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Electrodialysis desalination process in conditions of mixed convection

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ABSTRACT

An emergence of the gravitational convection in electromembrane systems (EMS) is experimentally detected with a number of methods. Gravitational convection, caused by density gradient due to concentration polarization, can presumably destroy the undisturbed layer and cause overlimiting electric current over EMS. But there are a number of experiments questioning the role of gravitational convection. The study is based on the two dimensional mathematical modeling of time-dependent nonisothermal transport of binary electrolyte in a desalination channel of EMS in intense electric current modes. The model developed by authors takes into account a combined effect of gravitational and forced convection, as well as Joule heating of the solution and a heat transfer through membranes. The model is based on Navier–Stokes, Nernst–Planck, and Fourier partial differential equations transformed by an original decomposition method to the system appropriate for computer simulation. Results of the simulation show the domination and the significant influence of gravitational convection on the ion transfer when Richardson number $Ri = Gr/Re^2 > 300$ (for horizontal oriented membranes channel) and $Ri > 1{,}000$ (for vertical).

Keywords: Mass transfer; Electromembrane system; Purification of water solutions; Water treatment; Forced convection; Gravitational convection; Mathematical modeling; Boundary value problems; Partial differential equations

1. Introduction

There are a number of experimental data, suggesting that overlimiting mass transfer in electromembrane system (EMS) is associated with some kind of convective mixing, evolving near membrane interface [1,2]. Measurement results of an electrochemical systems' impedance may be considered as confirmation of the phenomenon of gravitational convection. Additionally, heat generation proximate to the membrane is experimentally recorded in intensive electric current modes [3]. It was practically found that ion exchange membranes start to fuse when high current densities pass through the electrodialysis apparatus (overlimiting modes), the melting temperature of ion-exchange membranes is about 60°C, and the feed solution temperature is about 20°C. An emergence of the

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gravitational convection is experimentally detected with Schlieren method and laser interferometry [3].

It was suggested [2] that gravitational convection, caused by density gradient due to concentration polarization, can destroy the undisturbed layer and cause overlimiting current. Experiments on gel immobilization of depleted diffusion layer [4] showed that overlimiting conductivity disappears. This can be considered as indirect confirmation of gravitational convection. Thus, the presence of gravitational convection in EMS can be regarded as experimentally established.

At the same time, there are a number of experiments questioning the role of gravitational convection. For example, we can point to experiments on the change of the electromembrane cell orientation, the Earth's gravity field. They showed that the output current varies just for relatively wide channels at low pumping speeds, and therefore the gravitational convection effects on the mass transfer are used under these conditions only.

Contradictions in the experimental data and their interpretation make relevant theoretical study of the role of gravitational convection in EMS and the identification of the significance of its influence on the mass transfer of salt ions.

Modern state of the theory of mass transfer in electrode systems with gravity convection was described and analyzed in the review [5]. Description of gravitational convection in membrane systems, taking into account the variations in the concentration and Joule heating is presented in papers of Grigorchuk et al. [6]. However, these studies examined just a stationary transfer in underlimiting mode and did not consider forced convection as well as heat transfer through the membrane.

The [7] role of gravitational convection was theoretically analyzed using a mathematical model, and conditions under which it has a significant impact on heat and mass transfer were pointed out. The conditions, in particular, that require the width of the desalination channel is large enough. The role of gravitational convection for narrow channels is negligible. However, these findings were obtained from the analysis of mathematical models with the electroneutrality condition (underlimiting current mode). In the case of overlimiting current mode, significantly more heat is emitted in the area of a space charge than in the electroneutrality zone [8]. In this connection, there is a need for a theoretical study of gravitational convection and taking it into consideration the description and analysis of transport phenomena in electrochemical and membrane systems in an overlimiting current mode with the space charge taken into account.

In [9] the theory of electroconvective mechanism in overlimiting state under the conditions of forced convection is developed on the basis of mathematical modeling, but the contribution of the gravitational convection in the overlimiting mass transfer is not considered.

Imperfection of model concepts makes impossible, an adequate description of the processes occurring in the real electrochemical systems. The development of these model concepts, more correct mathematical description of conjugate convection and, in particular, the gravitational convection would reveal the conditions where this effect is most conducive to the intensification of mass transfer.

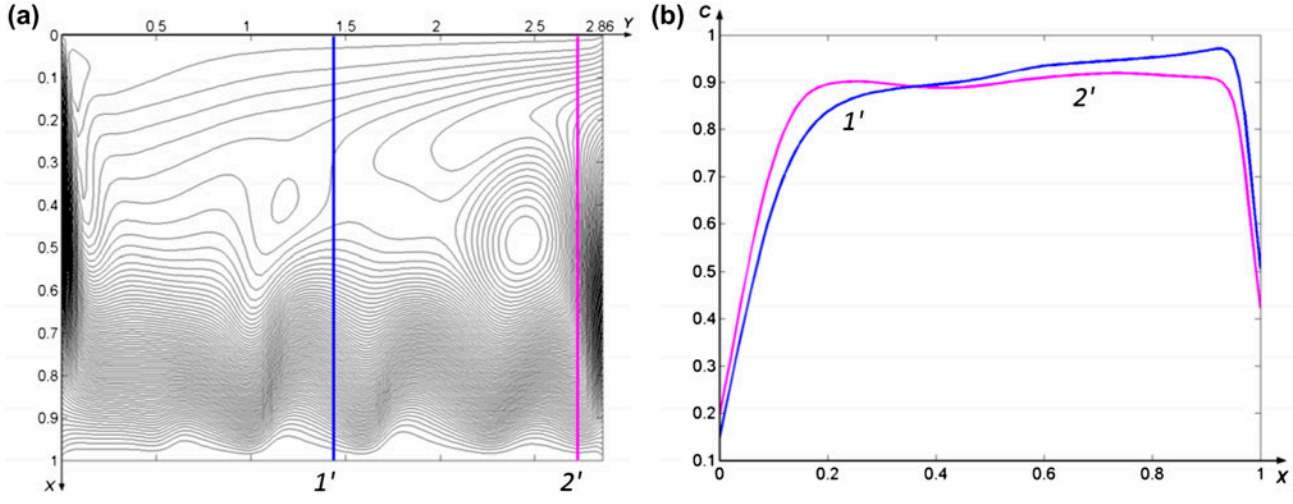

Fig. 1. Streamlines (a) and respective concentration profiles and (b) calculated with the model for the horizontal oriented membranes channel, 0.1 M NaCl solution, 0.01 cm/s forced convection, 0.3 V electric potential drop ($I \approx 1.9 \cdot I_{lim}$).

2. Results and discussion

Two dimensional mathematical model of time-dependent nonisothermal transport of binary electrolyte in a desalination channel of EMS in intense electric current modes is developed. The model takes into account a combined effect of gravitational and forced convection, as well as Joule heating of the solution and a heat transfer through membranes. The model is based on Navier–Stokes, Nernst–Planck, and Fourier partial differential equations transformed by an original decomposition method to the system appropriate for computer simulation. It is a generalization of the model presented in Pismensky et al. [7]. Results of the simulation show the domination and the significant influence of gravitational convection on the ion transfer when Richardson number $Ri = Gr/Re^2 > 300$ (for horizontal oriented membranes channel, Fig. 1) and $Ri > 1{,}000$ (for vertical).

3. Conclusion

The necessity of a theoretical investigation of the role of gravitational convection in overlimiting electric current modes is justified as well as a development of models of nonstationary transfer of binary electrolyte in diluted solutions in EMS takes into account a mixed convection, including forced and gravitational convections. Mathematical model of time-dependent non-isothermal transport process in an EMS, if formulated for a binary electrolyte takes into account a co-action of forced and gravitational convection in potentiodynamic mode.

Further research is dedicated to the model improvement with Poisson equation for the accounting of electroconvection influence.

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