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Electrodialysis with notched ion exchange membranes: Experimental investigations and computational fluid dynamics simulations

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ABSTRACT

Electrodialysis (ED), which equips ion exchange membranes (IEMs) in a direct current field, has widely been employed for desalination and separation of electrolytes. To date, IEMs for ED have commonly been plain, and should be stacked with spacers to provide water flow channels along membrane surface. This study reports a novel notched IEMs, which is a combination of a plain IEM and a spacer. Continuous-mode ED test has been performed to evaluate its desalination performance. Computational fluid dynamics (CFD) simulation of properties of the flowing solution gives an insight into advantages of the unique geometry of membrane surface. Particularly, results of CFD simulations are consistent with experimental investigations and conform that the notched membranes exhibit better performances than traditional plain ones for ED applications.

1. Introduction

Fresh water shortage has been a global problem throughout human history. Approximately 99% of surface and underground waters cannot be directly used without treatment [1]. Electrodialysis (ED), an energy effective and practical technology for treating unusable water, has been widely used in water desalination [2–4], the separation of electrolytes [5,6], and even in the purification of bio-solutions with bipolar membranes [7].

Electrodialysis is generally operated under direct current (DC), which provides the driving force for mass transport through membranes [8]. It is well known that there are at least five components in a common electrodialysis device [9]: (1) direct current supply, which provides the force for ion migration; (2) electrodes, where the reduction/oxidation reactions occur; (3) IEMs [10], the key component that permits the transport of counter ions and block the passage of co-ions; (4) spacers, which separate the membranes and assure mass transport through the membranes [11]; and (5) electrolyte solutions, which fill the space between membranes and act as the current carriers between the cathode and anode.

Among these components, the commonly smooth IEMs play the vital role in ion transport. A considerable amount of work has already been conducted towards the development of IEMs with optimal properties since their first synthesis in the 1950s [12]. Substantial progress has been achieved in the preparation of IEMs, such as homogeneous membranes [13–15], hybrid membranes [16–18], and bipolar membranes [19–21], which has increased their versatility and capability in industrial applications. However, most of above studies have focused on enhancement of ion transport through the membrane [9,22,23] ignoring concentration polarization. It is well known that cconcentration polarization happens at the interface between an IEM and an electrolyte solution (boundary layer) when an electric current passes through the system [24]. Ions usually transport by the convection and electromigration way in the main body of the solution, and by the electromigration and diffusion manners in the boundary layer [24]. To improve mass transport, independent spacers [25] or integrated spacers [26] are usually employed in ED devices to provide flow channels. However, spacers can only improve the convective mass transfer in the body area of solution by creating turbulent cross-flow, but have no significant improvement of ions transport in the boundary layer due to the slow fluid velocity [24].

In this study, notched membranes, which induce cross flow and even mitigate fouling in the boundary layer [27], were prepared and applied in ED process. The special geometry of notched membrane allows no use of non-conductive spacers, and significantly increasing the effective membrane area and making the stack more compact. Continuous-mode ED performances of notched membranes were investigated. Furthermore, computational fluid dynamics (CFD) simulation, which has usually been used to study the channels of spacers [28–30], was conducted to investigate

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Nomenclature

Abbreviations

ED	electrodialysis
CFD	computational fluid dynamics
DC	direct current
IEC	ion exchange capacity
IEM	ion exchange membrane
AEM	anion exchange membrane
CEM	cation exchange membrane
CV	constant voltage
CD	current density
LCD	limiting current density

Symbols

$\mathbf{P_{pump}}$	power of pump
D_{AB}	binary mass coefficient (m^2/s)
m_A	feed solute mass fraction ($kg\ kg^{-1}$)
Re	feed Reynolds number ($Re = \rho u_0 d/\mu$)
u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
w	velocity in z-direction (m/s)
x	x coordinate
y	y coordinate
z	z coordinate
ρ	density (kg/m^3)
μ	viscosity (kg/(m s))
d	bottom thickness (μm)
a	gap of protuberance (μm)
x	length of protuberance (μm)
y	width of protuberance (μm)
h	height of protuberance (μm)

properties of flowing solution in the boundary layer, including the velocity magnitude and the mass fraction of solute.

2. Experimental

2.1. Materials

The anion exchange membranes (AEMs) and cation exchange membranes (CEM) were kindly provided by the Hefei Chemjoy Polymer Materials Co., Ltd. The main properties of these membranes are listed in Table 1. Fabrics with three different mesh counts (60, 100, and 420) were purchased from the Sefar Group, China. The other chemicals were reagent grade and were used as received.

2.2. Preparation of notched membrane

The notched membranes were prepared by a hot-pressing process. Each commercial membrane was sandwiched between two pieces of fabric with the same mesh count and then hot-pressed by using a thermo-compressor (Dongguan Kesheng Co., Ltd.) at a constant temperature (135 °C) and pressure (8 MPa). Accordingly, the hot-pressed membranes contain notches with different dimensions due to the different mesh counts of the fabrics (60, 100, and 420).

Surface and cross-section morphologies of notched membranes were recorded by scanning electron microscopy (SEM, TM3000). Particularly, to obtain a sharp cross-sectional morphology, the samples were fractured in liquid nitrogen.

2.3. Continuous-mode ED

A schematic diagram of the continuous-mode ED stack is shown in Fig. 1A. Specifically, it is composed of (1) a cathode and an anode, which are made of titanium coated with ruthenium; and (2) two chambers, namely the electrode chamber (thickness of 1 mm) and the diluate chamber (thickness of 2 mm). The effective membrane area is 9×11 cm^2. Notably, there is no spacer between two neighbouring membranes to enable testing of the cross flow caused by the notched surface morphology. Two electrodes are connected to a direct current power supply (SHEKONIC, Yangzhou Shuanghong Co., Ltd.). A 0.1 M Na_2SO_4 solution is pumped into the electrode chamber, while a 0.01 M NaCl solution being fed into the diluate chamber. The electrode chambers are connected to a beaker, which allows the Na_2SO_4 solution being circulated by a submersible pump (HJ-311, Zhejiang SENSEN Industry Co., Ltd.) and prevents substantial pH changes in two chambers. The flow rate of the diluate solution (NaCl) is constant at 1.2 L/h, which is controlled by a peristaltic pump (BT100-1F, LongerPump Co., Ltd.). The resulting current across the stack is read directly from the instrument while the voltage across the electrodes is constantly at 60 V. The continuous-mode ED is conducted at room temperature.

Before the experiment, each chamber is circulated for 30 min to eliminate visible bubbles, which usually increase the resistance, voltage drop and energy consumption of the stack. Current and bubbles collaboratively divert to localised "hot-spots" with high current density on the interface between the solution and membrane, which may lead to membrane damage and thus reduce the membrane lifetime. After eliminating the visible bubbles, the diluate water is stored. The conductivity changes of the outflow solution are started to record by a conductometer (DDS-307, Shanghai Leici Co., Ltd.) when its volume is 10 ml.

2.4. Limiting current density

The limiting current density (LCD) of the notched IEMs is determined from current–voltage curves recorded using a similar ED stack (as shown in Fig. 1B) [31].

3. CFD simulation

3.1. Determination of physical models

The gaps between protuberances on notched membranes are determined from the surface SEM images in Fig. 2, whereas the

Table 1
The main characteristics of membranes used in the experiments.

	Membranes	Thickness (μm)	IEC (mmol/g)	Water uptake (%)	Area resistance (Ω cm^2)	Transport number (%)
AEM	JAM-II-07	170	1.6	28	3.5	94
CEM	JCM-II-07	170	1.8	38	3.2	95