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ELECTROMEMBRANE SEPARATION OF MINERAL SUSPENSIONS: INFLUENCE OF PROCESS PARAMETERS

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ABSTRACT

Results of a parameter study concerning cross-flow electromembrane separation of a solid/liquid suspension containing silicium oxide particles are presented. The effects of various operation parameters such as applied voltage (0–200 V), feed concentration (1–5 wt.%), temperature (15–50°C), transmembrane pressure (1–3 bar), and cross-flow linear velocity (0.1–0.34 m/sec) are examined and discussed.

The results clearly demonstrate the utility of the electromembrane process for concentration of mineral suspensions. Applied electric field strength of $E = 133\,\mathrm{V/cm}$ leads to permeate flux enhancement by 366% (enhancement factor 4.7) when a suspension containing 50 g/L of SiO_2 is treated at appropriate operation conditions.

It is proved that applying a constant electric field across the membrane significantly improves the permeation rate by reducing

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the solute-related resistance. Optimal experimental conditions were found at which the solute resistance could be practically eliminated. Data, which show that the influence of the temperature on the permeate rate is more sensitive when an electric field is applied, were represented.

Key Words: Membrane fouling; Electro-filtration; Separation; Electric field; Particle suspension; Electrophoresis

INTRODUCTION

Flux decline with time due to concentration polarization, filter-cake formation, and membrane fouling is a serious problem in membrane filtration. Various anti-fouling techniques have been developed to overcome this phenomenon, which hinders the widespread application of the membrane separation. In some cases, the problem has been solved with relative ease by feed pretreatment (pH or ionic-strength adjustment), selection of appropriate membrane material or, module configuration (1).

In other cases, the membrane fouling has been minimized by intensifying the hydrodynamics conditions in the membrane module. Recently, high "cross-flow" velocities (opposite to "dead-end" flow) have been used in an effort to increase permeate fluxes, introducing shear on the membrane's retentate side. Static or/and dynamic turbulence promoters have been inserted in the feed channels to create additionally turbulent eddies and shear stresses (2,3). Gas sparging, i.e., injecting of gas bubbles into the cross-flow stream to increase the turbulence, has also been applied (4,5). None of these methods could be considered as a universal solution in prevention of membrane fouling.

A promising approach towards improving the permeate flux in cross-flow and axial-membrane filtration is the use of an external electric field (6–10). The electromembrane separation represents a hybrid physical process, which combines the characteristics of pressure-driven membrane separation and electrophoretic transport of charged particles due to electrokinetic or zeta potentials. The electrophoretic strength, if directed opposite to the convective pressure-driven force, causes changes in the particle's trajectories. When an electric field of sufficient strength is applied to the solid–liquid feed stream, the mobile charged particles of the suspension migrate away from the retentate side of the membrane towards the appropriate electrode (electrophoresis). As a result, a "clear" boundary layer at the membrane–solution interface is created and the initial permeate flux could be kept constant. Moreover, the electric field induces in many cases a movement of the suspension's liquid (the continuous phase of the

suspension) through the stationary charged membrane surfaces, which leads to an additional enhancement of the filtration flux due to electroosmosis.

It must be emphasized that the main advantage of the electro-filtration as an anti-fouling technique lies in the possibility to prevent the membrane fouling without introducing additional shear strengths. It is gentle for the membrane material and harmless to the treated system.

The purpose of this paper was to identify important operation factors for flux improvement in electromembrane separation of mineral suspensions. To study the performance characteristics under a variety of conditions, the effect of main process parameters (electric field strength, feed concentration, transmembrane pressure and cross-flow velocity, and temperature) on the filtration efficiency of an aqueous–SiO_2 suspension was examined. The individual resistances (membrane-related and solute-related) to the permeate flux were determined for all the experimental conditions. Thus, the significance of each of the above-mentioned resistances to the overall resistance of the electromembrane separation process was known.

MATHEMATICAL DESCRIPTION OF ELECTROMEMBRANE SEPARATION

There is no generally accepted comprehensive model describing all the processes involved in the electrically enhanced cross-flow membrane separation. Usually, models for conventional cross-flow filtration have been adapted for this purpose (6,11,12).

In this study, the discussion is based on the resistance analysis, which gives reasonable results for interpretation and comparison of the experimental data. For this purpose, a modification of the "resistance-in-series model" proposed by Robinson et al. (13) is used. The permeate flux J_P is expressed as

$$J_P = \frac{Q_P}{A_M} = \left(\frac{\Delta P - \Delta \Pi}{R_T}\right) \tag{1}$$

where the total resistance to the membrane permeation R_T represents a sum of two main hydraulic resistances:

$$R_T = R_M + R_S \tag{2}$$

R_M is the membrane (filter medium) resistance due to the porosity of the membrane and the internal-pore residual fouling. R_S is the apparent solute-related resistance owing to phenomena like concentration polarization, cake or gel layer formation, membrane surface fouling by adsorbed solute particles, and pore occlusion.

EXPERIMENTAL

Materials and Reagents

Feed Solutions

The solid–liquid feed suspension was prepared using silicium oxide powder (SIKRON SF6000) obtained from Quarzwerke, Frechen, Germany. The properties of the feed system are summarized in Table 1. The mean particle's diameter was 3 μm, and zeta potentials and electrophoretic mobility as reported by Weigert et al. (14,15). The conductivity of the feed suspensions ranged from 25 to 100 μS/cm for various feed batches.

Membranes

In all the experiments, a micro-filtration membrane (No. NRG29325: modified nylon 6,6: Pall Europe Ltd., Portsmouth England) with a nominal pore size of 0.2 μm was used. Two ion-permeable membranes were selected as a barrier between the main streams (feed and permeate) and the electrode's rinsing electrolyte: anion exchange membrane (AHA, NEOSEPTA®, Tokuyama Corp., Tokyo, Japan) and cation exchange membrane (CMH, NEOSEPTA, Tokuyama Corp., Tokyo, Japan)

Experimental Set-Up

A schematic diagram of the cross-flow electromembrane equipment is shown in Fig. 1. The experimental set-up comprised a filter test installation

Table 1. Characteristics of the Feed Suspension

Parameter	Value
Dispersed phase	Cristoballite SF 6000 (99% SiO_2) $d_m = 3$ μm; d (95%) < 10 μm
Continuous phase	Distilled water
Feed concentration	10 ÷ 50 g/L
Feed volume	5 L
Feed pH-value	7–8
Particle's mobility	−3.69 (μm/sec)/(V/cm)
Particle's zeta-potential	Max value: −80 mV (at pH ~8.5) Min value: −10 mV (at pH ~2)

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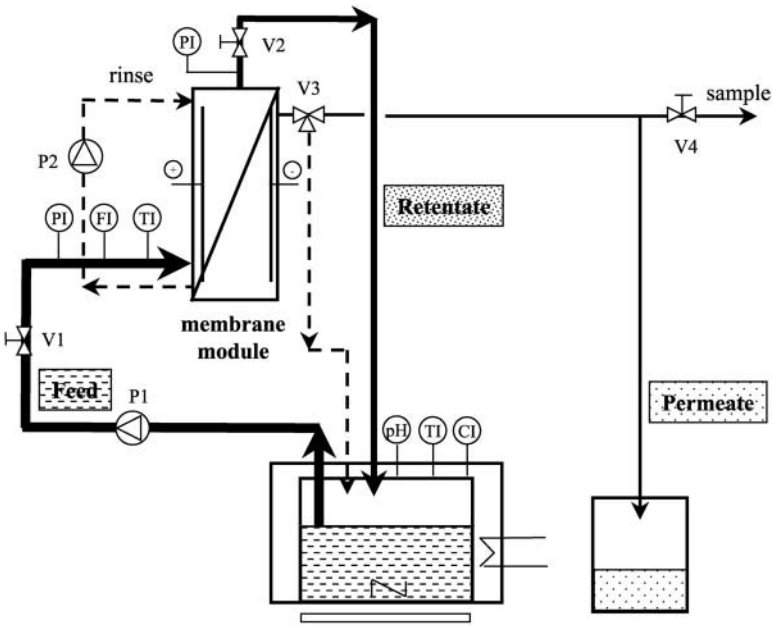

Figure 1. Schematic diagram of the experimental set-up.

(Amafilter Membrantechnik GmBH, Düsseldorf, Germany), a membrane module with one flat-sheet membrane and two electrodes, and a DC power supply unit (Austrian Research Centers, Seibersdorf, Austria) for generation of a constant electric field.

The main module characteristics are given in Table 2. The module assembly consisted of two main chambers, for feed and for permeate. Two platinized titanium-mesh electrodes are included on either side of the membrane, which permitted a constant electric field to be produced across it. The anode was situated on the feed side because the silica particles are negatively charged in the

Table 2. Membrane Module Characteristics

Module Characteristics	Dimensions
Effective membrane area	66.5 cm^2
Feed channel dimensions	19.3 cm × 3.5 cm × 0.7 cm
Electrode area	58.80 cm^2
Distance between electrodes	1.5 cm

entire pH range studied whereas the cathode was in the permeate side. In this way, a continuous electrophoretic velocity was imposed on the SiO_2 particles of the feed suspension, directed opposite to their convective movement towards the membrane. It has to be mentioned that a large channel depth of 0.7 cm was chosen to assure that low retentate circulation rates could be achieved using the available equipment. Therefore, the distance between the electrodes was relatively large (1.5 cm). The electrodes were rinsed continuously by an electrolyte solution (Na_2SO_4 salt dissolved in distilled water) to avoid changes in the process streams due to gas formation and other electrochemical reactions that occur at the electrodes. The feed and permeate streams were separated from the electrolyte solution by two ion-permeable membranes as given above: the anion-exchange membrane on the feed side and the cation-exchange membrane on the permeate side. Polymer spacers were used to form four separate flow channels (feed and permeate channels on both sides of the membrane and two channels for the rinsing electrolyte solution).

Experimental Procedure

All the experiments were conducted in a way to simulate a continuous-flow steady-state separation process. Both retentate and permeate were continuously recycled to the feed reservoir to keep the solute concentration and the solution volume constant. The suspension in the feed tank was maintained homogeneous by intensive agitation (Mixer: Heidolph, Model 50111, Germany) and kept at a constant temperature. The rinsing electrolyte solution was also pumped continuously in a closed loop (IKA-Schlauchpumpe PA-SF, Janke and Kunkel, Germany).

The following parameters were controlled during the experiments: pressure at inlet and outlet of the membrane module, feed and permeate-flow rates, pH (pH-electrode: SenTix41, Microprocessor pH96, WTW, Weilheim, Germany), conductivity and temperature of the feed (Conduktometer LF191, WTW, Weilheim, Germany). The applied electrical voltage (from 0 to 200 V) and the current were also measured continuously (Series Multimeter Fluke 75, USA).

The values of the retentate velocity v_F (water as feed) in the flow channel of the membrane cell, are given in Table 3.

The permeate flow was measured periodically by means of a graduated cylinder tube installed on the permeate outlet. The time interval for collection of exactly 4 mL of the permeate was measured three times and the permeate flux J_P was then calculated. The discharged permeate was returned instantly to the feed tank.

The pressure conditions in the system were varied using a valve installed in the retentate line outlet. The transmembrane pressure difference ΔP was

Table 3. Values of the Feed-Flow Velocities Studied

Q_F (L/hr)	V_F (m/sec)	Re_w
120	0.14	1634
200	0.23	2684
300	0.34	3968

calculated according to Eq. (3):

$$\Delta P = \frac{P_{in} + P_{out}}{2} \tag{3}$$

The permeation-rate data were obtained to determine the influence of main operation parameters in the following ranges: electrical voltage (from 0 to 200 V), flow rate (from 120 to 300 L/hr), pressure at the module outlet (from 1 to 3 bar), temperature (from 15 to 50°C) and feed concentration (from 10 to 50 g/L).

All experimental permeate flux data, shown in the figures, are steady-state values. The values of the membrane resistance R_M (at $E = 0$ or $E_{ap} \neq 0$), given in the tables, were calculated on the basis of experimental results obtained with distilled water (as feed) at the same operation conditions.

RESULTS AND DISCUSSION

Influence of the Electric Field Strength

The difference in the membrane separation behavior, when applying electric field, is studied at various operation conditions. Comparison of typical flux changes with time in conventional micro-filtration (zero electric field) and electro-filtration (with a constant electric field) is shown in Fig. 2 (feed concentration 50 g/L, cross-flow velocity 0.23 m/sec and $\Delta P = 2.1$ bar). Similar kinetic profiles were also attained at the other operation conditions tested. As expected, an initial period of a rapid and significant flux decline at zero electric field ($U = 0$) was observed. The reason could be phenomena like concentration polarization, surface fouling, and/or pore occlusion. The initial period was then followed by a long-term gradual flux decrease until a near-steady state of permeate flux was reached. It is seen that the permeate flux diminishes more then four times (from 172.5 to 39.3 L/m^2 hr) in the course of a 6-hr experimental run.

When a constant electric field was applied ($U = 200$ V, resp. $E_{ap} = 133$ V/cm; $I_{mes} = 35$ mA), the system behavior was found to be completely

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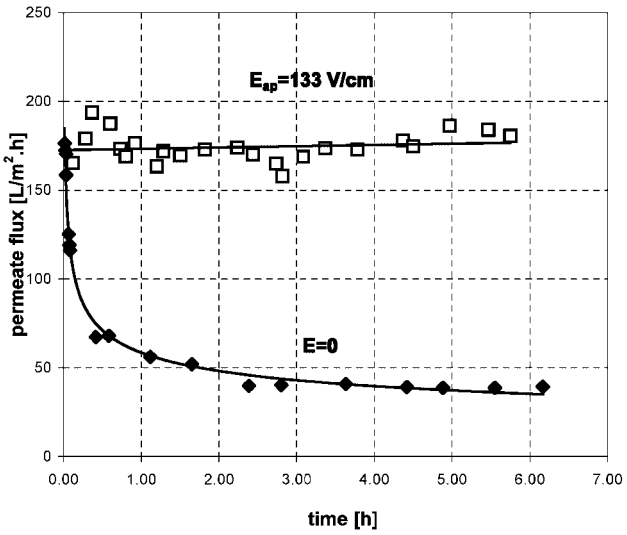

Figure 2. Comparison of kinetics profiles under conventional micro-filtration and electro-filtration ($\Delta P = 2.15$ bar, $v_F = 0.23$ m/sec, $C_F = 50.3$ g/L, $T = 20$°C).

different. The permeate flux did not drop in this case, it remained practically constant ($J \sim 173\,\mathrm{L/m^2\,hr}$), which means that deposition of particles and cake formation on the membrane surface are prevented under these experimental conditions. It was also observed that the permeate flux increases slightly with time due to decrease in the feed conductivity during the experiment. The comparison of the end flux values in both cases shows that by using an electric field, an enhancement factor of 4.7 ($J_{E\neq0}/J_{E=0}$) or 366% ($(J_{E\neq0} - J_{E=0})/J_{E=0}$) is achieved.

The effect of changing the applied electric field E_{ap} within the range 0–133 V/cm ($U = 0$–200 V) on the permeate flux (feed concentration of 10 g/L and $\Delta P = 2.1$ bar) is shown in Fig. 3. It can be seen that the dependence $J = f(E)$ is not linear for all the three cross-flow velocities studied. An increase in E_{ap} from 0 to ~80 V/cm enhances substantially the average permeation rate J. At higher voltage ($E > 80\,\mathrm{V/cm}$), the improvement in J decreases.

Effect of Cross-Flow Velocity

The effect of the retentate cross-flow velocity in electro-filtration at constant ΔP ($\Delta P = 2.1$ bar) is shown in Fig. 4. The permeate fluxes, influenced

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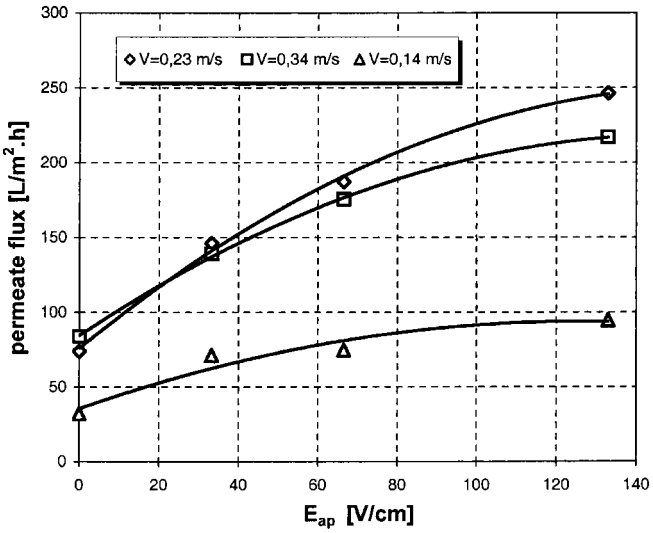

Figure 3. Effects of the applied electric field strength (E_{ap}) on permeate flux under various retentate-flow rates ($\Delta P = 2.15$ bar, $C_F = 10.1$ g/L, $T = 20$°C).

by constant electrical field, can be compared with those at zero field ($E = 0$). The experimental results show that at all the operation conditions an increase in cross-flow velocity up to 0.25 m/sec resulted in the enhancement of the permeation rate. Further increase in the linear velocity leads to the following results: when no electric field is applied ($E = 0$), J_P does not depend substantially on the velocity at values higher than 0.25 m/sec. It could be assumed that there is no cake formation at these conditions. If an electric field is available, there are optimal conditions at which maximal flux facilitation can be achieved. Retentate velocities higher than 0.25 m/sec reduce the membrane separation efficiency, as it can be seen, eventually due to the diffusive back-transport of the dispersed particles towards the membrane.

On the basis of these results, an important potential advantage of the electromembrane separation technique becomes clear: there is no need to use high cross-flow velocities in order to eliminate the cake formation. The electro-separation process can be performed at relatively low velocities.

The corresponding values of both the hydraulic resistances R_M and R_S and their contributions to the overall process resistance R_T are summarized in Table 4. It is seen that in case of conventional micro-filtration and low flow rates the solute-related resistance R_S is the process-limiting factor. At $Q_F = 120$ L/hr and $E = 0$, R_S represents 77% of the total resistance R_T. Increasing the flow rate

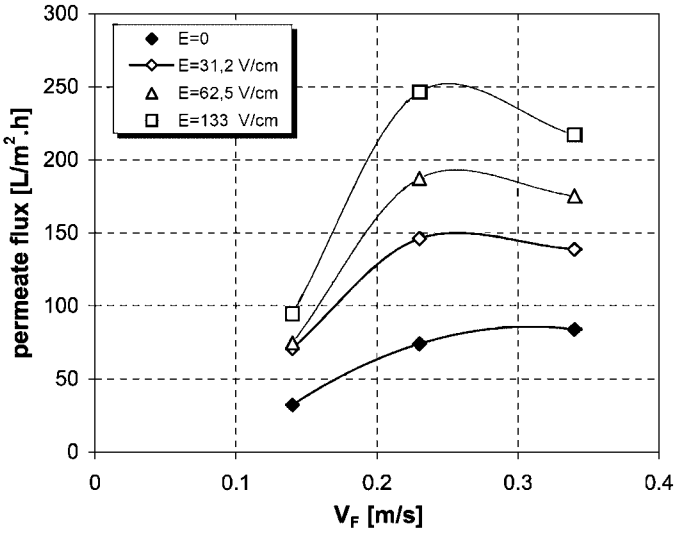

Figure 4. Influence of retentate linear velocity on permeate flux ($\Delta P = 2.15$ bar, $C_F = 10.1$ g/L, $T = 20$°C).

reduces this resistance and at $Q_F = 200$ L/hr both the resistances, R_M and R_S, become equal. At the highest Q_F-value (300 L/hr) examined, the value of R_S gets lower than R_M and the process is controlled preferably by the membrane characteristics.

The R_M-values received on applying electric field (using water as feed) show the influence of the electroosmosis in the electromembrane separation of the mineral suspension. Comparing the data at zero electric field and constant field, the following conclusion can be drawn: R_M can be reduced to 25% (at $Q_F = 300$ L/hr) due to electroosmosis.

Moreover, it must be pointed out that there are optimal experimental conditions at which no solute-related resistance R_S is established. For example, an electric voltage of 100 V (at $v_F = 0.23$ m/sec) or 200 V (at $v_F = 0.34$ m/sec) eliminates R_S completely.

Effect of Transmembrane Pressure

Figure 5 shows the dependence of the permeate flux on the transmembrane pressure difference, ΔP, for different electric field strengths, E. All the filtration curve profiles show that two ranges are available: one, till about 2.2 bar, in which

Table 4. Hydraulic Resistances at Different Flow Rates (Concentration 10 g/L, $T = 20°C$)

Q_F (L/hr) (v_F (m/sec))	ΔP (bar)	U (V) (E_{ap} (V/cm))	J_P (L/m^2 hr)	$R_T \times 10^{-10}$ (Pa sec/m)	$R_M \times 10^{-10}$ (Pa sec/m)	$R_S \times 10^{-10}$ (Pa sec/m)	R_M/R_T	R_S/R_T
120 (0.14)	2.05	0	32.3	2.285	0.520	1.765	0.227	0.773
		50	71.0	1.039	0.477	0.562	0.459	0.541
		100	74.6	0.989	0.483	0.506	0.488	0.512
		200	94.6	0.780	0.477	0.303	0.612	0.388
200 (0.23)	2.1	0	74.0	1.022	0.506	0.516	0.495	0.505
		50	146.0	0.518	0.467	0.051	0.902	0.098
		100	187.2	0.403	0.401	0.002	0.995	0.005
		200	246.3	0.307	0.306	0.001	0.997	0.003
300 (0.34)	2.25	0	83.9	0.965	0.520	0.445	0.539	0.461
		50	138.7	0.584	0.438	0.146	0.750	0.250
		100	175.2	0.462	0.418	0.044	0.905	0.095
		200	217.0	0.373	0.370	0.003	0.992	0.008

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the filtration rate increases with the pressure, and two, above 2.2 bar, where a further increase in ΔP leads to lower filtration rates. The results indicate that the electric field can reduce effectively the membrane fouling in both ranges: not only in the second "cake-limiting" phase, but also in the first stage where there is a pressure influence on the separation process.

At $E = 0$, the highest value of the permeate flux obtained was about $70\,\mathrm{L/m^2\,hr}$. When a constant electric field was applied, flux improvement was achieved in both ranges. The highest value of the enhancement factor ($\Phi \sim 3.5$) is reached at $\Delta P = 2.1$ bar ($J = 250\,\mathrm{L/m^2\,hr}$).

For a constant cross-flow velocity and fixed E value, the increase in pressure results in a higher convective-pressure force. Therefore, it can be assumed that in the second range ($\Delta P > 2.2$ bar) more particles tend to move towards the membrane as the pressure is increased. This phenomenon permits an increase in concentration and particle polarization. Therefore, lower enhancement factors (up to 2.5) are achieved at the highest pressure studied in the second range (when $\Delta P = 3.3\,\mathrm{bar} \rightarrow J = 150\,\mathrm{L/m^2\,hr}$).

Table 5 shows how the values of the hydraulic resistances change with the transmembrane pressure. At zero electric field, R_S is higher than R_M in all cases. The electric field reduces R_S drastically and transfers the process resistance from R_S to the membrane-related R_M.

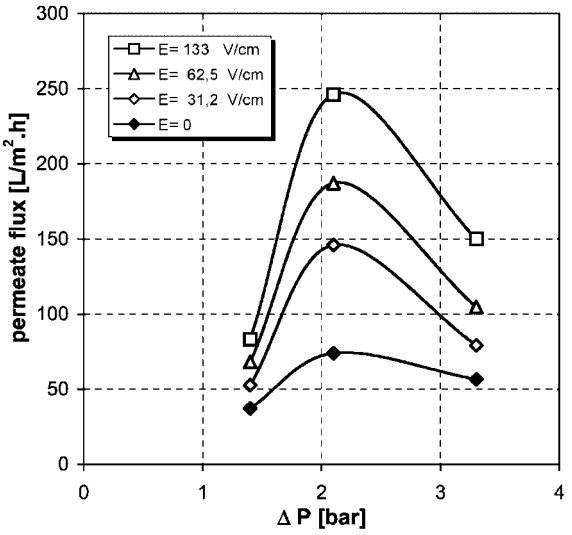

Figure 5. Influence of transmembrane pressure difference on permeate flux ($v_F = 0.23\,\mathrm{m/sec}$, $C_F = 10.1\,\mathrm{g/L}$, $T = 20°\mathrm{C}$).

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Table 5. Resistances at Different ΔP (Concentration 10 g/L, $T = 20°C$)

Q (L/hr) (v_F (m/sec))	ΔP (bar)	U (V)	J (L/m^2 hr)	$R_T \times 10^{-10}$ (Pa sec/m)	$R_M \times 10^{-10}$ (Pa sec/m)	$R_S \times 10^{-10}$ (Pa sec/m)	R_M/R_T	R_S/R_T
200 (0.23)	1.45	0	37.3	1.351	0.431	0.920	0.319	0.681
		200	83.3	0.605	0.316	0.289	0.522	0.478
	2.1	0	74.0	1.022	0.506	0.516	0.495	0.505
		200	246.3	0.307	0.306	0.001	0.997	0.003
	3.3	0	56.5	2.103	0.680	1.423	0.323	0.677
		200	150.1	0.792	0.603	0.189	0.762	0.238

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Effect of Feed Concentration

Experiments were carried out using various feed concentrations in the range 1–5 wt%. A liner dependence of $J = f(C)$ was observed in both cases: with electric field and with no field. It was observed that an increase in feed concentration causes a significant decrease in the permeate fluxes (Fig. 6). The most important result is, however, that the flux enhancement depends conversely on the feed concentration (see Fig. 7). The greatest relative improvement in permeate flux using electric field was observed in the case of the most concentrated suspension (50 g/L), which means that the process is very effective by treatment of high concentrated suspensions.

Table 6 represents the calculated R_T-data. At $E = 0$, a five-fold increase in the feed concentration results in a two-fold increase in the total resistance R_T. Under electro-filtration, the increase in R_T is lower because of the intensive electrophoretic transport of the charged particles away from the membrane surface.

Effect of Temperature

The influence of the temperature on the permeate flux is shown in Fig. 8. As expected, an increase in temperature resulted in an increase in the

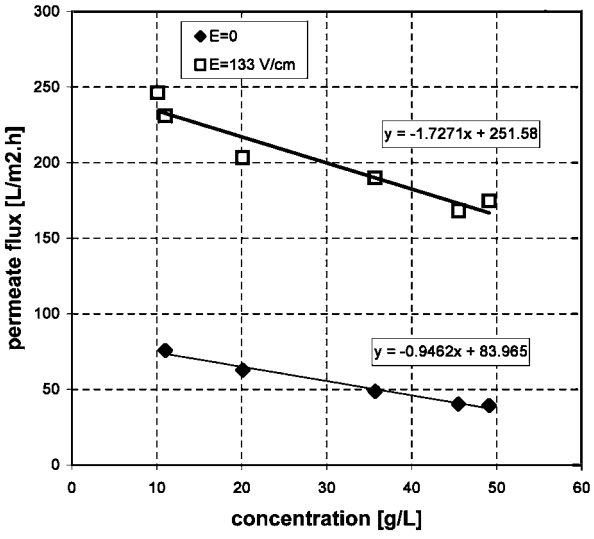

Figure 6. Effect of feed concentration on permeate flux ($\Delta P = 2.15$ bar, $v_F = 0.23$ m/sec, $T = 20$°C).

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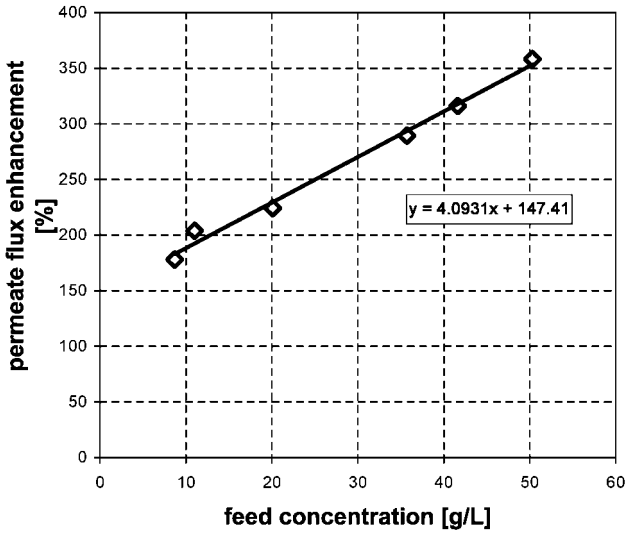

Figure 7. Dependence of permeate flux enhancement on feed concentration ($E = 133\,\mathrm{V/cm}$, $\Delta P = 2.15\,\mathrm{bar}$, $v_F = 0.23\,\mathrm{m/sec}$, $T = 20^{\circ}\mathrm{C}$).

flux due to decrease in the solution viscosity. It is also seen that the temperature affects the more sensitive J_p when an electric filed is applied, i.e., when the cake formation is minimized by the electrophoresis. The reason is that in the electromembrane process the temperature influenced by the viscosity of the feed solution affects two important parameters: not only the diffusion coefficients of the solid particles but also their electrophoretic mobility.

The corresponding R-values (see Table 7) allow the conclusion that R_S can be reduced and even eliminated by increasing the temperature of the feed suspension from 18 to 48°C (the results are shown at $C_F = 41.9\,\mathrm{g/L}$, $\Delta P = 2.25\,\mathrm{bar}$, $Q_F = 200\,\mathrm{L/hr}$, $E_{ap} = 133\,\mathrm{V/cm}$).

Flux Recovery

The enhancement of the permeate flux was found to be better when an electric field was applied from the beginning of the filtration process compared with application after a short period of filtration with no electric field. This means that an intermittent electric field is less useful in the treatment of mineral suspensions by electromembrane separation. The same conclusion for other systems has been drawn by Rios et al. (16) and Huotari et al. (9).

Table 6. Total Resistance at Different Feed Concentrations ($\Delta P = 2.2$ bar, $T = 20$°C)

Q (L/hr)	ΔP (bar)	U (V)	C (g/L)	J (L/m^2 hr)	$R_T \times 10^{-10}$ (Pa sec/m)
200	2.3	200	10.1	246.3	0.3282
			11.0	148.1	0.3501
			20.1	203.3	0.3976
			35.7	190.0	0.4254
			45.5	168.1	0.4809
			49.1	174.7	0.4627
		0	11.0	75.8	1.0664
			20.1	62.7	1.2892
			35.7	48.8	1.6565
			45.5	40.4	2.0009
			49.1	39.4	2.0517

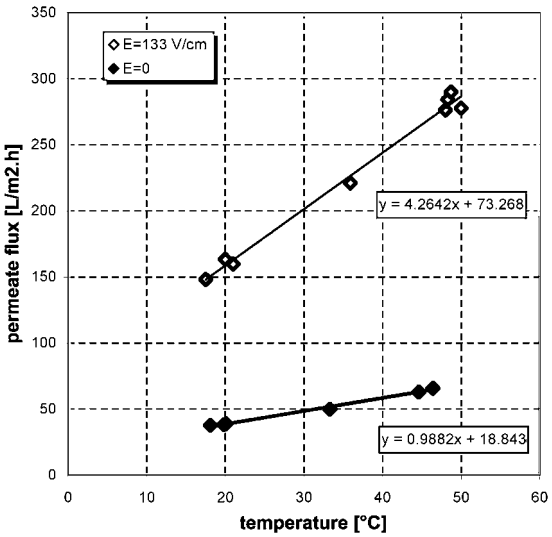

Figure 8. Temperature effects on permeate flux in micro-filtration and electro-micro-filtration ($\Delta P = 2.15$ bar, $v_F = 0.23$ m/sec, $C_F = 41.9$ g/L, $T = 20$°C).

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Table 7. Resistances at Different Temperatures (Concentration 41.9 g/L, $\Delta P = 2.25$ bar)

Q (L/hr) (v_F (m/sec))	T (°C)	U (V)	J (L/m^2 hr)	$R_T \times 10^{-10}$ (Pa sec/m)	$R_M \times 10^{-10}$ (Pa sec/m)	$R_S \times 10^{-10}$ (Pa sec/m)	R_M/R_T	R_S/R_T
200 (0.23)	18.1	0	37.6	2.149	0.598	1.551	0.279	0.721
	17.5	200	148.1	0.545	0.440	0.105	0.807	0.193
	19.8	0	38.2	2.116	0.584	1.532	0.276	0.724
	20.0	200	163.3	0.495	0.430	0.065	0.869	0.131
	33.3	0	49.9	1.620	0.449	1.171	0.277	0.723
	35.9	200	221.0	0.365	0.330	0.035	0.904	0.096
	44.6	0	62.9	1.285	0.384	0.901	0.299	0.701
	48.0	200	276.2	0.292	0.283	0.009	0.969	0.031

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CONCLUSIONS

The results of this study prove the potential utility of integrating two separation processes with different driving forces: pressure-driven membrane separation and electrophoresis based on the mobility of the charged particles in an electric field. The constant electric field reduced substantially the extent of concentration polarization and the associated membrane fouling. The enhancement of the permeate flux is mainly due to the decrease in the solute-related resistance.

It was found that there are specific optimal conditions for effective electro-filtration of mineral suspensions. For separation of a SiO_2 suspension in the electromembrane module construction used, the optimal process parameters (pressure difference, flow rate, and temperature) were determined.

SYMBOLS

S	feed channel area (m^2)
A	effective filter area (m^2)
Q	volumetric-flow rate (L/hr)
v	linear velocity (m/sec)
J	permeate flux (L/m^2 hr)
$\bar{t}$	mean time (sec)
T	temperature (°C)
V	volume (m^3)
R	hydraulic resistance (Pa sec/m)
U	voltage (V)
E	electrical field strength (V/cm)
ΔP	pressure driving force (bar or Pa)
$\Delta \Pi$	osmotic driving force (bar or Pa)

Subscript

F	feed
P	permeate
M	membrane
in	inlet
out	outlet
T	total
S	solute
ap	applied

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