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Araştırma Makalesi/Research Article

Cost Analysis of Membrane Capacitive Deionization and Comparison of Treatment Costs of Desalination Processes

Halil İbrahim Uzun[1]

[1]Department of Food Engineering, Mus Alparslan University, Mus, Turkey, ORCID: 0000-0001-6158-743X

Corresponding Author:ha.uzun@alparslan.edu.tr

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Abstract

Today, one of the most critical issues for people for food safety and economic reasons is the supply of drinking and utility water. Increasing living standards with social and economic growth also increases the need for drinking and utility water per capita. On the other hand, the total amount of water in the world is 1.4 million km^3, of which 97.5% is salt water in the oceans. Only 0.5% of the remaining water is fresh water, of which more than 90% is located at the poles and underground. Therefore, it is of great importance to remove salt from water. However, the most crucial handicap in desalination processes is that it is not economically sustainable. The membrane capacitive deionization Process is an effective method to remove ions from water. It has advantages such as low cost, flexible use, and low secondary pollution. In this study, the cost analysis of the MCDI process in removing salt from water; The treatment costs of desalination processes such as reverse osmosis, membrane processes, and electrodialysis were compared. MCDI is the most economical method for treating water with a conductivity below 5,000µS/cm. It is equivalent to reverse osmosis in the 5,000 - 7,000 µS/cm range. In addition, the treatment efficiency in the MCDI process can be changed by using variables such as potential and current so that demand-oriented treatment can be provided.

Keywords: Desalination, cost analysis, membrane capacitive deionization.

1. INTRODUCTION

Access to safe and usable water has always been a priority and the most pressing issue since the dawn. Water used for various purposes, especially drinking water, can be evaluated in two categories: surface water and underground water. Considering that 97% of the earth is composed of salt water, it will r resources used for water supply are pretty limited. However, the source of most of the surface water is groundwater. Groundwater refers to the waters located beneath the surface in a geological formation that has an impermeable layer with defined boundaries and a permeable layer [1]. Groundwater, widely used by people, especially in agricultural activities, meets about 50% of human needs today [2].

Rainfall is the primary source of groundwater. Precipitation, expressed as the primary source of groundwater, provides water with almost perfect purity, while groundwater has higher ion concentrations than surface water. Precipitation passes underground from the unsaturated region with the effect of gravity, according to ground conditions [3]. It reaches the aquifers located at the upper limit of the saturated underground zone and combines with previously collected groundwater. Because the water from the rains is constantly gaining minerals due to the rocks and soil, they come into contact with it while moving underground with gravity. However, groundwater quality varies according to the amount of precipitation, the chemical content of groundwater, and the physical and chemical possessions of the soil and rocks with which the water comes into contact [4]. Groundwater is generally used without the need for treatment because it is more sheltered when compared to surface waters. However, in addition to the economic and practical use of groundwater, factors such as ion concentrations exceeding permissible limits in many regions, salinization, and toxic ions from its widespread use necessitate groundwater desalination [5].

Toxic elements such as arsenic, boron, iron, and manganese and their radioactive nuclei can be found naturally in groundwater. They can degrade quality elements such as the water's color, smell, and taste [3]. Synthetic organic substances such as bacteria, hydrocarbons, and various petroleum products, mainly nitrate and fluoride, which originate from agricultural activities and mix with groundwater with precipitation, are classified as human-made pollutants. However, the most common problem with groundwater is due to natural minerals such as calcium and magnesium [6].

Today, membrane processes are widely and effectively used to treat underground water, defined as brackish water. In particular, many different techniques, such as ion exchange, electrodialysis, and coagulation, are evaluated in the disposal of ions. However, all these treatment methods have disadvantages, such as low treatment efficiency, a high volume of secondary pollution, and high energy consumption. For this reason, economical treatment methods with high efficiency, no secondary pollution, or low secondary pollution by volume are needed [5].

1.1. Capacitive Deionization

Capacitive deionization (CDI) works according to the principle of adsorbing ions in the water to the electrical double layer formed at the solution's interface with the porous, high surface area electrodes that are electrically charged by a power source. Issues such as increasing the surface area and electrical efficiency of the electrode materials have made the CDI process attractive, and there are still widespread development studies today. Many studies are being conducted on various topics, such as whether all ions can be adsorbed with high efficiency; whether the ions desired to be removed are adsorbed, whether dead zones in the reactor can be minimized, continuous and intermittent operation, and energy recovery [7].

For CDI electrodes, high electrical conductivity properties, rapid response to electrosorption-electrosorption changes, ability to work in wide pH ranges, rapid response to continuous potential changes, determination of material suitable for design, and creation of a material resistant to clogging are studied [4]. In addition to the theoretical working principle, the CDI process in practice can be summarized as the migration of ions from the solution to the charged electrodes and the adsorption of the ions in the electrical double layer, the transfer of the treated water, the execution of the desorption process by charging the electrodes with opposite charges, and the transfer of concentrated current [8].

1.2 Membrane Capacitive Deionization

Membrane Capacitive Deionization (MCDI) is a CDI modification. Unlike the CDI process, an ion-selective membrane is placed on the electrode surface. Although the resistance increases relatively with the MCDI process, especially in the desorption process, the migration of ions to the counter electrodes is prevented, increasing efficiency.

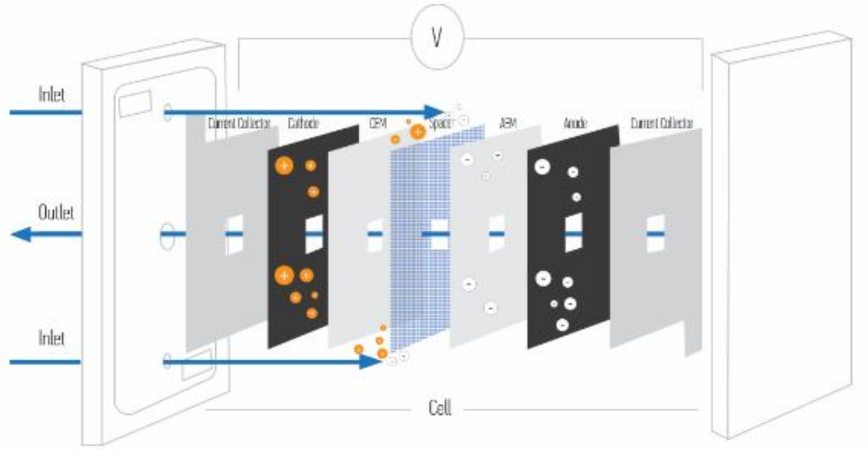
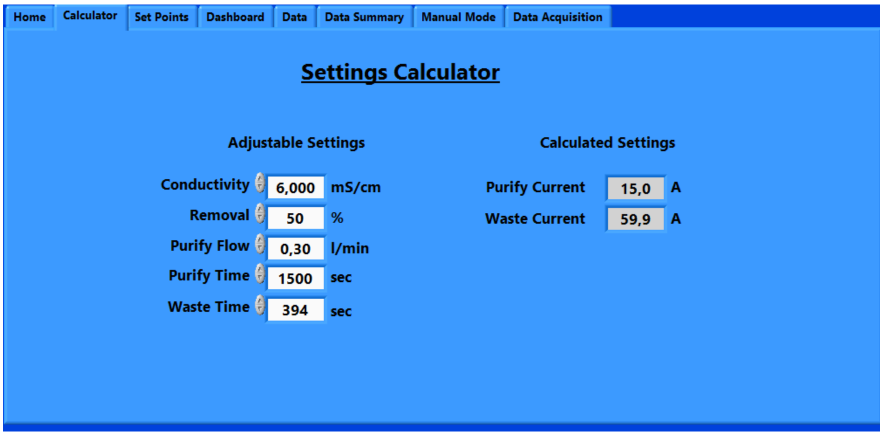


Figure 1. MCDI schematic representation [7]

This study will reveal the model's energy consumption and treatment-based groundwater treatment with the MCDI process. The cost data obtained for the desalination processes in the literature will be compared.

2. MATERIAL AND METHOD

MCDI can be operated with three-stage automatic and manual options such as "purification," "pre-treatment," and "waste." In the automatic option, the current calculation is made after data such as conductivity, flow, voltage, targeted removal efficiency, treatment time, and desorption time are used as inputs on the calculation screen of the device automation.



Settings Calculator

Adjustable Settings

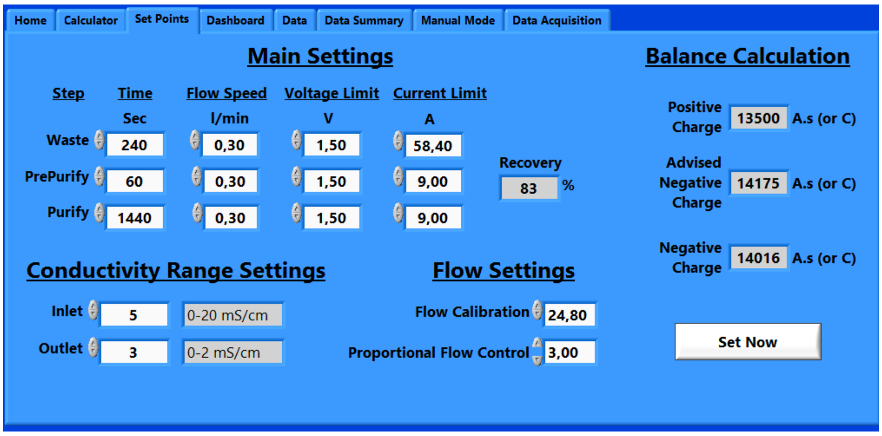
Conductivity 6,000 mS/cm
Removal 50 %
Purify Flow 0,30 l/min
Purify Time 1500 sec
Waste Time 394 sec

Calculated Settings

Purify Current 15,0 A
Waste Current 59,9 A

Figure 2. MCDI device current calculation screen [9]

The treatment is started by entering the automation's desired times, flow values, and currents produced into the command system.



Main Settings

Step	Time Sec	Flow Speed l/min	Voltage Limit V	Current Limit A
Waste	240	0,30	1,50	58,40
PrePurify	60	0,30	1,50	9,00
Purify	1440	0,30	1,50	9,00

Recovery 83 %

Balance Calculation

Positive Charge 13500 A.s (or C)
Advised Negative Charge 14175 A.s (or C)
Negative Charge 14016 A.s (or C)

Conductivity Range Settings

Inlet 5 0-20 mS/cm
Outlet 3 0-2 mS/cm

Flow Settings

Flow Calibration 24,80
Proportional Flow Control 3,00

Figure 3. MCDI command screen [9]

The conductivity-based treatment efficiency, potential, and current values are measured instantly, and the value corresponding to the second is recorded. However, the potential and current values vary according to the ionic content of the water. For this reason, there are differences between model values and actual values. Equation (1) calculates the power consumption [7].

$$Energy\ \text{Comsumption} = \left(\frac{kWh}{m^3}\right) = \frac{Voltage\ x\ \text{Current}\ x\ \text{Operating Time}}{Flow} \qquad (1)$$

0.076 $/kWh is used to convert energy consumption into cost-oriented value.

3. RESULT AND DISCUSSION

Membrane processes are widely used in the treatment of brine. In their widespread use, their advantages, such as high removal efficiency, practical installation, and operation, come to the fore. However, high energy costs arising from pumping and high maintenance costs remain a critical disadvantage.

In all desalination processes, the cost is categorized under two headings. These are the initial investment costs, operation costs, and maintenance costs. Operation and maintenance costs depend on factors such as energy and, if necessary, chemical requirements, the renewal of materials such as membranes and electrodes, maintenance, and water properties. A large part of the energy cost comes from the pumps in membrane processes where the driving force is pressure. In the blockages that occur in the membranes, chemicals that increase the cost are used, or there is a pre-treatment before the process.

Different efficiency treatment costs of some deionization processes in the literature are given in Table 1.

Table I. Costs of the desalination process [5]

Process	Conductivity µS/cm	Removal Efficiency %	Cost $/m³
Rever Osmosis – Sand Filter	1000	100	0.109
Nanofiltration – Sand Filter	1000	100	0.994
Rever Osmosis – Sand Filter	1000	80	0.094
Rever Osmosis – Sand Filter	1000	70	0.082
Rever Osmosis – Sand Filter	1000	60	0.07
Rever Osmosis – Pump Well	1000	100	0.196
Rever Osmosis – Sand Filter	2000	100	0.105
Rever Osmosis – Sand Filter	2000	80	0.102
Rever Osmosis – Sand Filter	2000	70	0.096
Rever Osmosis – Sand Filter	2000	60	0.091
Rever Osmosis – Sand Filter	5000	100	0.279
Rever Osmosis – Sand Filter	5000	80	0.274
Rever Osmosis – Sand Filter	5000	70	0.270
Rever Osmosis – Sand Filter	5000	60	0.265
Rever Osmosis – Sand Filter	10000	100	0.250
Rever Osmosis – Sand Filter	10000	80	0.249
Rever Osmosis – Sand Filter	10000	70	0.247
Rever Osmosis – Sand Filter	10000	60	0.245
Electrodialysis	4188	86	0.530
Electrodialysis	8400	86	1.050

In desalination processes, the conductivity value and the water's ionic content also affect the treatment costs, as seen in Table 1.

In addition to pressure-based systems such as membrane processes, electrically driven processes such as electrodialysis are also used as a deionization method. The electrodialysis data given in Table 1 were recorded due to the electrodialysis treatment of Gabes and Zarzis waters in Tunisia. The 500 mg TDS/L limit value determined by the WHO in the treatment efficiencies seen in Table 1 was accepted as the limit, and the water was purified according to this ratio [5]. The low treatment efficiency is because it provides flexibility in the treatment efficiency according to the demand in electrically driven systems.

3.1. MCDI Model Treatment Costs

Since the MCDI process is electrically driven, it has flexibility in terms of treatment efficiency. In the software written for the MCDI process, the conductivity values were written based on the purification of NaCl. Although many properties of ions affect adsorption, the model results prepared according to the case of single species and monovalent anions and cations in the MCDI process are given in Table 2.

Table 2. Model study treatment cost at different efficiencies with MCDI

Conductivity µS/cm	Purification Current (A) 50%	Purification Current (A) 75%	Purification Current (A) 100%	Cost $/m^3 (50%)	Cost $/m^3 (75%)	Cost $/m^3 (100%)
100	0.5	0.4	-	<0.01	<0.01	-
150	0.2	-	0.7	-	-	0.01
200	-	-	1	-	-	0.01
500	-	1.9	2.2	0.01	0.01	0.02
1000	1.2	3.7	5	0.02	0.03	0.04
1500	2.5	5.6	7.5	-	0.04	0.55
2000	-	7.5	10	0.04	0.06	0.08
2500	5	-	12.5	-	-	0.09
5000	12.5	18.7	25	0.09	0.14	0.19
10000	25	37.5	49.9	0.19	0.28	0.37

When Table 1 and Table 2 are evaluated together, when compared to other deionization processes, MCDI is more economical than all processes below 5000 µS/cm conductivity value. In addition, it is economical in the range of 5000 - 7000 µS/cm from processes other than reverse osmosis and is equivalent to reverse osmosis in the same range [5]. In addition, MCDI stands out with its flexibility in purification. Since the MCDI device can be operated at a maximum current of 60 A according to the model, it can provide purification up to a conductivity value of 12000 µS/cm. This is an essential advantage in terms of water quality and cost. Costs for 50%, 75%, and 100% treatment values are given in Table 2.

3.2. MCDI Groundwater Treatment Costs

In deionization processes, when calculating only the treatment cost, especially among the operating costs, the treatment processes using NaCl, as stated before, are taken into account. In the model prepared for MCDI, experimental studies on this principle constructed the current generation for the targeted treatment efficiency. The cost data obtained in the previous study with MCDI with groundwater taken from different regions and the data obtained as a result of the experimental study carried out in this study are given in Table 3.

Table 3. Cost of treating groundwater with MCDI

Conductivity (µS/cm)	Voltage (V)	Purification Current (A)	Treatment Efficiency (%)	Cost ($\$/m^3$)
409	1.25	6.1	99	0,006 [10]
984	0.9	5	96	0,022 [7]
1289	0.9	4.5	99	0,020
1413	1.2	6.3	99	0,038
1538	1.25	6.1	99	0,038
1547	0.95	9.2	99	0,043
1760	1.2	9	97	0,054 [11]
1915	1	7,6	99	0,040

When the data in the model studies are compared with the data obtained from groundwater treatment, it is observed that the costs of treating the groundwater are lower. The main reason for this difference is the applied potential. Because the potential is kept constant at 1.5V in the model and according to this value, treatment current is produced against values such as treatment time, flow rate, and water conductivity. In addition, these values are average values. In other words, as the surface area of the electrodes is filled with ions, the current increases, and the potential increases to provide the needed current. However, in experimental studies, it is seen that the potential providing the targeted current is used, so the operation continues at values below 1.5V, depending on the input parameters.

As a second point, the difference between the model and the experimental study is due to the difference in the ionic content. There is competition in the migration of ions to the electrodes depending on the properties of the ions. It is also known that the concentration of the ions and the ion species affect the purification efficiencies. Therefore, although the conductivity value gives an idea of cost calculations, it does not provide precise results.

4. CONCLUSION

Approximately 97% of the water on earth consists of salty waters in the seas and oceans. Groundwaters are the most attractive water sources because they are close to external influences, safe, easy to access, and clean. However, the salinization of groundwater, containing dangerous ions and high ionic content due to their structure, brings along many problems. Pressure and electrically-driven systems and chemical methods used for desalinating salty waters such as groundwater have disadvantages such as high energy consumption, secondary pollution, and impracticality. On the other hand, the Membrane Capacitive Deionization process stands out with its advantages, such as operating at low potentials such as 1.5 V, being economical, not needing chemicals, and producing secondary pollution in a lower volume.

Studies in the literature on the costs of desalination studies were examined, and the data obtained as a result of experimental studies with the MCDI process were compared. MCDI is the most economical method for treating water with a conductivity below 5,000µS/cm. It is equivalent to reverse osmosis in the 5,000 - 7,000 µS/cm range.

The experimental studies show that the MCDI process treats groundwater with lower energy consumption than the model. In the model, a cost of 0.02 - 0.08 \$ /m^3 occurs for water in the range of 500 - 2000 µS/cm, while a cost in the range of 0.004 - 0.05 \$ /m^3 occurs for ground waters with relative values.

The most vital element for the MCDI process is the electrodes and the capacity of the electrodes. Studies aimed at increasing the surface area of the electrodes will make the fact that MCDI is an economical process presented in this study sustainable.

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