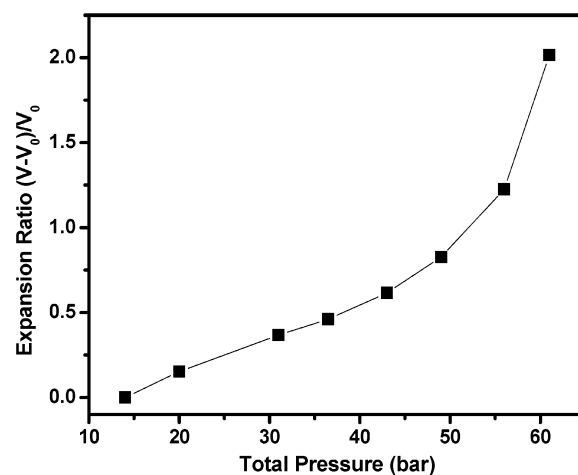


Figure 3. Volume expansion ratio of liquid R134a/CO₂ mixtures as a function of the total pressure at 55 °C.

of the compressed fluid mixture was less than a fifth of the pressure in the case of neat scCO₂).

A series of sedimentation polymerization reactions was carried out using mixtures of R134a and CO₂ as the sedimentation medium (entries 5–10). R134a and the redox co-initiator (TMEDA) were added to the reactor first, which was then heated to 55 °C. When the temperature had stabilized, CO₂ was added to achieve the desired total pressure. The system was then heated to the desired reaction temperature (Table 1). Three reactions were carried out under similar conditions but with varying concentrations of the redox co-initiator, TMEDA (entries 5–7). The aim of these experiments was to accelerate the gelation process at reduced temperatures and to increase the yield of the beads and the bead uniformity. Under these conditions, the aqueous monomer droplets were observed to sediment through the mixed compressed fluid medium at a reasonable rate (sedimentation time less than 10 s). The isolated yield of the beads was significantly improved in the presence of TMEDA. Neither the bead yield nor the uniformity of the beads improved much when the TMEDA volume was increased above 25 cm³, and it is possible that the rate of initiation reaches a plateau at around this TMEDA concentration, perhaps due to diffusion limits.

It was noticed that the height between the injection nozzle and the level of compressed fluid medium was

an important factor that affected the sedimentation process. For the sample prepared in entry 8, 185 cm³ of R134a was added (20 cm³ TMEDA), and then CO₂ was added to a total pressure of 41.4 bar. Although the standard deviation in bead diameter was low, the isolated yield of beads was also quite poor. Again, this was attributed to partial polymerization in the injection nozzle caused by the proximity of the hot sedimentation medium to the nozzle tip. When the amount of CO₂ was reduced (total pressure = 34.5 bar, entry 9), the isolated yield of beads was increased to 84% (Figure 1d).

The cross-linked polymer beads had skeletal densities, as measured by helium pycnometry, in the range 1.20–1.30 g/cm³, as listed in Table 1. The beads were found not to contain any permanent “dry porosity”, as confirmed by BET surface area measurements (<5 m²/g) and by scanning electronic microscopy (SEM). Similar observations were made for cross-linked poly(acrylamide) materials produced by templating of high internal phase CO₂-in-water (C/W) emulsions.⁸

In conclusion, we have prepared uniformly large polymer beads by sedimentation polymerization using compressed R134a or mixtures of R134a and CO₂ as the sedimentation medium. A high-pressure sedimentation reactor was developed, and polymer beads were produced with mean diameters in the range 1.3–1.9 mm and with standard deviations in the average bead diameter as low as 2.5%. At this stage, the control over bead size and morphology in this process is not quite as good as that achieved using hot oil as the sedimentation medium (see e.g., Figure 1a), but we believe that this is due to minor technical issues (e.g., distance of nozzle from fluid–vapor interface, temperature control, height of sedimentation column) that will be overcome in future studies. We will also investigate methods for controlling the size of the beads; for example, the average bead diameter might be reduced by decreasing the nozzle diameter and increasing the injection rate¹ or by spraying the monomer solution through a porous frit.

Our preliminary work has focused on acrylamide as the monomer, but it is anticipated that the system could be extended to a range of other water-soluble monomers (e.g., hydroxyethyl acrylate, acrylic acid) as we have shown in the case of O/W/O sedimentation using a conventional oil-based sedimentation medium.¹⁵ In principle, the process can be scaled up (e.g., larger columns, multiple injection nozzles, methods for separating the beads, etc.) to allow the production of more significant quantities of material in a semicontinuous manner, as proposed by DeSimone and co-workers for the precipitation polymerization of fluorinated monomers in scCO₂.¹⁹ Again, low operating pressures are advantageous when considering potential scale-up.

To summarize, the four main benefits of this process are (i) the ease of product separation and the large reduction in the volume of organic waste produced, (ii) the uniformity of the beads, (iii) the fact that the sedimentation medium density can be “fine-tuned” with pressure, and (iv) the relatively low pressures involved (≤50 bar). We anticipate that the use of redox co-initiation, in combination with a longer sedimentation column, will allow us in the future to carry out sedimentation polymerization in pure liquid CO₂ at ambient temperatures and modest pressures (<70 bar). A longer-

term goal is to extend this approach to the VOC-free production of porous polymer beads by the sedimentation polymerization of SCF-in-water emulsions^{8,20} (i.e., SCF-in-water-in-SCF sedimentation polymerization).¹⁵

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