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Colloid-Enhanced Ultrafiltration of Chlorophenols in Wastewater: Part V. Simultaneous Removal of a Chlorophenol and a Metal Ion

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Abstract: Polyelectrolyte micellar-enhanced ultrafiltration (PE-MEUF) is a separation process to remove target solutes from water using a mixture of a surfactant and an oppositely charged polyelectrolyte as a colloid. An organic solute and a metal cation can simultaneously associate with the colloid, which is subsequently ultrafiltered from solution. An organic solute solubilizes in the surfactant micelle-like aggregates whereas an inorganic cation binds onto the oppositely charged polyion chains. The solution is then passed through the membrane having pore sizes small enough to block the passage of the surfactant-polymer aggregates. In this work, PE-MEUF has been applied to mixtures containing dichlorophenol (DCP) and magnesium ion (Mg^{2+}), using cetylpyridinium chloride (CPC) and sodium poly(styrenesulfonate) (PSS) mixtures. It was observed that the presence of Mg^{2+} does not affect DCP rejection. The [CPC] to [PSS] ratio and colloid concentration have a significant effect on both DCP and Mg^{2+} rejections. Increased ionic strength from added salt increases the gel point (colloid concentration at which flux is zero). The viscosity of the colloid solution is inversely related to the gel point.

Keywords: Colloid-enhanced ultrafiltration, metal removal, surfactant-polymer interaction, viscosity, gel point

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INTRODUCTION

Wastewater streams containing dissolved organics are a common problem in the chemical industry. For example, highly toxic and persistent chlorinated phenolic compounds are formed during pulp bleaching when chlorine and chlorine derivatives are used and can be found in wastewater from pulp and paper mills. Nonprocess elements (NPEs) such as Mg^{2+} and Cu^{2+} are also found from pulping operations. These organic compounds and the NPEs must be removed before the water can be discharged to the environment or reused in the process. However, ordinary ultrafiltration is ineffective in the removal of these low molecular weight compounds which simply pass through even small pore membranes.

Colloid-enhanced ultrafiltration (CEUF) methods are novel separation processes for removing organic solutes or multivalent ions from aqueous streams. A comprehensive discussion of CEUF processes was cited in a previous paper (1). Micellar-enhanced ultrafiltration (MEUF) is one technique in which a micellar solution is added to a contaminated feed solution. Polyelectrolyte micellar-enhanced ultrafiltration (PE-MEUF) is a modified MEUF technique where a surfactant-polymer mixture is used as the colloid solution. This solution is then passed through a membrane, which has pores small enough to block the passage of micelles or surfactant-polymer complexes, removing the surfactant aggregates and solubilized organic solute. The permeate contains very low concentrations of organic solute and surfactant, and it can be discharged or recycled. The retentate contains very high concentrations of both solute and surfactant and has a much lower volume than the original process stream.

In previous papers (2–6), we have shown that the concentration of solute in the permeate (solution passing through the membrane) is approximately that expected if the system were at equilibrium; i.e., the permeate concentration is equal to the unsolubilized solute concentration in the retentate. Therefore, equilibrium solubilization measurements such as equilibrium dialysis (ED) or semiequilibrium dialysis (SED) can be used to determine the process efficiency of MEUF and PE-MEUF. In this paper, polymer-surfactant systems are investigated; the polymer is almost completely rejected by the membrane, so is present in insignificant concentration in the permeate; therefore, no surfactant-polymer aggregate forms in the permeate, so these dialysis experiments are "equilibrium dialysis or ED" experiment. It should be noted that the equilibrium dialysis experiments in MEUF system are called "semiequilibrium dialysis or SED," as mentioned in Part III (7).

One of the most important advantages of PE-MEUF is the ability to simultaneously remove dissolved organics and multivalent ions as depicted in Fig. 1. The organic solute will solubilize in the micelles whereas the divalent metal cation will bind onto the anionic polyelectrolyte chain. Dunn et al. have demonstrated the simultaneous removal of dissolved organics and multivalent metal cations from wastewater using MEUF (8). They

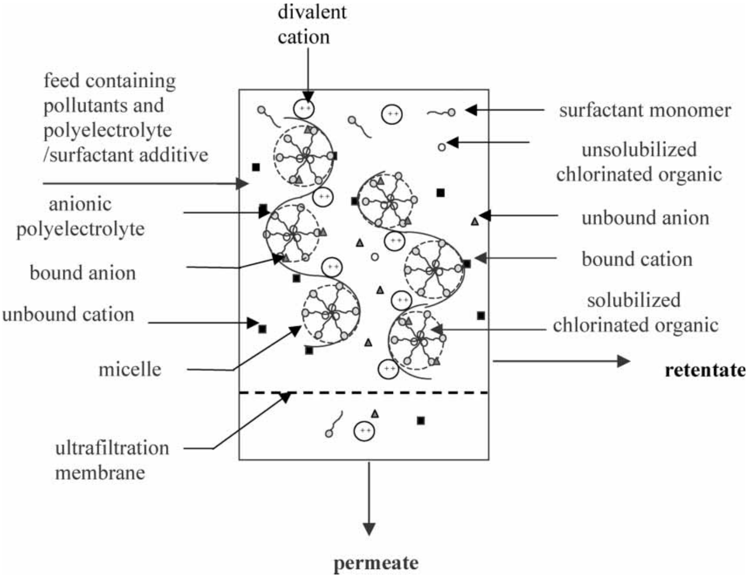

Figure 1. Schematic of polyelectrolyte micellar-enhanced ultrafiltration (PE-MEUF).

found that the presence of small concentrations of added multivalent counterions had no significant effect on rejection of the organic solutes and vice versa. A unique characteristic of PE-MEUF as opposed to MEUF is that the oppositely charged polyelectrolyte stabilizes the surfactant aggregate so the colloid is in equilibrium with a much lower surfactant monomer concentration, which results in the significant reduction in surfactant concentration in the permeate passing through the membrane or surfactant leakage (1, 9).

In Part I of this five-part series (1), we have performed an extensive series of both SED and ED experiments to investigate the solubilization of chlorophenols in micellar solutions and surfactant-polymer mixtures in the presence and absence of salt. It was found that surfactant micelles solubilize organic solutes better than surfactant-polymer complexes; however, high-solubilization constants were observed for both the micellar solutions and the surfactant-polymer mixtures, primarily for low water solubility solutes such as trichlorophenol (TCP) (1). In Part II of this series, distribution coefficient into the surfactant aggregate of the anionic species of a solute was found to be higher than that of the neutral species in micellar solutions; however, in the surfactant-polymer mixtures, the distribution coefficient of the neutral species is higher than that of the charged species (10). The added salt enhances the solubilization constant in the surfactant micelles, whereas it decreases the solubilization constant in surfactant-polymer complexes, as discussed in Part III (7). In Part IV, the surfactant leakage in MEUF was observed to be reduced by the addition of salt due to critical micelle concentration (CMC) reduction. However, in PE-MEUF, the surfactant leakage in the absence and presence of salt is not significantly different. This paper is a continuation of our previous work on using surfactant-polymer mixtures in the CEUF process. The primary purpose of this paper is to demonstrate the simultaneous removal of a chlorophenol and a divalent metal ion by using surfactant-polymer mixtures, and to use flux measurements to deduce the gel point for PE-MEUF at different salinities. Viscosity measurements help interpret the gel point results.

EXPERIMENTAL

Materials

Dichlorophenol (DCP) (99+% pure) was obtained from Aldrich Co. (Milwaukee, WI) and used without further purification. Magnesium chloride was obtained from Fisher Scientific (Fair Lawn, NJ) and was used as a target metal ion. High-quality (99+% pure) cetylpyridinium chloride (CPC) from Zeeland Chemical (Zeeland, MI) does not exhibit a minimum in a plot of surface tension vs. concentration, or show any impurities in HPLC chromatograms and was used as received. Poly (styrenesulfonate) (PSS) (100% pure), which has an average molecular weight of approximately 70,000 Daltons, was obtained from Alfa Aesar (Ward Hill, MA). The repeating unit of the polymer is $CH_2CH(C_6H_4)SO_3Na$. Lower molecular weight fractions were removed by using a spiral wound ultrafiltration unit as described in a previous paper (1). The final concentration of the purified polymer was measured by using a Total Organic Carbon analyzer or TOC (Rosemount DC-180). Water was doubly deionized and treated with activated carbon. Sodium hydroxide and hydrochloric acid solutions from Fisher Scientific (Fair Lawn, NJ) were used to adjust the pH of the solutions. Sodium chloride (certified ACS) from Fisher Scientific (Fair Lawn, NJ) is used as added salt.

Methods

A description of equilibrium dialysis or ED experiments was detailed in previous work (1). The ultrafiltration experiments were performed in a 400 mL stirred cell (Amicon 8400, Millipore) at 25°C and 414 kPa (60 psig) pressure using nitrogen gas. Spectrum 10,000 Da Molecular weight cut-off (MWCO) cellulose acetate membranes were used. A 300 mL solution of Mg^{2+}, DCP, and CPC-PSS mixture at pH 3 (only protonated or neutral DPC is present at this pH) was placed in the stirred cell wrapped with plastic tubing through which temperature-controlled water circulates to control the solution temperature to 25°C. The solution was stirred at a speed of approximately 800 rpm. The first 10 mL of permeate sample was discarded. Eight permeate samples of 25 mL each were collected, leaving approximately 90 mL of retentate solution. Fluxes were measured during the run by recording the time to accumulate each permeate sample. The concentration of the surfactant and the solute in the permeate was analyzed by using a Hewlett-Packard HP 8452A diode array spectrometer. Magnesium concentration was determined by using a Varian atomic absorption spectrophotometer (AA 30).

The viscosity was measured with a capillary viscometer (Wescan Viscometer Assembly) with optical system attached. The viscometer is connected to a viscosity timer (Model 221, Wescan) and immersed in a thermostated bath at 25°C ± 0.1°C. Flow times could be measured to the nearest 0.01 s. The volume of all samples in the viscometer was kept constant at 30 mL to control the hydrodynamic pressure. The flow time of water (reference) was approximately 400 s. The reduced kinematic viscosity of the sample was determined by using a simplification of Poiseuille's equation as follows

$$v_{sample} = v_{ref}\left(\frac{t_{sample}}{t_{ref}}\right) \tag{1}$$

where v_{sample} is the kinematic viscosity of a sample, v_{ref} is the kinematic viscosity of the reference liquid (water), and t_{sample} and t_{ref} are the flow times of the sample and the reference, respectively.

RESULTS AND DISCUSSION

Semiequilibrium Dialysis Experiments

The separation efficiency is expressed as a retentate-based rejection:

$$\text{Solute rejection (\%)} = (1 - \frac{C_{A,perm}}{C_{A,ret}}) * 100 \tag{2}$$

where $C_{A,perm}$ and $C_{A,ret}$ are the concentration of solute A in the permeate and the retentate solution, respectively.

The effect of Mg^{2+} concentration on Mg^{2+} and DCP rejections is shown in Fig. 2, and on surfactant leakage (permeate surfactant concentration) is shown in Fig. 3. The Mg^{2+} rejection decreases as Mg^{2+} concentration increases, whereas the Mg^{2+} concentration does not significantly influence DCP rejection and surfactant leakage; the DCP rejection and surfactant leakage are approximately 95% and 0.12 mM, respectively. The surfactant leakage is 10% of that in the absence of polymer (MEUF) under the same conditions, demonstrating a major advantage of PE-MEUF. For surfactant-polymer mixtures, the cationic metal binds onto the negatively charged polymer. At a given colloid concentration, polymer adsorption sites per target ion decrease as metal concentration increases, resulting in a lowered

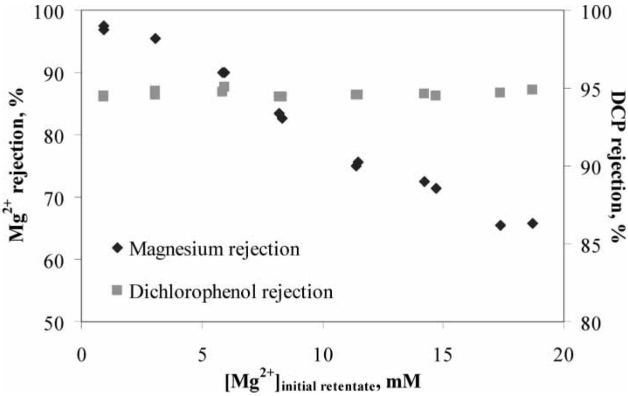

Figure 2. Effect of Mg^{2+} concentration on Mg^{2+} and DCP rejections. [CPC] and [PSS] are 25 mM to 50 mM, respectively. Initial [DCP] is 2.5 mM.

metal rejection. The mechanism by which organic solute and multivalent counterion attach to the surfactant-polymer complexes is different: the organic solute solubilizes in micelle-like surfactant-polymer aggregates, while the metal cations bind onto the polyanion chains; therefore, the presence of metal should only affect the solubilization of the organic solute if the polymer-stabilized micelles are affected by electrostatic ion binding on the polymer. Consequently, at a given surfactant concentration, the DCP rejection remains almost constant. The increased ionic strength from an increased metal concentration increases the critical aggregation concentration (cac) and hence, it might be expected to increase the surfactant leakage. However, the metal concentration used here is so low that this effect is

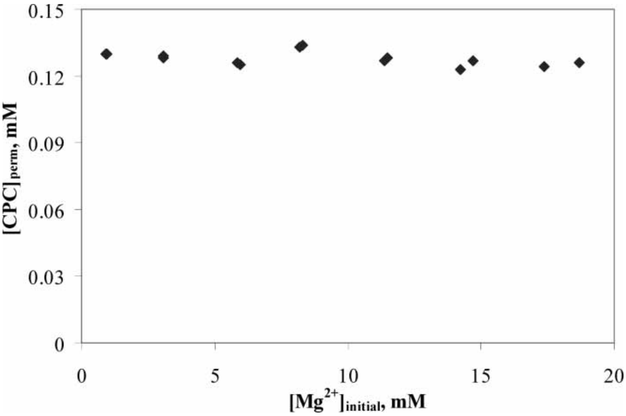

Figure 3. Effect of Mg^{2+} concentration on the surfactant leakage. [CPC] and [PSS] are 25 mM to 50 mM, respectively. Initial [DCP] is 2.5 mM.

negligible; therefore, the surfactant leakage is almost constant over the entire range of the metal concentration, as shown by Fig. 3.

The effect of [CPC] to [PSS] ratio on Mg^{2+} and DCP rejections is shown in Fig. 4. As [CPC] to [PSS] ratio increases from zero to 0.4, the Mg^{2+} rejection remains above 99%; when the ratio exceeds 0.4, the rejection decreases. The DCP rejection drastically increases, and then gradually levels off as the [CPC] to [PSS] ratio increases as shown in Fig. 4. It should be noted that, in the absence of CPC, although a DCP rejection of 62% is unacceptably low for a practical separation, it is higher than expected. As shown in Fig. 5, the surfactant leakage increases as the [CPC] to [PSS] ratio increases.

At a constant polymer concentration, as CPC concentration increases, available sites on the negatively charged polymer decrease due to surfactant-polymer binding. At a low [CPC] to [PSS] ratio, the number of available negatively charged sites on the polymer is large compared to the concentration of metal ions, resulting in a high level of metal cation binding and in a high Mg^{2+} rejection (99+%). At a higher [CPC]/[PSS] ratio than 0.4, the Mg^{2+} rejection decreases due to competition by surfactant for sites on the polymer. The higher the surfactant concentration, the fewer the available sites on the polymer for the metal to bind, resulting in lower metal rejection, as seen in Fig. 4. In contrast, as the [CPC] to [PSS] ratio increases, the DCP rejection increases because the concentration of polymer-bound micelles increases, and therefore increases the solubilization of the organic solute. As the [CPC] to [PSS] ratio increases above about 0.4, the increase in the concentration of the polymer-bound micelles is not great; hence, the DCP rejection does not drastically increase. Rejection of DCP of 62% in the absence of the surfactant is of interest. This might be

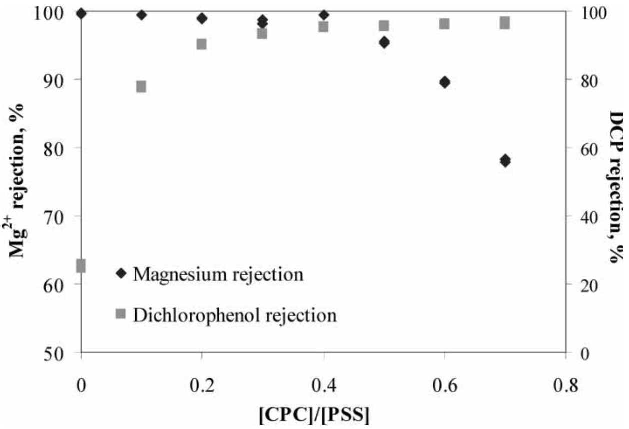

Figure 4. Effect of [CPC] to [PSS] ratio on Mg^{2+} and DCP rejections. Initial [PSS] is fixed at 50 mM. Initial [DCP] and $[Mg^{2+}]$ are both kept constant at 2.5 mM.

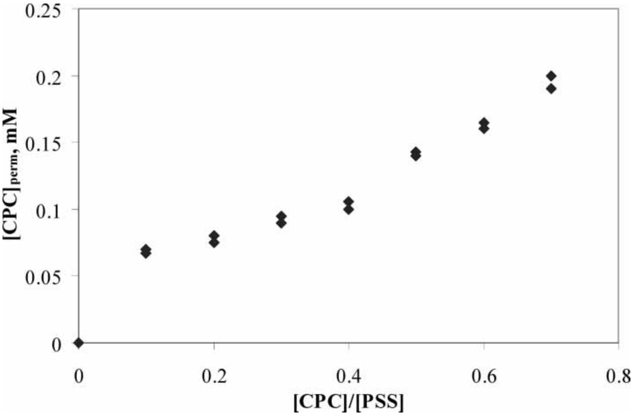

Figure 5. Effect of [CPC] to [PSS] ratio on the surfactant leakage. Initial [PSS] is fixed at 50 mM. Initial [DCP] and [Mg^{2+}] are both kept constant at 2.5 mM.

attributed to the hydrophobic binding between the organic solute and hydrophobic moiety of the polymer, resulting in the unexpectedly high rejection.

It was observed that cetylpyridinium cation is almost quantitatively associated with poly(styrenesulfonate) anion over the whole concentration range studied (11). According to a previous surface tension measurement (1), further added surfactant in the plateau region in a surface tension-surfactant concentration plot gives an increase in concentration of bound surfactant, while the concentration of the free surfactant monomer remains almost constant. After the plateau region, the concentration of the free surfactant monomer starts to increase, resulting in the increase in the surfactant leakage as seen in Fig. 5. It should be noted that the plateau region in the surface tension plot (in the presence of 50 mM [PSS]) corresponds to a range from 0.006 to 25 mM [CPC]. The surfactant leakage at retentate [CPC] above 25 mM, or a corresponding [CPC] to [PSS] ratio of 0.5, increases more drastically than that at lower CPC concentration.

The effect of polymer concentration and surfactant concentration on Mg^{2+} rejection and on DCP rejection is shown in Fig. 6. The [CPC] to [PSS] ratio is kept constant at 0.5. Rejection of Mg^{2+} is plotted as a function of PSS concentration in Fig. 6; as PSS concentration increases from 2.5 mM to 100 mM, the Mg^{2+} rejection drastically increases at low PSS concentrations and gradually levels off at higher PSS concentrations. A rejection of 97% is observed at 50 mM PSS although the rejection begins to plateau at 30 mM PSS, approximately. Analogous behavior is also observed for DCP rejection; that is, as CPC concentration increases, the DCP rejection increases before leveling off. A DCP rejection of 96% is also observed at 50 mM PSS, corresponding to 25 mM CPC. The surfactant leakage as a function of CPC concentration is shown in Fig. 7; the surfactant leakage increases with increasing initial retentate CPC concentration.

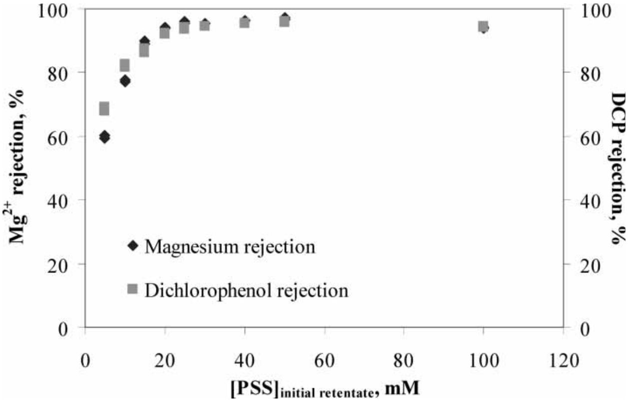

Figure 6. Effect of PSS concentration on Mg^{2+} and DCP rejections. [CPC] to [PSS] ratio is 0.5. Initial [DCP] and $[Mg^{2+}]$ are both kept constant at 2.5 mM.

At a constant initial Mg^{2+} concentration of 2.5 mM and a constant [CPC] to [PSS] ratio of 0.5, it is reasonable to expect an increase in anionic sites on the polyion chains per unit volume as the PSS concentration increases. Under the condition used here, the highest Mg^{2+} rejection is achieved when the [PSS] is equal to 50 mM, or the [PSS] to $[Mg^{2+}]$ ratio is approximately 20. The highest DCP rejection is attained when the [CPC] to [DCP] ratio is approximately 10 ([CPC] = 25 mM and [DCP] = 2.5 mM at maximum DCP rejection). This suggested that the removal efficiency can be maximized by controlling [colloid] to [solute] ratio. However, the Mg^{2+} removal efficiency at this [CPC] to [PSS] ratio of 0.5 is slightly lower than the efficiency for a

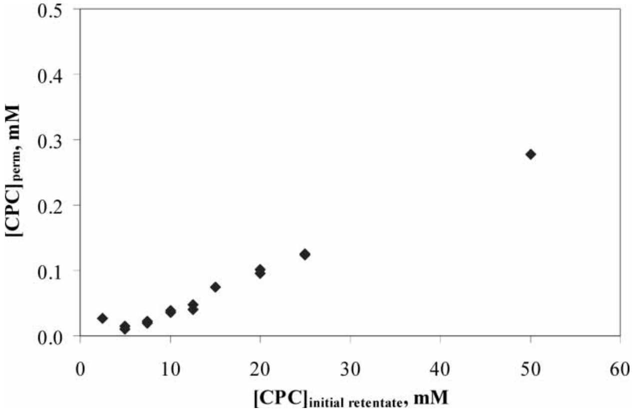

Figure 7. Effect of CPC concentration on the surfactant leakage. [CPC] to [PSS] ratio is 0.5. Initial [DCP] and $[Mg^{2+}]$ are both kept constant at 2.5 mM.

[CPC] to [PSS] ratio of 0.4 as seen in Fig. 4. As observed in previous work (9), where cac was determined at different salinities at constant concentrations of CPC and PSS of 25 mM and 50 mM, respectively, cac slightly increases as electrolyte concentration increases. The increased polymer concentration contributes to the increase in ionic strength, therefore increasing the cac as well as the surfactant leakage.

Kinematic Viscosity

Kinematic viscosity is plotted as a function of surfactant concentration at different salinities in Figs. 8 and 9. Fig. 8 shows the effect of the addition of NaCl and CPC on the kinematic viscosity of the polyelectrolyte at a fixed PSS concentration of 50 mM. As seen in Fig. 8, the kinematic viscosity of the polyelectrolyte solution in the absence of salt exhibits strong dependence on the concentration of the surfactant. In the absence of salt, the kinematic viscosity drastically decreases as CPC concentration increases and tends to level off at higher CPC concentrations. The kinematic viscosity starts to level off at an approximate CPC concentration between 20 mM to 25 mM. The dependence of kinematic viscosity on surfactant concentration is less pronounced for the systems with salt. At low surfactant concentration, a further decrease in the kinematic viscosity of the surfactant-polymer mixture is attained by adding salt, although addition of salt does not significantly change the kinematic viscosity of the surfactant-polymer mixtures at high surfactant concentrations. Fig. 9 shows the effect of added salt and surfactant concentration on the kinematic viscosity of the polyelectrolyte solution at a constant [CPC] to [PSS] ratio of 0.5. The

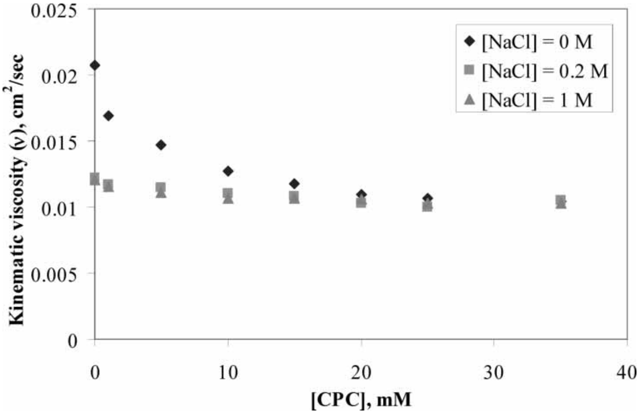

Figure 8. Kinematic viscosity of PSS solutions at different CPC concentration in the presence and absence of NaCl. [PSS] is kept constant at 50 mM. [CPC] to [DCP] and [PSS] to [Mg^{2+}] ratios are 10 and 20, respectively.

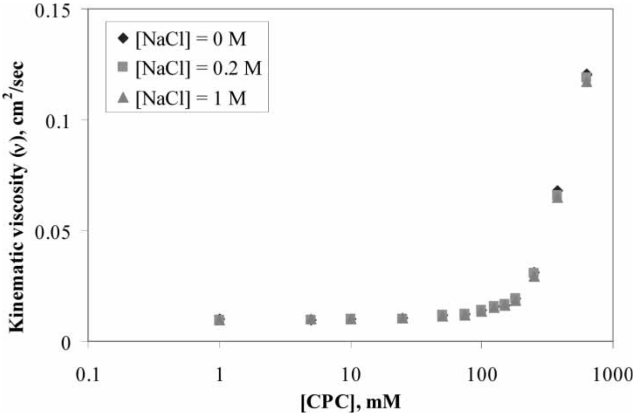

Figure 9. Kinematic viscosity of PSS solutions at different CPC concentration in the presence and absence of NaCl. [CPC] to [PSS] ratio is kept constant at 0.5. Initial [CPC] to [DCP] and [PSS] to [Mg^{2+}] ratios are 10 and 20, respectively.

kinematic viscosity increases as the colloid concentration increases. The kinematic viscosity is not significantly different as salt concentration increases. It should be noted that the experiments were performed at compositions where the surfactant and polymer do not precipitate.

The influence of additives (salt and surfactant) on the decrease in viscosity of polyelectrolyte is well known (12–16). Due to the repulsive electrostatic forces between adjacent charges on the polyion chain, the chain has a highly extended conformation in additive-free solutions. The added salt or surfactant results in shielding of ionic groups on the polyions. Consequently, the polymer coils up and coil dimension reduces and leads to a decrease in viscosity with increasing concentration of NaCl or CPC. However, it has been reported that the effect of surfactant on the reduction of the viscosity is stronger than the effect of simple salt (12). The explanation given is that in the case of surfactant cations, the addition effect can be expected since they bind to the polyion chain cooperatively in the form of "polymer-induced" micelles. That is to say, the surfactant ions are not evenly distributed along the chain but they are rather localized in the form of smaller or larger aggregates (17, 18). It is likely that polyelectrolyte chain encircles the surfactant micelles to some extent, and this is accompanied by a further decrease in dimension and viscosity. Due to the decrease in the kinematic viscosity by addition of surfactant, the addition of simple salt may not significantly affect the kinematic viscosity, primarily in the high surfactant concentration regime as seen in Fig. 8. However, an opposite trend was observed in an anionic surfactant/cationic polymer mixture (19); where a marked increase in viscosity of cationic cellulose ether (polymer JR) solutions with added sodium dodecylsulfate (SDS) was reported. This results from association of the alkyl chains of bound surfactant on separate polymer molecules, in effect generating a very high MW entity in solution. Moreover, it was observed that the kinematic viscosity levels off at a [CPC] to [PSS] ratio of 0.4–0.5; this is the ratio where we observe a maximum concentration of polymer-bound micelles (two anionic sulfonate PSS groups stabilize one aggregated cationic surfactant molecule) (1). As shown in previous work (1), as surfactant concentration increases above the cac, the number or concentration of the polymer-stabilized surfactant micelles increases; such micelles reduce the repulsion between the polyion chains, resulting in a decrease in viscosity. However, the kinematic viscosity does not significantly decrease after this [CPC] to [PSS] ratio of 0.4 to 0.5 because the increase in the concentration of the polymer-stabilized micelles is small.

At a constant [CPC] to [PSS] ratio of 0.5, the effect of the added salt on kinematic viscosity is slight, as shown in Fig. 9. It is commonly known that the viscosity increases as surfactant concentration increases as also seen in our previous work for CPC-only (6). As the surfactant concentration increases, the surfactant micelles may change their size and shape from nearly spherical micelles to rod-like aggregates. For example, spherical to rod-like transition for CPC was observed at 0.3 M; also an increase in salt concentration leads to an increase in micellar length and consequently to a rise in viscosity (20). It is also reasonable to expect that the size and shape of the surfactant-polymer aggregates changes as the colloid concentration increases. As colloid concentration increases, counterion concentration in the bulk solution tends to increase as well. Such free counterions reduce the repulsive force between polyion chains; therefore, the micelles on a string type of aggregates may turn to be a rod-like shape, which can cause an increase in viscosity. However, as seen in Fig. 9, these speculations either do not apply to our system or do not have a significant effect on viscosity.

Ultrafiltration Experiments

Flux is an important parameter in the economics of CEUF processes since capital cost is approximately inversely proportional to flux for treatment of large volume streams. Information about the dependence of the relative flux on colloid concentration can be used to calculate the gel point at which the flux becomes zero. Figs. 10 through 12 are semilogarithmic plots between the relative flux and retentate CPC concentration, along with kinematic viscosity in the absence and presence of salt. The kinematic viscosity results are shown in Fig. 9. The relative flux is defined as flux of sample divided by the flux of water containing the same added salt as the sample. Previous studies show that this semi-logarithmic plot is linear at high colloid concentration (5, 6, 21, 22). The colloid concentration, which is a total concentration of surfactant and polymer in this study, where the flux is zero, is called the gel concentration or gel point. The surfactant concentration corresponding to

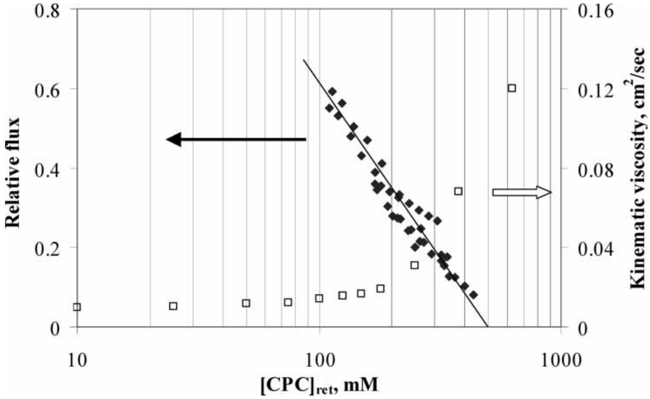

Figure 10. Relative flux and kinematic viscosity of surfactant to polymer mixtures as a function of [CPC] in the absence of NaCl. Initial [CPC] to [DCP] and [PSS] to [Mg^{2+}] ratios are 10 and 20, respectively.

the gel point at zero salt, 0.2 M NaCl, and 1 M NaCl is 500, 600, and 800 mM, respectively, resulting in the gel point (total colloid concentration) of 1500, 1800, and 2400 mM, respectively. Uchiyama et al. also observed that the gel point of CPC-PSS mixtures in the absence of salt falls in this range (22). It is seen in Figs. 10 through 12 that the decline in flux occurs concurrently with an increase in kinematic viscosity, as also seen in previous work (6). It should be noted that the viscosity measurement was carried out at a different solute concentration from the flux measurement. However, a previous study

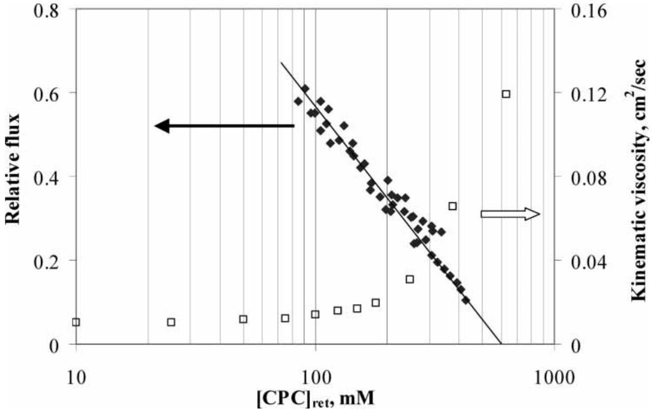

Figure 11. Relative flux and kinematic viscosity of surfactant-polymer mixtures as a function of [CPC] in the presence of 0.05 M NaCl. Initial [CPC] to [DCP] and [PSS] to [Mg^{2+}] ratios are 10 and 20, respectively.

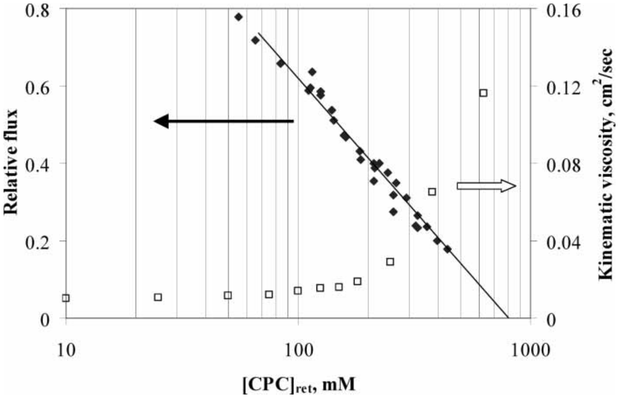

Figure 12. Relative flux of surfactant-polymer mixtures in the presence of 1 M NaCl. Initial [CPC] to [DCP] and [PSS] to [Mg^{2+}] ratios are 10 and 20, respectively.

showed that the surfactant concentration, not the solute concentration, controls the solution viscosity and the flux (6).

It was found in previous work that in the case of CPC solutions without added polymer, the gel point is 530 mM (5) whereas the gel point in the surfactant-free polymer solution is 600 to 800 mM (23). As mentioned earlier, for the system at a [CPC] to [PSS] ratio of 0.5, the gel point occurs at 1500 mM colloid concentration in the absence of salt. This indicates that the gel point for PE-MEUF is higher than the gel point for classical MEUF (500 mM) and PEUF or polyelectrolyte-enhanced ultrafiltration (800 mM). Therefore, the presence of polyelectrolyte increases the flux of the colloid solutions, resulting in a higher obtainable CPC concentration and colloid concentration before the flux becomes unacceptably low. Furthermore, the added salt further increases the gel point to a higher CPC concentration. This could be due to the slight reduction of the kinematic viscosity as salt is added. These high gel points for PE-MEUF improve the economic viability of the ultrafiltration process.

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