

Principle and Application of Continuous Electrodeionization

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1. Introduction

The continuous electrodeionization (CEDI) – also known as electrodeionization – is a hybrid separation process combining ion-exchange resins and ion-exchange membranes. The process is capable of achieving high levels of purification and concentration of dissolved ionic solutes without the use of chemical regenerants. In a CEDI equipment, the ion-exchange packing enhances the electrical conductivity of the diluting compartment.

The CEDI process uses an innovative design to produce high-quality deionized water. In the CEDI process, ions are removed from the water entering the CEDI module by a unique combination of ion exchange resin, ion exchange membranes, and electricity. Direct current from a DC power supply is applied to an electrode located on either end of the CEDI module. Direct current is the driving force for removing ions from the feed stream while continuously regenerating the resins inside the module. This process produces a consistent, predictable water quality better than 99 % removal with a feed water conductivity of 100 μ s/cm. The CEDI system can generally produce up to 18 M Ω -cm water when fed with RO product water that has a conductivity of less than 1 μ s/cm.

The CEDI technique has been reported in the literature since the mid-1950's. Waters, Weiser, and Marek [1] evaluated the technique for the concentration of radioactive aqueous wastes and proposed an ionic conduction mechanism through mixed bed ion-exchangers in contact with dilute solutions. In the late 1950's and 1960's, Burns and Glueckauf proposed a theory [2], based on data by Sammons, Gittens, and Watts,[3, 4], involving the diffusive transfer from the flowing solution into the particles combined with the electrolytic transfer of ions along ion-exchange resin particle chains. Electrodeionization principles were extended in the 1970's and new devices were proposed by a number of others in the 1970's and 1980's. The first commercially available module and component systems were introduced by Millipore in 1987 under the trade name Ionpure CDI. These plate and frame devices were based on the well-known multiple arrangements of alternating ion-depleting and ion-concentrating streams hydraulically in parallel and electrically in series [5].

In CEDI for the preparation of deionized water the process operates in two regimes, as illustrated in Figure 1 [6]: in the first, at high salinity, the resins in the depleting streams contain the salt forms, and high efficiencies are achieved due to the resin-enhanced electrical conductivity of the ion-depleting compartments; in the second regime, at low salinity, the resins are electrochemically converted to the hydrogen and hydroxide forms, and deionization takes place consistently like a continuously regenerated mixed bed ion-exchange column. In ultrapure water preparation, ion-exchange resins are typically two to three orders of magnitude more conductive than the water in which they are in contact, and it is therefore likely that ion transfer from the depleting compartment to the membrane surface is almost entirely mediated by the ion-exchangers, and relatively little transfer occurs directly through the water.

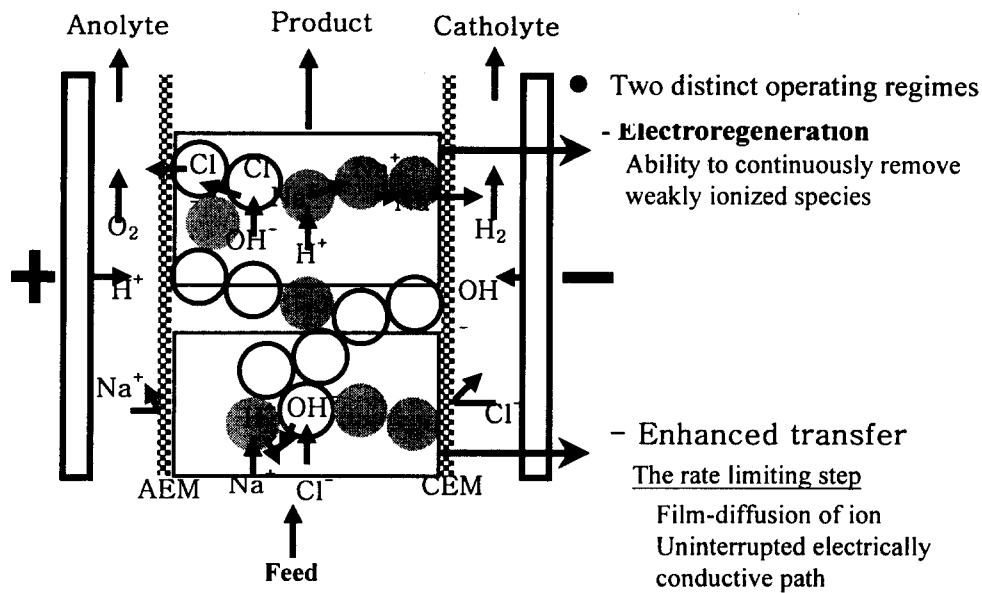


Figure 1. Principle of the CEDI process

Optimizing deionization performance of CEDI devices entails maximization of the deionization rate per unit effective membrane area in both the “enhanced transfer” and “electroregeneration” regimes. In the “enhanced transfer” regime it can be shown that for the deionization of tap water using ion-exchange resins, the transfer rates of ions in the depleting stream are for the most part film-diffusion controlled. Therefore, for given feed conditions and flow velocities, and at operating voltages that do not result in substantial electrochemical reaction products, improvements in ion transport can be made by increasing the “active surface area” of ion-exchange surface, per unit membrane area. The term “active surface area” is defined as the area both available to liquid flow and with an uninterrupted conductive path along the ion exchange resin to the appropriate membrane for effective deionization.

Performance per unit membrane area can be improved by increasing resin surface area, which can be accomplished by increasing the number of resin bead layers between membranes and/or by increasing the packing density of the resin. Performance is also improved by increasing the fraction of resin that conducts ions, which is accomplished by decreasing the number of resin bead layers between membranes. There is, therefore, an optimum number of inter-membrane resin layers for best CEDI performance. Increases in resin packing density result in both increased resin surface area and increased fraction of conducting resin unless the flow is interrupted.

2. Applications

2.1 Ultra-purification of Water for the Power Industry

The most common method of water purification for make-up feed to boilers is chemically regenerated ion exchange – traditional membrane purification techniques cannot provide the needed purity. The combination of reverse osmosis and CEDI is capable of producing water of equal or better quality than traditional ion exchange, and since RO/CEDI does not require the use of chemical regenerants, it generates a concentrate stream that can be readily used as cooling water. Figure 2 shows a flow diagram for a typical system and The performance test results for a pilot unit operated continuously at a power plant for approximately three months, show that the conductivity and silica were 0.062 μ S/cm and 0.005 mg/L, respectively, in the purified water. Essentially all of the CEDI concentrate was capable of recycle to the feed of the RO system. [7]

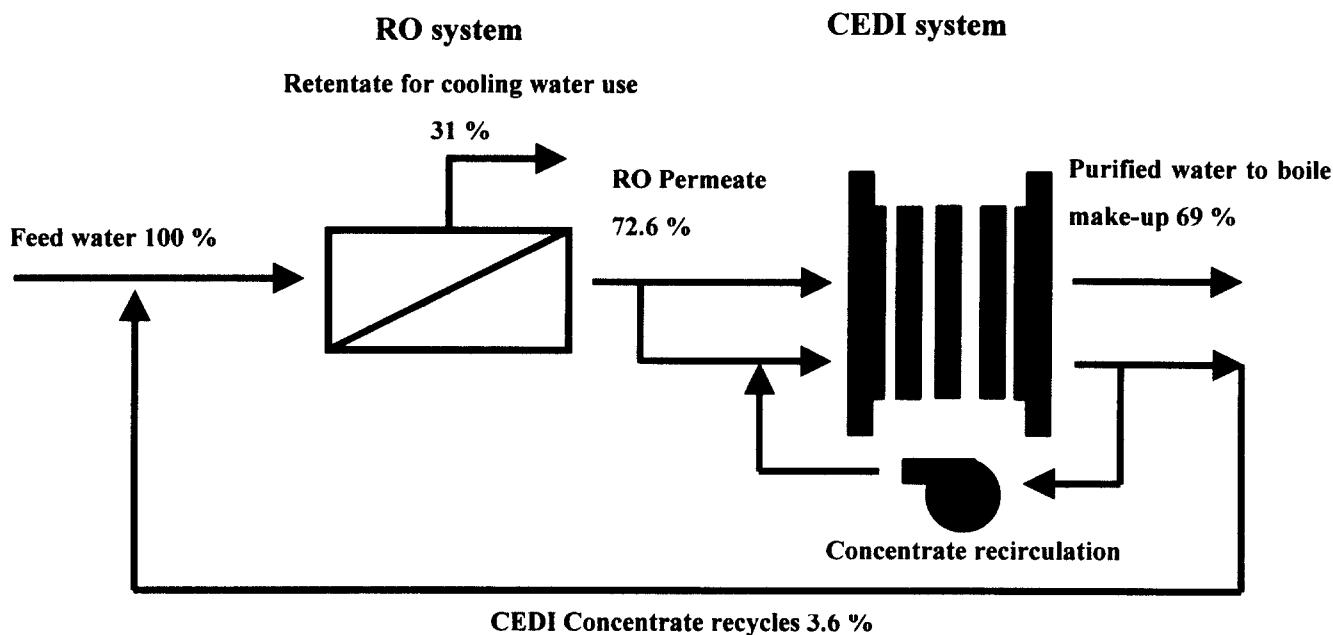


Figure 2. Flow schematic power industry application [7]

3. Nitrate Removal for Drinking water

Nitrate contamination of ground- and drinking water is of increasing importance and public concern in areas with industrial activity and intensive agricultural application of nitrogenous fertilizers. The performance of two membrane processes [electrodialysis (ED), electrodeionization (EDI)] using an monovalent selective anion exchange membrane was compared in removing nitrate from drinking water. The effects of operating parameters including feed concentration, current density and flow rate was investigated to determine the optimum experimental conditions. Because the relative transport number of nitrate and power consumption for ACS monovalent anion exchange membrane was much greater than those for AM-1 multivalent anion exchange membrane at 95 % nitrate removal, ACS monovalent anion exchange membrane was proved to be more suitable anion membrane than AM-1 multivalent anion exchange membrane. Electrodeionization (EDI) process was employed to overcome the limitations and disadvantages of electrodialysis (ED) and its parametric study was conducted for nitrate removal from drinking water.

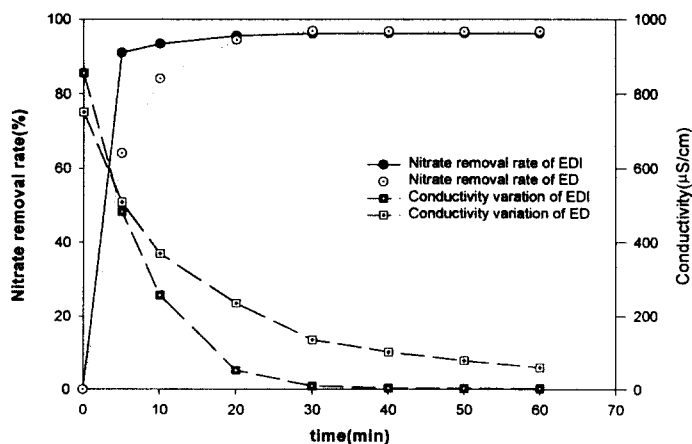


Figure 5. Nitrate concentration & removal rate with time by ED & EDI under constant voltage.

Imac HP 555 nitrate selective exchange resin and Amberlite IRA 402 anion exchange resin were tested to select the suitable resin in the EDI process. It was found that Imac HP 555 was a proper anion exchange resin than Amberlite IRA 402 due to its higher nitrate selectivity. Increase in linear velocity of the resin-filled compartment in EDI device resulted in greater nitrate removal rate and less power consumption. Based on mass balance of only nitrate, 19.2 % of the resin regeneration was obtained. When two membrane processes were operated at the

same condition, the power consumption under constant voltage was 0.05 Wh/L for EDI, 0.1 Wh/L for ED at 95 % of nitrate removal. In the constant current, the power consumption was 0.93 Wh/L for EDI, 1.03 Wh/L for ED at 95 % of nitrate removal. Therefore, it was clearly observed that EDI process was better than ED process for nitrate removal from drinking water in terms of power consumption and nitrate removal rate, as shown in Figure 5.

4. Radionuclides Removal for Primary coolant of Nuclear power plant

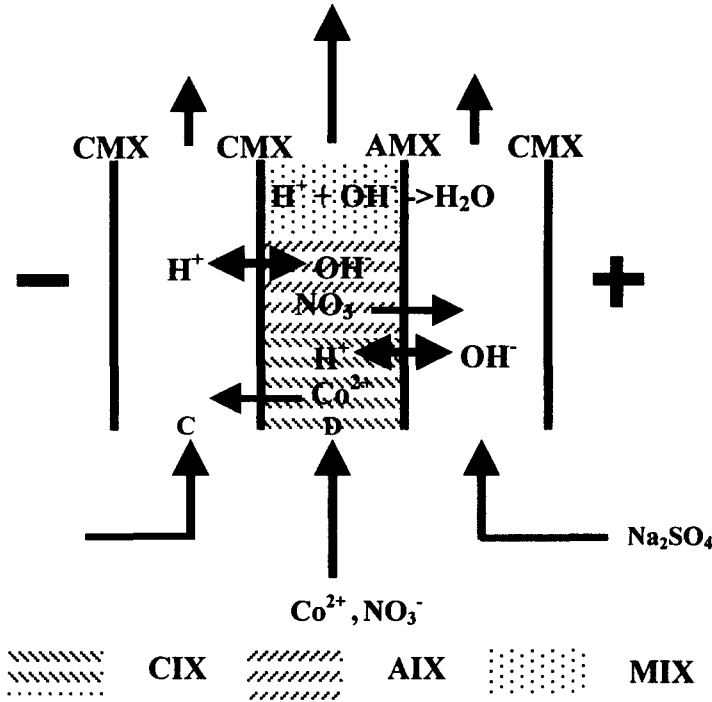


Fig. 9. Method of packing with layered bed in a diluted compartment
 CMX: cation exchange resin, AMX: anion exchange resin,
 MIX: mixed bed, Volume ratio: CIX:AIX:MIX=2:2:1

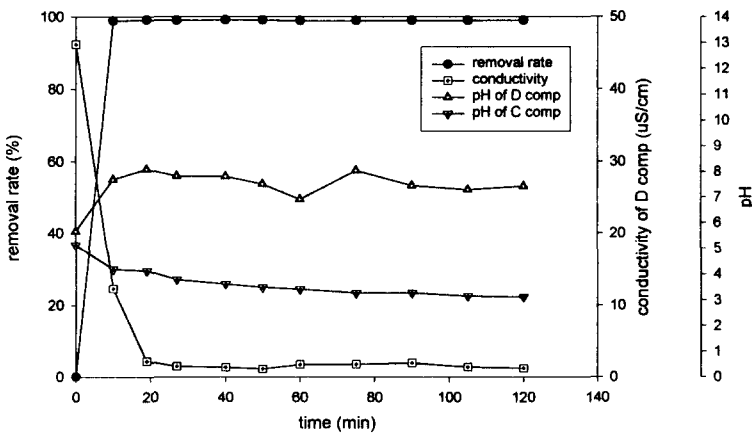


Figure 6. Variation of removal rate and pH with time
 when diluted compartment was packed with layered bed
 (Volume ratio: CIX:AIX:MIX=2:2:1)

Ion exchange resin has been broadly used in pressurized water reactor-type nuclear power plants for the purification of primary coolant system. The ion exchange method results in generation of waste resin that should be handled as radioactive solid waste. CEDI system was selected as an alternative process because it could overcome the drawback of the ion exchange method. Usually the packing material of the CEDI was mixed bed of cation and anion exchange resin. However, the CEDI with mixed bed alone can not be used to remove the ions from solutions containing metal ions because metal ions are precipitated with hydroxide that take place in the CEDI module spontaneously. Thus CEDI system was required to be improved to prevent the precipitation in the CEDI module for replacement of the ion exchange method in a nuclear power plant. The purpose of this work is to develop a CEDI system for preventing the precipitation with metal ions and hydroxide from primary coolant in a nuclear power plant. This method can be further utilized for the removal of heavy metal ions in the industrial plants such as plating effluents as well as nuclear primary coolant. CEDI system packed with a layered bed was operated with the cation exchange bed followed by the anion exchange bed and mixed bed. This stack configuration was effective in prevention of the reaction

between metal ion and hydroxide. As shown in Figure 6, the performance of CEDI with layered bed showed more than 99 % for ion removal and 30 % for current efficiency. The results show that an inlet conductivity of 40 $\mu\text{S}/\text{cm}$, a linear velocity of 4.17 cm/sec, an applied current density of 1.7 mA/cm², and an outlet conductivity of 0.5 $\mu\text{S}/\text{cm}$ was obtained with the CEDI process without preventing the precipitation with metal ion and hydroxide. This study was successfully demonstrates the feasibility of CEDI operation for removal of heavy metals at low concentration.

5. Conclusions

The experiments performed in this work show that the CEDI process is able to greatly decrease salt content in polluted water. In all cases the removal rates are higher than 95 %. The process is capable of achieving high levels of purification and concentration of dissolved ionic solutes without chemical regenerants.

In the nitrate removal for drinking water, even though electrodialysis and electrodeionization enabled to remove nitrate-nitrogen in drinking water effectively, electrodeionization performed better than electrodialysis for nitrate removal from drinking water in terms of power consumption and nitrate removal rate. Also, CEDI was successfully demonstrated to remove primary coolant corrosion species. CEDI with the layered bed enabled to prevent precipitation in the resin bed while the performance was maintained reasonably well in terms of the removal rate and the conductivity reduction.

Acknowledgement

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