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Prediction of the behavior of long electrodialysis desalination channels through testing short channels

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Abstract

A method to forecast behavior of electrodialyzers with long demineralization channels is suggested. It is based on the data obtained using a laboratory cell or an apparatus with short demineralization channels of similar construction. The results are presented as dimensionless parameters.

Keywords: Electrodialysis; Modelling; Current-voltage; Mass transfer; Concentration dependency

1. Introduction

The design of electrodialysis equipment with certain properties and modes of operation is one of the important problems for designers and researchers working in the field of electromembrane technology. Until now, no rigid system has been developed for the creation of new industrial equipment. Thus, much material and time is required. One of the difficulties is in the testing of large-overall apparatuses. Forecasting the behavior of an industrial electrodialyzer could easily be done using the data obtained for a laboratory cell or a small-overall apparatus due to lower expenditures for their assembly. There is the problem in testing short electrodialysis channels so that the data obtained may be used to calculate the operation of the long channels.

2. Accepted assumptions

Imagine the long channel as several short channels arranged successively. It might be possible to calculate parameters of the long channels with the short channels' concentration dependencies of basic characteristics. The different channels tested must be kept under the same conditions, such as flow rate through channels and voltage drop across a pair cell (the cell containing a concentration channel, and a demineralization channel with one anion- and one cation-exchange membrane). To correctly carry out the experiment it is necessary:

a) to fix the same acid-basic-salt form of ion-exchange materials contained in the systems before starting the experiment;
b) to stabilize a quasi-steady state of the system where its characteristics do not change with time;
c) not to change the concentration of the

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solution significantly while apparatus testing at circulation hydraulic mode so that the system could be brought to an equilibrium with a solution of a new concentration every time the concentration changes.

Changing a channel with length 2L by two successively arranged channels of L length, we take into account the presence of several boundary effects:

1) the difference of the profile shape of the velocity of the liquid flowing at the channel entrance and at the distance exceeding the length of its development;
2) the irregularity of the diffusion layer thickness distribution by the channel length;
3) the irregularity of local current density distribution due to the both above-mentioned boundary effects.

In studies on the first boundary effect [1, 2], it was shown that the length of concentration profile development of the liquid flowing is usually considerably less than the channel length. There are some models based on the convective diffusion theory [3, 4], where it is supposed that the surface of ion-exchange membranes is equipotential, and the boundary effects of current line distortions at the beginning and at the end of the channel may be neglected. Experimental verification of the models, conforming to empty smooth channels, demonstrated their high fitness. At the same time from the models it results that the diffusion layer thickness δ is the function of the longitudinal coordinate Y, for example, for empty smooth short channels:

$$\delta \sim Y^{1/3} \quad (1)$$

But reaching the channel length approximately equal to $Y = 0.004\ v_a\ h^2/D$ [4]

- the diffusion zone fills all the channel,
- the concentration profile takes a stationary parabolic form,
- the effective thickness of the diffusion layer (defined by crossing tangents to the concentration profile on the border with the membrane and in the maximum point of the curve C(X)) reaches stationary value ~0.37 h. Thus, the length of diffusion layer development for a smooth empty channel with $h = 8\times10^{-4}$ m and $v_a = 0.02$ m/s is equal to 0.034 m.

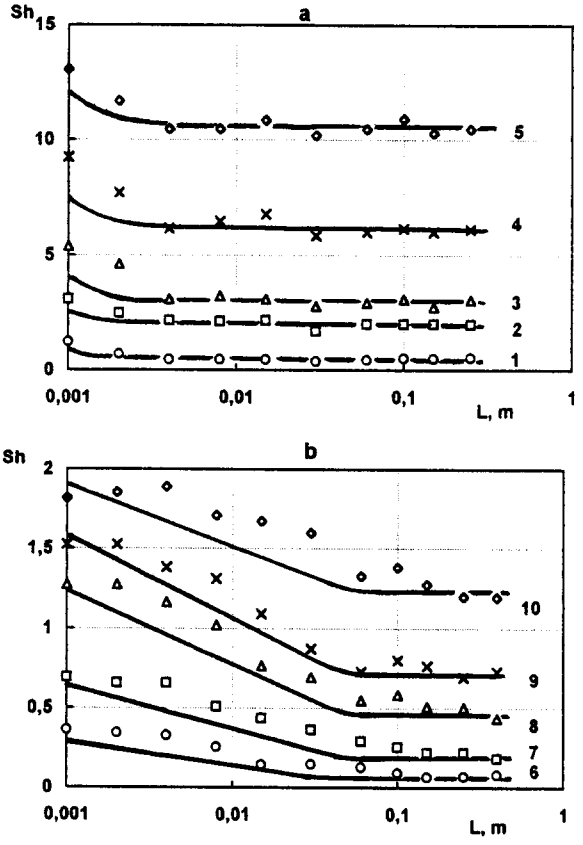

Fig. 1. Sherwood numbers averaged over channel length (points) and local Sherwood numbers (curves) as a function of channel length for spacers "punch-stretch" OST 6-19-298-79 (a) and OST 17-46-82, item 22K (b) at different flow rates of solution W (converted to a channel width of a = 1 m): (1) 0.8×10^{-6}, (2) 6.3×10^{-6}, (3) 37.0×10^{-6}, (4) 75.0×10^{-6}, (5) 100.0×10^{-6}, (6) 0.9×10^{-6}, (7) 9.0×10^{-6}, (8) 36.9×10^{-6}, (9) 130.0×10^{-6}, (10) 270.0×10^{-6} m^3/s.

However, for channels containing a spacer and/or ion-exchange granules as a filler, the length of the diffusion layer development (the length where the diffusion layer development occurs until it reaches δ_{st} stationary value

without changing with further increase of the channel length) is equal to 0.5–6.0 cm for a large number of spacers investigated [5]. The research, carried out by means of the electrochemical ferro-ferricyanide technique showed that the Sherwood number in such channels is changed slightly at the beginning of the channel and it is constant after reaching the development length (Fig. 1a and b). The Sherwood number is determined as:

$$Sh = \frac{id_e}{FDC_i} \quad (2)$$

The equivalent diameter is taken as 2h, as in [2].

It was also determined that the length of development is shorter for "better" spacer (having higher ability to turbulize the liquid flow). Therefore, for a majority of spacers it is possible to neglect the influence of the beginning part of the channel upon characteristics of an apparatus, with channel lengths of 10 cm and more.

We can assume now that long electrodialyzer's channels (L >20 cm), containing spacer and/or ion-exchange filler might be treated as some successively ordered electrodialyzers with a channel length of 10 cm and thus realize the idea proposed above.

3. Experimental

Three different electrodialysis systems were studied:

1) Laboratory cell containing a pair cell 10 cm long,
2) Laboratory apparatus with demineralization channels (DC) 10 cm long,
3) Pilot apparatus with DC 20 cm long.

DCs of two different designs were studied. For the first one, the channels were composed of ion-exchange membranes with physically modified surfaces (type I) [6] and for the second they contained a mixture of granulated ion-exchange resins (type II) [7].

The investigations were carried out with a NaCl model solution using a technique of working solution composition's regulation for a laboratory cell [8] and by methods of testing electrodialyzers suggested in [9].

To calculate theoretical characteristics of 20 cm long DCs, it is necessary to determine the outlet concentration from the corresponding inlet concentration. A corresponding function obtained during testing of an electrodialyzer with a 10 cm long DC in circulating hydraulic conditions is used (Fig. 2). Value C'_{di} is the DC outlet concentration normalized by the inlet one:

$$C'_{di} = C_{di} / C_i \quad (3)$$

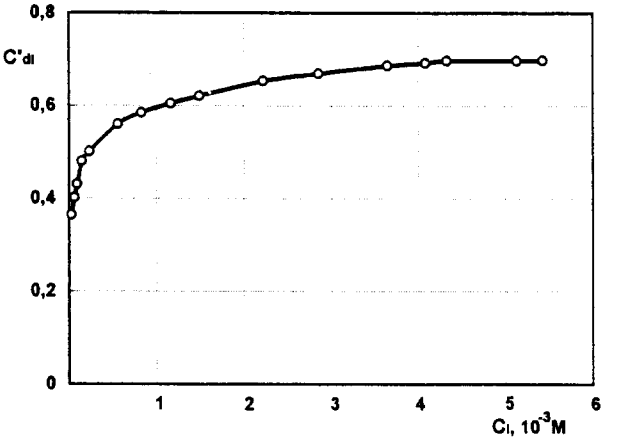

Fig. 2. Outlet solution concentration normalized on the inlet concentration against the inlet concentration obtained under testing of the laboratory electrodialyzer (channel's type I) in circulating hydraulic conditions: L = 0.1 m, a = 0.1 m, n = 10, U = 2.4 V, $W_{DC} = 8.7 \times 10^{-6}$ m^3/s.

Then considering the outlet concentration for the first part of the 10 cm long channel as the inlet concentration for the second part of the channel with a length of 10 cm, the new outlet concentration can be found on the same curve. This is the resulting outlet concentration for the 20 cm long channel.

Let us compare results obtained for the cell, small-overall and large-overall apparatuses. Fig. 3 a and b demonstrates that the results for the laboratory cell and the small-overall apparatus with the same channel length agree well (data 1, 2). The results calculated using the data of testing electrodialyzers of DC 10

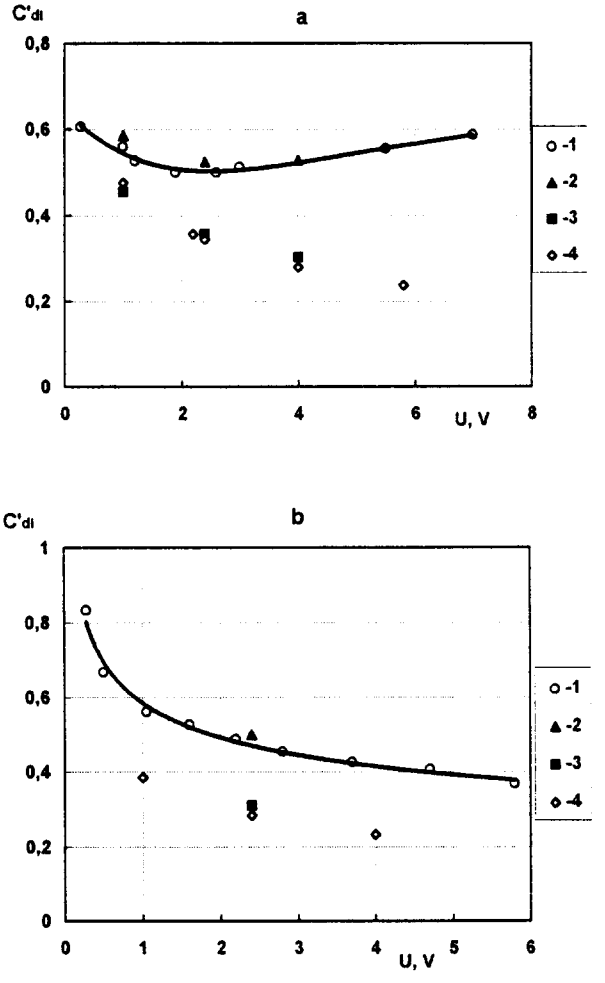

Fig. 3. Outlet solution concentration normalized on the inlet concentration of demineralization channels against voltage drop across the pair cell for the channels of type I (a) and type II (b), h = 8×10^{-4} m, C = 2×10^{-3} M: 1 - laboratory cell, L = 0.1 m, a = 0.03 m, n = 1, W_{DC} = 2.1×10^{-7} m^3/s, strait-flow hydraulic conditions; 2 - laboratory apparatus, L = 0.1 m, a = 0.1 m, n = 10, W_{DC} = 8.7×10^{-6} m^3/s, circulating hydraulic conditions; 3 - forecast of data for the electrodialyzer with L = 0.2 m, a = 0.2 m, n = 25; 4 - pilot electrodialyzer, L = 0.2 m, a = 0.2 m, n = 25, W_{DC}= 3.3×10^{-5} m^3/s, circulating hydraulic conditions.

cm length (data 3) and that obtained in testing apparatuses with length of channels 20 cm (data 4) are in agreement, too. The value of average current through the apparatus is determined similarly from dependence of current density versus inlet concentration of small-overall apparatuses (Fig. 4). Fig. 5 a and b shows the current-voltage characteristics of short channels, the forecast of these values for channels with length 20 cm and the data, obtained experimentally from these channels. The values are seen to correspond quite well also.

Knowing these two basic dependencies, other important characteristics of electrodialyzers can be calculated: salt output, degree of demineralization, mass transfer coefficient, current efficiency and energy consumption.

Dependencies of Sherwood number (Fig. 6 a and b) and current efficiency (Fig. 7 a and b) vs inlet concentration obtained after testing three electrodialysis systems are shown as examples. Current efficiency η_i for univalent ions, i, is connected with current value by the equation:

$$\eta_i = \frac{(C_i - C_{d_i})\, FW_{DC}}{nI} \qquad (4)$$

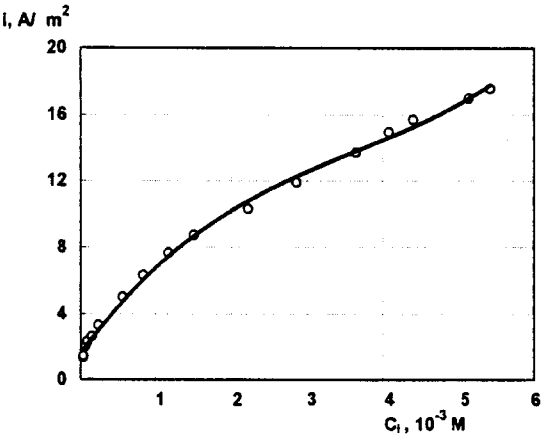

Fig. 4. Total current density against the inlet concentration obtained under testing of the laboratory electrodialyzer (channel's type I) in circulating hydraulic conditions: L = 0.1 m, a = 0.1 m, n = 10, U = 2.4 V, W_{DC} = 8.7×10^{-6} m^3/s.

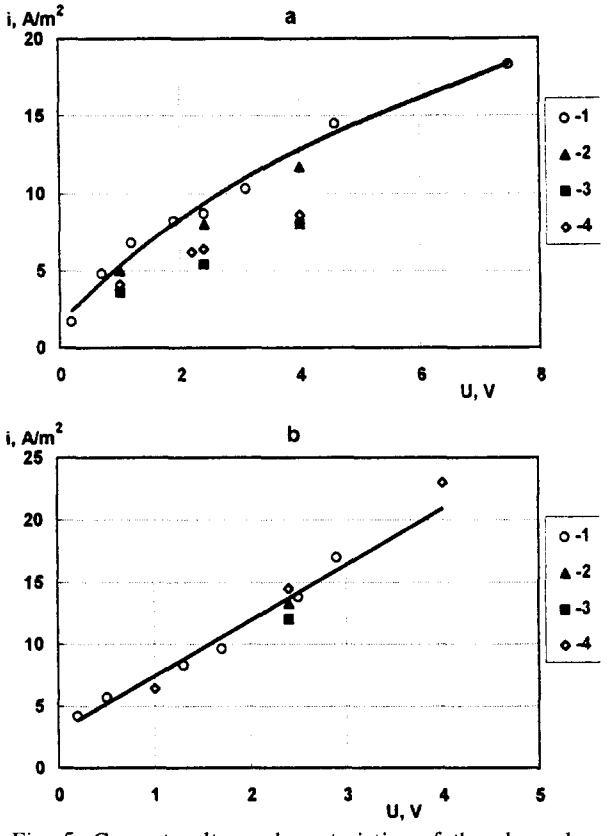

Fig. 5. Current-voltage characteristics of the channels of type I(a) and type II (b), h = 8×10^{-4} m, C = 2×10^{-3} M: 1 - laboratory cell, L = 0.1 m, a = 0.03 m, n = 1, W_{DC} = 2.1×10^{-7} m^3/s, strait-flow hydraulic regime; 2 - laboratory apparatus, L = 0.1 m, a = 0.1 m, n = 10, W_{DC} = 8.7×10^{-6} m^3/s, circulating hydraulic regime; 3 - forecast of data for electrodialyzer with L = 0.2 m, a = 0.2 m, n = 25; 4 - pilot electrodialyzer, L = 0.2 m, a = 0.2 m, n = 25, W_{DC} = 3.3×10^{-5} m^3/s, circulating hydraulic conditions.

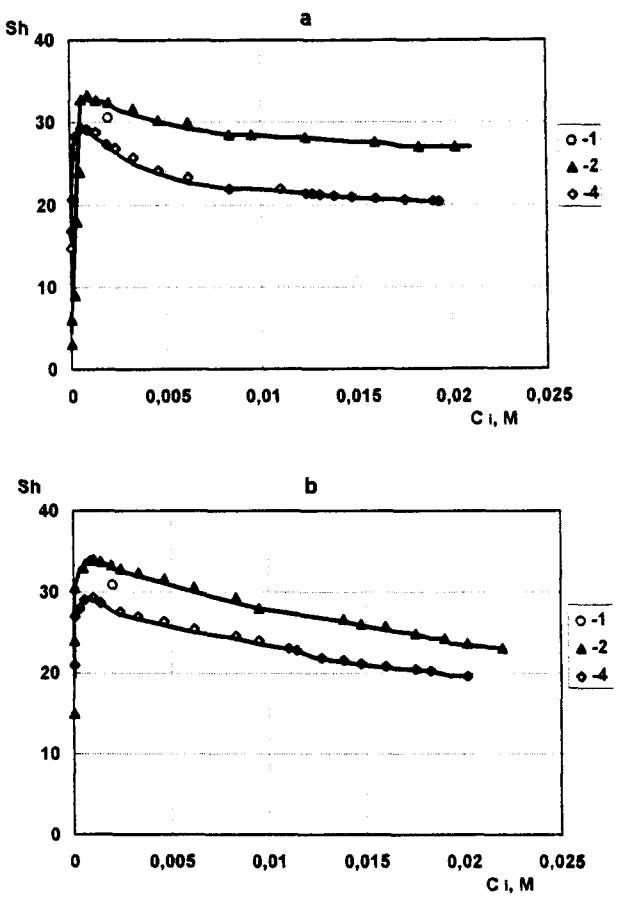

Fig. 6. Sherwood number vs the inlet solution concentration for the channels of type I (a) and type II (b), h = 8×10^{-4} m: 1 - laboratory cell, L = 0.1 m, a = 0.03 m, n = 1, W_{DC} = 2.1×10^{-7} m^3/s, strait-flow hydraulic conditions; 2 - laboratory apparatus, L = 0.1 m, a = 0.1 m, n = 10, W_{DC} = 8.7×10^{-6} m^3/s, circulating hydraulic conditions; 4 - pilot electrodialyzer, L = 0.2 m, a = 0.2 m, n = 25, W_{DC} = 3.3×10^{-5} m^3/s, circulating hydraulic conditions.

Also, the figures show the results of calculation of the characteristics mentioned by means data obtained under testing electrodialyzers with channel length of 10 cm. Taking into account that testing of large-overall apparatuses is carried out with an error of approximately 10%, the results presented by Fig. 6 a and b and 7 a and b agree well enough.

Thus, the experiments carried out by the cells and small-overall electrodialyzers enable the prediction of the behavior of industrial apparatuses, almost for any channel length and calculating their mass-exchange characteristics. It also enables considerable saving resources and time required for assembling and testing new designs of electrodialysis apparatuses.

4. List of symbols

a Width of a demineralization channel, m

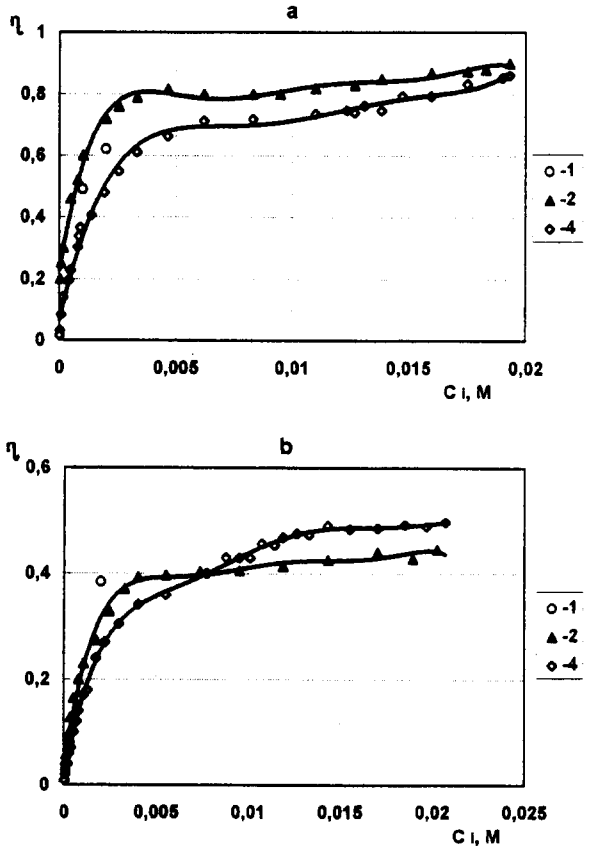

Fig. 7. Current efficiency vs the inlet solution concentration for the channels of type I (a) and type II (b), h = 8×10^{-4} m: 1 - laboratory cell, L = 0.1 m, a = 0.03 m, n = 1, W_{DC} = 2.1×10^{-7} m^3/s, strait-flow hydraulic conditions; 2 - laboratory apparatus, L = 0.1 m, a = 0.1 m, n = 10, W_{DC} = 8.7×10^{-6} m^3/s, circulating hydraulic conditions; 4 - pilot electrodialyzer, L = 0.2 m, a = 0.2 m, n = 25, W_{DC} = 3.3×10^{-5} m^3/s, circulating hydraulic conditions.

C_i Demineralization channel inlet concentration of i ions, M
C_{di} Demineralization channel outlet concentration of i ions, M
C'_{di} DC outlet concentration of i ions, normalized on the inlet concentration;
d_e Equivalent diameter, m
D Salt diffusion coefficient, m^2/s
F Faraday constant, A s/mol
h Height of demineralization channel, m
I Total current, A
i Average current density, A/m^2
i_i Partial current density of i ions, A/m^2
j_i Density of ions i flux through the membrane, $mol/(m^2 s)$
k_i Mass transfer coefficient, m/s
L Length of demineralization channel, m
n Number of demineralization channels in the electrodialyzer
S Working membrane area, m^2
Sh Sherwood number
U Voltage, V
v_a Average flow velocity, m/s
W_{DC} Volume flow velocity through the demineralization channel, m^3/s
X Normal coordinate, m
Y Longitudinal coordinate, m

Greek

δ Thickness of the diffusion layer, m
η_i Current efficiency

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References

[1] V.G. Levich, Disc. Faraday Soc. 1 (1947).
[2] D.J. Pickett, Electrochemical Reactor Design, Amsterdam, 1977.
[3] A. Sonin and R.A. Probstein, Desalination 3 (1968) 293–298.
[4] V.V. Nikonenko, N.P. Gnusin, V.I. Zabolotsky, and M.Kh. Urtenov, Elektrokhimiya (Electrochemistry, Rus), 21 (1985) 296–302.
[5] V.V. Nikonenko, N.D. Pismenskaya, and V.I. Zabolotsky, Elektrokhimiya (Electrochemistry, Rus), 28 (1992) 1682–1692.
[6] V.I. Zabolotsky, V.V.Nikonenko, N.D. Pismenskaya, V.F. Pismensky, and E.V. Laktionov, Electrodialyzer, Patent of Russia, N93006226, Int. Cl. V01D 13/02.
[7] G.N. Istoshin and V.I. Zabolotsky, Multichambered electrodialyzer, Int. Cl. V01D 61/44; Applied 23.04.93 to Patent Office of Russia, Decision to issue a patent of Russia, N 93-021494/26/ 020690.
[8] V.I. Zabolotsky, N.D. Pismenskaya, and V.V. Nikonenko, Elektrokhimiya (Electrochemistry, Rus), 26 (1990) 707–713.
[9] E.V. Laktionov, N.D. Pismenskaya, V.V. Nikonenko, and V.I. Zabolotsky, Methods of testing electrodialyzers, Presented at 1993 Intl. Congress on Membrane and Membrane Processes, Heidelberg, Germany, 1993.