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Cyclic Operation of Forced Flow Electrokinetic Separation for Simultaneous Separation and Concentration of Charged Molecules

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Cyclic Operation of Forced Flow Electrokinetic Separation for Simultaneous Separation and Concentration of Charged Molecules

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Abstract

A new cyclic operation of membrane separation in the presence of an electric field is developed. The microporous membrane/filter acts as a barrier between two adjacent solutions (i.e., the solution in the membrane cell and in the permeate). An electric field is applied across the membrane to induce electromigration of charged molecules whose molecular weights are much smaller than the molecular weight cutoff of the membrane used. The charged molecules move freely through pores of the membrane without hindrance. In the presence of an electric field, the concentration of charged molecules in the permeate stream is determined by the electromigration velocity and the permeation flow rate through the membrane. The permeation rate is controlled by the applied pressure drop, and the electromigration velocity can be controlled by the electric field strength applied. By applying a high electric field and a low pressure drop, the concentration in the permeate stream can be increased, thus resulting in enrichment of the charged molecules in the permeate. By applying an electric field such that the electromigration is in the opposite direction to the permeation flow, the permeate is depleted of the charged molecules. A continuously supplied feed stream to the membrane cell can be processed into a concentrated solution and a depleted solution by alternating the polarity of an electric field. This paper presents the experimental results of a cyclic operation for the simultaneous separation/recovery and concentration of acetate, phenylalanine, glycine, and aspartic acid.

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Key Words: Ion-exchange membrane; Forced flow electrophoresis; Electrokinetic separation; Electrofiltration; Cyclic operation

INTRODUCTION

It is well known that electrically charged particles tend to migrate under the influence of an applied electric field. If the particles are small molecular ions, the phenomenon is called ionic conductance; if they are larger units, such as protein molecules or colloidal particles, it is called electrophoresis. Based upon the electrophoresis phenomenon, a variety of separation methods, techniques, and processes have been developed for separating various substances ranging from rubber latex to enzymes (*1*, *2*). Electrodialysis based upon the ionic conductance phenomenon has been used for several decades for desalting sea and brackish water to render it potable or to produce deionized water for industrial use. Recently, it has been applied to remove salts and acids from pharmaceutical solution and in food processing (*3*), to separate carboxylic acids from one another or from nonpolar compounds (*4*, *5*), and to separate amino acids (*6*, *7*). In electrodialysis, the desalting is based on the electromigration of ions through cation- or anion-exchange permselective membranes that permits the passage of positive or negative ions, respectively. Electrolytic deacidification (*8*) was developed to recover the acid which is used for hydrolyzing starch and proteins. The acid dissociates in the digestion solution in the form of an anion. In the presence of an electric field, the anion migrates into the anodic cell where the anion reacts with a proton and is converted into the acid form. The coupling of electrodialysis and fermentation for simultaneous production and recovery of lactic acid was attempted to remove lactic acid produced from the fermentation broth by electrodialysis, and to maintain the pH of the broth at a favorable value. The attachment of microbial cells in the fermentation broth to the anion-exchange membranes, however, caused an increase in electric resistance and a decrease in the efficiency of electrodialysis (*9*). In most electrodialysis processes, concentration polarization ultimately limits the efficiency. Since the permeability of an ion-exchange membrane is usually significantly higher than that of the adjacent solution, the transport of charged molecules through ion-exchange membranes leads to a decreased concentration of counterions in the boundary layer at the membrane surface facing the processing solution and an increase at the surface facing the electrolyte solution near an electrode. The concentration due to an increase at the membrane surface in the electrode compartments leads to precipitation of salt at the surface. The decrease of the counterions in the processing solution directly affects the limiting current density and increases the electrical resistance in the boundary layer. The increasing electrical resistance of the solution results

in the dissociation of water, leading to pH changes and associated operational problems (*10*, *11*).

Electrokinetic separation devices have been developed using a porous membrane through which charged molecules move freely. The pore size of the membrane is much larger than the size of the charged molecules. In the presence of an applied electric field across the membrane, the transport rate of charged molecules is accelerated or retarded depending upon the charges of the molecules and the strength and polarity of the electric field. Based upon this concept, Bier (*1*) developed forced flow electrophoresis. The same concept has been practiced in electroultrafiltration (*12–16*) and crossflow electrofiltration (*17–20*). Cooper et al. (*21*) modified the original design of a forced flow electrophoresis process to a microelectrophoresis concentration process for the concentration and isolation of dilute contaminants in water. In this system, a filter separates the upstream compartment from the downstream compartment. The downstream compartment has a finite volume. The contaminants, such as 2,4-dichlorophenoloxyacetic acid and 2,4-dinitrophenol, are pulled through the filter and concentrated in the finite volume downstream compartment by the applied electric field, while the contaminated water crossflows through the upstream compartment. In this ionic conductance, electrokinetic process, only ions are transported from the process solution by electromigration through a filter or membrane into the collection compartment where the sweep solution is passed through to collect the ions. There is no convective flow of water through the filter or membrane. For combined separation and concentration purposes, this process is not optimal because the ions separated from the process solution are transferred into the sweep solution and become dilute in the sweep solution again.

In this paper a process incorporating ionic conductance with filtration based upon forced flow electrophoresis is developed to separate and concentrate dilute organic ions. The process utilizes a membrane which has a pore size much larger than the size of the organic ions. The organic ions carried by the pressure-driven filtration flow can pass through the membrane without hindrance exerted by pore walls. An electric field is applied across the membrane. The concentration of the ionic species in the permeate stream is then determined by the electromigration velocity of the ion and the permeation flow rate of water through the membrane. The electromigration velocity of the ion is controlled by the applied electric field strength. The permeation rate of water through the membrane is controlled by the applied pressure. By applying a high electric field strength and a low pressure drop across the membrane, a permeate stream with a high concentration of ions can be obtained. By applying an electric field opposite to the direction of pressure driven water flow through the mem-

brane, the transport of the ions will be retarded, resulting in a pure water permeate stream. If the process is operated in a cyclic mode (that is, switching the polarity of the electric field alternately), the permeate stream with concentrated ions will be collected in one cycle and water will be removed from the system in the next cycle. This mode of operation will find applications in simultaneous reaction and recovery processes, such as continuous fermentation and enzyme reactions, where the products need to be separated and concentrated; also, water should be removed. In this paper an organic ion (acetate) and amino acids (phenylalanine, glycine, and aspartic acid) are used as model compounds to investigate the cyclic operation for the separation and concentration of charged molecules.

PRINCIPLE OF CYCLIC OPERATION OF ELECTROKINETIC SEPARATION

The essence of electrokinetic separation process is illustrated in Fig. 1. A membrane separates the system into an upstream or bulk solution and a permeate stream. The pore size of this membrane is so large that charged molecules of interest can pass through the membrane without hindrance. The solution containing the charged molecules is continuously fed into the bulk solution. The bulk solution is forced through the membrane by an applied pressure gradient. The pressure driven permeation rate is denoted by J_v in Fig. 1. Without an electric field, the concentration of charged molecules in the permeate stream is the same as that in the bulk solution (Fig. 1a). When an electric field is applied across the membrane so that the transport rate of the charged molecules is increased by the electrophoretic force, the concentration in the permeate stream can be increased (Fig. 1b). The increase of the transport rate is μE, where μ is the electromobility and E is the electric field strength in the membrane. When the permeate flow rate is kept constant, the increase of the transport rate will enrich the permeate stream with the charged molecules. If the polarity of the applied electric field were reversed, the transport rate through the membrane would be slowed by the electrophoretic force, resulting in a decrease of the transport rate of the charged molecules by μE. As a consequence, the charged molecules in the permeate stream would be depleted here (Fig. 1c). In this case, water is collected as the permeate. If the process were operated in a cyclic mode, that is, to switch the polarity of the electric field alternately, the permeate with concentrated ions (product) would be collected in one cycle and water would be removed from the system in the next cycle. The extent of enhancement of the product transport rate across the membrane depends on the electromobilities of the charged molecules and the applied electric field strength. If there are two different kinds of charged molecules, the permeate enriched with one of the components will

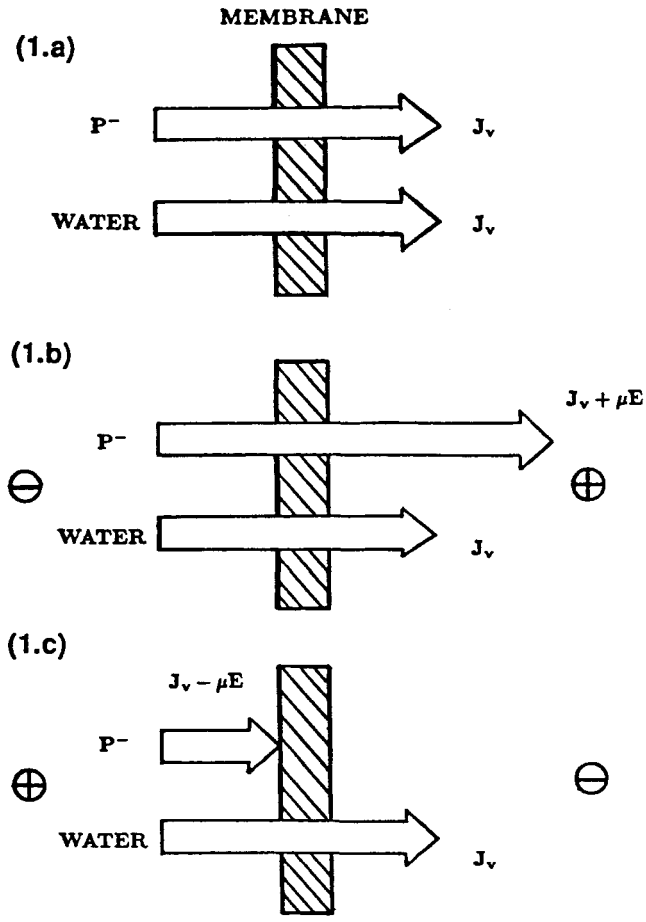

FIG. 1. Principle of cyclic operation of electrokinetic separation. Separation and concentration of charged molecules in the presence of an electric field. (1.a): No electric field. (1.b): An anode is located in the downstream side. The anion is pulled to the permeate stream by the imposed electric field. (1.c): A cathode is located in the downstream side. The transport rate of anions is retarded by μE. The net transport rate through the membrane is $J_v - \mu E$.

be collected in the alternate cycle. To do this, the solution properties, such as pH, should be adjusted so that the two components are oppositely charged. For a mixture of amphoteric components, such as amino acid and proteins, the pH will be adjusted in between the isoelectric points to render one component positively charged and the other negatively charged.

The cyclic operation of the electrokinetic separation process can be analyzed with a material balance around the cell as shown in Fig. 2. It is

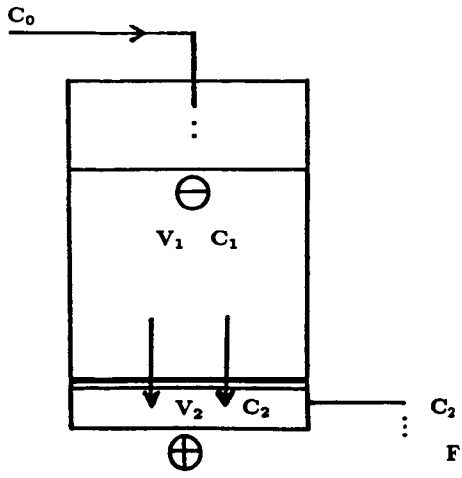

FIG. 2. A schematic diagram of a membrane cell. The feed stream is continuously fed to the membrane cell. The feed stream contains a charged species of interest at a concentration of C_0. The pressure-driven ultrafiltration flow rate is F.

assumed that both the bulk solution compartment V_1 and the permeate compartment V_2 are well mixed. The applied electric field pulls the charged molecules toward the permeate. The material balance equations are as follows:

$$FC_0 - (FC_1 + \mu EC_1A) = V_1dC_1/dt \tag{1}$$

$$(FC_1 + \mu EC_1A) - FC_2 = V_2dC_2/dt \qquad \text{at } t = 0, \quad C_1 = C_0, \quad C_2 = C_0 \tag{2}$$

where C_0, C_1, and C_2 represent the concentration of charged molecules in the feed solution, in the bulk solution compartment, and in the permeate compartment, respectively; F is the permeate flow rate; A is the area of the membrane; μ is the electromobility; and E is the electric field strength in the membrane. By integrating Eqs. (1) and (2), we obtain the concentration in the membrane cell, C_1, and the concentration in the permeate, C_2, as follows:

$$C_1/C_0 = F/\alpha + (1 - F/\alpha) \exp(-\alpha t/V_1) \tag{3}$$

$$C_2/C_0 = 1 + \beta(\exp(-\alpha t/V_1) - \exp(-Ft/V_2)) \tag{4}$$

where

$$\alpha = F + \mu EA$$

$$\beta = (\alpha/V_2 - F/V_2)/(F/V_2 - \alpha/V_1)$$

The simulation was carried out with the parameters V_1 = 210 mL, V_2 = 20 mL, E = 10 V/cm, A = 39.2 cm^2, μ = 6 × 10^{-3} cm^2/V·min, and F = 1.0 or 0.5 mL/min. The results are shown in Fig. 3. The concentration of charged molecules in the bulk solution (i.e., in the membrane cell) decreases with respect to time and levels off when the steady state is reached. The permeate stream, on the other hand, is enriched with the transported charged molecules. The enrichment of the charged molecules

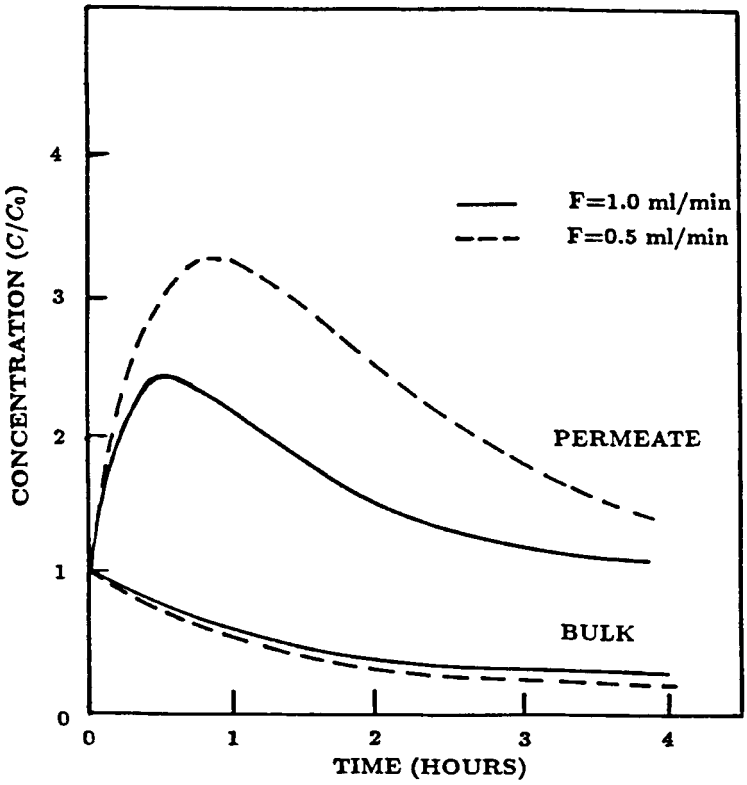

FIG. 3. Simulation results of enrichment of charged molecules in permeate stream. The material balance equations used for this simulation are Eqs. (1) and (2). The values of the parameters are given in the text.

in the permeate depends on the permeate flow rate and the electric field strength applied. At the same electric field strength, the lower permeate flow rate (i.e., $F = 0.5$ mL/min) results in a higher concentration in the permeate. In this process, however, the enrichment of the charged molecules in the permeate stream is not constant. It increases at the beginning, then decreases to the steady-state level. At steady state there is no enrichment in the permeate stream, i.e., the permeate concentration is equal to the concentration in the feed solution. Therefore, the permeate stream collected during the transient period will contain the charged molecules at a higher concentration than that in the feed solution. In other words, a simultaneous separation and concentration can be achieved.

EXPERIMENTAL

Materials

L-Phenylalanine, glycine and L-aspartic acid were obtained from Sigma Chemical Co. (St. Louis, Missouri, USA). The chemicals used were all analytical grade. The acetate solution was prepared by dissolving the glacial acetic acid in deionized water and adjusted with concentrated sodium hydroxide solution to pH 11. The amino acid solutions were prepared by dissolving the amino acids in deionized water. The pH of the solutions was adjusted to desired values by the addition of potassium hydroxide solution. For the solution in the membrane cell at pH 11, 0.02 N sodium or potassium hydroxide solution was used as electrolyte in the anode and cathode compartments. For the solution in the membrane cell at pH 4, 0.1 M sodium acetate buffer of pH 4 was used as electrolyte in the electrode compartments.

Analysis

Acetate concentration was determined by the lanthanum colorimetric method (*22*). L-Phenylalanine concentration was measured by the UV absorbance at 257.5 nm. The other amino acids were determined by the copper complex method (*23*).

Apparatus and Experimental Procedures

A schematic diagram of the apparatus is shown in Fig. 4. The principal component of the system is the Plexiglas membrane cell assembly, and its detailed drawing is shown as Fig. 5. The cell assembly consists of two electrode compartments and one permeate compartment. The top electrode compartment is immersed in the solution and located 5.5 cm above the membrane surface. The volume of this cell is 400 mL. A microporous

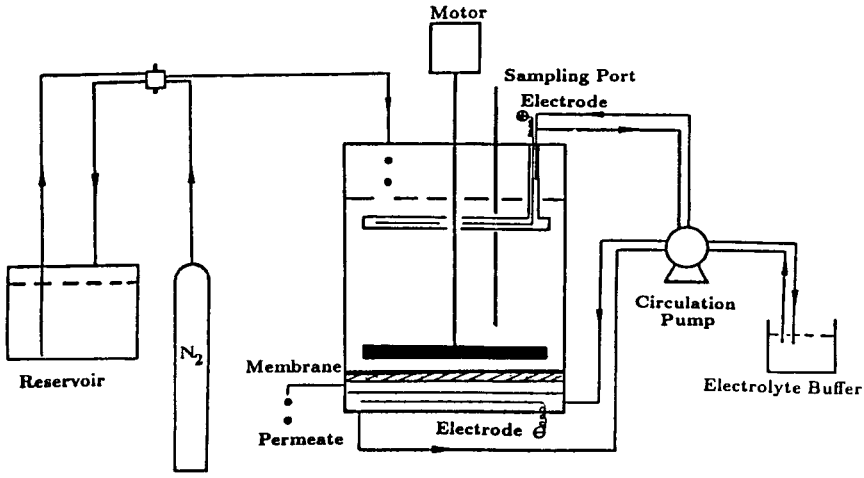

FIG. 4. A schematic diagram of a membrane cell coupled with electrophoresis.

PM-10 membrane (polysulfone, Amicon Co., Massachusetts, USA) was used throughout the experiments. The molecular weight cutoff of this membrane (area 39.2 cm^2) was reported by the manufacturer to be 10,000. L-Phenylalanine, glycine, aspartate, and acetate could move freely through pores of the membrane. In the absence of an electric field, the pressure-driven permeate stream contained these components at concentrations equivalent to those in the membrane cell. This indicates that the transport rates through the membrane were determined by the convective transport by the pressure-driven permeation. In order to prevent pH variation in the electrode compartments due to electrolysis reactions, the buffer electrolyte was circulated in both the anode and cathode compartments. The permeate stream was separated from the bottom electrode compartment by a cellophane film. The top electrode compartment and the solution in the membrane cell were also separated by a cellophane film. Platinum wires were used as electrodes. The temperature of the solution inside the cell was controlled by the heat exchanger coil suspended in the solution. An electric field was applied between the two electrodes by a dc power supply. The permeate flow through the membrane was driven by pressurizing the system with nitrogen. The pressure drop applied across the membrane was in the range of 2 to 3 psig throughout the experiments. A constant liquid level in the cell was achieved by continuous replacement of solution from the pressurized reservoir matched with the permeate rate. For all the experiments, the liquid volume in the cell was kept constant at 210 mL. The bulk solution in the membrane cell was stirred at 200 rpm by a stirrer

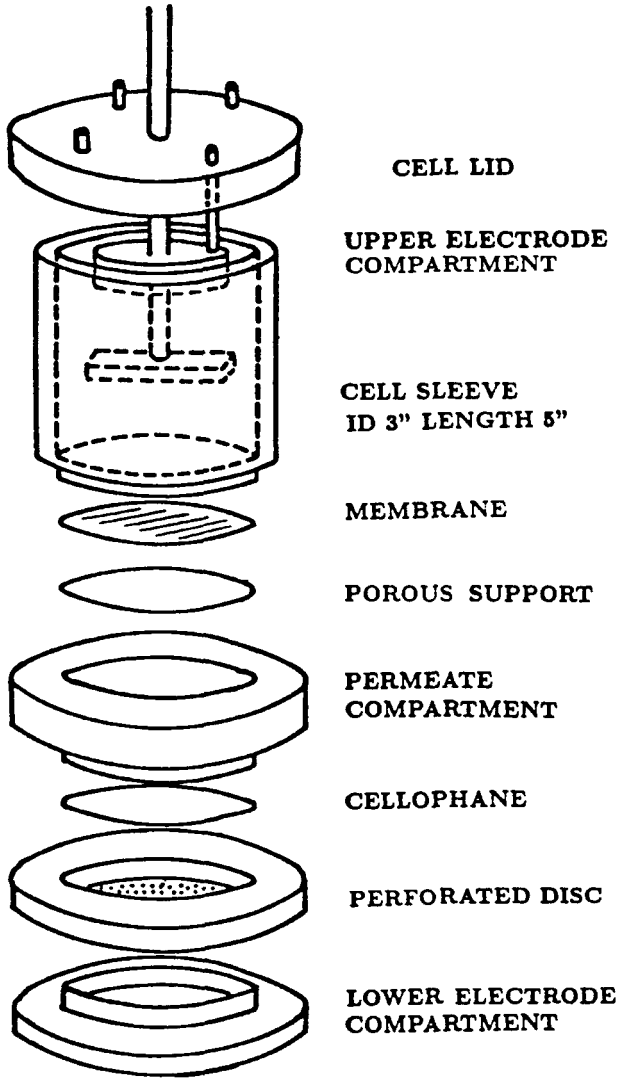

FIG. 5. A membrane cell with two electrode compartments.

located 1 cm above the membrane surface. The temperature of the solution was controlled at 18°C. Typical experiments were run by initially charging the membrane cell to a desired volume with feed solution. The reservoir was charged with the feed solution, too. At this point the nitrogen cylinder was opened to pressurize the reservoir and the cell. The feed solution was

supplied continuously to the membrane cell by gravity, while the liquid volume inside the cell was kept constant. Electrolyte buffer solution was circulated between the two electrode compartments. The voltage was applied between two electrodes, and the experiment was started.

RESULTS AND DISCUSSION

Recovery and Concentration of Acetate Ions

The enrichment of acetate ions in the permeate was first carried out. The feed solution contained 0.1% acetic acid. In order to have all the acetic acid molecules ionized, the pH of the solution was adjusted to 11 by adding sodium hydroxide solution. Figure 6 shows the experimental results. The permeation rate was maintained at 0.5 mL/min, and the voltage applied between two electrodes was 250 V. Since the anode was located below the permeate compartment and acetate ions are negatively charged, the permeate was enriched with acetate ions during the transient period while the concentration in the bulk solution decreased continuously. The maximum concentration of acetate in the permeate was about 1.7 times of the feed stream. The trends shown in Fig. 6 are consistent with the predictions shown in Fig. 3. In an ideal case, the amount of acetate ions depleted from the bulk solution should be the same as the gain of acetate in the permeate. The experimental results, however, showed that the loss in the bulk solution was larger than the gain in the permeate collected. This discrepancy could be attributed to incomplete mixing in the permeate compartment. In the permeate compartment, the acetate was more concentrated near the surface of the cellophane film because of the electrophoretic migration of the acetate ions toward the cellophane film below which the anode was located. This nonuniform concentration of acetate in the permeate compartment was experimentally observed. The acetate concentration in the permeate compartment after the membrane cell was disassembled was much higher than that in the permeate. As mentioned earlier, steady-state operation cannot achieve separation or concentration in this process. In other words, the permeate concentration is the same as the feed solution concentration at steady state. Therefore, in order to use the membrane cell for a continuous processing of the feed solution, the cyclic mode operation was employed. With the continuous, cyclic operation, the feed stream is continuously fed to the membrane cell and two permeate streams are collected alternately; one contains acetate at a higher concentration than that in the feed stream and the other at a very low acetate concentration. Figure 7 shows the results of the cyclic operation. In the first half cycle, 200 V with the anode below the permeate compartment was applied, thus enriching

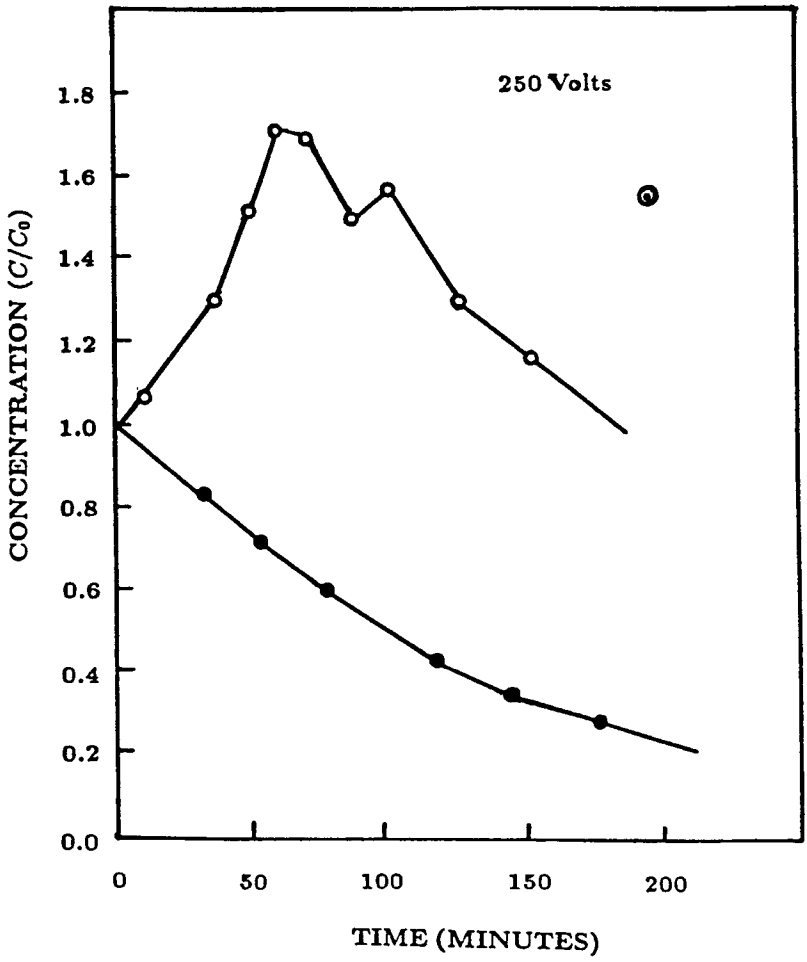

FIG. 6. Concentration of acetate solution (C_0 = 0.1%) with a permeation rate of 0.5 mL/min: (○) in the permeate stream; (●) in the membrane cell, bulk solution; (⊙) acetate concentration in the permeate compartment at the end of the experiment.

the permeate with acetate ions. The pressure-driven permeation rate was kept constant at 0.5 mL/min. The concentration in the permeate was increased up to twice as much as that in the feed solution. During this first half cycle, the acetate ions were removed from the membrane cell and concentrated in the permeate stream. After the electrical polarity was reversed (400 V with the cathode located below the permeate compartment), the concentration of acetate ions in the permeate decreased very

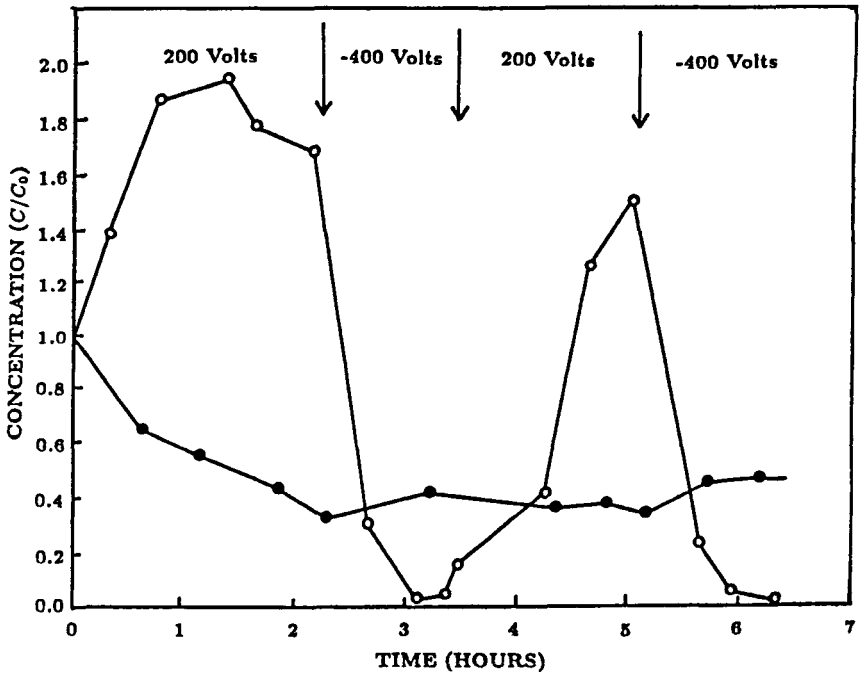

FIG. 7. Cyclic operation of the electrokinetic separation of acetate solution (C_0 = 0.1%) with a permeate flow rate of 0.5 mL/min. The experimental results with two cycles are shown: (○) in the permeate stream, (●) in the membrane cell.

rapidly to almost 0%, while the concentration in the bulk solution increased slowly. This latter half cycle is considered as a stage of the water removal from the solution in the membrane cell. The second cycle was started when the polarity (200 V) was reversed. The results followed the same trends as that in the first cycle. These results clearly demonstrate the feasibility of cyclic operation for simultaneous recovery and concentration.

Recovery and Concentration of Amino Acid

Amino acids are amphoteric in nature. These molecules can be protonated when the pH of the solution is lower than the isoelectric point, thus forming positively charged species. Similarly, for pH values higher than the isoelectric point, negatively charged species are formed. Therefore, the recovery and concentration of amino acids can be achieved by the cyclic operation. The amino acids used in this study were phenylalanine, glycine, and aspartic acid. The feed solutions were adjusted to pH 11 by adding

potassium hydroxide. At pH 11, both phenylalanine and glycine are anions because their isoelectric points are 5.9 and 6.0, respectively. In order to enrich these anions in the permeate, the electrode in the permeate compartment was used as an anode. The solution containing phenylalanine at a concentration of 1% was first used as a feed solution. The permeation rate was maintained at 2 mL/min. The first half cycle was carried out at 75 V. The results are shown in Fig. 8. As expected, the permeate was enriched with phenylalanine. However, the enrichment was only about 10%. The low enrichment was due to the low electric field strength and the relatively high permeate flow rate (2 mL/min). When the electric polarity was reversed with the cathode in the permeate compartment (170 V between the two electrodes), the concentration of phenylalanine in the permeate stream decreased, but the extent of depletion was not significant. This was also due to a relatively high permeation rate. To achieve a significant enrichment of the permeate with phenylalanine, the flow rate was reduced to 0.5 mL/min. As shown in Fig. 9, the permeate concentration was increased up to three times higher than the concentration in the feed

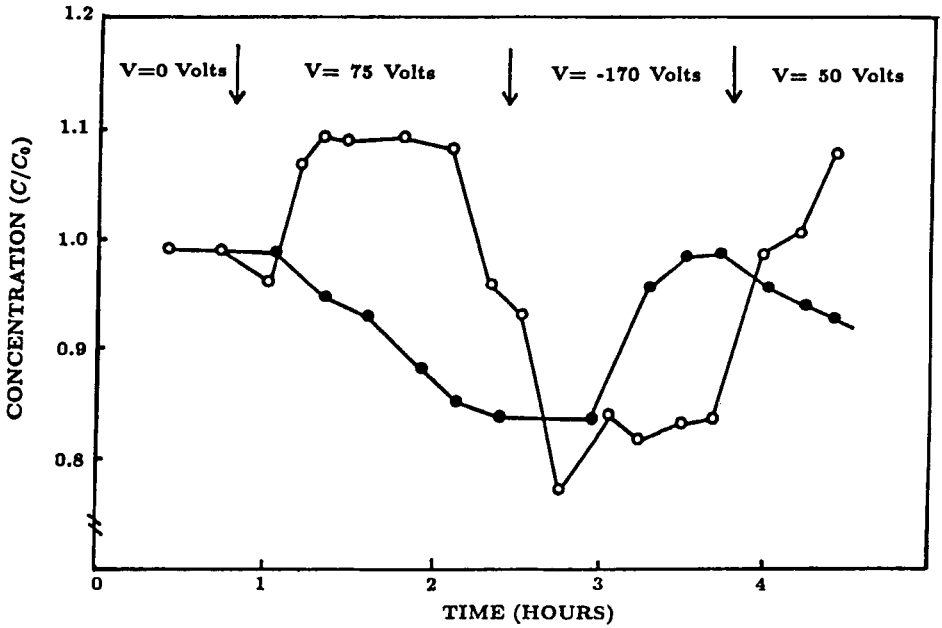

FIG. 8. Cyclic operation for the separation and concentration of phenylalanine (C_0 = 1%). The permeation flow rate was relatively high, 2 mL/min: (○) in the permeate stream, (●) in the membrane cell.

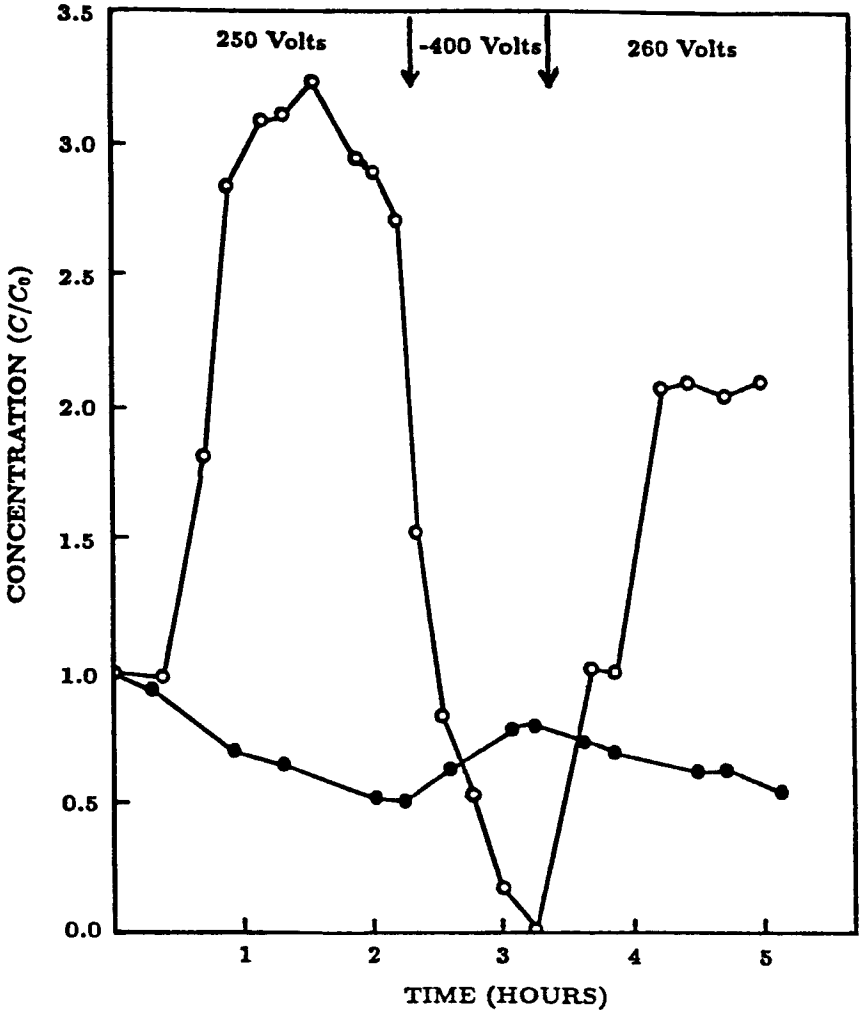

FIG. 9. Cyclic operation for the separation and concentration of phenylalanine (C_0 = 0.1%). The permeation flow rate was relatively low, 0.5 mL/min: (○) in the permeate stream, (●) in the membrane cell.

solution during the first half cycle with 250 V. It dropped almost to zero when the polarity was reversed, so that the cathode was in the permeation compartment (V = 400 V). A similar experiment was also carried out with glycine. As shown in Fig. 10, the recovery and concentration of glycine was also achieved.

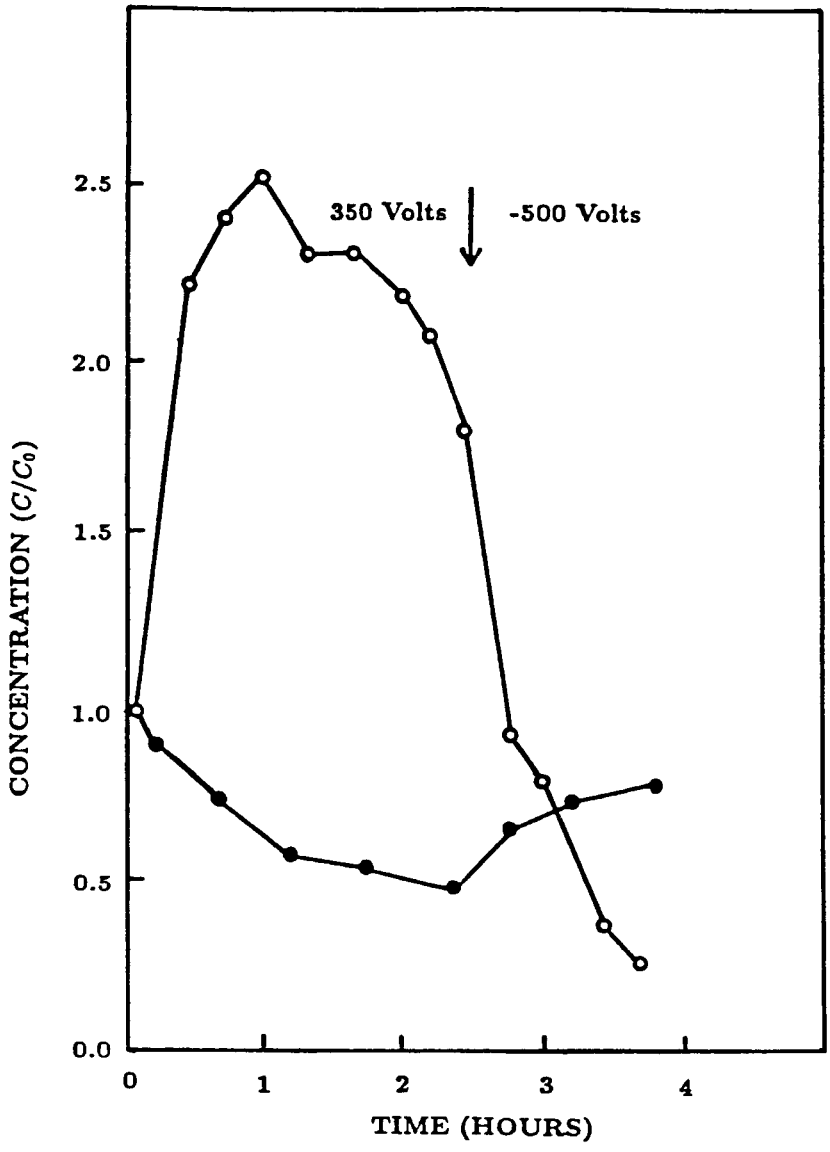

FIG. 10. Concentration of glycine (C_0 = 0.05%) with the permeation flow rate at 0.5 mL/min: (○) in the permeate stream, (●) in the membrane cell.

Concentration of a Mixture of Amino Acids

A mixture of phenylalanine and glycine was chosen as a model mixture. The process solution contained equimolar concentrations of each amino acid, and the pH of the solution was adjusted to 11 by adding sodium hydroxide. The isoelectric points of phenylalanine and glycine are 5.9 and 6.0, respectively (*24*). Therefore, the phenylalanine and glycine molecules in the solution at pH 11 are anions. In the presence of an electric field, the direction of electromigration of phenylalanine is expected to be the same as that of glycine. The experimental results are shown in Fig. 11. The permeation rate throughout the experiment was constant at 0.5 mL/min. The voltage applied during the first half cycle was 200 V. The extents of enrichment in the permeate stream for both phenylalanine and glycine were about the same. The trends shown in Fig. 11 were followed as expected. Therefore, the recovery and concentration of these two amino acids in the permeate stream was achieved simultaneously. This is because the phenylalanine and glycine have very close isoelectric points. At pH 11,

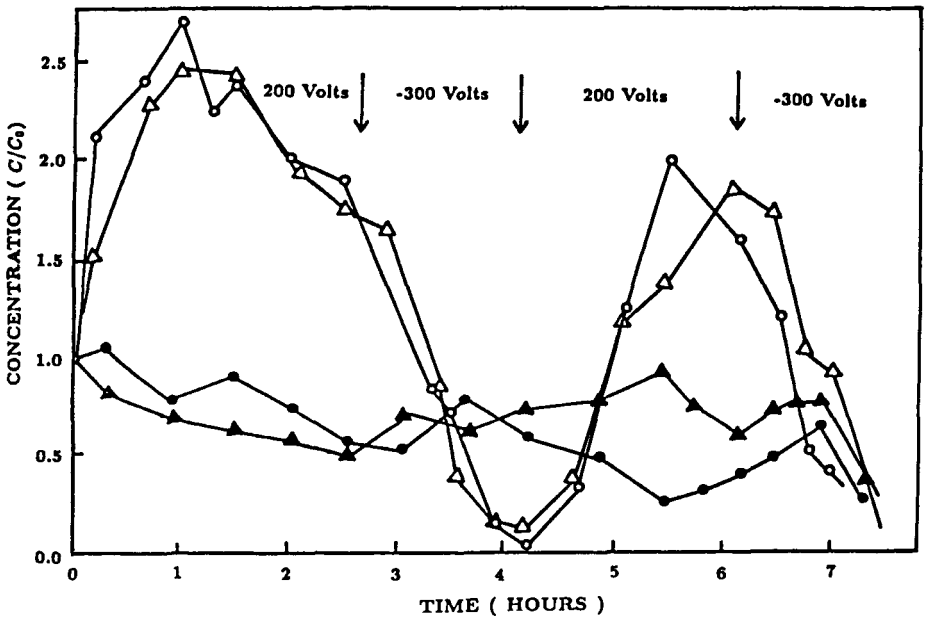

FIG. 11. Cyclic operation for concentration of a mixture of phenylalanine (C_0 = 0.1%) and glycine (C_0 = 0.045%) with a permeation flow rate of 0.5 mL/min: (○) glycine in the permeate, (●) glycine in the membrane cell, (△) phenylalanine in the permeate, (▲) phenylalanine in the membrane cell.

most phenylalanine and glycine molecules are dissociated and carry negative charges. Under the influence of an electric field, they migrated toward the anode at almost the same velocities, which cannot result in a separation. The separation of phenylalanine from glycine at pH 11 is not possible with this process; however, the concentration of both of these amino acids could be achieved.

Separation of Amino Acids

A mixture of amino acids with different isoelectric points can be separated by adjusting the pH of the solution in this electrokinetic separation process. In order to demonstrate the separation capability of this process, a pair of amino acids with a wider difference in isoelectric points was then employed in the system. Phenylalanine (pI 5.9) and aspartic acid (pI 2.77) (*24*) of equal molarity were mixed in water. The pH of this solution was adjusted to 4 by adding sodium hydroxide. At pH 4 most of the phenylalanine molecules remain slightly positively charged or almost neutral; only a small fraction of them carry a net positive charge. The ratio of the positively charged form to the neutral molecules can be calculated by the Henderson–Hasselbalch equation (*25*). On the other hand, most of the aspartic acid molecules carry negative charges at pH 4. Therefore, the separation of these two amino acids can be carried out. As shown in Fig. 12, when an electric field (400 V) was applied with the anode located below the permeate compartment, the aspartic acid concentration in the permeate could increase up to three times higher than the feed concentration while the phenylalanine concentration remained almost constant and equivalent to the feed concentration. The concentration of phenylalanine in the permeate is nearly the same as that in the feed solution because of the slightly positive or neutral charge of phenylalanine at pH 4.0. The separation of these two amino acids was achieved in the sense that the permeate stream is more concentrated with aspartic acid while the concentration of phenylalanine remains nearly equal to that in the feed stream. However, the aspartate concentration in the permeate stream decreased very rapidly and even dropped below the feed concentration. This phenomenon is different from those for the cases with phenylalanine, glycine, and acetate as shown in Figs. 7, 9, and 10. As mentioned earlier, this was partially due to the accumulation of aspartate near the cellophane film which separates the permeate stream from the electrolyte solution in the bottom electrode compartment. Also, to check the possibility of the transport of aspartic acid through the cellophane film toward the anode, the membrane cell was disassembled and the concentration of aspartic acid in the anolyte solution of the bottom electrode compartment was measured. Indeed, aspartic acid

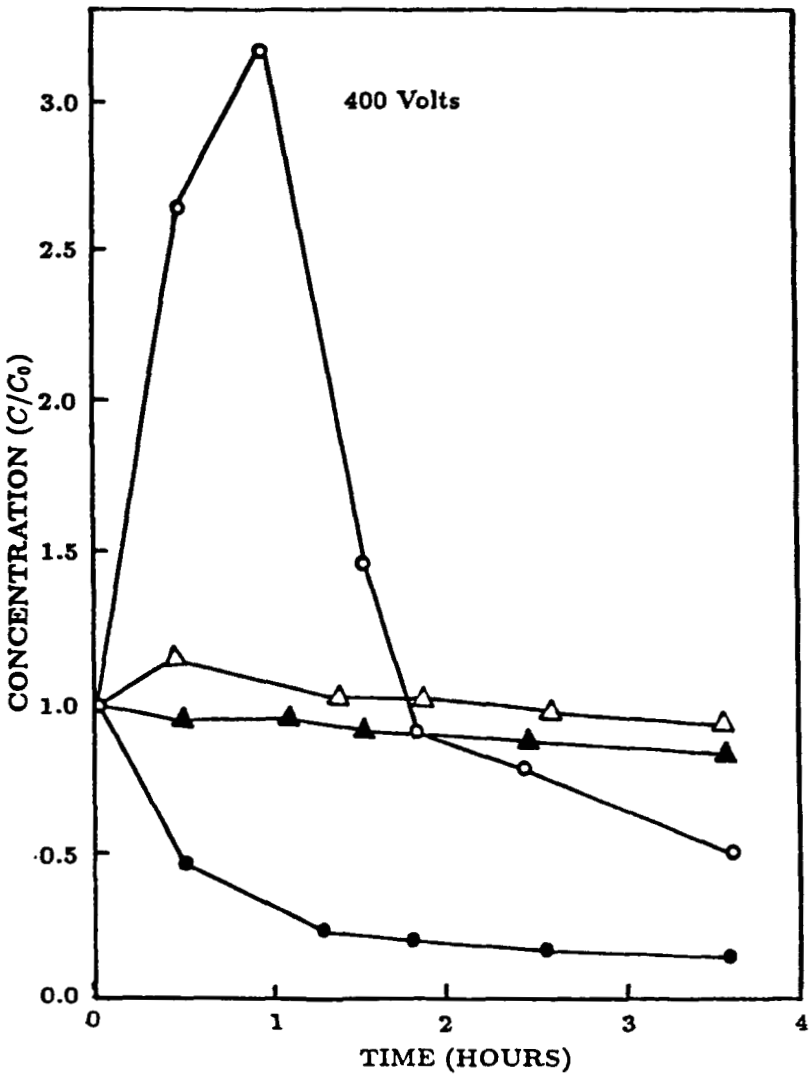

FIG. 12. Separation of phenylalanine (C_0 = 0.1%) and aspartic acid (C_0 = 0.08%) and the concentration of aspartic acid in the permeate stream. The permeation flow rate is 0.5 mL/min: (○) aspartic acid in the permeate stream, (●) aspartic acid in the membrane cell, (△) phenylalanine in the permeate stream, (▲) phenylalanine in the membrane cell.

was detected. However, the transport of aspartic acid through the cellophane film cannot be a serious problem. It can be prevented by replacing the cellophane film with a cation-exchange membrane which rejects anions.

CONCLUSIONS

The cyclic operation of the electrokinetic separation process which combines ultrafiltration with ionic conductance can separate and concentrate dilute solutions of organic acid and amino acids. It can be carried out continuously by alternating the polarity of an applied electric field. To achieve the separation of amino acids, the pH of the solution should be adjusted in between their respective isoelectric points. A pH higher or lower than the isoelectric points of the amino acids can also result in concentrating the amino acids. Another area of potential application for this process is enzyme reaction in a membrane reactor. Enzymes here are retained by a membrane in the reactor while the product is continuously removed in the permeate. If the product from an enzyme reaction were electrically charged, it would be preferentially removed from the reaction solution by an electric field and enriched in the permeate stream. This would be particularly attractive for enzyme reaction systems governed by product inhibition. The same is true for fermentation processes such as lactic acid fermentation, acetic acid fermentation, and anaerobic digestion, to name a few.

NOTATION

A	membrane surface area (cm^2)
C_0	concentration in feed stream (wt%)
C_1	concentration in the membrane cell (i.e., in the bulk solution) (wt%)
C_2	concentration in the permeate stream (wt%)
E	electric field strength in the membrane (V/cm)
F	permeation flow rate (mL/min)
J_v	permeation flux (cm/min) ($= F/A$)
t	time (min)
V_1	liquid volume in the membrane cell (mL)
V_2	liquid volume in the permeate compartment (mL)
μ	electromobility (cm^2/V/min)

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