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Donnan dialysis − a new predictive model for non−steady state transport

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Abstract

A bond−graph model has been developed and applied to analyze the non−steady state transport kinetics of K^+ cations in the Donnan dialysis (DD) process. The model is based on a pseudo−thermodynamic network analysis and takes into account all the simultaneously occurring processes and phenomena, i.e. diffusion through aqueous layers, interfacial and membrane ion−exchange kinetics, interdiffusion of K^+ and H^+ cations, diffusion of a free electrolyte in the membrane, and the osmotic transport of water. Moreover, membrane morphology represented by its heterogeneity and non−uniform distribution of ionogenic groups has been included in the model.

The numerical simulations of fluxes demonstrated that the DD efficiency in the investigated system results from osmotic water transport as well as an electrolyte solution sorption into the cation−exchange membrane. These phenomena cause dilution of the stripping phase and enable free diffusion of the electrolyte between the external solutions, respectively. The reverse K^+ ions flux from the stripping solution into the feed one observed in DD experiments results from the interdiffusion and non−exchange diffusion of the electrolyte.

The numerical calculation results were compared with the experimental data measured for the DD systems operating with a low feed solution concentration (c_f=0.01 M) and high stripping solution concentration (c_s up to 1 M) resulting in observable osmotic flux of water. It was found that the developed model can be applied for the prediction of time−dependent concentration in the DD system. Consequently, the prediction of fluxes, concentration factors, recovery factors, etc. is also possible. The model calculations enable also the prediction of the experimental results as dependent on one of the main factors which influence DD efficiency, i.e. the stripping phase concentration.

Key: Donnan dialysis; Bond−graph modeling, Osmotic transport, Reverse flux, Non−steady state flux

1. Introduction

Donnan dialysis (or ion−exchange dialysis) is a membrane separation technique in time of which the coupled transport (countertransport) of ions through the ion exchange membrane occurs [1]. Macroscopically, DD is based on the stoichiometric exchange of ions of the same sign between two solutions, separated by an ion exchange membrane [2−4]. This membrane allows the transport of polyelectrolyte counter−ions with the simultaneous exclusion of co−ions. The general scheme of ideal DD transport throughout the cation exchange membrane is shown in Fig. 1

Fig. 1.

It was reported previously that DD can be applied for the removal, recovery, separation, and concentration of cations such as Mn^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+} [3,5,6], or Al^{3+} [7,8], radioactive ions [9,10], and many other metal ions [11−15] including cations from electroplating rinse solutions [16, 17]. Moreover, DD with an anion exchange membrane was reported to be applicable for the separation of amino acids [18,19], the removal of NO_3^- and F^- ions from water [20−23], and other anions separation [24−37].

The transport of ions in the ion−exchange membranes is a complex and multistage process. The functioning of the system under specific operational conditions may result in the concentration of the transported ions in the stripping solution (up−hill transport). In order to improve understanding, predicting the membrane transport efficiency and its performance under different operational conditions, various mathematical models (complex or simplified) were formulated. Most mathematical models used to describe the DD kinetics result from conversion of the Nernst−Planck equation:

$$J_A = -D_A^{(m)} \frac{d\, c_A^{(m)}}{dx} - z_A c_A^{(m)} D_A^{(m)} \frac{F}{RT} \frac{d\varphi}{dx} \qquad (1)$$