The Effect of Temperature on Electrodialytic Demineralization

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Saline water conversion, a relatively new field, has shown considerable progress in the past ten years although the conversion of sea water by simply boiling it and collecting the vapors was practiced over two centuries ago. Among the various desalination techniques, distillation is still the most feasible one for highly saline waters. For the conversion of slightly brackish waters, however, electrodialysis is considered to be one of the most promising methods.

Electrodialysis.—In this process demineralization is achieved with the aid of electrical energy. Salt ions, confined into compartments bounded by ion-selective polymer membranes, move towards the oppositely charged electrodes from compartments 1, 3, 5, ⋯, etc. (see Fig. 1). Ions from compartments 2, 4, 6, ⋯, etc. cannot pass through the membranes because of the repulsion between the like charges on the ions and membranes. As a result, demineralization of the feed solution occurs in the odd numbered cells while the even numbered ones increase in concentration.

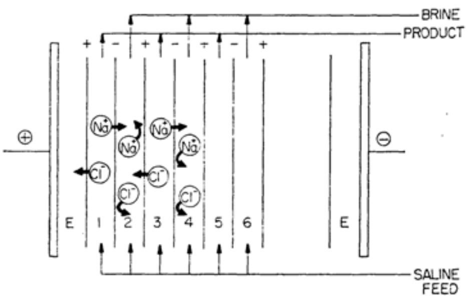

Fig. 1. Schematic of a multicompartment electrodialysis stack.

One of the major factors which limits the practical and economical application of electrodialysis is polarization. This phenomenon arises when a certain limiting current density is exceeded.[1] Under severe polarization conditions the current is used partly to transport salt ions, partly to transport H^+ and OH^- ions. This not only results in decreased coulomb efficiency, but can give rise to harmful scale formation.

Polarization is a function of several variables: throughput velocity, stack geometry, feed concentration, temperature and others. This paper describes the changes observed when the feed solution temperature was varied from 5°C to 35.5°C and 40°C.

Prior Work. — Several variables influencing polarization characteristics were investigated at our Laboratory[2,3] using a modified Aquafresh stack (manufactured by the American Machine and Foundry Company). It was found that under 4 cm./sec. velocity a straight line correlation existed between the polarization parameter J_{lim}/N_{do}, (mamp./cm^2)/(eq./l.) and the throughput velocity, but over 4 cm./sec. no such correlation could be established. In this region the limiting current density was found to be a function of the product normality and could be expressed as

$$J_{lim}=6400\ (N_{do})^{1.65} \text{ for countercurrent NaCl solutions}$$

$$J_{lim}=3000\ (N_{do})^{1.55} \text{ for countercurrent San Francisco Bay water}$$

where J_{lim}=limiting current density (mamp./cm^2) and N_{do}=dialyzate stream concentration at the stack outlet (eq./l.) Feed solution temperatures in these experiments were all around 20°C.

Experimental Procedure

The modified Aquafresh stack was used with 8 cell pairs in series. To obtain higher temperatures

1) N. W. Rosenberg and C. E. Tirrell, *Ind. Eng. Chem.*, **49**, 780 (1957).

2) P. M. Rapier, S. A. Weiner and W. K. Baker, "Salt Water Demineralization with a Modified Aquafresh Electrodialytic Stack," Sea Water Convertion Laboratory Issue 28, University of California, Berkeley (1962), p. 24.

3) P. M. Rapier, S. A. Weiner and W. K. Baker, "Experimental Study of Some Basic Parameters in Electrodialysis," Sea Water Conversion Laboratory Report No. 63-4, University of California (1963), p. 43.

the brine and dialyzate feed tanks were equipped with immersion heaters; Fenwal thermoswitches served as regulators. Constant air agitation was used to insure uniform temperature throughout the five-gallon capacity containers. The dialyzate stream flow was approximately constant in all runs at around 6.5 cm./sec. Feed concentrations were varied from 0.0148 to 0.246 N.

A very simple but effective arrangement was used to obtain the desired low temperature. Water was placed in a three-gallon plastic pail which was embedded in a salted, crushed-ice bed. Circulation of the cooling water was achieved by a small Eastern pump. Four coils, constructed from 3/8″ copper tubing, were immersed in each feed tank, connections were made from flexible plastic tubing. The recirculation created enough turbulence in the bucket to prevent ice formation next to the walls. Crushed ice was also added to the water directly, Temperatures as low as 3.5°C could easily be maintained with very little deviation. Our experiments were conducted around 5.3°C; the concentration of the feed solutions ranged from 0.0168 N to 0.245 N. For the complete set of experimental data see table below.

Discussion and Results

The role of temperature in electrodialytic demineralization cannot be dismissed by simply stating that the total resistance of the system changes about 2% per °C. True, one of the advantages of operating at elevated temperatures is the reduced resistance, or in other words the decreased power consumption, but there is another very important factor to be considered. This is the variation of the limiting current density with temperature. Our experiments revealed that the limiting current density is increased at elevated temperatures. The straight line relationship between current density and product normality could be expressed as

$$J_{lim}=5500(N_{do})^{1.53} \text{ at } 40°C$$

$$J_{lim}=4600(N_{do})^{1.53} \text{ at } 35.5°C$$

and is plotted on Fig. 2. Should one operate at elevated temperatures, the current density could be increased (required membrane area decreased) or keeping the area constant a greater degree of demineralization could be achieved. The estimated 20—30% power reduction is another favorable feature. Experiments with a pilot-plant size stack, that was constructed at the University of California, yielded similar results.

In many parts of this country and abroad, well waters have considerably lower temperatures than 18—20°C. A good example is Webster, South Dakota, where the Office of Saline Water electrodialysis demonstration plant has to cope with a 9°C feed water. It was of interest, therefore, to examine the effect of low temperatures on the electrodialytic desalination process. Our experiments yielded the following observations: (a) while the limiting current density was found to be a function of product normality over 4 cm./sec. at feed temperatures of 15°C and over, no such correlation could be established for runs at approximately 5°C (Fig. 2); (b) with feeds more concentrated than 0.05 N (3000 p.p.m. sodium chloride) very strong back pressure in the electrode compartments was noticeable (in

TABLE I. EXPERIMENTAL DATA—AMF STACK
(8 cell pairs in series*)

Run No.	N_o eq./l.	N_{do} eq./l.	I_{lim} amp.	J_{lim}/N_{do} (mamp./cm²)/(eq./l.)	Dialyzate stream flow rate ml./min.	Velocity cm./sec.	f %	Temp. dialyzate °C	Temp. brine °C	$R=E/I$ ohm.
38	0.241	0.0438	1.60	942	38.0	6.26	81.8	35.5	35.4	
39	0.201	0.0380	1.31	886	38.8	6.40	81.1	35.6	35.0	
40	0.0528	0.0154	0.321	537	39.5	6.51	70.8	35.6	35.4	
41	0.0148	0.0058	0.078	345	39.7	6.55	60.8	36.4	36.4	
46	0.0315	0.0097	0.184	490	41.0	6.76	69.2	40.2	40.4	23.3
47	0.0522	0.0133	0.328	636	40.0	6.60	74.6	40.1	40.1	17.7
49	0.246	0.0431	1.59	952	38.8	6.40	82.6	40.0	40.2	6.62
50	0.140	0.0270	0.909	870	39.5	6.51	80.7	40.1	40.3	9.72
51	0.0173	0.0064	0.101	407	40.8	6.74	63.0	40.1	40.3	46.1
52	0.0168	0.0076	0.087	295	41.3	6.81	54.8	5.95	6.23	67.5
53	0.0334	0.0128	0.162	326	42.2	6.96	61.7	5.06	5.22	44.5
54	0.0528	0.0192	0.302	405	42.8	7.06	63.7	5.17	5.39	39.7
55	0.147	0.0589	0.813	357	42.3	6.98	60.1	4.78	5.01	
56	0.145	0.0489	0.888	496	42.8	7.06	66.3	5.45	5.50	
58	0.0900	0.0345	0.449	336	40.0	6.61	61.8	5.38	5.55	

* Countercurrent flow, NaCl feed in all runs, AMF membranes

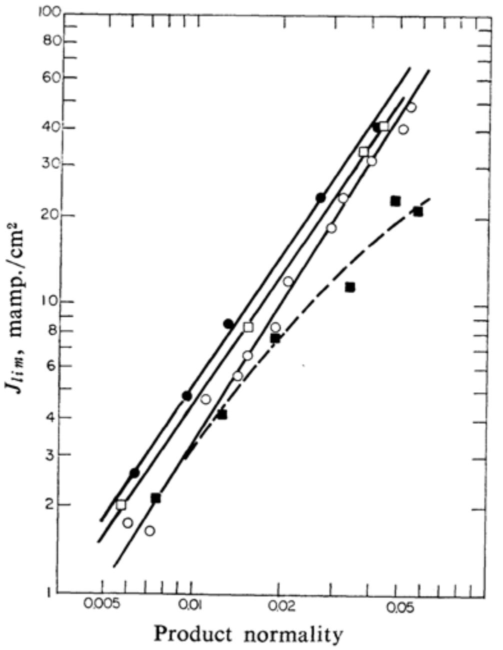

Fig. 2. Polarization characteristics-limiting current density versus product normality.

■ ~5°C ○ Room temperature
□ ~35.5°C ● ~40°C

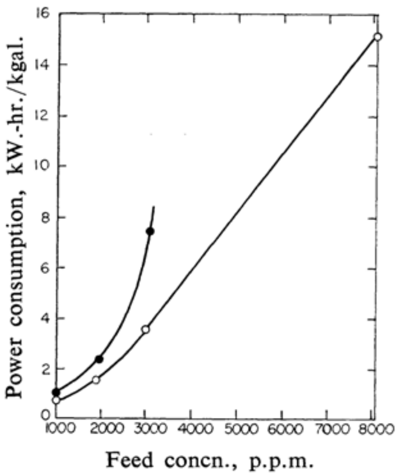

Fig. 3. Power consumption as a function of feed concentration at different temperatures. Values extrapolated to 350 p.p.m. product.

● ~5°C ○ ~40°C

the run with $N_o = 0.245$ N this was so pronounced that the electrode rinse flow was completely stopped) ; (c) polarization occurred at decreased current densities ; (d) by comparing power consumptions at 40°C and 5°C (Fig. 3) it can be seen that while there is no significant increase for feeds of 1000 p.p.m., the increase is considerable at $N_o > 2000$ p.p.m.

Conclusions

Our experiments quantitatively demonstrated that electrodialytic demineralization at elevated temperatures has two attractive features : higher limiting current density and lower power consumption. These savings cannot, however, be achieved without the installation (and maintenance) of expensive heat exchange equipment. The question arises : would the additional cost in equipment be counterbalanced by the gains resulting from elevated temperature operation. Only an extensive economic analysis could give a definite answer to this important question.

Summary

The process of electrodialysis, as a means of demineralizing brackish water, is briefly described. Polarization, a limiting factor in the practical application of the process, is a function of several variables, one of which is temperature. In this study the temperature dependence of limiting current density and power consumption was examined. Experiments conducted at elevated temperatures (35.5°C and 40°C) showed that the limiting current densities are increased and the power consumption is decreased. At low temperatures (5°C) marked decrease in limiting current density was observed. Comparison of power consumption data at 40°C and 5°C show that significant differences occur with feeds more concentrated than 2000 p.p.m.

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