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Electrodeionization (EDI) Process – A Detailed Review

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Abstract: Electrodeionization (EDI) process becoming increasingly popular as pretreatment steps or as replacements for ion-exchange systems altogether. EDI removes ions (organic and inorganic) using semi-permeable membranes and ion exchange resins that are continuously regenerated by an electric field. It can provide very high levels of demineralization and offer the advantage of continuous operation. Moreover, this processes is not as mechanically complex as ion-exchange systems.

Keywords: ED, EDI, RO, CEM, AEM, Ion exchange resin, Deionization.

I. INTRODUCTION

The concept of water purification process is improving day by day by the involvement of latest technologies in it. It is essential to use such processes because of the involvement of unnecessary matter in water. Traditionally, Ion Exchange process is widely used for getting high purity water, which can be further used in power generation industries, semiconductor industry, research laboratories & hospitals. Ion Exchange process uses chemically activated ion-exchange resin which interchange their ions with water & there by purifies water. The purity level of such process is around 16-18 MΩ-cm. So, it is broadly accepted by most of industries throughout the world. The major drawback of using the ion exchange process for the water purification is that ion exchange resin once discharged, requires acid / caustic regeneration for cation exchange resin (CER) / anion exchange resin (AER) respectively.

Another well-known method is electrodialysis (ED). In that, water is purified by using membrane technology. Water is allowed to pass through the passages made by membrane under potential gradient. The potential gradient splits water into ions viz. cation & anion, these ions are migrates towards electrodes through respective membrane like anionic exchange membrane (AEM) can allow anions to pass through it & cation exchange membrane (CEM) can allow cations to pass through it. This process makes one stream dilute & another stream concentrated. The major drawback of this process is concentration polarization. This requires more power for purification.

A novel technology, which eliminates drawbacks of above two process & merges good features of both is an electrodeionization (EDI) process. EDI is an ultrapure water treatment process that polishes reverse osmosis (RO) permeate without chemical regeneration. EDI has been in existence for over 55 years. It has become a proven and acceptable technology for all industrial water treatment users who require high purity.

EDI removes ionizable matter from liquids using ionically active media and uses an electrical potential to influence ionic transport. Electrodeionization processes can be batch or continuous. Continuous Electrodeionization (CEDI) is an Electrodeionization process where the ion transport properties of the active media are the primary scale-up parameters. There are also batch electrodeionization processes, such as capacitive deionization, [1] where the ion capacity properties of the active media are the primary sizing parameters.

EDI units are electrochemical devices. Since each EDI module is driven by electrical energy from an outside power supply, more specifically it is an electrolytic cell. Each EDI module consists of five primary components: Ion exchange resin, two ion exchange membranes and two electrodes

II. ELECTRODEIONIZATION BACKGROUND

The concept of EDI has been investigated since the mid-1950s. A batch electrodeionization process was investigated by Walters et al. [2].

In the late 1950s and early 1960s, the theory, design, and operating conditions of the CEDI process were investigated by Glueckauf [3]. He produced a theoretical model based on a two-stage removal of ions: the diffusive transfer of ions from flowing solution to ion exchange resin and the transfer of ions along the chain of ion exchange beads. Sammons and Watts [4] had experimentally demonstrated CEDI. The effects of parameters such as type of resin filling, cell width, resin particle size and liquid flow velocity was not investigated in detail.

The first patent for an electrodeionization device has been applied by a Dutch Company in 1953. They demonstrated the deionization of salt-containing liquids by using layers of anion and cation resins. The patent was granted in 1957. [5] A patent was also granted to Kollsman in 1957 [6] describing a CEDI apparatus for the purification of acetone. During this, so many patents were granted for various types of EDI devices. [7-10]

The first commercially continuous electrodeionization modules and systems were introduced by Ionpure in 1987. A more comprehensive review of the technical literature on electrodeionization is given by Ganzi et al. [11] A recent review of EDI technology was provided by Henley [12].

III. ELECTRODEIONIZATION PROCESS

EDI process produces water of consistent quality, requires less energy, cost effective operation and maintenance, etc. The EDI cell uses the benefits of ion exchange and Electrodialysis while reducing the problems of each of these separate technologies. The operating principle of EDI is shown in figure 1. The multiple EDI compartments, which are known as treated chambers and concentrated chambers are packed together by placing electrodes both the sides.

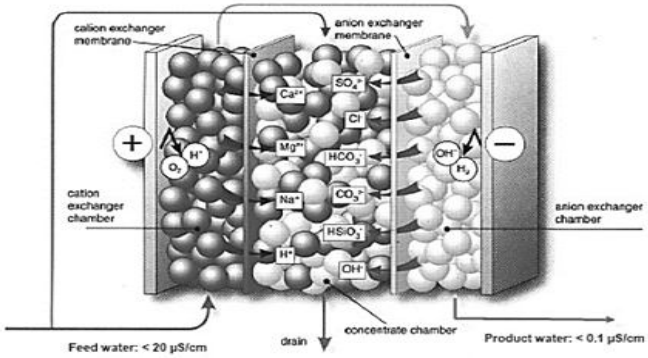

Fig. 1. Principle of EDI

The ion exchange resin used in EDI cell provide high ionic conductivity. The resin increases the residence time of the ionic contaminants inside the cell & allows more time for the transport of these ions into the appropriate compartments. A potential gradient generated by electrodes enhance ionic movement within the cell. Water dissociated into H^+ and OH^- due to potential gradient helps to regenerate the resins on-line, so no need for regenerative chemicals as in ion-exchange.

As shown in figure 1, there are mainly two types of chambers in an EDI device. Treated chambers (T-chambers) are the area where water is purified or diluted of ions. Concentrated chambers (C-chambers) are the areas where water is concentrated of ions, and becomes waste water. Both the T-chambers & C-chamber contain mixed bed ion exchange resin. The T and C chambers are separated by ion exchange membranes. The membranes are similar in material and charge to the ion exchange resin. Water and oppositely charged ions may not pass across the ion exchange membrane used in EDI.

There are three processes occurring simultaneously as water flows through the EDI module and power: The deionization process where the water is purified by ion exchange; ion migration where the ions are removed from the resin; and continuous regeneration of the resin. All these three processes are further explained as below:

Deionization

Deionization, also referred to as demineralization, is an ion-exchange process wherein virtually all of the dissolved ions in the water can be removed, producing pure water. Deionization removes both cations and anions. Cations are positively charged ions because they have a loss of one or more electrons. For example, the sodium ion (Na^+) is positive because the ion lost one electron. Anions contain a negative charge because they contain one or more additional electrons. The chloride ion (Cl^-) is formed when chlorine gains one electron. Figure 2 shows the ion exchange process.

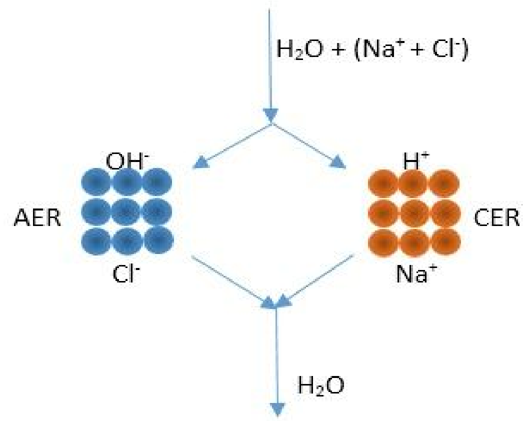

Fig. 2. Principle of Deionization

The cation exchange resin is in the regenerated hydrogen (H+) form. As the feed water passes through the resin, the cations like Ca^{+2}, Mg^{+2}, Na^+ and K^+ have a higher affinity to the CER than a hydrogen ion. The CER releases a hydrogen ion to bond with the cation. Similarly, anion exchange resin is in the regenerated hydroxide (OH-) form. The anions like CO_3^{-2}, Cl^-, SO_4^{-2} and boron have a higher affinity to the AER than hydroxide. The AER releases a hydroxide ion to bond with the anion. The released hydrogen and hydroxide ions combined to form water. Water is deionized by the removal of the cations and anions as it flows through the mixed resin bed.

Ion Migration

The second process in electrodeionization is ion migration.Movement of ions produced by the application of a n electric potential between electrodes. In conventional ion exchange process, resin becomes exhausted after certain period of time. For using the same resin again, it is required to perform chemical regeneration. Whereas in EDI, a DC electrical current is applied between the two electrodes. An electrical current provides the motive force for movement of electrons between the electrodes, from the anode to the cathode. The electrode with a negative charge is the cathode (electrons are available). The electrode (takes electrons) with a positive charge is anode. The ions removed from the feed water are kept with resin as per their charge. Further, this ions are transported towards the electrodes. The cations are attracted to the negative cathode. Similarly, the anions are attracted to the positive anode.

The positively charged ions will migrate from the cation resin bed through the CEM to the concentrate chamber due to their attraction to the cathode. Negatively charged ions will migrate from the anion resin bed through the AEM to the concentrate chamber due to their attraction to the anode. Once the ions are in the concentrate stream, further, they can't continue their migration to the electrode by placing an oppositely charged ion exchange membrane which does not allow entry to the adjacent treated chamber. Concentrate water is generally sent to drain. EDI waste water can be recovered by sending it to a ventilated raw water storage tank.

Resin Regeneration

The third process which occurs as the ions are removed and migrate to the concentrate chamber is resin regeneration. In ion exchange method, the resin is regenerated with acid and caustic chemicals. Hydrochloric acid (HCl), or sometimes sulphuric acid (H_2SO_4), is applied to cation exchange resin to regenerate. This process again replaces H^+ with the cations on the resin. Sodium hydroxide (NaOH) is applied to anion exchange resin and the concentration of OH^- replaces the anions from the resin. EDI replaces this laborious work. Instead, it uses the electrical current that is applied across the EDI module. In the presence of the electrical field, a phenomena known as "water splitting" occurs. The electricity causes a small percentage of water molecules to split into hydrogen and hydroxide ions which continuously regenerate the resin bed:

$$H2O \leftrightarrow H^+ + OH^-$$

Therefore, EDI operation is continuous. The ions are continuously removed, and the resin is continuously regenerated without chemicals. This provides a significant advantage to ultrapure water users over either onsite or offsite chemically regenerated ion exchange. The operation of the EDI system is as simple as operating a reverse osmosis system and the results of EDI are more reliable than chemically regenerated ion exchange.

IV. ADVANTAGES OF EDI

With comparison to conventional resin-based, chemically regenerated deionization equipment, EDI systems has a variety of benefits. Very fundamental advantage is the elimination of the regeneration process and hazardous regeneration chemicals, acid and caustic. Since EDI operates in a combination of ion transfer across the resins and membranes, the resins and membranes are never fully exhausted which provides dynamic stability of the process.

In addition, the product water quality stays constant over time, whereas in regenerable deionization, product water quality depends on the ion exchange capacity of the resin which degrades as the resins approach exhaustion. For those processes requiring deionized (DI) water on a continuous basis, requires more than one plant at same location, so that one system can provide water while the other is regenerated. This further adds cost, complexity, and size to conventional DI systems. EDI is continuous, and not a batch process, single unit can fulfil the requirements and its life may around 3-4 years. As a result, EDI system footprints are often one half of the size of their conventional counterparts.

The elimination of regeneration also has a cost benefits. The costs of regeneration labour and chemicals are replaced with a small amount of electrical consumption. Roughly, A typical EDI system will use approximately 1 kW-hr of electricity for deionize 1,000 gallons from a feed conductivity of 50 S/cm to 10 MΩ-cm resistivity. The waste stream concentration are 5–20 times higher concentration of feed water, it can be discharged without treatment.

Thus, it helps to reduce cost since waste neutralization equipment and ventilation for hazardous fumes are not necessary. By eliminating hazardous chemicals, workplace health and safety conditions can be improved.

V. APPLICATIONS IN WATER PURIFICATION

U.S. Filter has installed over 1300 CDI systems worldwide. These range in flowrate from 1 to 960 gpm. In addition, Millipore Corporation has sold over 2000 units for low flow rate laboratory applications, less than 100 lph.

Many different industries require deionized water, having specific requirements for the quantity and quality of water. EDI systems are now used by variety of industries, from process feed water in pharmaceutical, biotechnology and food and beverage applications to high quality rinsing water for electronics, surface finishing and optical glass applications.

More recently, higher flowrate capability and silica removal have made the EDI process an alternative for boiler makeup in power and cogeneration as well as for semiconductor manufacturing. EDI systems have also been installed at institutions such as hospitals, universities and dialysis centers.

EDI system polishes pretreated water and produces ultrapure water. The current trend combines EDI with reverse osmosis (RO) to produce ultrapure, mixed-bed quality water. Currently, the pharmaceutical industry is biggest user of this technology.

The electronics industry also requires high purity water for critical rinsing steps in the fabrication of semiconductor wafers. This shows the ability of the EDI system to provide a continuous reduction in total organic carbon (TOC) [13]. The storage tanks commonly blanketed with nitrogen gas and sparged continuously with ozone for microbial control. UV light is required for eliminating microbial contamination, followed by 0.5 micron cartridge filtration, and finally 0.1 micron cartridge filtration. This ultrapure water is distributed to the points of use, with a recirculation loop returning unused water to the storage tank. The systems typically meet ASTM specifications for "Electronics Grade Water."

EDI systems are also employed for low & medium quality water for general industrial applications. In these cases, the RO is not necessary, as EDI can remove around 95- 99% of the dissolved ions from pretreated tap water. Systems have been installed for such applications as electro coating, painting, chemical manufacturing, electroplating, bottle washing, humidification, and optics manufacturing.

The EDI process has wide range of applications that requires economic removal of impurities. It is also used for separation of chemicals from industrial effluents. Other applications include biotechnology, laboratories, pharmaceutical industries, reuse of residual water in food and beverage industries, for chemical production, electronics, cosmetics, Hospitals, as a process water and in power plant as boiler water etc

VI. THE FUTURE OF EDI TECHNOLOGY

The EDI process is a feasible alternative to conventional deionization systems. Since the initial commercialization in 1987, EDI systems have found wide range of application in industries with the most demanding high purity water requirements. Typical of any high technology product of this age, EDI is constantly evolving, with improvements in deionization performance and increases in single module flow rate capability arising with each new generation, such as the 80 gpm "all-filled" industrial EDI module. Future improvements will likely produce more energy efficient deionization and even higher flow rates. Fundamentally, EDI process is mainly used for water purification. [14] Many non-aqueous applications for EDI in such areas as food and beverage manufacturing and chemical processing. Some of these applications are presently under investigation, and EDI equipment is already in use for fruit juice deionization. [15]

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