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Development of a Spacer for the Diluting Compartment of EDI-LB (Electrodeionization-Layered Bed) Device

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Abstract

With the product water from a one-stage reverse osmosis (RO) process as the feed water, ultrapure water has been prepared by a self-designed module for one-stage one-pass RO/EDI/LB filtration system (the thickness of spacer for diluting compartment is 10 mm). This paper evaluates the changes in voltage-current, resistivity of product water and conductivity of concentrate water, and achieves a proper spacer for diluting compartment. This spacer ensures an even distribution of fluid in diluting compartment, effectively avoids the intermixing between different layers, and realizes the deep removal of ions. It indicates that the resistivity of product water is higher than 17 MΩ·cm, water output per effective membrane area reaches 5.5×10^{-5} $m^3/(cm^2\cdot h)$, and power consumption per ton water is less than 0.7 kW·h when the module is assembled with the modified spacer.

Keywords: Electrodeionization, Ion exchange membrane, Structure of diluting compartment, Layered bed, Ion migration

1. Preface

EDI (electrodeionization), an advanced membrane separation technology, has been widely applied in the preparation of ultrapure water. At present, EDI process mainly consists of mixed bed EDI and layered bed EDI. Ion exchange resins in diluting compartment of mixed bed EDI module are mixed packed, which leads to adverse effects on the desalination efficiency, output of product water, tightness and etc.; whereas, ion exchange resins in LB-EDI module are layer packed, which results in positive effects on the resistivity of product water, product flux per effective membrane area, tightness and etc.. Therefore, more and more attention is being given to the development of LB-EDI technology (Kunin, R et al, 1950, p. 109; Walters, W R et al, 1955, p, 61-67).

The design of spacer for the diluting compartment is one of the essentials of EDI technology. Reasonably designed spacer has good hydrodynamic performances, ensures uniform contact between the fluid and resin, eliminates the channeling, improves the ion exchange properties, minimizes the adverse effects on ion exchange caused by alluvial sediments of resin, avoids the blockage of the channel entrance and exit by resin particles, and increases the tightness of ion exchange membrane. The strict control on the length, width and thickness of compartment and subcompartment, as well as the structure of catchment channel network play important roles in the design of spacer for the diluting compartment (Giuffrida, A J et al, 1986; Ganzi, G C et al, 1987, p. 43-50; Kitty, K S et al, 1988; Keith, A P, 1989; Parsi, E J et al, 1991). As for LB-EDI process, besides the above-mentioned requirements, the spacer should have no intermixed area among various resin layers under the force of the current so as to ensure the stratification of bed. This paper compares the different spacers, and achieves a reasonably designed spacer, which is valuable for broader applications.

2. Experiment device and process flow

2.1 Experiment device

EDI module: a self-designed one-stage one-pass module and a diluting compartment.

Spacer for the diluting compartment: blind pass, loop-free, 325.44 cm^2 of effective membrane area, 10 mm of thickness, and ABS resin plate as a plating material.

Spacer for the concentrate water compartment: blind pass, loop-free, 4 mm of thickness, and ABS resin plate as a plating material.

Spacer for the electrolyte water compartment: 0.5 mm of thickness, and equipped with in-built inert screen.

Sealing material: silica gel plate of 1 mm thickness.

Cathode: stainless steel plate.

Anode: titanium-plated ruthenium plate.

Ion exchange membrane: low permeability EDI membrane from Shanghai Shanghua Water Treatment Material Co., Ltd.

Ion exchange resins: gel-type strongly acidic cation exchange resins (001×7) and gel-type strongly basic anion exchange resins (201×7), from the Chemical Plant of Nankai University.

2.2 Process flow

Figure 1 is a process flow diagram of the experiment.

Product water from one-stage RO passes through the feed water tank, and splits into two ways which in turn enter into the diluting compartment and concentration compartment of EDI module, respectively. Effluent from the diluting compartment is product water; whereas, effluent from the concentration compartment is concentrate water, i.e. electrolyte water, which passes through anode compartment and cathode compartment, and then is discharged. Two rotameters are used to regulate the concentrate flux and the product water flux, respectively. Voltage and current of the module can be directly indicated on the D.C. display panel. Resistivity of the product water and conductivity of the concentrate water are measured with resistivity meter and EC meter, respectively.

3. Results and discussions

It is difficult for the mixed bed EDI process to form an ion exchange channel, therefore, the spacer for diluting compartment is designed to be thinner, usually 2~3 mm. However, ions are much easier to migrate in resin with same polarity, and it is more likely for LB-EDI process to form an ion exchange channel, therefore, the spacer for diluting compartment can be designed to be thicker, usually 8~10 mm. The increase in thickness of spacer has following advantages: (1) water output per effective membrane area increases, and less cell pairs are needed to produce the same amount of product water; (2) the spacer is enhanced, and effectively resists distortion under high clamping pressures, as a result, the spacer can prevent leakage effectively, and increase the safety of the module; (3) the increase in thickness of spacer causes that the adverse effect of potted component on the ion exchange and module resistivity decreases, therefore, potted components can be inserted between spacers, which makes it possible to increase the pressure of feed water. It can be concluded that thick spacer is much more suitable to the LB-EDI process.

However, it is difficult for LB-EDI process to ensure even distribution of fluid and complete isolation among various resin layers at the same time. In order to solve this issue, we have modified the spacer by inserting three self-designed distributors along the vertical axis against the water flow direction. These distributors divide the diluting compartment into four subcompartments along the water flow directions, each of which is packed with the same ion exchange resin to obtain a completely isolated resin layer.

This paper investigates the effects of five different spacers on the preparation of ultrapure water by LB-EDI process. The structures of these five spacers are listed below.

(1) Without any distributor, the diluting compartment is directly packed with four layers of ion exchange resins, each of which has a height of 90 mm.

(2) The diluting compartment is divided by thin plate distributors of 1 mm thickness each into 4 subcompartments, and packed with 4 layers of ion exchange resins, respectively. Each of resin layers has a height of 90 mm. The thin plate distributor has many slits, each of which has a width less than 0.3 mm.

(3) The diluting compartment is divided by slit-type distributors of 25 mm width each into 4 subcompartments, and packed with 4 layers of ion exchange resins, respectively. Each of resin layers has a height of 80 mm. The slit-type distributor has many slits, each of which has a width about 0.3 mm.

(4) The diluting compartment is divided by channel-type distributors into 4 subcompartments, and packed with 4 layers of ion exchange resins, respectively. Each of resin layers has a height of 80 mm. The distributor is covered with a 35-mesh polypropylene screen, and has a channel diameter of 4 mm.

(5) The diluting compartment is divided by screen-type distributors of 35 meshes each into 4 subcompartments, and packed with 4 layers of ion exchange resins, respectively. Each of resin layers has a height of 90 mm.

The corresponding modules for the above-listed diluting compartments are coded with M1, M2, M3, M4 and M5, respectively. The structures of M2, M3 and M4 are shown in figure 2 and figure 3.

The parameters of these five modules are listed in table 1.

3.1 Effect of spacer structure on current change of module

Figure 4 exhibits the *U-I* curves of M1, M3 and M4.

Figure 4 reveals that the current increases with the rise of voltage in all three curves. But it can be seen that the different structures of diluting compartments result in obvious differences among these three curves: (1) The slope of M1 is the largest. It is because without distributor, resin layers in M1 contact closely, and occur obvious intermixing at their interfaces under the force of the water flows, which accelerates the rise of current, especially when the voltage reaches a given value. (2) At the same current value, the voltage of M3 is the highest, and much higher than that of M1 or M4, however, the voltage of M1 is similar to that of M4. It is because M3 is equipped with slit-type distributors made of inert materials, and is much wider the other two modules, which results in a much higher resistivity and a much lower current. Therefore, it is necessary to increase the operation voltage of M3 to obtain the same current. In addition, M4 is equipped with channel-type distributor, which has a much smaller size and a much better stratification effect than slit-type distributor has. Therefore, the shielding effect of M4 decreases, as a result, the operation voltage of M4 is similar to that of M1 at the same current (Jinwoo Lee et al, 2007, p. 276-285; Songjung Hoon et al, 2007, p. 165-171).

3.2 Effect of spacer structure on resistivity of product water

Figure 5 exhibits the effect of spacer structure on the resistivity of product water under certain operation conditions (listed in table 2).

Figure 5 reveals that curves of M1~M4 change in the same trend and the resistivity of them reaches 18 MΩ·cm in the end. However, the screen-type distributor in M5 becomes deformed under the force of the water flows, which causes the intermixing of resin layers as a result, the resistivity of product water declines to about 1 MΩ·cm, and has no obvious change throughout the operation. It indicates that if resin layers can not be completely isolated by distributors, they will intermix , which will lead to the decrease of ion exchange and water dissociation efficiency, no way to regenerate the resin layers (figure 6), and an obvious decline in resistivity of product water. Therefore, compared with mixed bed, layered bed has obvious advantages.

Among M1~M4, the resistivity of product water of M4 increases the most rapidly, and is the first to reach 18 MΩ·cm. It is because the distributor in M4, through modification based on the former three distributors, realizes the complete isolation of resin layers, improves the stratification effect, increases the ion exchange efficiency, reduces the electric-field shielding, and accelerates the resistivity of product water to reach 18 MΩ·cm and stay stable.

Intermixing of resin layers can be identified by disconnecting the module and observing the color of resin layers. In addition, there is an obvious difference in density between anion exchange resin particles and cation exchange resin particles; therefore, it also can be identified by placing resin layers from the diluting compartment into deionized water, and keeping stationary for a given period.

3.3 Effect of spacer structure on conductivity of concentrate water

Figure 6 exhibits the effect of spacer structure on the conductivity of concentrate water under certain operation conditions (listed in table 3).

Figure 6 reveals that curves of M1 and M4 change in the same trend, the conductivity of concentrate water increases continuously at the beginning of the operation, and reaches the maximum, then declines rapidly to a lower value. However, curve of M3 appears that the conductivity stays stable at a peak value during the beginning period, and then declines continuously to a lower value. Conductivity of M5 keeps stable at a lower value throughout the whole operation.

M1, M3 and M4 are layered-packed, and the conductivity of concentrate water therefrom has the maximum value. It is because the same resin in LB is more concentrated, which promotes the formation of the ion exchange channel, accelerates the ion exchange, increases the desalination efficiency, results in a higher ion concentration gradient in diluting compartment, intensifies the water dissociation, and improves the ion removal efficiency (figure 5). However, resin layers in M5 occur obvious intermixing, which causes M5 to be in a contrary state (figure 5). It demonstrates that effective stratification can increase the ion exchange rate, accelerate the water dissociation, form the regenerated resin bed of a certain height, and increase the desalination rate.

The results of experiment on the modified spacer indicate that the end resistivity of product water is higher than 17 MΩ·cm; water output per effective membrane area is more than 5.5×10^{-5} $m^3/(cm^2\cdot h)$, and power consumption per ton water is less than 0.7 kW·h under the conditions that the voltage is 35 V, product flux is 36 L/h, water recovery rate is 90%, and conductivity of feed water is between 5 $\mu S\cdot cm^{-1}$ and 20 $\mu S\cdot cm^{-1}$. Comparing with other similar modules (Colbert, G L et al, 1997, p. 57-61), this modified module has much more excellent performances under the almost same power consumption.

Therefore, the self-designed spacer can realize deep deionization, and has good uniformity of water distribution, wherein, the combination performances of module M4 are much better.

4. Conclusion

As regards EDI, layered package has obvious advantages. However, the key issue involved is to achieve well-layered resins, which in turn promote the formation of ion exchange channel, increase current density and current efficiency, and then realize deep deionization. This self-designed diluting spacer ensures the uniform contact between the fluid and resin, achieves the well-stratified resin layers, avoids the intermixing of various resin layers, and increases the desalting efficiency. Wherein, module M4, based on the modifications of the other modules, completely ensures the uniform distribution of fluid, successfully achieves the well-stratified resin layers, and avoids to the full extend the decreases of effective membrane area and effective bed height resulted from the installation of distributor. The experiment results demonstrate that the improvement on the structure of diluting spacer achieves remarkable accomplishments. For example, the end resistivity of product water is higher than 17 MΩ·cm, water output per effective membrane area reaches 5.5×10^{-5} $m^3/(cm^2\cdot h)$, and power consumption per ton water is less than 0.7 kW·h under the proper conditions.

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Table 1. The parameters of modules

Modules	Diluting compartment	Concentrate water compartment; Electrolyte water compartment
M1	Without any distributor; 4 layers of resins; the 1st and 3rd layers are packed with the mixture of anion exchange resin and cation exchange resin; the 2nd and 4th layers are packed with anion exchange resin.	All concentrate water compartments are packed with cation exchange resin. Electrolyte water compartment, for circulation of concentrate water, is equipped with an in-built inert screen, and has 0.5 mm of thickness.
M2	4 layers of resins divided by thin plate distributors; the 1st and 3rd layers are packed with the mixture of anion exchange resin and cation exchange resin; the 2nd and 4th layers are packed with anion exchange resin.	
M3	4 layers of resins divided by screen-covered slit-type distributors; the 1st and 3rd layers are packed with the mixture of anion exchange resin and cation exchange resin; the 2nd and 4th layers are packed with anion exchange resin.	
M4	4 layers of resins divided by screen-covered channel-type distributors; the 1st and 3rd layers are packed with the mixture of anion exchange resin and cation exchange resin; the 2nd and 4th layers are packed with anion exchange resin.	
M5	4 layers of resins divided by screen-type distributors; the 1st and 3rd layers are packed with the mixture of anion exchange resin and cation exchange resin; the 2nd and 4th layers are packed with anion exchange resin.	

Table 2. The operation conditions of M1~M5

Modules	Operation voltage	Product flux	Concentrate flux	Conductivity of feed water
M1	20 V	M1: 24 L/h The others: 36 L/h	M1: 2.4 L/h The others: 3.8 L/h	5~20 μS·cm^{-1}
M2	30 V			
M3	75 V			
M4	35 V			
M5	35 V			

Table 3. The operation conditions of M1, M3, M4 and M5

Modules	Operation voltage	Product flux	Concentrate flux
M1	20 V	24 L/h	2.4 L/h
M3	75 V	36 L/h	3.8 L/h
M4	35 V	36 L/h	3.8 L/h
M5	35 V	36 L/h	3.8 L/h

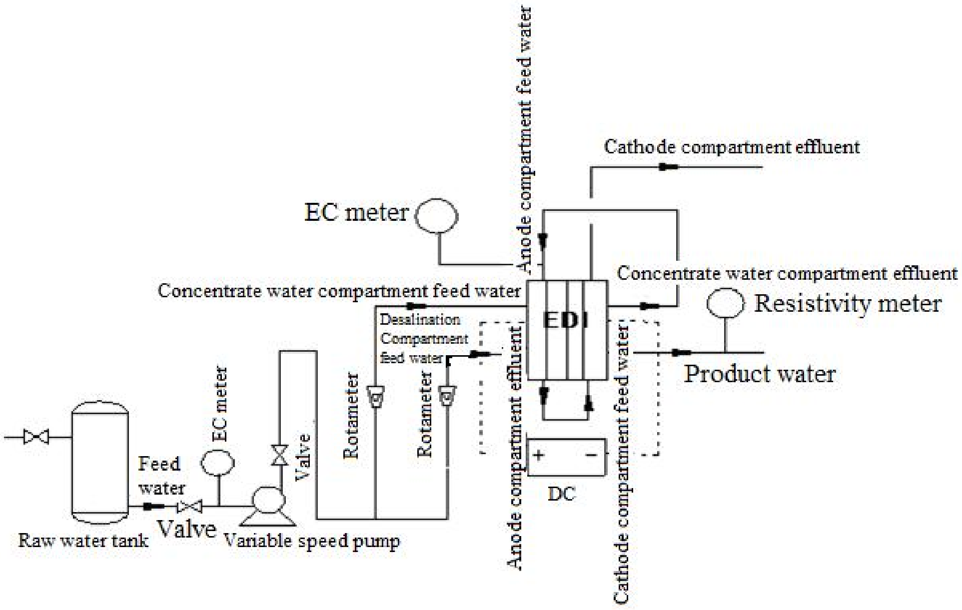
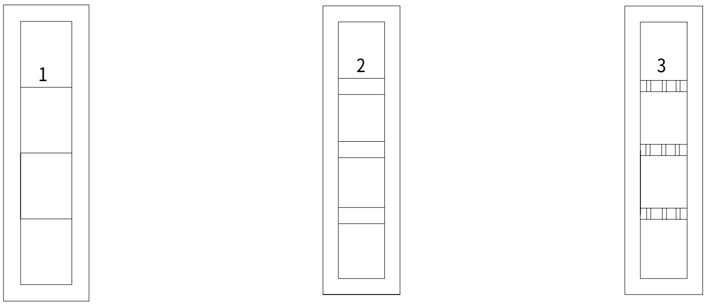


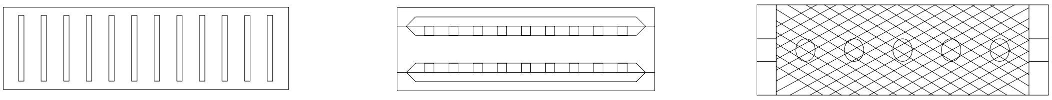
Figure 1. Process flow diagram of the experiment



1– Thin plate distributor 2– Slit-type distributor 3– Channel-type distributor

M2 M3 M4

Figure 2. Schematic diagram of spacer for diluting compartment



Thin plate distributor Slit-type distributor Channel-type distributor

Figure 3. Schematic diagram of distributor

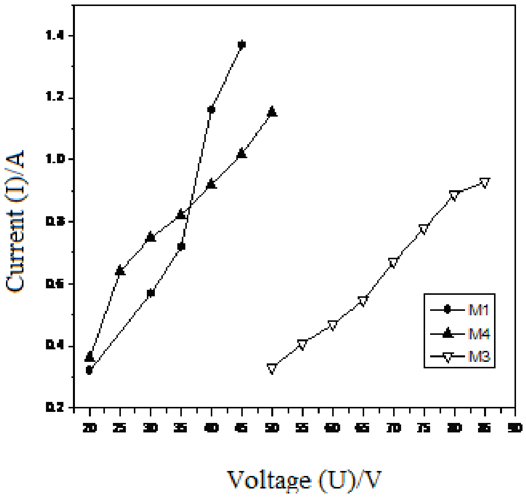


Figure 4. *U-I* curves of M1, M3 and M4

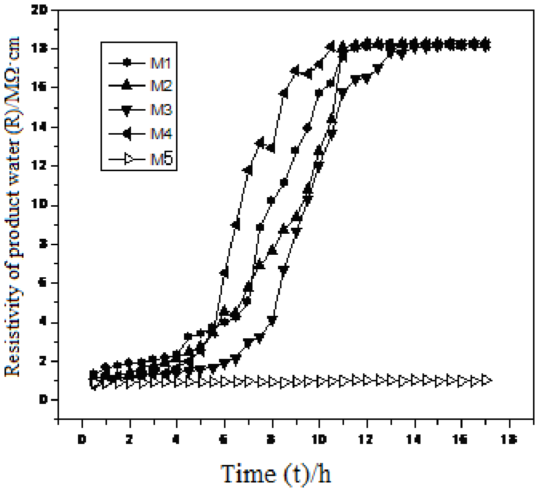


Figure 5. The relationship between resistivity of product water and operation time of M1~M5

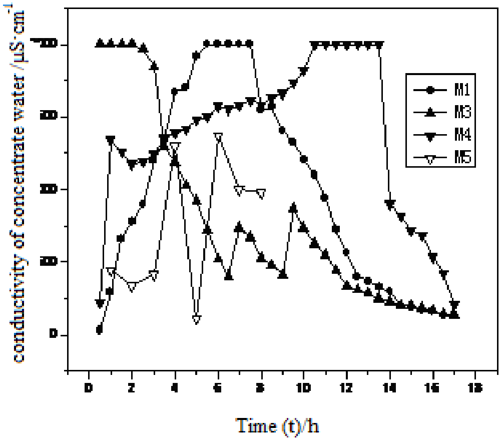


Figure 6. The relationship between conductivity of concentrate water and operation time of M1 and M3~M5