Production of Ultrapure Water by Using Continuous Electro-deionization (CEDI) Technique

Anil D. Kate[1, 2], G. R. Desale[1], V. N. Raibhole[2],

1#CSIR-National Chemical Laboratory, Pune
2#Modern Education Society's College of Engineering, Pune

***Abstract*—Continuous Electro-deionization (CEDI) technology is now commonly used as a post RO treatment, makeup demineralization process in a variety of applications, such as microelectronics, power, biotechnology, pharmaceutical, and food and beverage. The CEDI unit consist of ion exchange membrane, mixed bed resin (MB-12) and positive and negative electrode to remove impurities from feed water. The performance of ions exchange membrane is investigated for removal of numbers of ions in each compartment. The variation in the quality of purified water depends on parameters namely, inlet water conductivity, flow rate, applied current and voltage, types of membranes, resin used, and design of CEDI unit, etc. Higher quality of ultra-pure water is obtained when the maximum number of ions is transferred through the membranes. All the experiments were carried at constant applied voltage. It is observed that the resistivity of water increases with increasing the time at constant flow rate.**

***Keywords*- Ultrapure water, Continuous Electrode-ionization (CEDI), Ion exchange resin, Ion exchange membrane.**

I. INTRODUCTION

Water is a good solvent and picks up impurities easily. Pure water, tasteless, colorless, and odorless is called the universal solvent. Water is a ubiquitous chemical substance that is composed of hydrogen and oxygen and is vital for all known forms of life. Water is one of the most common substances on the Earth. Covering over approximately 70% of the surface of the Earth, it is easy to find. Even in a desert, it is not hard to find water. Water descends from the clouds in rain, and which forms rivers, lakes, seas, etc. Water is the chemical substance with chemical formula H_2O: one molecule of water has two hydrogen atoms covalently bonded to a single oxygen atom. The angle between two hydrogen atoms is 104.5°.

Total dissolved solids (TDS) are a measure of the combined content of all in-organic salts(calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and organic substances contained in a liquid in molecular, ionized or micro-granular (colloidal solid) suspended form. TDS in drinking-water originate from natural sources, sewage, urban run-off, industrial wastewater, and chemicals used in the water treatment process, and the nature of the piping or hardware used to convey the water, i.e., the plumbing. Total Dissolved Solids (TDS) in water is measured in parts per million (PPM) or parts per billion (PPB). There are methods of measuring total dissolved solids i.e. gravimetric and conductivity. Electrical conductivity of water is directly related to the concentration of dissolved ionized solids in the water. Ions from the dissolved solids in water create the ability for that water to conduct an electrical current, which can be measured using a conventional conductivity meter or TDS meter

TABLE I
Classification of Water

Type of Water	TDS
Fresh Water	<1,000mg/L TDS
Brackish Water	1000 to 10000 mg/L TDS
Saline Water	10000 to 30000 mg/L TDS
Brine	>30000 mg/L TDS

Conductivity measurements are used routinely in many industrial and environmental applications as a fast, inexpensive and reliable way of measuring the ionic content in a solution. Ultrapure water has a very low, but not quite zero, electrical conductivity. Ultra-Pure water without any chemical impurities will still have conductivity because of the presence of H^+ and OH^- ions due to the self-ionization of water. Ultra-pure water has a conductivity of 0.055 µSiemens/cm or a resistivity of 18.18 mΩ·cm at 25 °C.

Resistivity in water is the measure of the ability of water to resist an electrical current, which is directly related to the amount of dissolved salts in the water. Water with a high concentration of dissolved salts will have a low resistivity, and vice versa. Ultrapure water, with impurities at or below the sub-parts-per-billion range, is used extensively in many critical applications. Applications include chip fabrication for semiconductors, intravenous solutions for pharmaceuticals, and in high pressure boilers for power generation.

II) LITERATURE REVIEW

The method of producing ultrapure water is a hybrid process combining two technologies–CEDI and Reverse Osmosis (RO). The RO product water is given to CEDI unit in 3 streams as product water, concentrate water and electrode wash (electrolyte stream). The electrolyte stream is first passed through the anode compartment, where Cl_2 and O_2 gases are generated. This stream is then passed through cathode compartment where H_2 gas is generated. Thus this stream expels the chlorine, oxygen, hydrogen gas from electrodes. From the product water dissolved gases (CO_2 and

O_2) and weakly ionized inorganic compounds – Boron and Silica are removed by CEDI [1].

CEDI was studied during 1950s & 1970s. The first commercial process was sold in 1987. Many research papers have been published during 2000. They clearly show that behavior of ion exchange resin, design configuration of unit under the applying flow rate and current conditions are not entirely elucidated. These confirm the research tendency towards the optimization of performance of CEDI unit. The performance of CEDI unit is affected by flow rate of feed in treated and concentrate compartment, current intensity, conductivity of feed water, pH of feed water [1-3]. The hydrodynamic characteristics and design of unit also plays an importance role for maintaining the quality of ultrapure water [4].

Various ion transfer media can be used in CEDI, like IEM (ion exchange membrane), IEX (ion exchange resin), IET (ion exchange textile). Out of them combination of either IEM and IEX or IEM & IET can be utilized to make treated and rejected compartments of CEDI unit [4]. Either one or both compartments can be partially filled with resin. The resin may be single or mixed bed. The advantage of cost and quality can be achieved by keeping the thickness of treated compartments more than the thickness of concentrate compartments. Selemion CMV, Asahi Glass Company is the major supplier of cation & anion exchange membranes and textiles [2, 5, and 6].

Generally, three processes namely, deionization (mixed bed resin column), Electrodialysis and Continuous electro-deionization are used for production of ultrapure water. In the conventional deionization (DI) system water is passed through the mixed bed resin column. The unwanted ions (impurities) from the water get adsorbed on the resin. However, this mixed bed resin get exhausted after a short period of time and unable to purify the water. Regeneration of exhausted resin is required for its reuse in the process. Normally, chemical treatment is given for its regeneration and this disturbs the water purification process [7].

Lozier et al. [8] have designed the demineralization system for surface water treatment. The pilot plant based on the techniques, namely, Reverse osmosis (RO) and Electro dialysis Reversal (EDR) was installed in the city of Sherman, Texas for surface water treatment. They have described the Treatment Process Selection and the pilot testing was performed to establish the design criteria. The results of the pilot program indicated that both RO and EDR are suitable for desalinating including following advantages such as greater product recovery and reduced susceptible to fouling and sulphate scaling on the membrane surface.

Banasaik et al. [9] have conducted desalination experiments with reverse osmosis using an aqueous solution containing 5 and 10 g/L NaCl to determine the optimum operating conditions of an Electro-dialysis (ED) system. Further desalination solutions containing 1, 5, 10, 20, 25 and 35 g/L NaCl at an optimum applied voltage of 12 V was conducted to determine the influence of initial salt concentration on the desalination process. A laboratory electro-dialysis stack containing seven cation-exchange membranes and six anion-exchange of 56 cm^2 effective area was used. They have reported that the NaCl concentration in the dilute compartment rapidly decreases within the initial 30 minutes after that the salt concentration slowed down.

Danielssonet. al. [10] has conducted the flow distribution study for a new Elector dialysis module. They have investigated the flow distribution for three different designs of 4mm thick frames (compartments). The incompressible Naviers- stokes mode of Femlab software was used to solve the averaged Navier- Stokes equations and Darcy flow mode was used for the Thin Film approximation theory (TFT) equations. Based on the analysis of three frames, better flow distribution frame was manufactured and tested experimentally. They have reported the CFD results are well in the agreement with the experimentally results. The efficiency of the unit is determined by the water residence time distribution which depends on the velocity field.

There are various methods for producing Ultrapure water i.e. Purification through Crystallization, Deionization, Electro dialysis, Continuous Electro-Deionization etc.

III) CONTINUOUS ELECTRO-DEIONIZATION (CEDI)

Continuous Electro-deionization (CEDI) process is used for the production of ultra pure water. The CEDI is the process of removing ions from feed water by applying electrical potential at the electrodes. Most commercial CEDI devices, have ion exchange resins ’sandwiched’ between alternate anion and cation exchange membranes forming separate treated and reject compartments. Both anion and cation membranes are selectively permeable to either anions or cations, i.e. cation exchange membranes (CEM) will allow only cations having positive charged ions to pass through, and anion exchange membrane (AEM) will allow only anions having negative charged ions. Compartments bound by an AEM facing the positively charged anode and a CEM facing the negatively charged cathode.

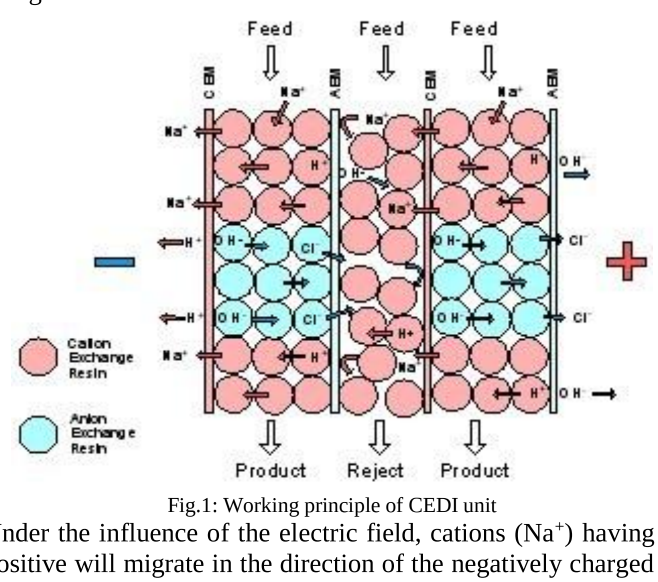

Fig.1: Working principle of CEDI unit

Under the influence of the electric field, cations (Na^+) having positive will migrate in the direction of the negatively charged cathode, through the cation-exchange resin, cation-permeable membrane only and thus into the reject stream. An anion permeable membrane on the opposite side of that stream prevents further migration, effectively trapping the cations (Na^+) in the concentrating steam, the process for anion removal is analogous, but in the opposite direction, toward the positively charged anode is as shown in Fig.1.

Applying a direct current (DC) electric potential causes ions to move from treated compartment to reject compartment through ion exchange membrane. So the concentration of ions is reduced in treated compartment and increased in the reject compartment. Due to electrical potential +ve and –ve charged ions moves towards their opposite charged electrodes as shown in Fig.2.

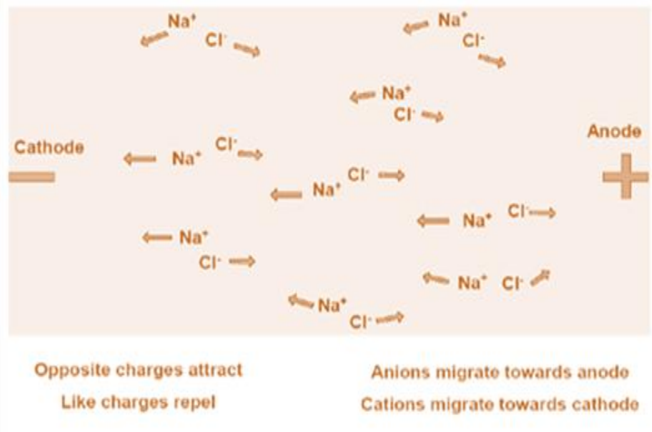

Fig. 2: Salt movement in solution with electric field

Merits:

1) Effectively removes most particles, pyrogens, enzymes, microorganisms, and colloids above their rated size, retaining them above the ultra-filter surface.

2) It is continuous process there is no "breakthrough" of ions as happens in conventional ion exchange operations, therefore the quality of the water remains at a constant high level of purity.

3) Faster installation and smaller footprint than with conventional ion exchange systems.

4) No need of regeneration of chemicals, less raw water consumption, and substantial reduction in costs.

Demerits:

1) Will not remove dissolved inorganic or organic substances.

2) May clog when challenged by an excessive level of high-molecular-weight contaminants.

Applications of CEDI Process:

1) Ultra-Purification of water for the power industry.

2) Recycle of waste brine and water for the chemical process industry.

3) Removal of traces ions from a waste stream.

4) Process Feed water in pharmaceutical, biotechnology and food and beverage applications.

5) High-Quality rinsing water or electronics, surface finishing and optical glass applications.

6) Institutions such as hospitals, universities and dialysis centres.

7) Separation of Uranium from waste brine solution

IV) PARAMETERS AFFECTING THE PERFORMANCE OF CEDI UNITS [12]

The variation in the quality of purified water depends on parameters namely,

*1) **Inlet water conductivity**:* The quality of inlet water is dominant parameter which affects the quality of product water. Decreasing the number of ions in the feed water either increases the productivity of the unit or increases its quality.

2) ***Flow rate**:* Constant flow rate of water is important for CEDI unit. If the concentrate flow is lower than required, the concentrate will be more conductive and the current will increase and there are chances of failure of membrane.

*3) **Voltage**:* Voltage is the driving force, which pulls the impurity ions from the treated compartments into the reject compartments. The local voltage gradients also cause H_2O to split into H+ and OH- ions. The optimum voltage depends first on the number of cells in the module. Normal operating voltage range is approximately 5 to 8 Volts/cell pair. The optimum voltage also depends on temperature, concentrate conductivity and concentrate flow rate (recovery).

*4) **Current**:* Current is proportional to the total number of ions moved. These ions include the impurity ions in the RO permeate, such as Na^+ and Cl^-, and the ions caused by water splitting, H^+ and OH^-. The water splitting rate depends on the local voltage gradients, so that higher voltages across the resin chambers leads to higher quantities of H^+ and OH^- to be moved.

*5) **Ion Exchange Resin Selection**:* Ion exchange resins are polymers that are capable of exchanging particular ions within the polymer with ions in a solution that is passed through them. The synthetic resins are used primarily for purifying water, but also for various other applications including separating out some elements. Ion exchange resins function much differently in CEDI device. In CEDI, the function of the exchange resin is to transport ions towards the surface of the ion exchange membranes is much more important than the ion exchange capacity of the resin. The resins are therefore not optimized for capacity, but for other properties that influence transport, such as water retention and selectivity.

*6) **Ion Exchange Membrane Selection**:* Ion exchange membranes are selectively permeable, as they will allow the passage of counter ions while excluding co-ions. When placed in a water solution and an electric field, a CEM will permit the passage of cations only, while an AEM will allow the passage of anions only.

Important properties of ions exchange membrane are

- Low water permeability
- Low electrical resistance
- High permselectivity
- High strength
- Resistance to contraction or expansion
- Resistance to high and low pH

*7) **Effective membrane area utilized***: In CEDI unit design, maximum effective area of membrane has to be utilized for maximum water flow through compartment for maximum ion transportation rate.

*8) **Design of CEDI unit**:* The design of CEDI unit consist of layers of ion exchange resin beds with ion exchange membrane, and resin filled treated and reject compartments. These prevent external leakage; reduce electrical resistance and simply overall system design by eliminating concentrate recirculation.

V) EXPERIMENTAL SETUP

Fig. 3: Experimental Set up

1) AC/DC Rectifier 2) Peristaltic Pump 3) Inlet RO water 4) CEDI Unit
5) RO unit 6) Resistivity Meter 7) Treated Watere i.e. ultrapure water
8) Reject Water 9) ppm meter

The CEDI unit consist of nine alternate treated and rejected compartments packed in between two electrodes housing one for anode and other for cathode. The provision was made to collect the sample of treated water at the outlet of each compartment. The rigid PVC plate of 4.5 mm thickness and two Electrodes housing of 16mm thickness are used for construction of CEDI unit as shown in Fig. 4.

Fig. 4: Continuous Electro-deionisation Unit

The holes for water passage are arranged in such a way that the treated inlet water will go only in all the alternate treated compartment and reject water in all the alternate reject compartments in series. The water entering inside the compartment is distributed evenly with the help of perforated slit mounted at inside of gasket and collected with the similar slit at the other side. The size of membranes (anion and cation) and rubber gaskets (thickness 0.5 mm) and arrangement of holes are kept similar to that of the PVC gasket. The rubber gaskets are provided on the both sides of PVC gasket to make the stack leak proof.

On the both sides of the rigid PVC gasket cation and anion exchange membranes are placed alternatively to form a compartment which is filled by mixed bed resin. The treated compartments are bound by an anion exchange membrane (AEM) facing the positively charged anode and a cation exchange membrane (CEM) facing the negatively charged cathode. The concentrated compartments are bound by AEM facing the cathode and CEM facing the anode. The two electrode housings with electrode, PVC gaskets with resin, rubber gaskets and anion and cation membranes are packed in the pressing assembly with nuts and bolts. When electric field is applied, ions in water are attracted to their respective counter electrodes. The result is that the diluting compartments are depleted of ions and concentrating compartments are enriched with ions.

VI) RESULT AND DISCUSSION

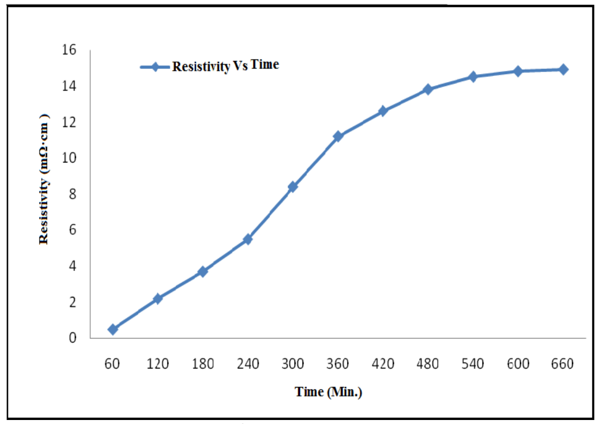

Fig. 5: Resistivity of treated water with operating time

The resistivity of treated water from CEDI unit was measured with operating time and graphically presented in Fig. 5. It is observed that the resistivity of treated water increases with increasing operating time. After around 10 hours operating time the CEDI unit is able to produce the treated water of 14 mΩ·cm resistivity.

VII) CONCLUDING REMARKS

The construction of CEDI unit using PVC plates, rubber gaskets and ion exchange membranes packed with nut and bolts is leak proof. After around 10 hours operating time the CEDI unit is able to produce the treated water of 14 mΩ·cm resistivity.

ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support from CSIR-NCL Pune and thankful to Dr. Ashwini Nangia, Director, and Dr. Vivek Ranade, Chair, CEPD Division and ***Dr. Girish R. Desale, Principal Scientist***, CEPD Division, CSIR-NCL Pune.

REFERENCES

1. R. Wen, S. Deng, Y. Zhang, The removal of silicon and boron from ultrapure water by electrodeionization, Desalination 181 (2005) 153-159.
2. K. Bouhidel, A. Lakehal, Influence of voltage and flow rate on electrodeionization (EDI) process efficiency, Desalination 193 (2006) 411-421.
3. J. Wang, S. Wang, M. Jin, A study of the electrodeionization process high purity water production with a RO/EDI system, Desalination 132 (2000) 349-352.
4. E. Dejean, E. Laktionov, J. Sandeaux, R. Sandeaux, G. Pourcelly, C. Gavach, Electro-deionization with Ion-exchange textile for the

production of high resistivity water: Influence of the nature of textile, Desalination 114 (1997) 165-173.
5. A. D. Jha, J. D. Gifford, Ultrapure CEDI for Microelectronics Applications: A cost Effective4 Alternative to Mixed Bed Polishers, Ion-pure technologies.
6. N. Mastuda, W. Agui, T. Tougou, H. Sakai, K. Ogino, M. Abe, Disinfection of viable Pseudomonas stutzeri in ultrapure water with ion exchange resins, Colloids and Surfaces, B: Biointerfaces 7 (1996) 91-100.
7. F. DiMascio, J. Wood, J. M. Fenton, Production of High purity water without regeneration of chemicals, The Electrochemical Society Interface Fall, 1998
8. James C. Lozier, Gary Smith, Jerry W. Chapman, David F. Gattis. Selection, design, and procurement of a dimineraliztion system for a surface water treatment Plant. *Elsevier Science Publishers , Desalination* 1992.
9. Laura J. Banasiak, Thomas W. Kruttschnitt, Andrea I. Schafer. Desalination using Electrodialysis as a function of voltage and salt concentration.*Elsevier desalination* 205(2007) 38-46.
10. Carl-Ola Danielsson, Anna Velin, Anders Dahlkild & Marten Behm, Flow Distribution Study of a New Electrodialysis Module, 2004.
11. Maya Jeswani, Girish R. Desale, S.K. Thampy, N.G.Borle, Girish Karhadkar, "Production of ultra pure water using indigenously developed inter polymer ion exchangemembranes", T-103, InDACON-2008.
12. CEDI UNIVERSITY , The online centre of electro-deionization.