A Study on Fouling Mitigation Using Pulsing Electric Fields in Electrodialysis of Lactate Containing BSA

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Abstract−Fouling tendency in electrodialysis was investigated using the electrochemical and physical properties of the foulants and ion exchange membranes. It was found that bovine serum albumin (BSA), a large molecular weight protein, fouled the AMX membrane irreversibly by deposition on the membrane surface. Electrodialysis experiments of lactate with 1.0 wt% of BSA were performed using the square wave powers at different frequencies to examine the pulsing power influences as a fouling mitigation method, and the results were compared with the data obtained using the DC power. Reduced fouling potentials were observed when the square wave powers were used in the electrodialysis of lactate and confirmed the membrane fouling index for electrodialysis (EDMFI). The pulsing electric fields enhanced the mobility of the charged particles in the fouling layer and decreased the electric resistance of the electrodialysis cell. It was clearly observed that the pulsing electric fields with different frequencies reduced the fouling potentials, and consequently the power consumption was reduced significantly as a fouling mitigation method.

Key words: BSA (Bovine Serum Albumin), Fouling, Fouling Mitigation, Pulsing Electric Field, Electrodialysis

INTRODUCTION

Electrodialysis (ED) is a membrane process using an electrical potential difference as a driving force [Kang et al., 2002; Choi and Jeong, 2002]. Applications of ED can be found in environmental and biochemical industries as well as in the production of table salt and the desalination of seawater. In spite of the perspectives of ED, fouling of ion exchange membranes is the most significant limitation in the design and operation of the electrodialysis process. Fouling occurs in many streams due to organic foulants, such as humate, biomass, proteins, surfactants and others [Lee et al., 2002].

It is generally accepted that the flux decline caused by proteins present in the bioprocess streams is attributed to the following phenomena during membrane processes: (i) protein adsorption, (ii) protein deposition, and (iii) mass-transfer limitation due to accumulation of retained proteins on the surface of the membrane [Marshall et al., 1993; Belfort et al., 1994; Chang et al., 2000]. Fouling of BSA, a large molecular protein, proceeds in two consecutive steps during a membrane process. In the first step, the pre-adsorption of BSA results in a flux decline with only a minimal effect over the initial stage of filtration due to the absence of any protein retention [Belfort et al., 1994; Choi et al., 2000]. In the second step, fouling occurs due to cake filtration by the formation of a compressible protein deposit (or cake) on the surface of the membrane [Jönsson and Jönsson, 1996; Benavente and Jonsson, 1998]. The transition between these two steps depends on the membrane structure and bulk

protein concentration [Kelly and Zydney, 1995].

QUANTITATIVE ANALYSIS OF FOULING MITIGATION IN PULSING ELECTRIC FIELDS

Although chemical cleaning is the most extensively used method for CIP (cleaning-in-place) and fouling control in membrane processes [Sheikholeslami, 1999; Scott, 1995], the application of electric fields has been tested and was found to be an effective means to remove deposits from membrane surfaces in pressure-driven membrane processes [Bowen and Ahmad, 1997; Guizard and Rios, 1996; Oussedik et al., 2000]. It was reported that the DC electric fields created a higher filtrate flux with a protein solution than with pure water in a system fouled with BSA (bovine serum albumin), the gel layer on the membrane surface being completely removed [Bowen, 1993; Huotari et al., 1999]. The DC electric field has been studied with process variables such as the applied electric field, the pulse interval, the pulse duration and the feed solutions in the pressure-driven membrane processes [Bowen and Ahmad, 1997; Zumbush et al., 1998; Bowen et al., 1989; Bowen and Sabuni, 1992].

Recently, the pulsing electric fields with different frequencies demonstrated an ability to minimize membrane fouling when applied at an optimal frequency as both a fouling mitigation and a CIP method in electrodialysis [Lee et al., 2002]. Instead of physicochemical methods for fouling mitigation, the application of pulsing electric fields was assumed to provide turbulence effects, resulting in the movement of charged species away from the membrane surface and improving the permeability of ions through ion exchange membranes.

It is of importance to analyze the fouling mitigation quantitatively using a defined fouling index. In this study, the reduced fouling potentials by pulsing electric fields were analyzed quantitatively us-

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ing the membrane fouling index for electrodialysis (EDMFI), which was defined as the slope between time and $E(t)/I^2$ under a constant current [Lee et al., 2002; Lee and Moon, 1998]:

$$\frac{E(t)}{I^2} = \frac{R_m}{I} + K\frac{C_b r_c}{C_g A^2}t = \frac{R_m}{I} + (EDMFI)t. \tag{1}$$

It is suggested that a pulsing electric field gives perturbations within the fouling layer formed on the membrane surface. However, it is difficult to estimate the fouling layer thickness precisely although the mass balance can be used to obtain the amount of deposited foulant. The fouling layer thickness in the fouling gel layer model was expressed as follows [Lee et al., 2002]:

$$\delta = \frac{KQC_b}{C_g A}. \tag{2}$$

Of the parameters in Eq. (2), the values of K and C_g are assumed to be dependent on the operating conditions. The resulting equations for the ratios of the EDMFIs and the fouling layer thicknesses under DC power and a pulsing electric field show the same results:

$$\frac{\delta_{pulse}}{\delta_{DC}} = \frac{\left(\dfrac{K_{pulse}QC_b}{C_{g,pulse}A}\right)}{\left(\dfrac{K_{DC}QC_b}{C_{g,DC}A}\right)} = \frac{K_{pulse}C_{g,DC}}{K_{DC}C_{g,pulse}} \tag{3}$$

$$\frac{EDMFI_{pulse}}{EDMFI_{DC}} = \frac{\left(\dfrac{K_{pulse}C_b r_c}{C_{g,pulse}A^2}\right)}{\left(\dfrac{K_{DC}C_b r_c}{C_{g,DC}A^2}\right)} = \frac{K_{pulse}C_{g,DC}}{K_{DC}C_{g,pulse}} \tag{4}$$

where the subscripts, pulse and DC, mean the cases of the pulsing electric field and the DC power, respectively. The equations imply that differences in the fouling index directly represent the thickness of the fouling layer.

The influences of pulsing electric fields on fouling mitigation can be estimated by the changes in the fouling layer resistance and the membrane resistance. The membrane resistance, R_m, was estimated from the intercept at the y axis in the plot between time and E/I^2. The fouling layer resistance of the effective membrane area, R_f, is the product of the thickness and the specific resistance of the fouling layer [Lee et al., 2002; Lee and Moon, 1998]. Thus, R_f is estimated by using the fouling index, i.e.:

$$R_f = K\frac{C_b r_c}{C_g A^2}Q = (EDMFI)Q \tag{5}$$

where Q is the accumulated electrical charge over the period of an experiment.

The objective of this study is to observe fouling phenomena during the electrodialysis of a solution containing BSA. Also, fouling mitigation by the pulsing electric fields with various frequencies was examined quantitatively using the fouling index.

EXPERIMENTAL

1. Characterization of BSA

Bovine serum albumin (BSA) solutions were prepared from the heat-shock-precipitated BSA (Sigma, USA). It was reported that BSA has a net negative charge of −25 mV at pH 7.4 and a molecu-

lar weight of 68,000. The isoelectric point of BSA is known to be pH 4.8 [Do and Elhassadi, 1985; Pieracci et al., 1999]. All BSA solutions were stored at 4 °C and used within 48 hours of preparation. For determination of BSA concentration, the UV absorbance was measured at 280 nm with a UV-Visible spectrophotometer (Lambda 12, Perkin Elmer) with a 1 cm quartz cell. The pH effects on the zeta potentials were investigated after the pH was adjusted with 0.1 N HCl and 0.1 N KOH. The zeta potential was estimated from the measured electrophoretic mobility in an electrophoretic apparatus (ELS-8000, Otsuka Electronics, Japan) [Oka and Frusawa, 1998].

2. Characterization of the Anion Exchange Membranes

An anion exchange membrane (NEOSEPTA® AMX, Tokuyama Corp., Japan) was used in this study. Characterized properties included the hydrophobicity, electric resistance, ion exchange capacity and the zeta potential. Using a sessile drop technique, the contact angles of deionized water on the surface of the dried membranes were measured by a contact angle meter (FACE CA-S150, Kyowa Interface Science, Japan) [Zhang et al., 1989]. The virgin and fouled AMX membranes were pre-soaked in 0.1 N NaOH solution to exchange the counter-ion from Cl⁻ to OH⁻ [Yoshida et al., 1998]. After the surface water was removed, the concentration of OH⁻ was estimated by the amount of 0.01 N HCl consumed during titration to an end-point of pH 7. The exchange capacity was expressed as meq/g-dried membrane. The electric resistance in a 0.5 M NaCl solution at 25 °C was measured with an LCZ meter (NF 2321, NF Electronic Instruments, Japan) set at 100 KHz and expressed as Ω-cm² [Lindstrand et al., 2000]. The streaming potentials of the membrane surface were measured with a streaming potential measurement cell (BI-EKA, Brookhaven Instruments Corp., USA) and the corresponding zeta potentials were then calculated from the Smoluchowski-Helmholtz equation [Möckel et al., 1998].

3. Fouling Mitigation of a Solution Containing BSA Using Pulsing Electric Fields

To observe the fouling phenomena, a 2-cell pair unit consisting of CMB and AMX membranes (NEOSEPTA®, Tokuyama Corp., Japan) with an effective area of 100 cm² each, was assembled in a TS-1 electrodialysis stack with flow-sheet spacers (Tokuyama Corp., Japan). Lactic acid was purchased from Junsei Chemical (Japan) and synthetic solutions of sodium lactate were prepared for electrodialysis by adding NaOH to lactic acid solution until the pH reached 5.5 [Kim and Moon, 2001]. As an initial dilute solution, 1 L of 80 g/L sodium lactate was used for the reference experiment and 1.0% (w/v) of BSA was added for the fouling experiments. One liter of a solution containing 30 g/L of sodium lactate was prepared for an initial concentrate solution. Both solutions were circulated at a flow rate of 0.25 L/min. For an electrode rinse solution, 800 mL of 3.0% Na₂SO₄ was circulated during electrodialysis. Constant direct current was supplied at 0.6 A (current density 6.0 mA/cm²) throughout electrodialysis experiments. For all experiments, the final pH value in the dilute solution was around 5 to prevent coagulation of the BSA particles in the solution.

In a series of experiments, square wave powers having various frequencies were used to observe the influence of the pulsing electric fields on the fouling potentials during electrodialysis of BSA and their performance was compared with those of the DC power. The square wave powers were supplied during electrodialysis by using a function generator (33210A, Agilent, USA) and a dual type

power supplier (UP-100D, Unicorn, Korea) connected to an amplifier [Lee et al., 2002]. The current patterns of the square wave powers were observed with an oscilloscope (HP 5820 B, Hewlett Packard, USA) set at 150 MHz and were collected by a data acquisition system in a computer. The cell voltage drop was measured by a digital multimeter (34401A, Agilent, USA) during electrodialysis of BSA.

The concentration of lactate was measured by liquid chromatography (Waters 600, Waters, USA) with an analytical column (Aminex HPX-87H, BIO-RAD, USA). A mobile solution (0.01 N H_2SO_4) was supplied at 0.6 ml/min and the response was detected at 210 nm with a UV spectrometer (M710, Young-Lin, Korea) [Kim and Moon, 2001].

RESULTS AND DISCUSSION

1. Characteristics of BSA and Fouling Phenomena During the Electrodialysis

The fouling potentials in membrane processes are related to the interaction between the membrane surfaces and foulants in the solution, depending partly on the electrochemical properties of the membranes and the foulant and partly on their hydrophobicity, as well as other physical properties [Schoeman and Thompson, 1996]. It is known that the electrochemical interactions can be determined by the zeta potential [Zhu and Nyström, 1998]. Fig. 1 illustrates the zeta potential values of BSA as a function of pH. The zeta potentials were highly negative under high pH values of the solution, while they became more positive at low pH values of the solution. The zeta potential approached zero at pH 4.7, corresponding to the isoelectric point (IEP) [Do and Elhassadi, 1985; Zhu and Nyström, 1998]. Since the pH values of the dilute solution throughout the experiments were between 5.0 and 5.5, BSA was assumed to have negative charge and the deposition of the protein occurred on the AMX membrane surface with positively charged functional groups.

The AMX membranes were soaked for two days in solutions with various concentrations of BSA to determine the minimal concentration of BSA fouling on the membrane surface. The electrical resistances of soaked AMX membranes were measured with an LCZ meter and the results are shown in Fig. 2. Fouling effects were clearly observed at the BSA concentration of 1.0 wt% or higher.
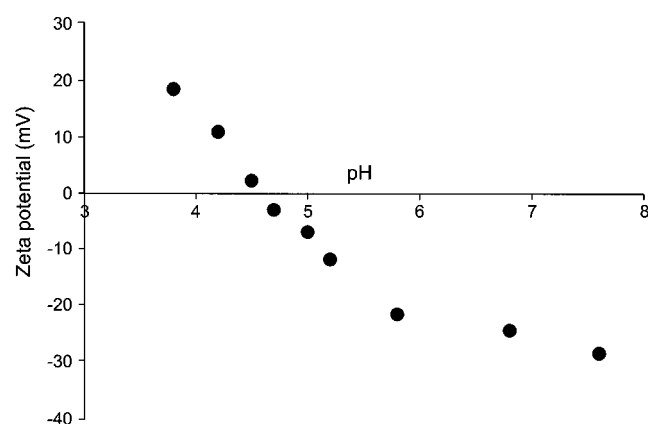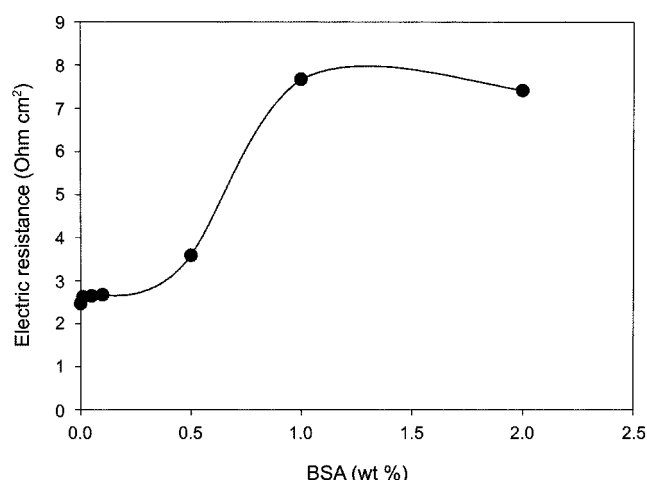

Fig. 2. Electric resistance as a function of BSA concentration (frequency: 100 KHz, electrolyte: 0.5 M NaCl).

Therefore, the concentration of BSA in the solution for fouling experiments was determined as 1.0 wt% throughout study.

To study the influence of BSA on the transport of lactate, electrodialysis experiments were performed according to the following steps: (i) electrodialysis of lactate, (ii) fouling experiment of lactate in the presence of BSA, and (iii) electrodialysis of lactate. Little difference was observed in the conductivity decreasing rate in the dilute solution, and in the lactate transport rate into the concentrate solution did not decrease even in the presence of BSA (data not shown). However, the cell resistance increased significantly in the presence of BSA, as shown in Fig. 3. The result indicates that adsorption of BSA on the anion exchange membrane surface fouled the membrane during electrodialysis.

Table 1 summarizes the electrodialysis performance in terms of lactate flux, current efficiency and power consumption. The flux of lactate was nearly unchanged, even in the presence of BSA because the experiments were carried out in a constant current mode. However, the performance of the fouled membrane was not recov-

Fig. 1. Influence of the solution pH on the zeta potential (BSA concentration: 1.0 wt% in 10 mM KCl).
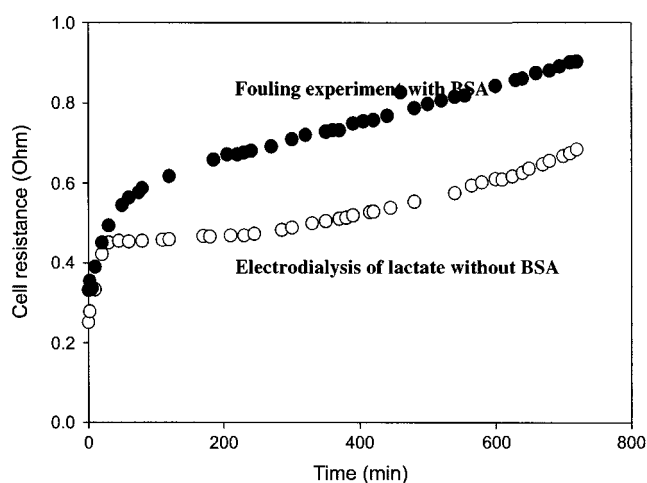

Fig. 3. Influence of BSA on cell resistances according to time (2 cell pairs of CMB and AMX, operating current density: 6.0 mA/cm²).

Table 1. Electrodialysis performance in the presence of BSA[a]

	Flux of lactate (mol/m^2·hr)	Current efficiency of lactate (%)	Power consumption (Wh/mol lactate)
Electrodialysis of lactate (Before fouling)	1.81	86.7	4.87
Fouling experiment with BSA	1.89	84.7	6.89
Electrodialysis of lactate (After fouling)	1.81	77.5	6.96

[a]Remark: The values of solution pH during electrodialysis were in the range of 5.0-5.5.

**Table 2. Characteristics of the virgin and fouled AMX membranes**

Membrane	Electric resistance (Ohm cm^2)		Range of contact angle (Degree)	Exchange capacity (meq/g-dried membrane)		Zeta potential at pH 7.0-7.3 (mV)
	Referred[a]	Measured		Referred[a]	Measured	
Virgin AMX	2.5-3.5	2.41	89-96	1.4-1.7	2.62	-4.1
Fouled AMX	-	2.33	92-96	-	1.56	-8.0

[a]Data are taken from Bulletin of NEOSEPTA, Tokuyama Corp.

ered due to the deposition of BSA. In particular, the power consumption during the fouling experiment with BSA increased by 41%. The results imply that the BSA fouled the anion exchange membrane irreversibly. It was found that the current efficiency and the power consumption were not recovered during the second electrodialysis of lactate without BSA.

Changes in the properties of the virgin and fouled membranes are crucial since a foulant causes the electrochemical and physical properties of the membranes to change. Table 2 shows the changes in the electrical resistance, hydrophobicity, exchange capacity and the zeta potential after the AMX membrane was fouled in the presence of BSA. The deposition of BSA did not significantly affect the electrical resistance and hydrophobicity of the AMX membrane. However, the exchange capacity of the fouled membrane decreased by 42%, and the zeta potential became more negative due to adsorption of BSA on the surface.

2. Fouling Mitigation During the Electrodialysis of Lactate with BSA
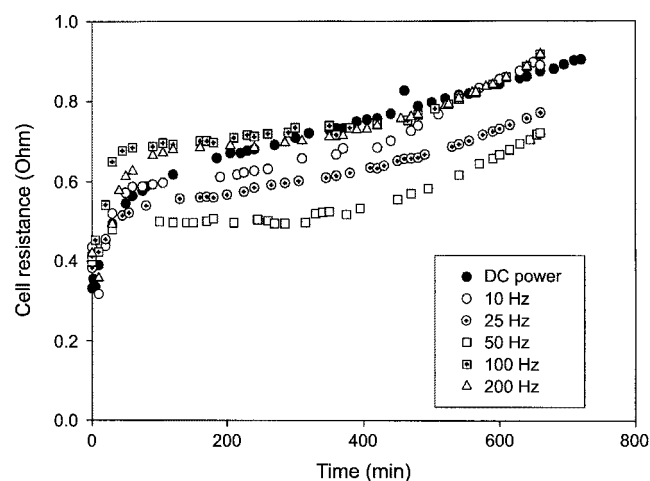
Fig. 4. Time course of the cell resistances for the pulsing electric fields with different frequencies and for the DC power supply.

The electrodialysis performance was investigated in terms of conductivity changes, transport rate of lactate into the concentrate solution, cell resistance changes and power consumption during the electrodialysis experiments with the application of square wave powers set at different frequencies. The results were compared with those of the DC power. Little difference in the conductivity changes and the transport rates of lactate was observed between the pulsing electric fields and the DC power (data not shown). However, the cell resistances in the experiments with the pulsing electric field showed somewhat lower values when compared to those of the DC power (Fig. 4). For all experiments the resistance increased with elapsed time due to the deposition of BSA on the surface. It is interesting that application of different frequencies resulted in different fouling effects. Pulsing electric fields with lower frequencies (10 Hz, 25 Hz and 50 Hz) reduced the fouling potentials compared with the results of the DC power. In particular, the square wave power at a frequency of 50 Hz minimized the cell resistance. Meanwhile, the pulsing electric fields at frequencies of 100 Hz and 200 Hz increased the cell resistance slightly, suggesting that the higher frequency caused a close packing of the foulants in the fouling layer, resulting in a reduced fouling mitigation during electrodialysis [Lee et al., 2002; Zumbush et al., 1998].

Table 3 summarizes the electrodialysis performance of the different power sources during BSA fouling experiments in terms of

Table 3. Performances with different frequencies during the electrodialysis of BSA

		Current efficiency of lactate (%)	Flux of lactate (mol/m^2·hr)	Power consumption (wh/mol lactate)
Square	10 Hz	92.5	2.39	7.56
wave	25 Hz	94.5	2.80	5.49
powers	50 Hz	93.7	2.57	4.67
	100 Hz	95.2	2.32	6.09
	200 Hz	95.7	2.49	5.75
DC power (∞)		84.7	1.89	6.89

the current efficiency, flux of lactate and the power consumption. The current efficiency and the flux of lactate increased for the pulsing electric fields with all frequencies. As shown in the third column of Table 3, all the square wave powers reduced the power consumption except for the frequency of 10 Hz. In particular, a frequency of 50 Hz resulted in the least power consumption, 67.8%, of the DC power. It was clearly observed that the electrodialysis performances were affected by the pulsing electric field with the specific frequencies and that membrane fouling was significantly reduced compared with the results of the DC powers.

To investigate the influence of the pulsing electric fields on the foulant behavior, the transport rate of BSA and the deposition on the membrane surface were observed. Fig. 5 presents the time course of BSA transported into the concentrate solution, showing that more BSA transported during the operation with the pulsing power of 25 Hz. The total amount of BSA transported was 1.4% of the initial amount present in the dilute solution when the pulsing electric field was applied, while only 0.7% of that transported through the AMX membrane by using the DC power. In addition, the flux of
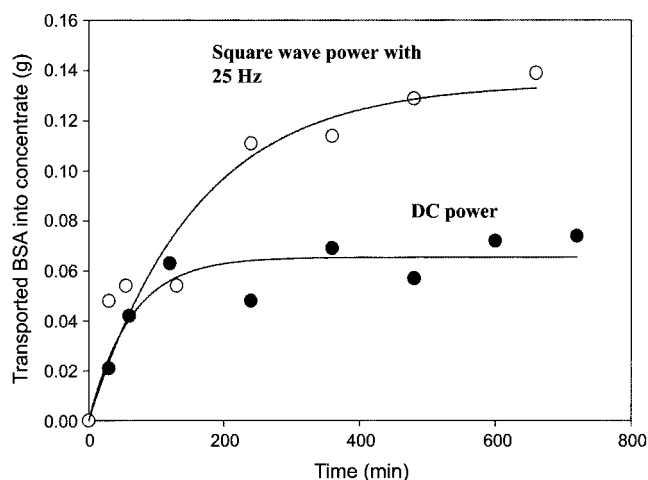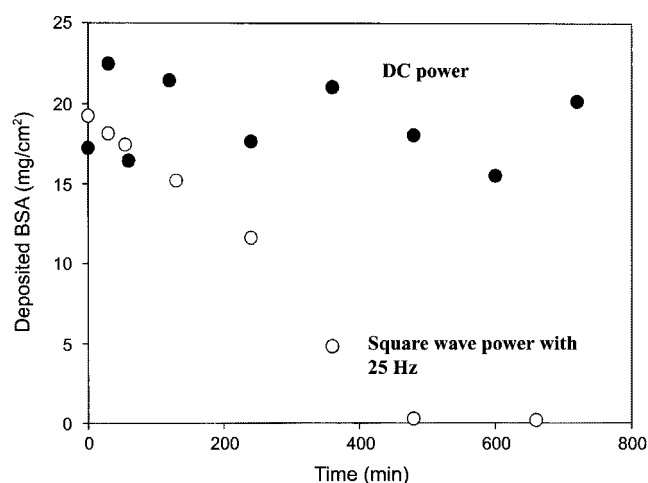
the BSA through the AMX membrane was 0.28 g BSA/m^2·hr in the DC power experiment. The pulsing electric field of 25 Hz led to a higher flux, 0.56 g BSA/m^2·hr. It is clearly observed that the pulsing electric fields increased the permeability of the protein through the membrane. Deposited BSA on the membrane surface was estimated from the mass balance. During electrodialysis with the DC power, the amount of deposited BSA remained fairly constant throughout the experiment at about 18.9 mg/cm^2 as observed in Fig. 6. However, the amount of deposited BSA decreased with time for the 25 Hz pulsing electric field, implying that the electric pulses enhanced the mobility of BSA from the fouling layer, thereby removing the deposited foulants having charges from the membrane surface during electrodialysis [Guizard and Rios, 1996].

3. Quantitative Analysis of the Fouling Mitigation in the Pulsing Electric Fields

Fouling potentials for the pulsing electric fields with different frequencies were compared in Fig. 7 by using the membrane fouling indices for electrodialysis. The frequencies of 25 Hz and 50 Hz reduced the fouling potentials the most compared with those of the DC power. Meanwhile, the frequencies of 100 Hz and 200 Hz did not reduce the cell resistance as shown in Fig. 7. Of the square wave powers tested, those of 25 Hz and 50 Hz showed the notable fouling mitigation effects. In the quantitative analysis of the fouling potentials, the square wave powers also demonstrated an ability to reduce the membrane fouling.

To obtain the quantitative analysis of the fouling mitigation effects due to the pulsing electric fields, the fouling indices, the fouling layer thickness, the membrane resistances and the fouling layer resistances were examined. The results are listed in Table 4. The fouling layer thickness estimated in Eqs. (3) and (4) decreased for the pulsing electric fields with other frequencies except for the 10 Hz. The results can be explained as the square wave powers having the pulsing effect caused the perturbations on the fouling layer, decreasing the fouling layer thickness near the anion exchange membrane surface.

It is noted that the 50 Hz square wave power reduced the fouling layer thickness by about 40% compared with the DC power. Differences in the membrane resistance (ΔR_m) and the fouling layer

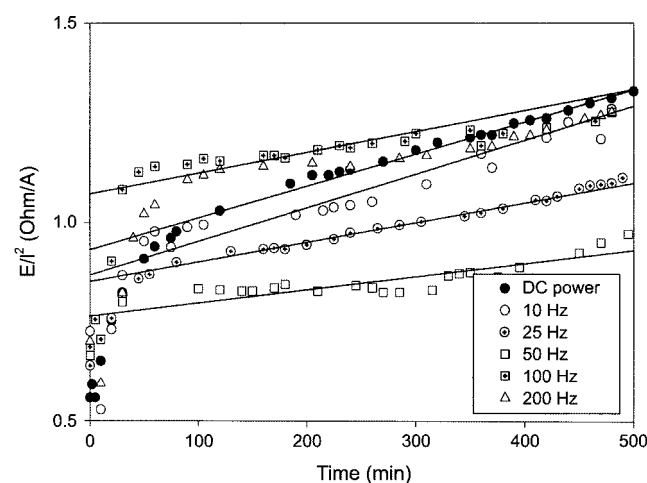**Fig. 5. Influence of the pulsing electric field on BSA transported through the AMX membrane.**

Fig. 6. Influence of the pulsing electric field on the deposited BSA on the AMX membrane surface.

Fig. 7. Quantitative analyses of the fouling potentials using the fouling index.

Table 4. Investigation of reduced fouling potentials according to the frequencies

|		EDMFI (Ohm/A·min)	$\delta_{pulse}/\delta_{DC}$	R_m (Ohm)	ΔR_m (Ohm)	R_f	ΔR_f (Ohm)
Square	10 Hz	0.00085	1.06	0.521	−0.038	03337	−0.011
wave	25 Hz	0.00050	0.62	0.511	−0.048	0.197	−0.151
powers	50 Hz	0.00033	0.41	0.458	−0.101	0.132	−0.216
	100 Hz	0.00052	0.65	0.644	0.085	0.208	−0.140
	200 Hz	0.00065	0.80	0.601	0.042	0.256	−0.092
DC power (∞)		0.00080	1.00	0.559	0	0.348	0

resistance (ΔR_f) in Table 4 were obtained from changes between the values for the square wave powers and those for the DC power. It was found that the pulsing electric fields set at the lower frequencies (10 Hz, 25 Hz and 50 Hz) reduced R_m compared with the DC power. Slight increase in R_m was observed for the higher frequencies (100 Hz and 200 Hz) during the fouling experiments. Considering the differences in the fouling layer resistance, as shown in the fourth column of Table 4, the pulsing electric fields reduced R_f, decreasing the fouling layer thickness on the surface at certain frequencies [Huotari et al., 1999]. The largest decreases in the resistances (R_m and R_f) were observed in the pulsing electric fields with the 50 Hz.

4. Consideration of Fouling Mitigation During the Electrodialysis of Lactate with BSA

During fouling mitigation with a pulsing electric field, one cycle of pulsing may be divided into three stages [Oussedik et al., 2000; Bowen, 1993; Czekaj et al., 2000]: (i) formation of the cake layer on the membrane surface, (ii) movement of the charged foulant (BSA) in the pulsing electric field in the opposite direction, and (iii) movement of the particles dispersed in the boundary layer near the membrane surface and the formation of a layer on the membrane surface. In the first stage, the suspended particles deposit on the membrane surface during electrodialysis and the fouling layer forms on the membrane surface, thereby increasing the cell resistance, irrespective of the power sources. It is assumed that the fouling mitigation effects can be understood by the second and the third stages during electrodialysis under the pulsing electric fields.

The cell voltage drop according to time was measured during the electrodialysis experiment with the pulsing electric field of 25 Hz and the results are shown in Fig. 8(b) immediately after beginning. In the figure, both positive and negative potentials were observed even though a constant current was supplied by using an on-off mode without a change in the electrode polarity [Fig. 8(a)]. The slightly reversed polarity of the voltage drop might be due to the movement of the charged foulants during electrodialysis. When the constant current is supplied with a square wave profile, the BSA particles move toward the anode resulting in the positive potential. Meanwhile, the charged BSA particles move away from the membrane surface when the current is shut-off in the pulsing electric field.

The movement of the BSA in the opposite direction resulted in a negative potential, along the opposite direction of the supplied current and reduced the fouling layer thickness in the pulsing electric field, thus increasing the BSA concentration in the bulk solution (Fig. 9). When the current is supplied at a given value, the foulants move toward the membrane surface and again the fouling layer
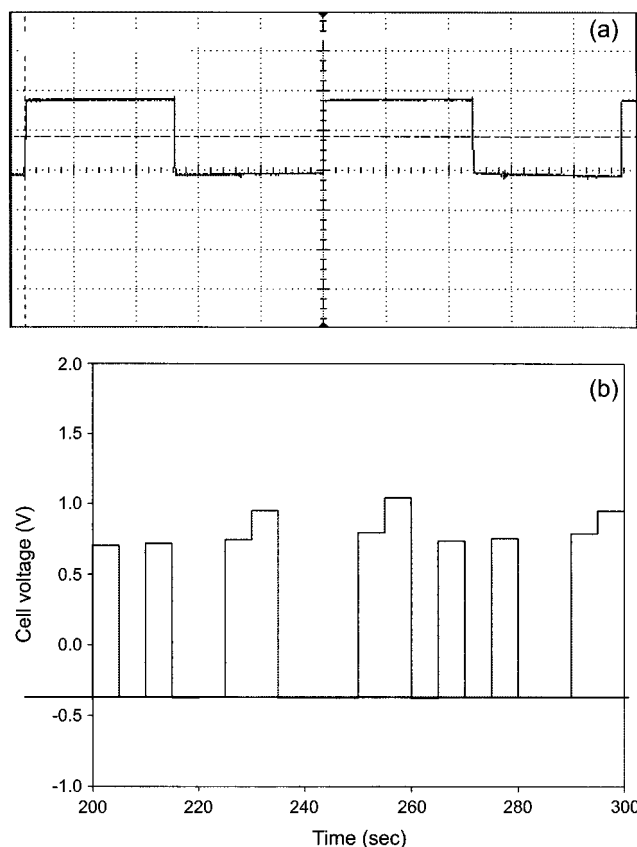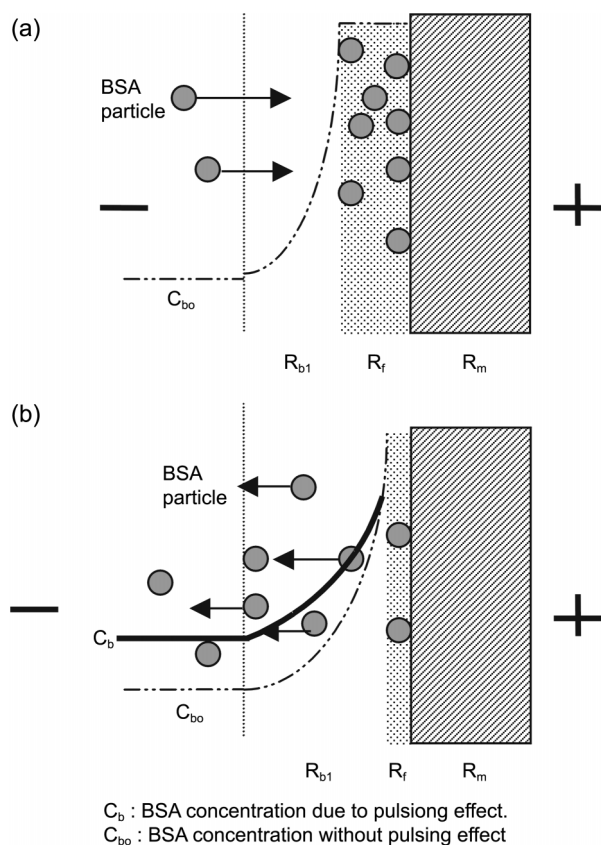

Fig. 8. Observation of the supplied current and the cell voltage drops for the pulsing electric field.
(a) Current form observed for the square wave voltage using an oscilloscope (x-axis grid: time scale, 20 ms and y-axis grid: potential scale, 100 mV), (b) Observation of cell voltage drops using a multimeter at the data acquisition speed of 5 Hz.

forms. However, the fouling layer is thought to form loosely packed layer on the membrane surface since the pulsing electric fields do not provide enough time to form a packed layer [Czekaj et al., 2000; Rodgers and Sparks, 1992].

CONCUSION

Previously, many approaches have been studied to minimize fouling during electrodialysis. In this study power sources including DC power as a reference and the pulse power with various frequencies were used. The square wave powers were employed to investigate the effects of the frequencies on the fouling mitigation

(a)

BSA particle

C_{bo}

R_{b1} R_f R_m

(b)

BSA particle

C_b

C_{bo}

R_{b1} R_f R_m

C_b : BSA concentration due to pulsiong effect.
C_{bo} : BSA concentration without pulsing effect

Fig. 9. Illustration showing the influence of the pulsing electric field on foulant movement related to Fig. 8 (C_{bo} and C_b: concentration of the foulant, R_{bl}: the boundary layer resistance, R_f: the fouling layer resistance, R_m: the membrane resistance).

(a) Accumulation due to electromigration toward the anode, causing a positive potential, (b) Reduced fouling layer thickness due to movement away from the deposited fouling layer, causing a negative potential.

during fouling experiments of BSA by using the EDMFI.

It was found that the BSA, a large molecular weight protein, deposited on the anion exchange membrane surface, increasing both the cell resistance and the power consumption. The fouling experiments with 1.0 wt% of BSA were performed with square wave powers having different frequencies. It was found that the electric pulses enhanced the mobility of the charged particles in the fouling layer and decreased the electrical resistance of the electrodialysis cell, resulting in a decrease in the fouling layer thickness and in the resistances of the membrane and the fouling layer. Also, the pulsing electric field having a square wave profile demonstrated a reduction in membrane fouling.

ACKNOWLEDGEMENT

NOMENCLATURE

A : effective membrane area [m^2]
C_b : concentration of foulant [kg/m^3]
C_g : foulant concentration in fouling layer [kg/m^3]
E : voltage [V]
I : operating current [A]
K : constant [m^3/Coulomb]
Q : accumulated electrical charge [Coulomb]
R_f : fouling layer resistance [ohm]
R_m : membrane resistance [ohm]
r_c : specific resistance [ohm-cm]
ΔR_f : fouling layer resistance difference between square wave power and DC power [ohm]
ΔR_m : membrane resistance difference between square wave power and DC power [ohm]
δ : fouling layer thickness [m]
δ_{DC} : fouling layer thickness for DC power [m]
δ_{pulse} : fouling layer thickness for pulsing electric fields [m]

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