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Separation of Phenylacetic Acid, 6-Aminopenicillanic Acid, and Penicillin G with Electrodialysis under Constant Voltage

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ABSTRACT

The separation behavior of phenylacetic acid (PAA), 6-aminopenicillanic acid (6-APA), and penicillin-G (Pen-G) with electrodialysis under constant voltage was studied. The effects of ionic concentrations and electric field strength on their separation behavior were investigated. The sorption of PAA, 6-APA, and Pen-G in the anion-exchange membrane, and the variations of current and current efficiencies with time during electrodialysis, were also examined. The electrodialysis of PAA, 6-APA, and Pen-G was closely dependent on their ionic size and their affinity toward the anion-exchange membrane. Phenylacetic acid had the lowest affinity toward the membrane but the fastest transport rate. Penicillin-G had the highest affinity toward the membrane but the slowest transport rate. The concentration polarization of Pen-G in the vicinity of anion-exchange membrane severely retarded the transport of PAA and 6-APA, and became more serious with the increase of Pen-G concentration. The increase of electric field strength accelerated the transport of PAA, 6-APA, and Pen-G. However, more serious concentration polarization of Pen-G occurred and the separation ratio of PAA to 6-APA decreased.

Key Words. Phenylacetic acid; 6-Aminopenicillanic acid; Penicillin G; Separation; Electrodialysis

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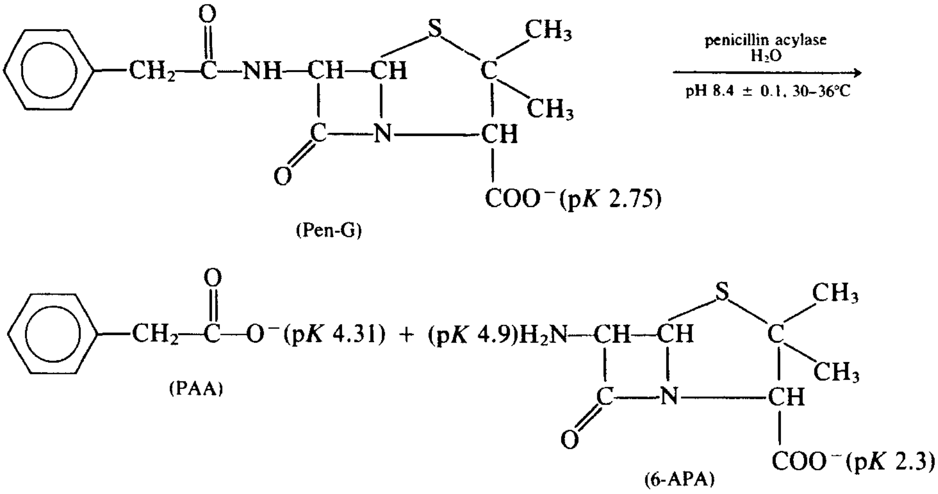
INTRODUCTION

The deacylation of penicillin G (Pen-G) by immobilized penicillin acylase has become an important commercial process for the manufacture of 6-aminopenicillanic acid (6-APA), which is a basic raw material for the industrial production of semisynthetic penicillins. The reaction scheme can be expressed as follows (1):



(1)

Since the by-product phenylacetic acid (PAA) inhibits severely the enzyme reaction and results in a pH decrease of the reaction mixture, it is important to maintain a low concentration of PAA during the enzymatic hydrolysis of Pen-G. However, no measures have been taken for the continuous removal of PAA from the reaction mixture in practical application up-to-date.

Ion-exchange membrane electrodialysis is a rapid and effective process for the separation of ionic species. It can be widely utilized in the desalination and concentration of seawater (2–4), the removal or recovery of heavy metal ions and toxic compounds in wastewater (5–7), the desalination in food and pharmaceutical industries (8–11), and the separation of amino acids and proteins (9, 12).

The combination of electrodialysis and immobilized enzymes has attracted our attention. We have developed a urea-removal electrodialyzer with immobilized urease (13, 14). Such a device also could be utilized for the more efficient enzymatic hydrolysis of Pen-G because the PAA could be removed from the reaction mixture continuously with electrodialysis.

Recently, Ishimura and Suga (15) presented a similar idea. However, little attention was paid on the transport and separation mechanism of PAA, 6-APA, and Pen-G in electrodialysis. We also have interest in the selective transport of ions with electrodialysis and have conducted several investigations (16–18). Since PAA ($pK = 4.31$), 6-APA ($pK_1 = 2.3$, $pK_2 = 4.9$), and Pen-G ($pK = 2.75$) are all present in this type of monovalent anion at pH 8.5, we believe that the selective transport of PAA, 6-APA, and Pen-G with electrodialysis must play a key role for the application of electrodialysis to enhance the efficiency of the enzymatic hydrolysis of Pen-G.

In this work the separation behavior of PAA, 6-APA, and Pen-G with electrodialysis was studied under constant voltage. The effects of ionic concentrations and electric field strength on the separation behavior of PAA, 6-APA, and Pen-G were investigated. The sorption of PAA, 6-APA, and Pen-G in the anion-exchange membrane, and the variations of current and current efficiencies with time during electrodialysis, were also examined.

EXPERIMENTAL

Chemicals

6-Aminopenicillanic acid and penicillin G were purchased from Sigma Chemical Co. (St. Louis, Missouri). Phenylacetic acid was the reagent of E. Merck (Darmstadt) for synthesis. All other chemicals were E. P. grade or guaranteed reagents commercially available. Reagent-grade water produced by Milli-Q SP Ultra-Pure-Water Purification System of Nihon Millipore Ltd., Tokyo, was used throughout this work.

Analytic Methods

The concentrations of 6-APA, PAA, and Pen-G in the solutions were determined by HPLC on a Lichrosorb RP-18 column (4 mm $\phi \times 12.5$ cm) (Merck) at 37°C, using the first mobile phase of 10 mmol/dm^3 phosphate buffer (pH 7.0)–acetonitrile (100:1 v/v) at a flow rate of 0.6 cm^3/min in the first 16.5 minutes for analysis of 6-APA and PAA, and the second mobile phase of 0.3 mol/dm^3 KH_2PO_4–acetonitrile (8:2 v/v) at a flow rate of 0.8 cm^3/min during the following 17 minutes for analysis of Pen-G. The detection was performed with a UV detector at 230 nm.

Electrodialysis Apparatus

The electrodialysis apparatus was similar to that used in our previous work (13, 14). A five-compartment electrodialyzer was made of two anion-exchange membranes and two cation-exchange membranes, forming one dilute compartment, two concentrate compartments, and two electrode compartments, as illustrated in Fig. 1. The ion-exchange membranes were Selemion AMV and CMV, produced by Asahi Glass Co., Japan. Their properties can be found elsewhere (19). The frames of the electrodialyzer were made of Teflon. The solution containing PAA, 6-APA, or Pen-G flowed through the central (dilute) compartment between an anion-exchange membrane and a cation-exchange membrane. The two concentrate compartments were on both sides of the central compartment. Each of the dilute and concentrate compartments had a PU foam sheet (5 cm in diameter and 1 mm thick), and for each PU foam two polyvinyl chloride spacers with a diameter of 5 cm were placed against its two sides to keep

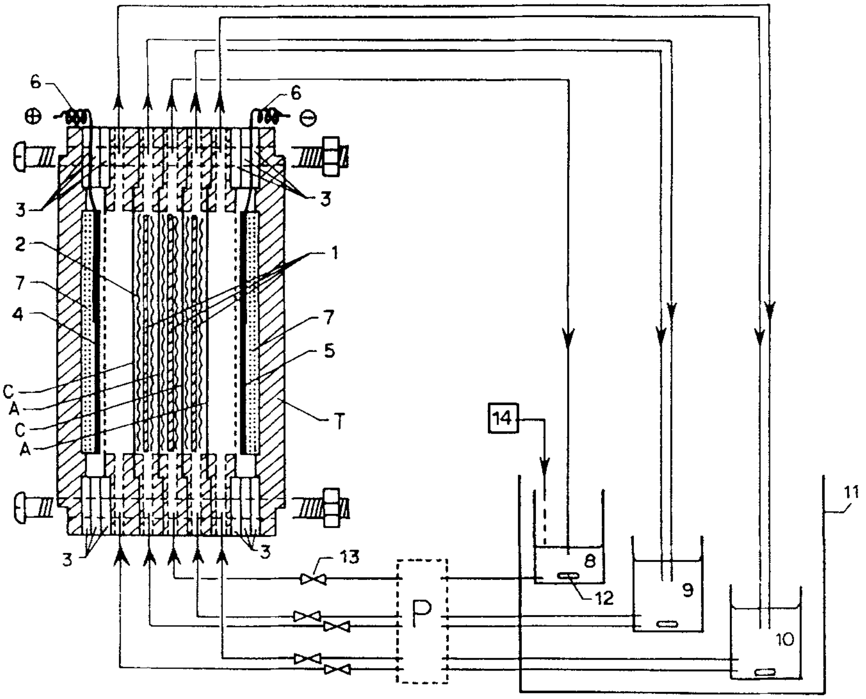


FIG. 1 Electrodialysis apparatus and flow scheme. A: Anion-exchange membrane (Selemion AMV); C: cation-exchange membrane (Selemion CMV); P: five-head tubing pump; T: Teflon frame; 1: PU foam; 2: PVC spacer; 3: rubber gasket; 4: graphite (anode); 5: stainless steel (cathode); 6: platinum wire; 7: adhesive foam sheet; 8: dilute solution; 9: concentrate solution; 10: electrode rinse; 11: constant-temperature water bath; 12: stir bar; 13: variable area flowmeter; 14: pH stat (NaOH).

the PU foam flat and to decrease the aqueous film resistances on the ion-exchange membranes and on the PU foams. The anodic and the cathodic electrode compartments were separated with concentrate compartments by cation- and anion-exchange membranes, respectively. For each electrode compartment, three rubber gaskets of 2 mm thick were interposed between two frames to allow the platinum wires connected to the graphite anode or stainless steel cathode to extend out of the compartment. Each of the dilute and the concentrate compartments had a diameter of 5 cm and a width of 5 mm. The effective areas of each membrane and of each electrode were 20 cm^2.

Sorption Experiments

For each run, about 0.1 g small pieces of anion-exchange membrane was placed in 12 cm^3 boric buffer solution (40 $mmol/dm^3$, pH 8.5) containing PAA, 6-APA, or Pen-G. The mixture was kept in a water bath at 35°C and stirred continuously with a magnetic stirrer. After each preset time interval, 0.2 cm^3 sample was pipetted out for analysis of PAA, 6-APA, or Pen-G concentrations. For all sorption experiments, the initial concentrations of PAA, 6-APA, or Pen-G were 50 $mmol/dm^3$. The quantities of PAA, 6-APA, and Pen-G sorbed in the anion-exchange membrane were calculated from the change of solution composition.

Electrodialysis Experiments

The flow scheme for the separation of PAA, 6-APA, or Pen-G in the five-compartment electrodialyzer is illustrated in Fig. 1. Initially, the dilute solution was the boric buffer solution (40 $mmol/dm^3$, pH 8.5) containing PAA, 6-APA, or Pen-G, the concentrate solution was the aqueous solution containing 0.05 mol/dm^3 Na_2SO_4 and 0.005 mol/dm^3 NaCl, and the electrode rinse was 0.5 mol/dm^3 NaCl. The electrode rinse, dilute solution, and concentrate solution, kept in the same constant temperature bath, were pumped into the electrodialyzer from their storage bottles and were circulated by a five-head MasterFlex tubing pump (Cole-Parmer) at a flow rate of 60 cm^3/min. When the flow of solutions reached steady state (about 1 minute), the electric field was applied by an ELBA D6012 dual-digital-power supply for the electrodialysis of PAA, 6-APA, or Pen-G. The current and the voltage applied to the system were measured by two Escort EDM-2116 digital multimeters. The volumes of dilute solution, concentrate solution, and electrode rinse initially were 100, 200, and 200 cm^3, respectively. The temperature was fixed at 35°C. During the electrodialysis, the pH of the dilute solution was automatically maintained at 8.48 ± 0.02 by adding 0.5 mol/dm^3 NaOH solution with a pH stat (TOA

AUT-211). At each pre-set time interval, 0.2 cm^3 dilute solution and/or 0.5 cm^3 concentrate solution was removed for analysis of PAA, 6-APA, or Pen-G concentrations.

Calculation of Current Efficiency

The current efficiency (*CE*) for transporting PAA, 6-APA, or Pen-G through the anion-exchange membrane can be defined as

$$CE\ (\%) = 100NF/i \qquad (2)$$

where i is current density, F is Faraday's constant, and N is the mole flux of PAA, 6-APA, or Pen-G. N can be represented as

$$N = (V_c/A_m)dC_c/dt \qquad (3)$$

where V_c is the volume of concentrate solution, A_m is the effective area of the membrane, C_c denotes the concentration of PAA, 6-APA, or Pen-G in the concentrate solution, and t is time.

In this work, the dC_c/dt at each time was obtained by differentiating the polynomial equation best fitting the time course of PAA, 6-APA, or Pen-G concentration. Since the variation of current with time was measured, the current efficiencies for transporting PAA, 6-APA, and Pen-G through the anion-exchange membrane at each time could be calculated according to Eqs. (2) and (3).

RESULTS AND DISCUSSION

Sorption of PAA, 6-APA, and Pen-G in Anion-Exchange Membrane

The sorption behavior of PAA, 6-APA, and Pen-G in the anion-exchange membrane may be an important factor for their separation with electrodialysis owing to the selectivity of the membrane. The sorption curves for the single-, binary-, and ternary-component sorption of PAA, 6-APA, and Pen-G in the anion-exchange membrane are shown in Fig. 2.

In the case of single-component sorption, the sorption rate of PAA in the anion-exchange membrane was the fastest and reached equilibrium after about 15 minutes. This could be due to the fact that PAA has the smallest ionic size and thus the largest diffusivity. Both the individual sorption of 6-APA and Pen-G in the anion-exchange membrane exhibited two-stage behavior, which could result from both the surface sorption and interior sorption. The initial sorption rate of Pen-G was the slowest, but its affinity toward the anion-exchange membrane was the highest.

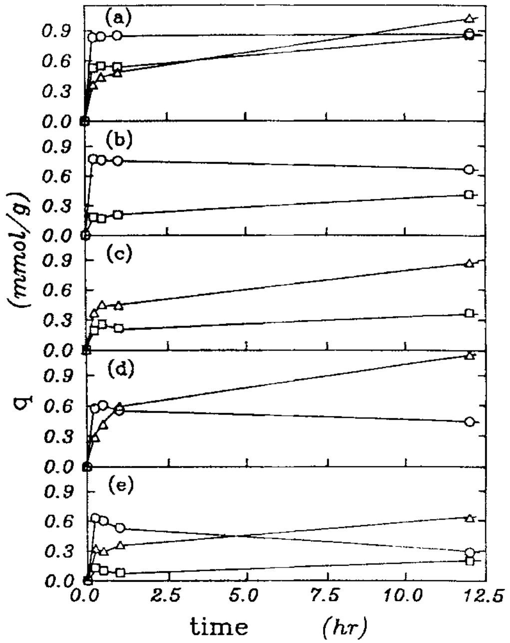


FIG. 2 Sorption curves of PAA, 6-APA, and Pen-G in anion-exchange membrane. (a) Single-component sorption; (b)–(d): binary-component sorption; (e): ternary-component sorption. Initial concentrations of PAA (○), 6-APA (□), and Pen-G (△): 50 mmol/dm^3; boric buffer: 40 mmol/dm^3, pH 8.5, 12 cm^3; membrane weight: 0.1 g; 35°C.

The competitive sorption of PAA, 6-APA, and Pen-G in the anion exchange membrane was significantly observed in the cases of binary- and ternary-component sorption. Although the initial sorption rate of PAA was the fastest, it desorbed from the membrane after several hours in the presence of 6-APA or Pen-G. Also, both the sorption capacity and initial sorption rate of Pen-G were larger than those of 6-APA. This might be due to the fact that the diffusivity of 6-APA was slightly larger than that of Pen-G, and the competitive sorption of 6-APA and PAA was mainly dependent on their affinity toward the anion exchange membrane.

Accordingly, it was concluded that the competitive sorption behavior of PAA, 6-APA and Pen-G in the anion-exchange membrane was dependent on the following two factors: 1) the diffusivity, which was inversely proportional to the ionic size and increased in the sequence Pen-G < 6-

APA < PAA; 2) the affinity toward the anion exchange membrane, which increased in the sequence PAA < 6-APA < Pen-G.

Electrodialysis of PAA, 6-APA, and Pen-G

Single-Component Electrodialysis

In order to obtain fundamental information, the single-component electrodialysis of PAA, 6-APA, and Pen-G was studied under a constant voltage of 10 V. Their initial concentrations were constant at 25 mmol/dm^3. As can be seen from Fig. 3(a), the removing rates of the three anions from the dilute solution decreased in the sequence PAA > 6-APA > Pen-G, indicating that ionic size may play a key role in individual transport.

The current is the sum of the total ionic fluxes. Its variation with time during electrodialysis was also examined. The results for the individual electrodialysis of PAA, 6-APA, and Pen-G are shown in Fig. 4(a), in which the result for the electrodialysis of a blank solution is also indicated for comparison.

As can be seen from Fig. 4(a), the presence of PAA or 6-APA in the dilute solution resulted in an increase of current compared with the blank

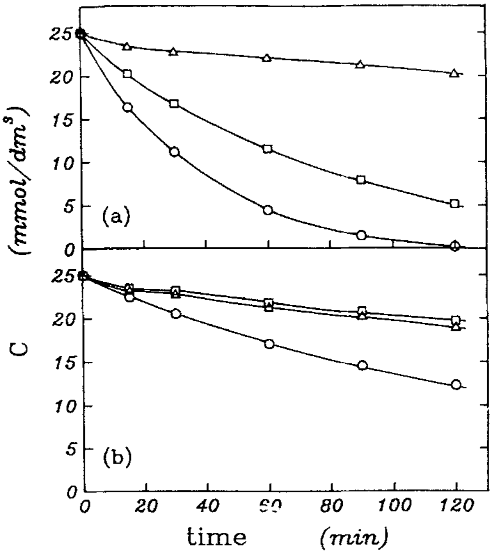


FIG. 3 Removal of PAA, 6-APA, and Pen-G from dilute solution with electrodialysis under a constant voltage of 10 V. (a) Single-component system, (b) ternary-component system. (○): PAA, (□): 6-APA, (△): Pen-G.

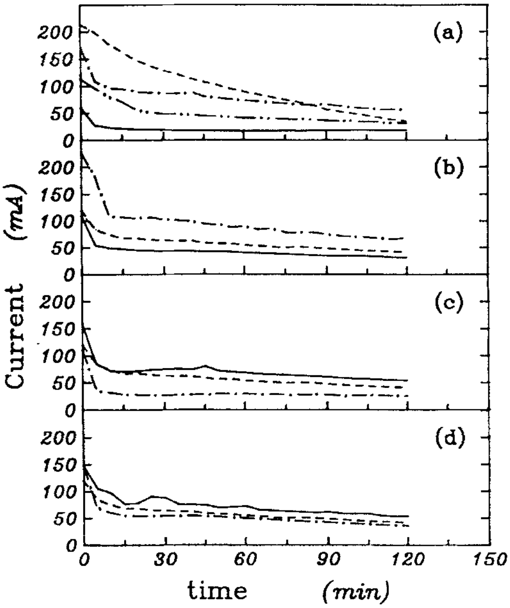


FIG. 4 Variation of current with time under a constant voltage of 10 V. (a) Single component electrodialysis: blank solution (–··–), $[\mathrm{PAA}]_0$ = 25 mmol/dm^3 (---), $[\mathrm{6\text{-}APA}]_0$ = 25 mmol/dm^3 (–·–), $[\mathrm{Pen\text{-}G}]_0$ = 25 mmol/dm^3 (——); (b) Pen-G concentration effect: $[\mathrm{PAA}]_0$ = $[\mathrm{6\text{-}APA}]_0$ = 25 mmol/dm^3, $[\mathrm{Pen\text{-}G}]_0$ = 0 (–·–), 25 (---), 50 (——) mmol/dm^3; (c) PAA concentration effect: $[\mathrm{6\text{-}APA}]_0$ = $[\mathrm{Pen\text{-}G}]_0$ = 25 mmol/dm^3, $[\mathrm{PAA}]_0$ = 0 (–·–), 25 (---), 50 (——) mmol/dm^3; (d) 6-APA concentration effect: $[\mathrm{PAA}]_0$ = $[\mathrm{Pen\text{-}G}]_0$ = 25 mmol/dm^3, $[\mathrm{6\text{-}APA}]_0$ = 0 (–·–), 25 (---), 50 (——) mmol/dm^3.

solution. This is due to the fact that both PAA and 6-APA were dissociated into ionic species. For the cases of the blank solution, PAA, and 6-APA, it was also observed that the current decreased with time during electrodialysis because of the reduction of the buffer agent, PAA, and 6-APA concentrations in the dilute solution. In addition, the current for the electrodialysis of PAA was higher than that of 6-APA. This could be attributed to the fact that 6-APA has a larger ionic size and a higher affinity toward the anion-exchange membrane, which resulted in its lower transport rate.

The significant decrease of current in the presence of Pen-G should be particularly noted. According to Fig. 4(a), the current for the electrodialysis of Pen-G decreased quickly in the first 10 minutes and then remained at a low value throughout the following period. This could be attributed to the fact that Pen-G has the largest ionic size and highest affinity toward the anion-exchange membrane, which resulted in the lowest transport rate through the membrane. Initially, Pen-G was moved to the vicinity of the anion-exchange membrane and sorbed on the membrane surface. Because of its large ionic size, the transport rate of Pen-G through the anion-exchange membrane was very slow, and serious concentration polarization took place in the vicinity of membrane. Hence, the current decreased quickly. As the concentration polarization of Pen-G and its transport rate through the anion-exchange membrane gradually approached a steady state, the current kept a steady value.

After the electrodialysis of Pen-G, we observed that there was a precipitate of Pen-G on the surface of the anion-exchange membrane facing the dilute solution. This indicated that the Pen-G removed from the dilute solution was not completely transported to the concentrate solution. Most of the Pen-G removed was sorbed on the surface of the anion-exchange membrane or precipitated in the vicinity of the membrane. This phenomenon was not observed for PAA and 6-APA. It could be due to the excessive concentration polarization of Pen-G, and also could explain why the current was so small and had a quick decrease in the early period.

Comparison of Single- and Ternary-Component Electrodialysis

The ternary-component electrodialysis of PAA, 6-APA, and Pen-G was compared with their individual electrodialysis under a constant voltage of 10 V and an initial concentration of 25 mmol/dm^3 for each, as shown in Figs. 3(a) and 3(b).

The removal rate of PAA was higher than those of 6-APA and Pen-G in the ternary-component system. Also, the removal rate of PAA in the ternary-component system was smaller than that in the single-component system. This result might be due to the following two factors: 1) the mole fraction of PAA in the dilute solution was smaller in the ternary-component system; 2) Pen-G was sorbed on the surface of the anion-exchange membrane and caused serious concentration polarization in the vicinity of the membrane, and this retarded the transport of PAA.

The removal rate of Pen-G was slightly higher than that of 6-APA in the ternary-component system, which was contrary to what was observed in the single-component system. This indicated that the retarding effect of Pen-G on the transport of 6-APA due to concentration polarization of Pen-G was due to the effect of their ionic size.

Effects of PAA, 6-APA, and Pen-G Concentrations

The effects of PAA, 6-APA, and Pen-G concentrations on their competitive transport with electrodialysis were investigated under a constant voltage of 10 V. The variations of PAA, 6-APA, and Pen-G concentrations in the dilute solution with time during electrodialysis are shown in Figs. 5A, 5B, and 5C. The variations of current with time are indicated in Figs. 4(b), 4(c), and 4(d).

From Figs. 5A(a) and 5A(b), it was found that the removal rate of PAA decreased significantly with an increase of Pen-G concentration. This phenomenon can be attributed to the fact that, with increasing Pen-G concentration, the mole fraction of PAA decreased and the concentration polarization of Pen-G in the vicinity of the anion-exchange membrane became much more serious.

Figure 5A(a) indicates that the removal rate of PAA was reduced remarkably by the addition of 6-APA in the absence of Pen-G. This is due to the fact that the mole fraction of PAA became small when 6-APA was added. However, as shown in Fig. 5A(c), the effect of 6-APA concentration (0–50 mmol/dm^3) on the removal rate of PAA was quite small in the presence of 25 mmol/dm^3 Pen-G. This indicates that the effect of Pen-G on the removal rate of PAA is much larger than that of 6-APA.

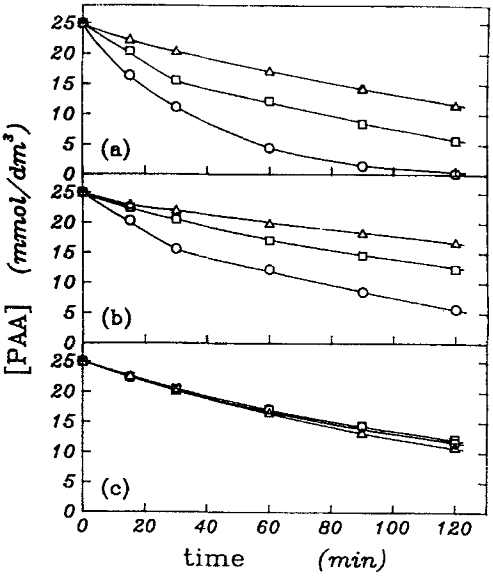


FIG. 5A Effects of 6-APA and Pen-G concentrations on the removal of PAA from dilute solution with electrodialysis under a constant voltage of 10 V. The initial concentrations of PAA/6-APA/Pen-G in dilute solution: (a) 25/0/0 (○), 25/25/0 (□), 25/0/25 (△); (b) 25/25/0 (○), 25/25/25 (□), 25/25/50 (△); (c) 25/0/25 (○), 25/25/25 (□), 25/50/25 (△) mmol/dm^3.

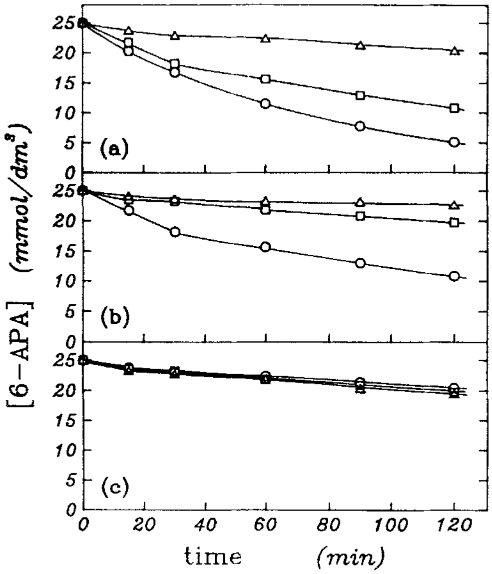


FIG. 5B Effects of PAA and Pen-G concentrations on the removal of 6-APA from dilute solution with electrodialysis under a constant voltage of 10 V. The initial concentrations of PAA/6-APA/Pen-G in dilute solution: (a) 0/25/0 (○), 25/25/0 (□), 0/25/25 (△); (b) 25/25/0 (○), 25/25/25 (□), 25/25/50 (△); (c) 0/25/25 (○), 25/25/25 (□), 50/25/25 (△) mmol/dm^3.

Like PAA, Figs. 5B(a) and 5B(b) showed that the removal rate of 6-APA decreased significantly with an increase of Pen-G concentration. This phenomenon can be attributed to the fact that the mole fraction of PAA decreased and the concentration polarization of Pen-G in the vicinity of anion exchange membrane became much more serious when the concentration of Pen-G increased. Also, Fig. 5B(a) indicates that the removal rate of 6-APA is reduced remarkably by the addition of PAA in the absence of Pen-G because the mole fraction of 6-APA decreases. But from Fig. 5A(c), the effect of PAA concentration (0–50 mmol/dm^3) on the removal rate of 6-APA was very small in the presence of 25 mmol/dm^3 Pen-G, indicating the effect of Pen-G on the removal rate of 6-APA was much larger than that of PAA.

Figure 5C shows that the concentrations of both 6-APA and PAA (0–50 mmol/dm^3) had no significant effect on the removal rate of Pen-G (25 mmol/dm^3).

The effects of Pen-G, PAA, and 6-APA concentrations on the electrodialysis current are shown in Figs. 4(b), 4(c) and 4(d). It can be clearly

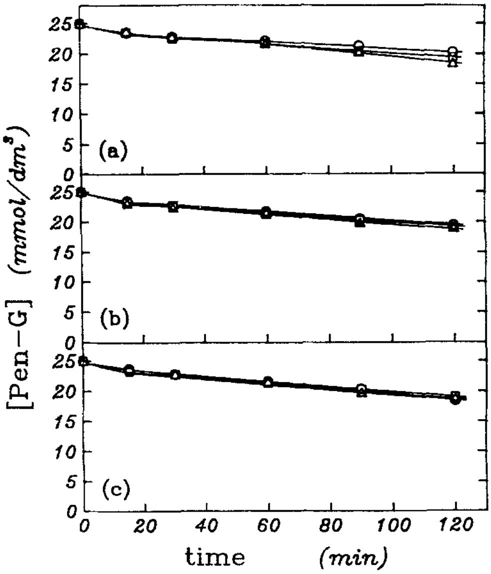


FIG. 5C Effects of PAA and 6-APA concentrations on the removal of Pen-G from dilute solution with electrodialysis under a constant voltage of 10 V. The initial concentrations of PAA/6-APA/Pen-G in dilute solution: (a) 0/0/25 (○), 0/25/25 (△), 25/0/25 (□); (b) 0/25/25 (○), 25/25/25 (□), 50/25/25 (△); (c) 25/0/25 (○), 25/25/25 (□), 25/50/25 (△) mmol/dm^3.

seen that the current increased with an increase of PAA and 6-APA concentrations, while it decreased with an increase of Pen-G concentration. This phenomenon is due to the fact that PAA and 6-APA are dissociated into ionic species and that there is serious concentration polarization of Pen-G in the vicinity of the anion-exchange membrane.

Effect of Electric Field Strength

Electric field strength is an important operational factor for the separation of PAA, 6-APA, and Pen-G with electrodialysis. The experiments were conducted under constant voltages of 3 and 10 V. The dilute solution contained 50 mmol/dm^3 of PAA, 6-APA, and Pen-G initially. The compositions of both the dilute and concentrate solutions were measured. The amounts of PAA, 6-APA and Pen-G sorbed in/on the anion-exchange membrane and precipitated in the vicinity of the membrane (only Pen-G) were determined by mass balance. The variations of these concentrations and amounts with time are shown in Figs. 6A and 6B.

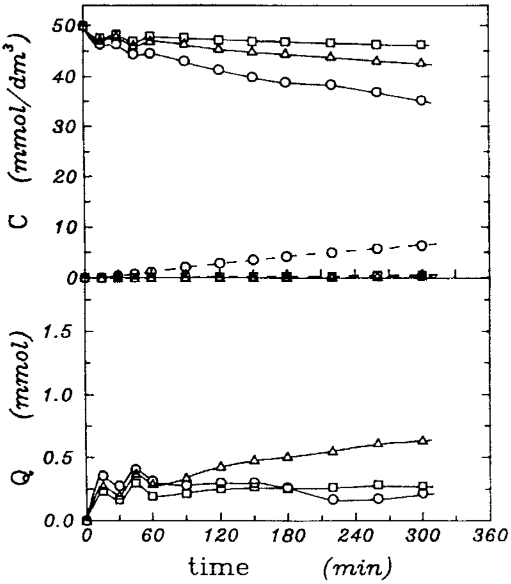


FIG. 6A Time courses for the electrodialysis of PAA, 6-APA, and Pen-G under a constant voltage of 3 V. (a) Variations of the concentrations of PAA (○), 6-APA (□), and Pen-G (△) in dilute solution (——) and in concentrate solution (---) with time. (b) Variations of the amounts of PAA (○), 6-APA (□), and Pen-G (△) sorbed and/or precipitated in/on anion-exchange membrane with time.

According to Figs. 6A and 6B, the transport rates of PAA, 6-APA, and Pen-G from dilute solution to concentrate solution increase with an increase in the electric field strength. However, the amounts of Pen-G and 6-APA sorbed and/or precipitated in/on the anion-exchange membrane also increased with an increase of electric field strength. This reveals that the concentration polarization of Pen-G becomes more serious under higher electric field strength.

From Figs. 6A and 6B it is also seen that the concentration ratio of PAA to 6-APA in the concentrate solution was reduced from 13.3 to 2.8 after 300 minutes when the electric field strength was raised from 3 to 10 V. This indicates that the separation ratio of PAA to 6-APA is reduced with an increase of electric field strength.

The variations of current with time are indicated in Fig. 7. It is reasonable that the current increases with an increase of electric field strength.

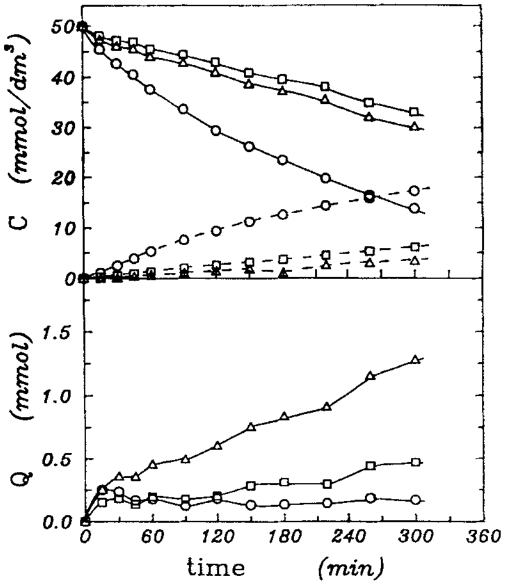


FIG. 6B Time courses for the electrodialysis of PAA, 6-APA, and Pen-G under a constant voltage of 10 V. (a) Variations of the concentrations of PAA (○), 6-APA (□) and Pen-G (△) in dilute solution (——) and in concentrate solution (---) with time. (b) Variations of the amounts of PAA (○), 6-APA (□), and Pen-G (△) sorbed and/or precipitated in/on anion-exchange membrane with time.

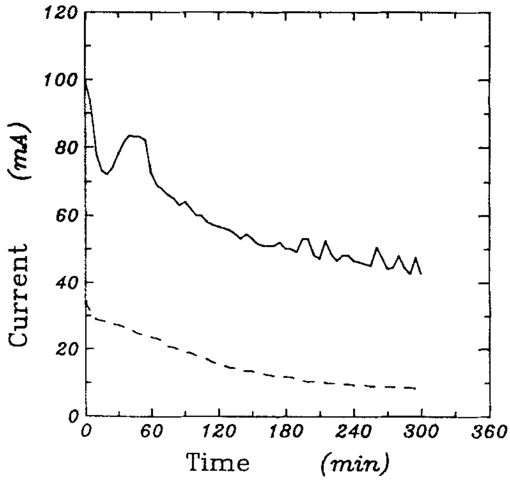


FIG. 7 Variations of current with time. Voltages: 3 (---) and 10 (——) V.

Current Efficiency

Current efficiency is an important performance index for electrodialysis processes. From the data shown in Figs. 6A, 6B, and 7, the variations of the current efficiencies for transporting PAA, 6-APA, and Pen-G with time under constant voltages of 3 and 10 V can be calculated according to Eqs. (2) and (3). The results are shown in Fig. 8.

Under a constant voltage of 3 V, the current efficiencies for transporting PAA, 6-APA, and Pen-G decrease in the sequence PAA (25–65%) $\gg$ 6-APA (0–11%) ~ Pen-G (1–8%). The current efficiencies for PAA, 6-APA, and Pen-G increased with time. This can be due to the sorption and concentration polarization of Pen-G which gradually became steady, and hence the transport of PAA, 6-APA, and Pen-G from dilute solution to concentrate solution became easier.

Under a constant voltage of 10 V, the current efficiency for transporting PAA, 6-APA, and Pen-G decreases in the sequence PAA (15–40%) > Pen-G (8–14%) > 6-APA (5–9%). The current efficiency for transporting Pen-G is larger than that for transporting 6-APA. This can be attributed to the fact that the concentration polarization of Pen-G was larger under higher electric field strength, which strongly retarded the transport of 6-APA. In addition, the current efficiency for transporting PAA decreased

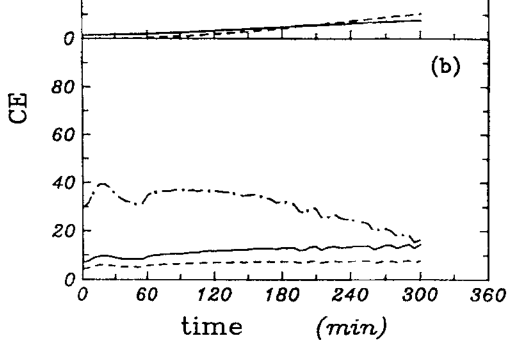


FIG. 8 Variations of current efficiencies with time. Voltages: (a) 3 V, (b) 10 V. (–·–) PAA, (——) 6-APA, (---) Pen-G.

with time. This might be due to the fact that the concentration and mole fraction of PAA in the dilute solution decreased with time.

Although the transport rate of PAA increased with an increase of electric field strength as shown in Figs. 6A and 6B, the current efficiency for transporting PAA under a constant voltage of 10 V was smaller than that under a constant voltage of 3 V. This can be attributed to the fact that the concentration polarization of Pen-G was more serious, and the concentration and mole fraction of PAA in the dilute solution during electrodialysis were lower under a higher current density.

CONCLUSIONS

The separation behavior of PAA, 6-APA, and Pen-G with electrodialysis under constant voltage was studied. The competitive sorption of PAA, 6-APA, and Pen-G in the anion-exchange membrane was dependent on their ionic size and their affinity toward the membrane. The initial sorption rate of PAA was the fastest, and the affinity of Pen-G toward the membrane was the highest. For the electrodialysis of PAA, 6-APA, and Pen-G, their ionic size and affinity toward the anion-exchange membrane also played a key role. The transport rate of PAA was the fastest, the transport rate of Pen-G was the slowest, and Pen-G had serious concentration polarization in the vicinity of the anion-exchange membrane due to its large ionic size and high affinity toward the membrane. With an increase of Pen-G concentration, its concentration polarization in the vicinity of the anion-exchange membrane became very serious, which severely retarded the transport of PAA and 6-APA. The increase of electric field strength accelerated the transport of PAA, 6-APA, and Pen-G but resulted in a more serious concentration polarization of Pen-G and a reduction in the separation ratio of PAA to 6-APA.

The results obtained in this work may be helpful for the application of electrodialysis to enhance the efficiency of the enzymatic hydrolysis of Pen-G.

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NOMENCLATURE

A_m	effective area of membrane (cm^2)
C	concentration of PAA, 6-APA, or Pen-G ($mmol/dm^3$)

C_c	concentration of PAA, 6-APA, or Pen-G in concentrate solution (mmol/dm^3)
CE	current efficiency (%)
F	Faraday's constant (coulomb/mol)
i	current density (mA/cm^2)
N	mole flux of PAA, 6-APA, or Pen-G (mmol/cm^2·min)
Q	quantity of PAA, 6-APA, or Pen-G sorbed and/or precipitated in/on anion-exchange membrane (mmol)
q	quantity of PAA, 6-APA, or Pen-G sorbed in anion-exchange membrane (mmol/g)
t	time (min)
V_c	volume of concentrate solution (dm^3)
[6-APA]	concentration of 6-APA (mmol/dm^3)
[6-APA]$_0$	initial concentration of 6-APA (mmol/dm^3)
[PAA]	concentration of PAA (mmol/dm^3)
[PAA]$_0$	initial concentration of PAA (mmol/dm^3)
[Pen-G]	concentration of Pen-G (mmol/dm^3)
[Pen-G]$_0$	initial concentration of Pen-G (mmol/dm^3)

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