펄스 전기장하에서 막오염저감에 미치는 주파수의 영향

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Effects of frequencies in pulsing electric fields on membrane fouling mitigation

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Introduction

Electrodialysis (ED) is an ion exchange membrane separation process using an electrical potential difference as a driving force. In various ED applications, fouling of ion exchange membranes is one of the most significant limitations in the design and operation of electrodialysis process. Fouling occurs in many streams due to organic foulants, such as humate, biomass, proteins, surfactants and others [1]. Many approaches have been considered to minimize fouling during electrodialysis. Of all the methods, cleaning-in-place (CIP) is still necessary in practical membrane processes. However, CIP can be applied only at the end of the processes [1,2].

To mitigate fouling during membrane processes, the pulsed DC electric field has been considered with process variables such as the applied electric field, the pulse interval, the pulse duration and the feed solutions [3,4]. In the case of ED process, several power sources were tested using the half-wave power and the square wave power as the pulsing electric power source, showing that the pulsing electric fields reduced the fouling potentials and improved electrodialysis performances [1,5,6].

In this study, the ED performances in the pulsing electric fields were compared with the DC powers. And it was shown that the fouling system could be operated during the extended period without CIP.

Experimental

In this study the DC power was considered as a reference and the pulsing electric fields with various frequencies were used after generated by modification of the DC power with a function generator and a dual-type power supplier connected to an amplifier [1].

For the fouling system, 2-cell pair unit consisting of CMX and AMX with effective area of 100 cm^2 each was assembled in a TS-1 electrodialysis stack with flow-sheet spacers (Tokuyama Corp., Japan). The initial diluate solution in each experiment was 5.0 L of 0.1 M NaCl containing 100 mg/L of sodium humate (Aldrich, USA), whose molecular weight was reported as 50,000 g/mol [1,7]. As an initial concentrate solution, 5.0 L of 0.05 M NaCl was used in the ED experiments. The flow rates of diluate and concentrate were maintained as 0.2-0.3 L/min. For the electrode rinse solution, 800 mL of 3 % Na_2SO_4 was used. In electrodialysis experiments a constant current of 0.6 A (current density: 6.0 mA/cm^2) was supplied. The performances of pulsing electric fields with various frequencies in the cell structure were compared with those of the reference power (the DC power). With the determined optimum frequency for the pulsing electric field, continuous batch tests were carried out to investigate the effects of electric pulses on the membrane fouling in a semi-continuous operation.

Results and Discussion

Even with different frequencies for the square wave powers in ED of NaCl solution containing humate, little difference was observed in the time course of NaCl concentration in diluate in the cell of CMX and AMX. Also, cell resistances between different frequencies did not show significant differences. The similar performances for the pulsing electric fields may be related to the fouling mechanism of humate. It was found that the humate in electrodialysis experiments fouled anion exchange membranes through deposition and formation of the loosely packed fouling layer rather than the fouling gel layer, resulting in little difference in the conductivity change. When the results of ED of lactate in the presence of bovine serum albumin (BSA), it was suggested that the pulsing electric field reduced fouling potential by the movement of charged foulants on the membrane surface away from the surface [8]. It was suggested that BSA fouled anion exchange membranes by formation of the gel layer on the membrane surface.

Considering the power consumption for the different powers, the square wave pulse powers with the frequencies showed the similar power consumption up to 600 min. It is considered that deposited amount of the humate as a foulant increased around the anion exchange membrane surface. The power consumption of the DC power, however, increased after 600 min. The DC power showed the highest increasing rate of cell resistance, assuming that it is due to the concentration depletion when there did not exist the mobile ions (Na^+ and Cl^-) in diluate solution. The result implies that amount of water splitting in the DC power is much higher than in the pulsing electric fields. Contribution of water-splitting in electrodialysis can be obtained by the transport number of protons [9,10]. In the estimated transport numbers for the different powers, the higher transport number of proton represents the higher production of the water-splitting. The transport numbers in the pulsing electric fields were much lower than that in DC power, indicating the reduced water splitting at the concentration polarization on the boundary layer [9,10]. It was shown that the pulsing electric fields provided turbulence effects, thus decreasing the amount of water-splitting in the concentration polarization layer.

Considering the current efficiencies as a function of frequency, the current efficiencies at the frequencies of 100 Hz, 200 Hz and the DC power showed below 90 %, while those for lower frequencies (10 Hz, 25 Hz, and 50 Hz) showed a higher value than 90 %. Particularly, the current efficiency at 50 Hz showed the highest value among the examined frequencies. The results indicate that the pulsing electric field reduced the fouling rate in electrodialysis of solution containing humate, and there exists an optimal frequency.

The electrodialysis performances for various frequencies were compared with the DC power in terms of flux, power consumption and the water transport (Table 1). The transport of NaCl at 50 Hz and 100 Hz showed slightly higher values for the other frequencies. However, the ion transport rate (or flux) increases with increasing accumulated amount of electric charges, which is so-called the Ohm's law when the ion transport is not affected by foulants in a constant current operation. Therefore, it is not critical parameters to decide the electrodialysis performances. For the power consumption and water transport, the frequencies of 50 Hz showed the least value. As mentioned before, the power consumption for the DC power showed a similar increasing rate compared with the pulsing electric fields until the water-splitting occurred around the operating time of 600 min. However, the DC power showed large increase in the power consumption due to water-splitting, resulting in the largest power consumption among examined powers in Table 1. In the case of water transport per transported mol of NaCl, the higher amount of water transport implies the lower current efficiency in a concentrate solution. The value of the 50 Hz showed the least as the best performance in this study. It is considered through investigation of electrodialysis performances that the optimum frequency was 50 Hz for the fouling mitigation experiments of humate.

For the effects of electric pulses on the membrane fouling, batch tests in series were carried out in a semi-continuous operation without cleaning procedures between batch tests. A constant current of 0.6 A in the DC power was supplied for the first and the second batch to observe the increasing fouling behavior in electrodialysis of NaCl containing humate. And then, the square wave power having the frequency of 50 Hz was supplied for the third batch. When the changes of conductivity in diluate solution are considered, the conductivity of diluate solution reduced to 0.8 mS/cm at the first batch.

And, the conductivity in diluate at the second batch decreased down to 1.8 mS/cm using the DC power due to deposition of humate. Using the square wave power having pulsation effect, the conductivity in the diluate solution at the third batch decreased down to 0.9 mS/cm, the similar level of the first batch. It was clearly observed that the pulsed power reduced fouling potential in the fouling experiments of humate.

The fouling mitigation effects at the continuous batch runs were observed mainly in terms of cell resistance changes and the conductivity removal rates. As shown in Fig. 1, notable increasing aspects in the cell resistances were observed when the DC power was used as a power source at the first and second batch, showing significant fouling effects in the presence of humate. At the third batch, the square wave pulse power having the frequency of 50 Hz reduced membrane fouling potential. The cell resistance of the first batch increased up to 19.0 Ohm and increased more for the second batch using the DC power. However, the square wave power with the frequency of 50 Hz could reduce cell resistance even at the third batch, showing 7.1 Ohm at the final. It was considered that the electric pulses enhanced the mobility of the charged particles in the fouling layer and decreased the electric resistance of the electrodialysis cell [11]. Also, the square wave pulsed power with various frequencies demonstrated an ability to minimize membrane fouling with an optimal frequency. Through the semi-continuous batch, it was clearly observed that the pulsing electric field enabled to reduce fouling potential of already fouled membrane, thus increasing electrodialysis performance.

Conclusion

In this study power sources including the DC power as a reference and the pulse power with various frequencies were used. The square wave pulse powers were employed to investigate the effects of the frequencies on the fouling mitigation during fouling experiments of humate. Little difference in the cell resistance and the removal rate of conductivity were observed in the fouling experiments of humate, probably due to the loosely packed fouling layer of deposited humate. However, the optimum frequency was determined as 50 Hz in terms of the overall electrodialysis performances. Also it was confirmed that the pulsing electric field with the optimum frequency reduced the fouling potential in the semi-continuous batch. In this study, the electric pulses enhanced the mobility of the charged particles in the fouling layer and decreased the electric resistance of the electrodialysis cell, showing an ability to reduce membrane fouling with an optimal frequency.

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Table 1 Performances with different frequencies in electrodialysis of humate

Power sources		Flux of NaCl ($mol/m^2.hr$)	Power consumption (wh/mol NaCl)	Water transport (L of water /mol NaCl)
Square wave pulse power	10	2.02	8.66	0.34
	25	2.04	9.00	0.33
	50	2.09	7.35	0.22
	100	2.13	10.14	0.32
	200	2.00	9.20	0.25
DC power (∞)		2.04	16.42	0.45

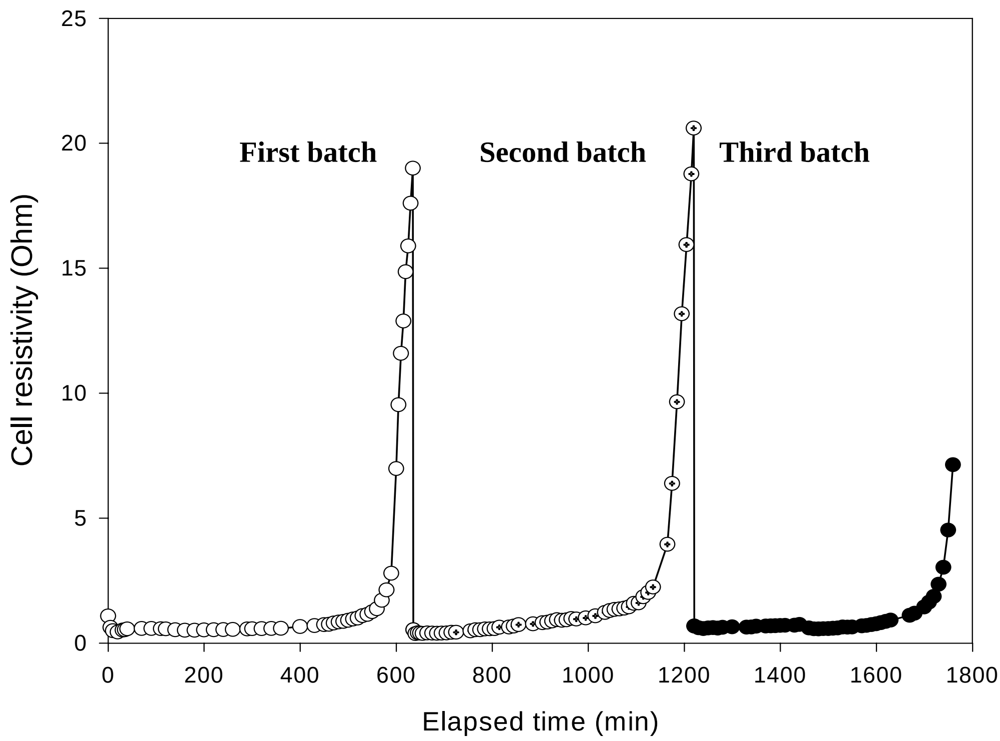

Fig. 1. Cell resistance changes in the semi-continuous batch (the DC power for the first and the second batch, and then the pulsing electric field having 50 Hz for the third batch).