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An experimental study on the performance of an electro-dialysis desalination using hollow cubic assembled porous spacers fabricated by a 3D printer

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ABSTRACT

In order to improve the performance of a filter press type electro-dialysis (E.D.) system, 5 types of hollow cubic assembled porous spacer fabricated by a 3D printer were applied instead of the conventional mesh spacers. The effects of structure of porous spacers on the E.D. system performance were experimentally investigated in terms of limiting current density, stack voltage and pressure drop. It was found that the porous spacer with vertical staggered arrangement normal to membrane surface and with smaller interfacial surface area between spacer and membranes contributes a higher limiting current density, which is about 2.5–3.0 times higher than that of E.D. system without spacer. Moreover, this spacer filled in E.D. system results in a relative lower electrical resistance and a smaller pumping power compare to other spacers. Since the vertical staggered structure is able to mix the flow (i.e. mechanical dispersion), supplies ions in the flow towards membranes, and suppresses concentration polarization, so that increases the LCD at expense of slightly increase in electrical resistance. Moreover, dimensionless mechanical dispersion coefficient towards membranes was estimated by fitting the experimental data with the analytical solution proposed in previous paper. Finally, a suggestion for making a good porous spacer has been proposed.

1. Introduction

Electro-dialysis (E.D.) remains a focus of attention since it meets the needs of desalination of wastewater for human and ions separation in many fields [1–3]. The electro-dialysis stack is divided into pairs of dilute compartment and concentrate compartment by alternately arranged cation exchange membranes and anion exchange membranes. Due to the selectivity of ion exchange membrane, the feeding solution can be diluted or concentrated at the exit of channel. Nowadays, either improving the efficiency or saving cost in electro-dialysis process has been taken into account. In such a state, various methods such as inserting spacer into testing channel [4] or improving membrane conditions [5] have been proposed.

The performance of the electro-dialysis system has been evaluated in terms of the limiting current density, stack voltage and pressure drop. The limiting current density [6, 7] is of an important parameter in E.D. system, which is the maximum available current density in electro-dialysis procedure. On the other hand, the stack voltage and pressure drop were concern associated with the electrical power consumption and pumping power. The concentration polarization has been investigated in widely experimental studies [8–11]. This phenomenon arises at the interface between an ion exchange membrane and ionic solution in the dilute side [12], so that salt ions getting less in a boundary layer for the desalting phase. The excessive consumption of ions drastically increases the electrical resistance as well as stack voltage, which greatly reduces efficiency of process. In addition, according to A. Campione et al. [13] and Abu-Rjal et al. [14], the concentration polarization may significantly affect counter-ions transport through the membrane as the electric current changes. Subsequently, water dissociation [15] takes place on a desalting surface of the membrane to relieve the scarcity of conductive ions. The current density, in such an occasion, is termed as the limiting current density (LCD). However, an intensive water dissociation generates amount of acid and alkali, which may bring a damage to the ion exchange membranes. Therefore, the investigation on the limiting current density and increasing its value become important and necessary.

According to Hicks [16], ionic mass transfer increases by inserting mesh spacers in dilute and concentrate channels of an electro-dialysis.

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In addition, the application of mesh type spacers in electro-dialysis has been reported in amount of literatures [17–23]. They found that the spacer is effective to suppress the concentration polarization and enhance the ionic mass transfer as a result of hydrodynamic mixing of the fluid. J. Balster [24, 25] substantiated an obvious increment in the limiting current density value by improving the structure of spacers. On the other hand, Nakayama et al. [26] proposed an analytical solution for predicting the limiting current density as well as evaluating effect of fluid mixing on the limiting current density. He claimed that mechanical dispersion would be significant for increasing the limiting current density. Subsequently, Sano et al. [27] examined the usefulness of porous spacer made of ceramic foam, which illustrates the fluid mixing in the porous materials can suppress the concentration polarization and increase the limiting current density.

With the emerging of 3D printing technology, the 3D printer has become widely applied in a variety of fields. This promising technology is able to create objects with complicated structures and produce an assembly in a single-step process [28, 29]. Therefore, the fabrication of the present structure, hollow cubic assembled object, can be realized. On the other hand, the parameters, such as size, porosity, interfacial area and structure arrangement are controllable and can be easily tuned.

In this study, 5 types of porous spacers with distinctive structures were fabricated by 3D printer. A series of experiments were carried out to improve the performance of E.D. system, namely, the limiting current density, the stack voltage and the pressure drop. The effects of structure of porous spacers on the E.D. system performance were investigated by comparing the performance of E.D. system in which applied each of porous spacer. Furthermore, dimensionless mechanical dispersion coefficient towards the membrane has been estimated by fitting the experimental data with the analytical solution proposed in our previous study [26]. Finally, a suggestion for making a good porous spacer has been proposed in terms of LCD and energy consumption.

1.1. Methods and theories

Instead of the conventional non-woven net spacers, 5 types of porous spacers with distinctive structures were applied in this study. All porous spacers were arranged based on the unit element as shown in Fig. 1. The sizes of element characterizing a hollow cubic are tabled in Table 1. The length of the cubic is 3.72 mm (i.e. a). The hollow cubic consists of 12 rectangular ribs with the length of 0.64 mm (i.e. c). Therefore, 6 rectangular holes are formed with the length of 2.44 mm (i.e. b). In this study, porous spacers were fabricated by a 3D printer (Replicator 2X, MarkerBot). All porous spacers were made of acrylonitrile butadiene styrene with the electrical insulation property. For convenience, we numbered them from spacer 1 to spacer 5.

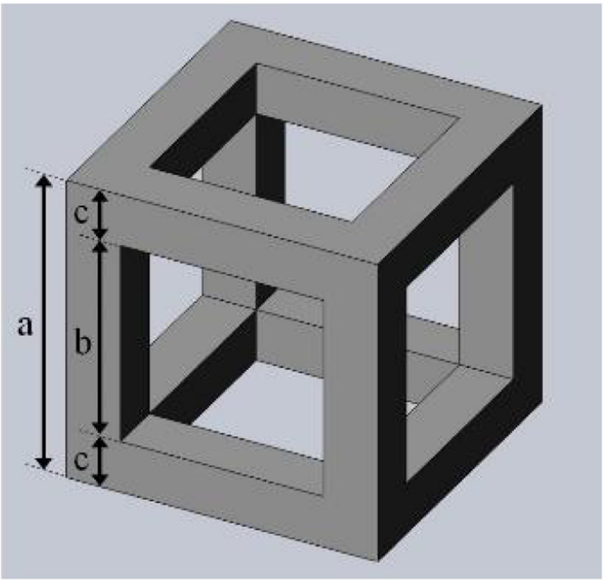

Fig. 1. Basic component of porous structures.

Table 1
Sizes of element for a basic component.

Basic element	a[mm]	3.72
	b[mm]	2.44
	c[mm]	0.64

Fig. 2 shows both CAD picture and physical photo of spacer 1, which is the most basic square array structure composed of basic cubic units. In this figure, x direction is the flow direction of ionic solutions, while z direction is normal to the membranes. The rest of porous spacers are presented with CAD pictures in Fig. 3 and with physical photo in Fig. 4. Both spacer 2 and spacer 3 are staggered arrangement structures based on the spacer 1. In the spacer 2, half amount of the basic cubic elements were alternately shifted towards y direction (i.e. parallel to membranes), which is called as the transverse staggered structure in this study. On the other hand, spacer 3 was alternately shifted by half cubic unit towards z direction (i.e. perpendicular to membranes), which is called as the vertical staggered structure in this study. Moreover, spacer 4 is a structure in which all cubic elements were integrally shifted by half cubic unit towards z direction. In spacer 5, cubic elements were alternately shifted by 1/3 cubic length towards z direction based on the spacer 4. More details of geometric parameters of the present porous spacers are listed in Table 2. All the porous spacers were correspondingly manufactured as a block with the size of 100 mm × 20 mm × 5 mm, and successively located in the test section, which has the size of 600 mm × 20 mm × 5 mm.

As we can see from the Fig. 3 and Fig. 4, for spacer 1 and spacer 2, the interfacial area is about 37.2% of the total effective ion transport surface area, i.e. $0.012 \times 37.2\% = 0.00446\,\mathrm{m}^2$. For the spacer 3, the interfacial area is 29% of the total effective ion transport surface area, i.e. $0.012 \times 29\% = 0.00348\,\mathrm{m}^2$. For spacer 4 and spacer 5, the interfacial area decreases to about 3% of the total effective ion transport surface area, i.e. $0.012 \times 3\% = 0.00036\,\mathrm{m}^2$.

The flow routes, fluid mixing and interfacial surface area between spacer and membrane can be varied by inserting the 5 types porous spacers in both dilute and concentrate compartments in E.D. system. The effects of structure of porous spacer on the performance of the ED system can be investigated in terms of these physical factors.

The experiment setup applied in this study as shown in Fig. 5, more details about the stack and cell configuration were described in our previous paper [27]. In this experiment, the 2% (0.342 M) NaCl solution and 5% (0.352 M) Na_2SO_4 solution were applied as the electrolyte solution and electrode solution, respectively. The inlet flow velocity varied under 0.5 cm/s–2.5 cm/s. The stack voltage of a unit cell and pH values at the outlet of dilute and concentrate channels were measured to estimate the limiting current density. The pressure drop was also measured by manometers connected at the inlet and outlet in dilute channel. In our experiment, all the measurements were conducted with the duration of 5 min after reaching steady state. Each experiment was repeated 3 times, and the average value has been obtained for the result.

An expression for estimating limiting current density of spacer-less channel was derived in our previous study [26]. Which solves Nernst-Planck equation associates with the local electro-neutrality assumption.

$$i_{\mathrm{lim}} = 2.366\frac{\mathrm{F}\mathrm{D_e}c_{din}}{L}\left(\frac{u_d L^2}{D_e W}\right)^{1/3} \tag{1}$$

where c_{din} and u_d are inlet concentration of the ionic solution and inlet mean flow velocity. Moreover, F, De, W and L indicate Faraday constant, effective diffusion coefficient, the height and length of the