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Ruhr – Universität Bochum
Vietnamese – German University

**Flow-electrode Capacitive Deionization: Mechanisms,
Electrodes Development, Cell Designs and Operation
Performance in various condition**

Thesis for degree of
BACHELOR OF ENGINEERING



Vietnamese-German University

By

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Vietnamese-German University

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Abstract

The Flow-electrode Capacitive Deionization (FCDI) system is considered to be a new potential advancement and is more efficient than earlier Capacitive Deionization (CDI) and Membrane Capacitive Deionization (MCDI) systems in addressing brackish water and freshwater demand issues in salty locations. The report will dig into detail regarding the FCDI cell's architecture in this research, as well as methods to manage the pumping system to obtain the best desalination performance possible.

Applying the capacitive adsorption property and providing voltage at both ends of the electrode, salt ions will migrate and adhere to the surface of the matching electrode. Furthermore, the electrode will be cycled through the system to replace it continually throughout the operating process. Experiment findings show that with a modest beginning salt content (from 1g/L NaCl to 5g/L NaCl), 5% grams of salt may be eliminated from the solution after just 15 minutes of operation. In addition, variation in voltage also have certain effects on the desalination ability of the FCDI system. There is a clear difference with 1.1V voltage applied at the two polars of the cell only an average of 28.33mg of salt is removed, whereas with 1.5V an average of 45mg of salt is removed. This is an excellent result when compared to previous research publications using the same FCDI method, given that the major components of the electrode in this study are: water, salt, and activated carbon.

This paper will emphasize the potential of Flow-electrode Capacitive Deionization in handling the fresh water problem caused by brackish water intrusion. Furthermore, the optimization and cost reduction for performing the FCDI desalination system are included in here as the new feature in this report.

Keywords: Flow-electrode Capacitive Deionization (FCDI), water desalination, flow-electrode, system operation optimization, cost reduction.

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List of Abbreviations

FCDI	Flow-electrode Capacitive Deionization
CDI	Capacitive Deionization
MCDI	Membrane Capacitive Deionization
V	Voltage (V)
A	Ampe (A)
m	meter
s	second
I	current (I)
U	electrical potential (V)
v _d	dilute volumetric (ml/min)
g	grams
L	litre
IEM	Ion exchange membrane
AEM	Anion exchange membrane
CEM	Cation exchange membrane
AC	Activated carbon
wt%	percentage by weight
NaCl	Sodium chlorine
min	minute
P	Power (Watts)



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1. Introduction

1.1 Influence of water pollution and brackish water in Vietnam

1.1.1 General information about brackish water in Vietnam

Due to the upgrading of human living standards and spectacular economic expansion in certain nations in the past few decades, the demand for freshwater has rapidly increased. It has become one of the most pressing issues in numerous newly industrialized countries with strong agricultural exports, including Vietnam. The water resources in Vietnam include 2,000 rivers, which are mostly used to support agriculture, the country's primary source of food supply, and agriculture occupies more than 70% of the total consumption of water in Vietnam.

However, there are always various implications associated with water resource problems for fast-emerging countries, such as Vietnam, which are developing at a rapid pace. According to Sasha Kong, the lack of adequate access to freshwater for at least 13 million Vietnamese directly affects daily routines, production, and business, especially for 2.5 million residents who live in agricultural areas that are unable to access clean water for farming and cultivating cattle. Furthermore, approximately 80% of all diseases in Vietnam most likely originate from contaminated water, including diarrhea, typhoid fever, dysentery, and malaria. (Kong, 2022)

Nevertheless, the essential problem that Vietnam has recently had to cope with is the saltwater intrusion, which is the major issue that causes the scarcity of water. In 2020, according to the Ministry of Agriculture and Rural Development's Directorate of Water Resources, the Mekong Delta recorded a significant value of salinity boundaries that reached 4 g/l for 65 kilometers upstream. At the same time, the rural areas around the Mekong River and other rivers in the nearby area get affected by the brackish water, which reduces agricultural output. According to Luong Van Anh, deputy head of the Directorate of Water Resources at the Ministry of Agriculture and Rural Development, the saltwater intrusion has, until now, had insignificant impact on agricultural productivity (VNA, 2022). However, the

more intrusion into the land, the less effective it is for producing and cultivating agricultural products. In order to solve this problem, this paper will cover several desalination methods, especially intended to analyze and improve the efficiency of Flow-electrode Capacitive Deionization.

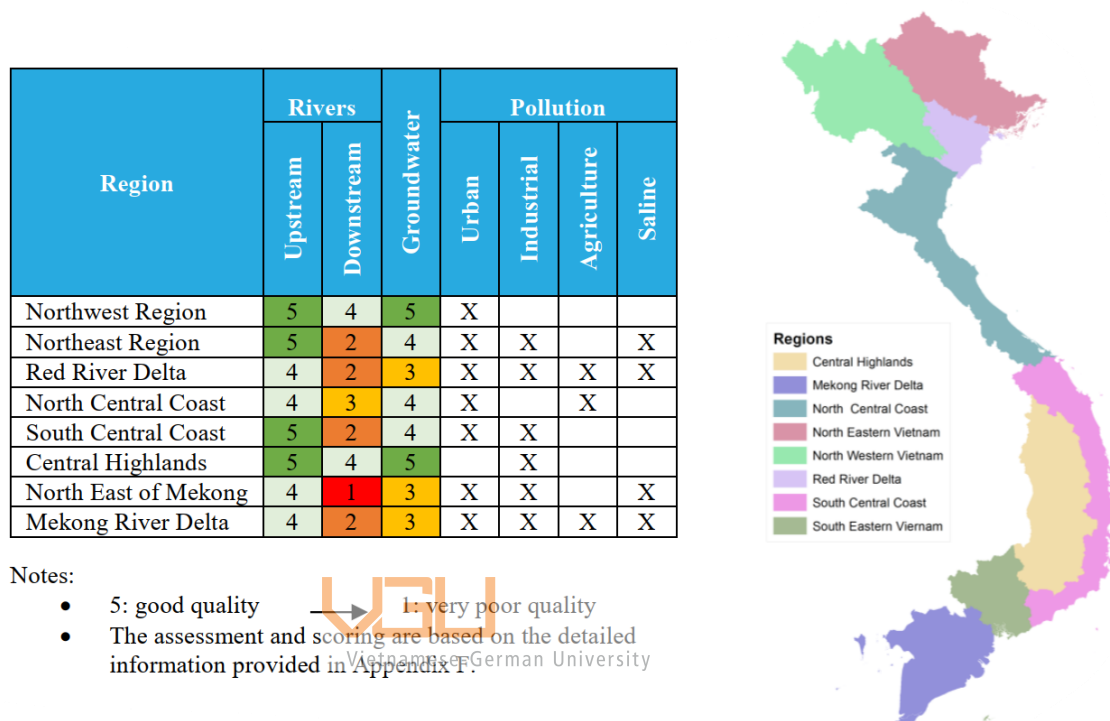


Figure 1. River status in Vietnam 2020

1.1.2 Brackish water intrusion in Mekong Delta area

The Mekong Delta (MRD) is the Mekong River's downstream section, bounded by the sea, with low and reasonably flat terrain and two big low-lying regions, Dong Thap Muoi and Long Xuyen Quadrangle. Along with the main streams - Tien River and Hau River - the Mekong Delta has an intricate network of canals with an average density of 4 km per 1 km², creating favorable conditions for saltwater intrusion due to tides bringing salt water deep into the river and inland fields, especially during the dry season when the flow from the Mekong River upstream is low. (Xâm nhập mặn tại Đồng bằng sông Cửu Long, 2016)

The changes in salinity in the region are highly complex. Because of the impact of tides in the East Sea, West Sea, or both, the highest salinity generally emerges around April or May. Furthermore, the low flow from the Mekong River upstream is the key element impacting the status of saltwater intrusion in the Mekong Delta's coastal estuaries, where tides are the driving factor, bringing Seawater with salt penetrates deep into the field's core, but water from upstream is still restricted. Reduced rainfall and significant water evaporation are other elements influencing the saltwater intrusion process. In addition to natural factors, human factors such as excessive exploitation and use of groundwater to meet the needs of development, production, and local life, as well as changes in land use purposes, all contribute significantly to saltwater intrusion.

Salinity intrusion has highly catastrophic implications, impacting the whole Mekong Delta region's daily life and production. In instance, saltwater intrusion in the Mekong Delta was deemed to be the worst in 100 years between the end of 2015 and the beginning of 2016. Since February, salinity has been high and dangerous. The salinity on the Tien and Hau rivers exceeds 45, penetrating up to 70 km deep from the river mouth, and even up to 85 km in some locations (although the Center for Natural Disaster Prevention and Mitigation considers salinity equal to 4 to be saline intrusion).

1.2 Solution for brackish water and pollution water resources in Vietnam

1.2.1 Definition of brackish water

Brackish water has a higher salt concentration than seawater in comparison to fresh water. The real level of salinity in brackish water varies based on environmental circumstances and is unstable over time. In valuation, the salinity of brackish water is frequently measured at intervals. In most cases, the salinity variation range will be spread between 10% and 35%, and the salinity in fresh water is 0.5%. The origins of brackish water come from the mixing between seawater and freshwater in the estuaries and also from human contributions by creating dikes and flooding coastal marshes. The brackish water is hazardous to the environment, especially animals and plants, if the salinity of the water is not controlled. (Brackish water, n.d.)

1.2.2 Prominent Desalination Technology in Vietnam

Numerous techniques have been developed to address both issues at once, as indicated above, in order to decrease brackish water and increase freshwater availability. Each solution is used in a specific circumstance and is dependent on the quantity of pollution or brackish water as well as the possibility for economic gain. The technology for desalination can be divided into four group in Figure 2:

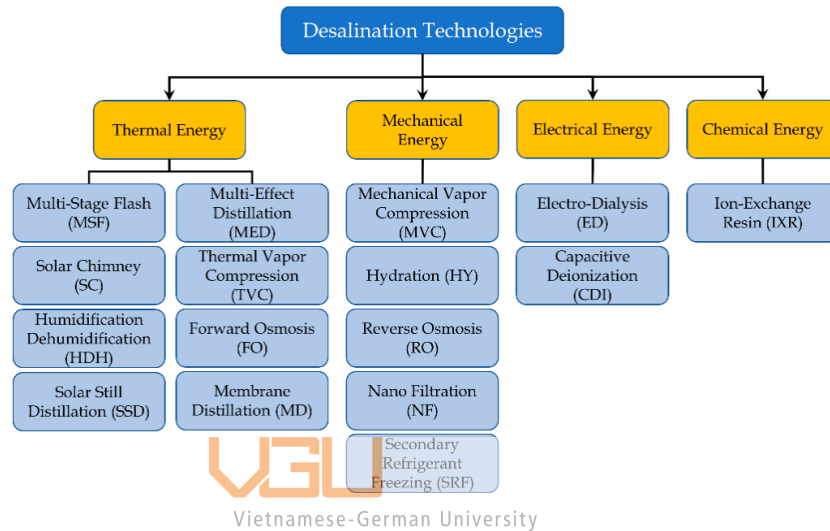


Figure 2. Popular desalination method based on types of energy input

1.2.3 FCDI – potential solution for brackish water issue

Among the desalination methods that are being applied on the commercial and in developments, the Flow-electrode Capacitive Deionization is rising its popularity in the water treatment researchers due to the potential of achieving high efficiency for treating the brackish water. The advantages of this desalination method include high salt ion removal rate in short operation time, low energy consumption, continuous desalination and applicable for large scale brackish water treatment.

The detail of this salt ions removal method will be introduced in this report with the working principle, cell design, system operation and desalination result.

2. Literature Review

2.1 Water treatment methods

Many techniques of water filtration, wastewater treatment, and water desalination have been created and commonly employed across the world up to this point. Every method has advantages and downsides and could potentially be used based on the circumstances. A few popular water treatment methods are listed below.

2.1.1 Reverse Osmosis (RO)

Reverse osmosis, more commonly known as RO, is a water filtration method that uses a semi-permeable membrane for desalination and filtration to remove undesirable large-size particles and unwanted contamination in drinking water, such as salt, dirt, chlorine, or heavy metal chemicals. This filtering process may also remove bacteria, contaminants, and sediments.

There are four major steps included in reverse osmosis filtering: sediment filter, precarbon block, RO membrane, and postcarbon filter. Firstly, with the purpose of preventing the sediment filter from getting clogged, the sediment filter is set up in order to remove large size particles, including dirt, sand, rust, etc... The following step will apply the pre-carbon filter as indicated in Figure 3, with activated carbon acting as the main component for attaching the positive charged ions and eliminating chemical compounds (chlorine and chloramines). The most significant step in RO filtration is the water passing through the semi-permeable membrane. At this stage, any particles or molecules larger than water will be discharged from the liquid. The most common discharged components are salt, high lead levels, dissolved minerals, and fluoride. Finally, the post-carbon filter polishes the water.

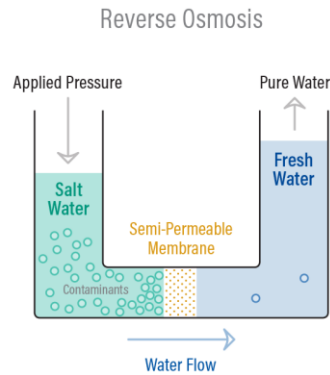


Figure 3 Reverse Osmosis major principle

The most outstanding benefit of RO filtration is that all of the particles with has the diameter that larger than 0.01 micrometer would be eliminate from the water, and also get rid of germs, fluoride and lead. According to the Environmental Protection Agency (EPA), this filtration method is ranked as the top of many other pollution water and salt water processes, that has achieved the highest efficiency in removing most of the disease and chemical contaminants (Scavetta, n.d.). Moreover, the convenience that RO filtration brings to the users, that only require to turn on the tap to use the water. This will lead to the environmentally friendly by reduction of the usage of plastic product for containing water.

Besides that, Reverse Osmosis still have few drawbacks in filtration and operation, especially about the problem of wasted water after treatment. The amount of the water supply to the system get squander according to some studies is that it is ranged between 3 and 20 percent compare to the water output after the filtration process. This problem would lead to the increasing the water bills for homeowners and wasteful for the environment. Another downside is that, this filtration system will also remove the beneficial minerals including the magnesium, calcium, potassium, and the most important is fluoride from agricultural purposes. Furthermore, reducing the minerals also lead to the decrease of pH in the treated water, and lead to more acidic in the processing water. This acidic water may not cause harmful to human. In the other hand, the plumbing systems and pipes will get affected, which removing lead and copper from it, then mixing these material components with the water. This would cause hazardous to the environment, especially for animals and plants. (Scavetta, n.d.)

2.1.2 Multi-effect distillation (MED) and Multi-stages Flash (MSF)

Multi-stage flash distillation (MSF) is the water desalination using the distilled method in which a part of the water is flashed into the steam form in several stages for countercurrent in the heat exchanger. Normally, multi-stage flash distillation has approximately 30 stages. Though in the old days this method contributed around 26% of all fresh water in the world, at the moment people prefer to use reverse osmosis rather than MSF due to the lower power consumption. The main procedure of MSF includes providing potable water from seawater to distilled water. The word "effect" in the method's name means that, through each "effect" or stage, the water is condensed on the surfaces of the low temperature tube, which is used for collecting high purity water. For the evaporator effects, the lower temperature and pressure are the major working processes in the multi-effect evaporator. The main process includes heating by hot water or steam flow along with the evaporator effect. After that, the seawater is sprayed on the surface of the tube for each effect. For heat reuse purposes, the pressure is reduced in each effect because of the preceding effect. Next, the boiling process operates at a lower temperature until the feed water goes through the next steps. After all, the final processed water is collected. (Toth, 2020) Figure 4 displays the Multi-stage flash process principle operation.

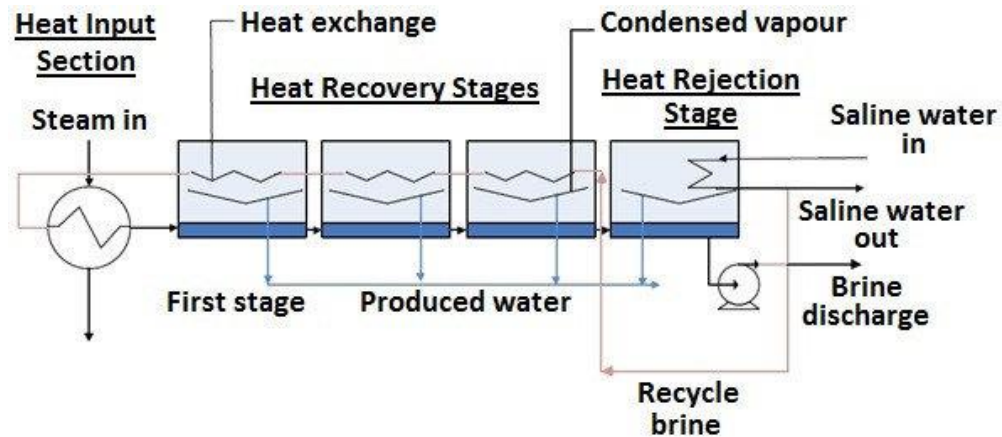


Figure 4 Multi-stage Flash Process

When compared to other technologies, multi-stage flash distillation offers various benefits, including cheap operating costs, reusable waste heat in the distillation process, and feed saltwater quality for import. Furthermore, the multi-stage flash system's gain output

ratio is large, implying that the volume of water generated by the steam condensed in the brine heater is substantial. The downsides of this technology, on the other hand, are that when waste heat is scarce, the operational costs skyrocket when compared to conventional desalination procedures. Furthermore, due to the dependent working circumstances, the corrosion rate is expected to grow.

Multi-effect distillation (MED) is the distillation method which is applied widely for desalination of seawater in industries. With the same approach of Multi-stages flash (MSF), this method also include some effects or phases. At each stage, the feed water is heated by steam in tubes, which are often misted with salt water. After that, more water is added in to the system, in other to be heated and evaporated. This will result the steam would be flow in to the tubes of the next effect. The same procedure applied on the MSF, the temperture and pressure are decreased in each step until get passed through all the effect and collect the final product. In addition, in between steps, this steam uses heat to pre-heat entering salty water. (Qasim Khan et al, 2021)

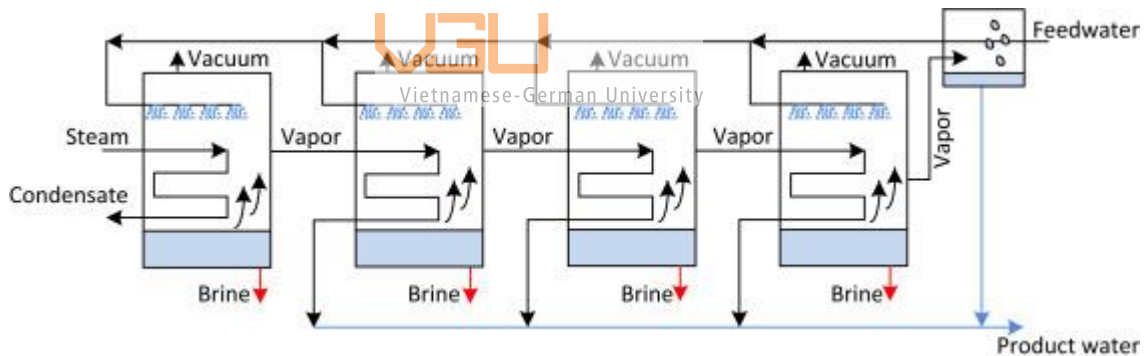


Figure 5 Multi-effect desalination

The same with the MSF, the Multi-effect desalination does not consider the quality of the imported seawater as the important factor for operation. This will lead to the low cost for preparation and pre-treatment steps in MED. Futhermore, the effeciciency of MED for desalination seawater is higher MSF according to many researchs and practical application. However, there are certain drawbacks to the MED process, including incompatibility with higher temperature heat sources due to scaling challenges during spray evaporation and difficulty scaling down to tiny sizes due to complexity and a large number of pieces required.

2.1.3 Capacitive deionization (CDI)

By applying the electrical potential different over two porous carbon electrodes, the Capacitive Deionization (CDI) is raising relatively as the new approach for seawater desalination. The operation of CDI is using the electro-sorption method, which mean is the combination of carbon-based material and applied voltage different in both side in order to detached the ions and charged particles (normally Na^+ and Cl^- in seawater desalination). Anions, or negatively charged ions, are extracted from the water and kept in the positively polarized electrode. Similarly, cations (positive charge) are held in the cathode (negatively polarized electrode). (S. Porada et al)

A standard CDI system operates in two phases are shown in the Figure 6:

1. Desalination phase: During this phase, a potential difference between two electrodes is applied, when ions are adsorbed from the water. These ions are carried from the porous carbon electrode to the intraparticle pores in CDI with porous carbon electrodes, that formed into electrical double layers (EDLs).
2. Electrode-regeneration phase: After the electrodes saturated with ion, the reverse voltage difference is applied for the electrode regeneration by released adsorbed ions. These ions are excluded with the brine stream with high salt concentration.

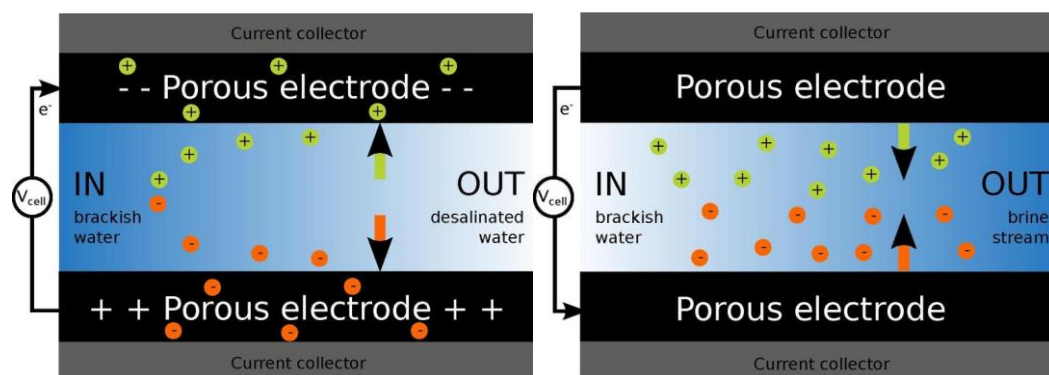


Figure 6 CDI systems principle – Adsorption phase and Desorption phase

CDI benefits include cheap investment and infrastructure costs since, unlike membrane or thermal processes, this desalination method does not require high pressures or temperatures in the operation process. Furthermore, the energy cost per volume of treated

water is the other advantages which is proportional to the amount of salt extracted from the water sources, whereas about reverse osmosis which the desalination energy scales roughly with the volume of treated water. As a result, CDI is a promising option for desalinating low-salt content streams, especially brackish water.

However, the most impactful disadvantage of this technology is its incapable of removing contaminants rather than ions including viruses, bacteria, etc.

2.1.4 Ion-exchange Resin (IXR)

The phrase "ion-exchange resin" (IXR) refers to a number of organic substances that have undergone chemical processing to react with the ions in a solution, capturing some of the solution's ions and releasing other ions from the resin into the solution. The manufacture of soft water, the purification of sugar, and the extraction of high economical value elements as gold, silver, and uranium from mineral ores are the applications for ion-exchange resins in both commercial and home settings. The purpose of the acid resins, also known as cation resins, is to trap positive ions including Ca^{2+} , Na^+ , Mg^{2+} , K^+ and release H^+ ions. As a result of the increasing concentration of H^+ ions in the water, the hardness decreases but the acidity increases. When negative ions like Cl^- , NO_3^- , SO_4^{2-} , SiO_2^- , and CO_3^{2-} are captured, the basic resins, also known as anion resins, release OH^- ions.

The process of Ion-exchange resin desalination plant is including several steps. The salinity-containing water initially passes through the highly and mildly acidic resins. The acidity of the water is enhanced after this stage. A degasser is needed because bicarbonates in the water solution combine with H^+ ions to produce CO_2 . Following this, water flows between the weakly basic resin and the highly basic resin, increase the pH value of the water. To finish the ion elimination, an amphoteric resin which a combination of acid and basic is usually applied. Resins are gradually saturated by ion exchange throughout the usual process. As a result, regeneration is necessary on a regular basis to replenish the resins. Acid solutions (H_2SO_4 and HCl) are used for acid resin regeneration, whereas basic solutions (NaOH and NH_4OH) are used for basic resin regeneration. (Jaloliddin Eshbobaev et al, 2003)

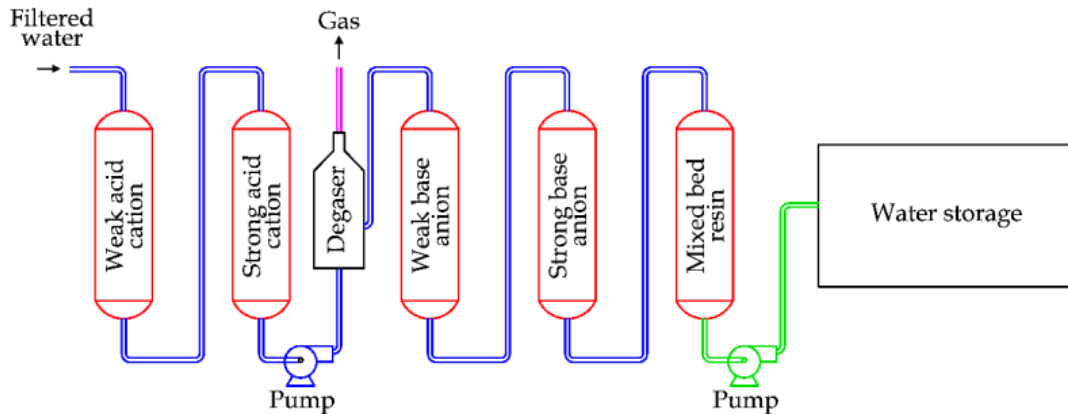


Figure 7 Ion-exchange Resin power plant scheme

2.2 General Information of Flow-electrode Capacitive Deionization (FCDI)

The Flow-electrode Capacitive Deionization (FCDI) method is considered a substantial upgrade from the old CDI system. This system still follows the same working concept as classic CDI systems: providing a voltage potential to two electrodes made of materials with a wide surface area, such as activated carbon, to adsorb more salt ions on the surface. The distinctive point that makes the FCDI system more popular is that its unique characteristic is the application of a liquid electrode system that can be pumped in and out instead of utilizing static electrodes, which is important to have a charging and discharging process for long-term usage. Therefore, the FCDI system has certain remarkable benefits when improving the capacity to treat water without necessarily needing to discharge ions from the electrode to minimize the amount of power and time needed to run. Compared to conventional CDI systems, the technology and materials utilized to create electrodes are more cost-effective.

2.2.1 Historical development of Flow-electrode Capacitive Deionization (FCDI)

In 2013, the FCDI system was first released with a design consisting of three primary parts: a water tank and two electrode compartments, with the invention of an electrode

circulation pump system. The FCDI system at that time was regarded to have the ability to replace traditional CDI systems with greater advantages.

In the following years, the FCDI system was considerably improved with system design adjustments which included operating two modules in parallel, increasing the number of stacks for desalination, and building a 3D system for FCDI cells. In addition to improving physical design components, researchers are focused on improving the electrode system and enhancing electrode quality in FCDI. For example, the electrode solution is supplemented with chemicals such as magnetic iron oxide and polyaniline to boost the capacity to adsorb ions onto the surface of the electrode and diversify the sorts of ions that the electrode can extract from the water source to be treated.

There have been several research publications published since 2021 on electrode development, operating systems, and applications of ion exchange membranes using FCDI systems. The existing FCDI technology should be studied further, since a future system with numerous advancements might replace various desalination and water filtering processes, such as reverse osmosis.

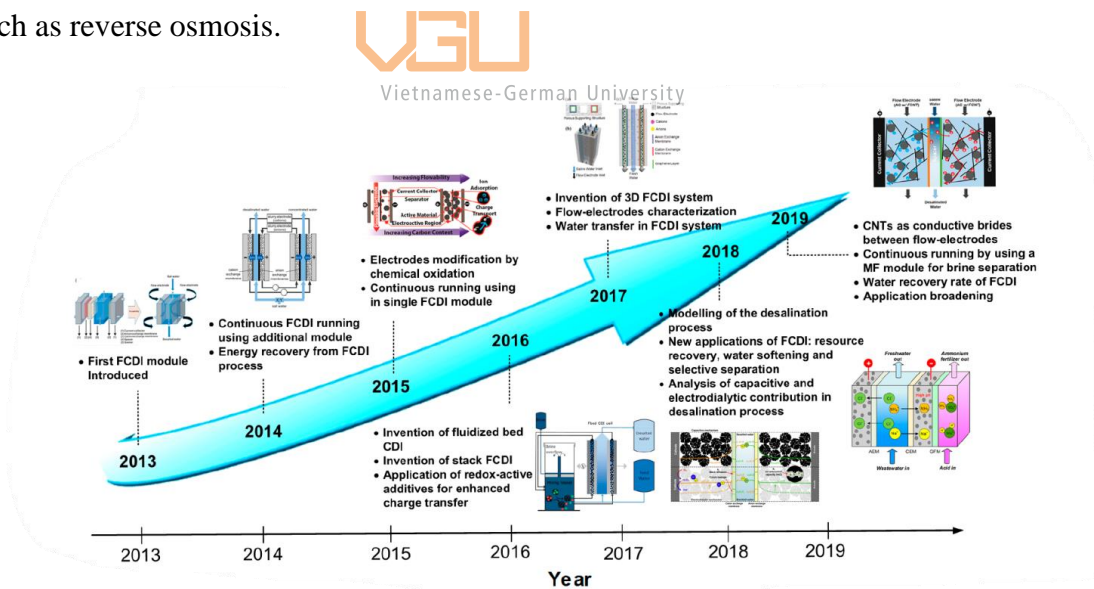


Figure 8 FCDI development in the last decade

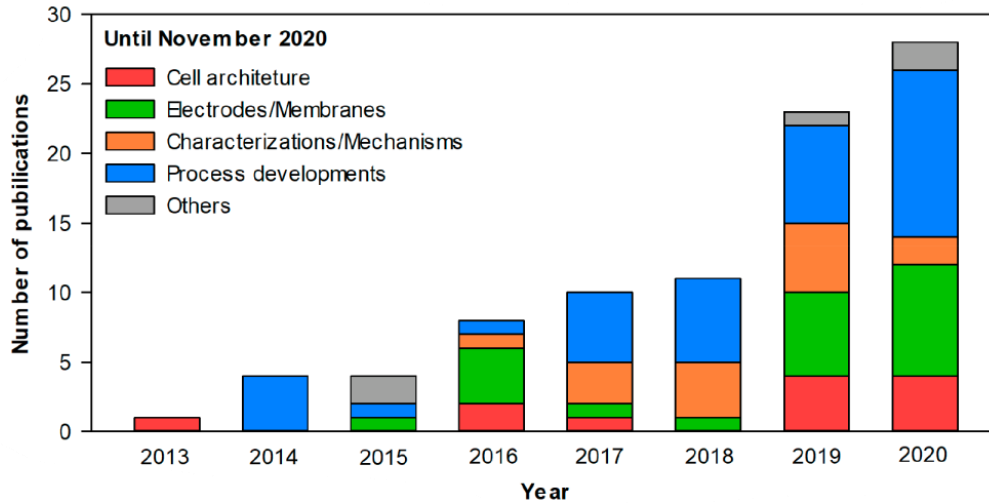


Figure 9 Number of FCDI publications in the last decade

2.2.2 Operation condition background

a) Operating principle of FCDI

Electrodialysis is a water desalination technology that uses electricity to push spontaneously sodium chloride throughout an ion exchange membrane in order to separate the water from the salts, which is the main function that is applied throughout the whole FCDI desalination process. When a limited potential difference (typically ≤ 1.23 V to avoid water hydrolysis) is applied, cations and anions in salt solution flow between a pair of porous carbon electrodes are transferred to the electrodes with the opposite charge resulting in a desalinated stream. When the electrodes are short-circuited or reverse-connected, the adsorbed ions are released into the bulk solution, culminating in a concentrated stream, and then the electrodes are regenerated, restoring their initial ion sorption capacity.

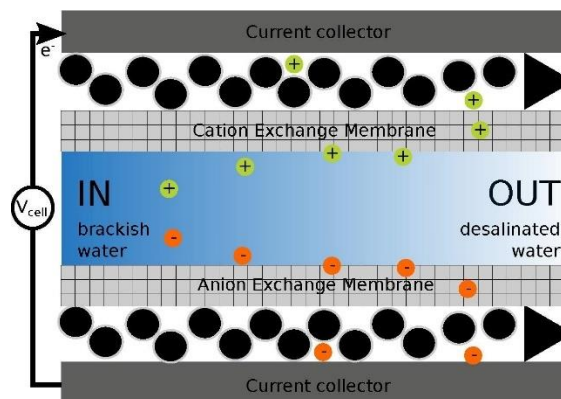


Figure 10 FCDI working principle

b) Flow-electrode

In the FCDI system, the flow-electrode are often composed by combining 3 components, including active materials (usually activated carbon are chosen), conductive and electrolyte with an appropriate ratio. The total percentage of solid weight percentage (wt%) can be calculate by:

$$\text{solid content (wt \%)} = \frac{\text{active materials} + \text{conductive additive (solid)}}{\text{active materials} + \text{conductive additive (solid)} + \text{electrolyte}} \quad (1)$$

- Active materials

The active material is selected with the properties such as high porous surface, good conductivity and economical advantage in order to have high efficiency in transferring electrons and improve the rate of ion adsorption during the electro dialysis process. In general terms, depending on the ion adsorption operating mechanism, there are two categories of active materials. Electrical double layers (EDLs) are used by carbon-based materials as ion storage spaces during the electro dialysis process. The next category includes charge-transfer materials, which have the property of capturing and reversibly introducing an ion into the host. In this scenarios, the activated carbon mateial will be applied.

The benefits of carbon-based materials as flowable electrodes have been thoroughly studied and applied due to it large size of porous area and high conductivity at a cheap commercial price. Activated carbon, (AC), mesoporous carbon (MC) and graphene (GN) are a several recommendation of these materials. Additionally, this particular type of material can be modified chemically through processes like chemical oxidation, nitrogen doping to significantly enhance the properties for electro dialysis, such as larger capacitance, a sustainable flow rate, etc.

- Conductive Additives

Conductive additives plays an important roles in the flow electrode performance in desalination process. The more conductive of the flow electrode, the more effeciciency desalination be. In this case, there are two options including highly conductive solid

substances such as carbon black, carbon nanotubes (CNTs), etc and aqueous electron-mediators (hydroquinone (H₂Q), indigo carmine, p-phenylenediamine (PPD),...). In this work, carbon black are chosen due to the availability in the laboratory and affordable in the commercial.

A particularly prevalent conductive additive used with flowable or static electrodes is carbon black. Mixing approximately 1.5 weight percent of carbon black with the flow electrodes considerably improves the salt removal rate (SAR) and charge efficiency of the desalination system, despite the fact that the carbon black particles have a low specific porous surface area (120 m² g⁻¹) is indicated in Figure 11. This may be determined by the fact that the electron transport between the activated carbon particles and the current collector has improved due to numerous collisions between the particles and the current collector's surface. Additionally, the basic characteristics, such as powder size, size distribution, powder shape, pore structure, and, most crucially, conductivity, have a significant impact on how well the desalination process works. (Changyong Zhang et al, 2021)

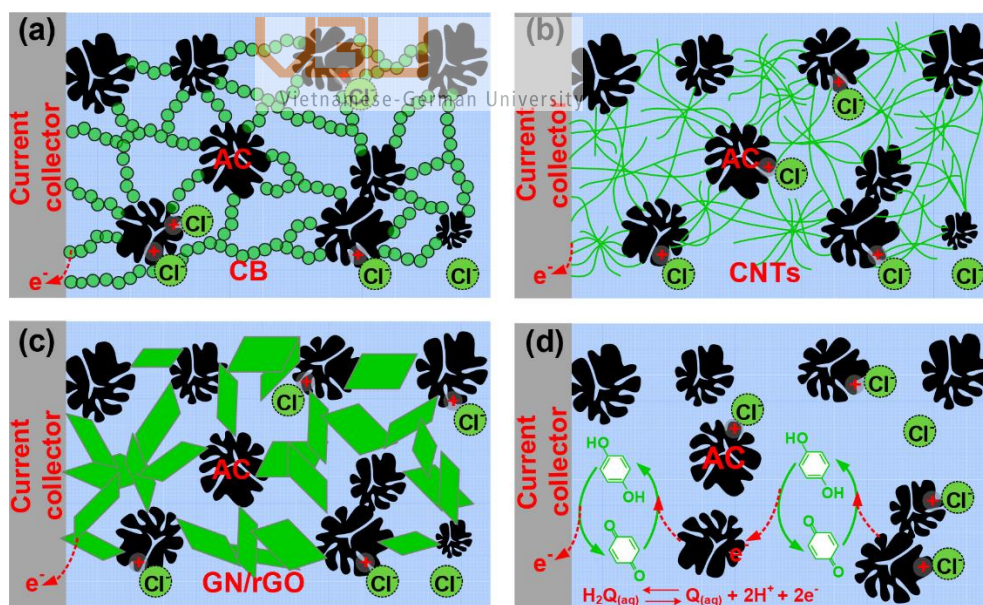


Figure 11 The representation of the role of the conductive additive in flow electrode systems. These are including (a) carbon black (CB), (b) carbon nanotubes (CNTs), (c) graphite (GN) and (d) hydroquinone and benzoquinone (H₂Q/Q)

Due to the justification described above, carbon black was selected as the conductive additive in this study, as well as the price is plausible.

- Electrolyte

Taking the highest percentage of weight in the flow electrode (approximately 80 wt%), electrolyte plays an important role in the flow electrode. By adding an appropriate amount of NaCl to the electrolyte, the entire cell's ohmic resistance is reduced, which consequently improves FCDI desalination efficiency. According to several studies, by increasing the NaCl concentration between 0.5 and 1.25M in the electrolyte, about a 25% improvement in the electrical conductivity can be observed when performing the process. Though this method increases the performance, as mentioned above, the drawback is the stability of the slurry. This can be explained by the addition of salt to the electrolyte, which leads to a higher slurry viscosity and more particle agglomeration along the path, which require more pumping energy for electrode recycling in the system. Concerns continue to exist regarding the potential rise in counterion back diffusion, co-ion leakage, and water carries electrolyte salinities, which might impair Coulombic effectiveness and desalting performance.

c) Current collector



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Although the current collectors are typically thought of as static components of the FCDI cell, they act as an essential part. With the purpose of transferring current and distributing charge to the flow electrode particles, the couple of current collectors in FCDI also control the flow of suspension electrodes while providing the chamber separators structural support (usually ion exchange membrane). Ideally current collectors have to be self-supporting, portable, reasonably priced, and possess characteristics include excellent electrical conductivity as well as formidable mechanical strength. Ideally, these materials should also be easily accessible, have a good anticorrosion resistance, and be simple to machine.

The following ideas should be considered while designing high-efficiency FCDI current collectors and flow channels: in order to facilitate the fast charge distribution to the carbon particles, it is important to

- Improve the surface contact area between the current collectors and the flow electrodes.
- Smooth surface channel for flowing of slurry electrodes.
- Minimize the cost while optimize the electrode chamber weight.

In addition, the current collector design may be facilitated by computational fluid dynamics (CFD), resulting in an optimization for both cost and power consumption.

The frequent FCDI current collectors' materials are metal-based (stainless steel) as well as graphite-based, with performing as both charge conductor and flow channel for the flow electrode. Although stainless steel has significant mechanical strength and outstanding conductivity, they were only utilized in the few numbers of FCDI investigations and be preferred less since, presumably because it was time consuming to carve the flow channel and due to the impactful property of corrosivity.

Nevertheless, since the FCDI cell in this work is only utilized briefly and on a small scale, stainless steel would be a fantastic choice for the current collector in this circumstance.

d) Separators



In the case of FCDI, the system has three different chambers, including two chambers for electrodes and one chamber for saline water. The separators selection has to fulfill several requirements in order to operate smoothly:

- Perform as the barriers between water and electrodes which allows ions and water to pass through.
- High ionic permselectivity and electrical conductivity
- Outstanding specific ions selectivity

Thus, normally in the FCDI system, the cell is equipped with a couple of IEMs, including a cation exchange membrane (CEM) and an anion exchange membrane (AEM). When applying electrical potential to two current collectors, the chlorine ions in the NaCl solution pass through the AEM easily due to the existence of the fixed positive groups and are blocked by the fixed negative groups that are included in the CEM. In the other hand, the sodium ions migrating to the CEM and permeate into the membrane and stalls on the surface

of the AEM. This leads to an increase in the salinity of the electrodes flowing through the system and a simultaneous decrease in the NaCl content in the effluent flow. Therefore, a couple of IEMs are the best choice for this design cell.

In this situation, the concentration polarization must be counted due to its impact on membrane performance. Then an electrical difference is applied, the ions in the solution immediately stick to the membrane surface. As the volume increases for achieving the higher flux of ions through the membrane, the salt solution will lack permeating ions. As a result, the total energy consumed for ion transport through the membrane rises significantly. The concentration polarization can be controlled by making the saline solution circulate in the system at high flow rates. Furthermore, each IEM has its own limit current density (mA/cm²). When the value reaches the peak, the increase in voltage across the membranes for higher ion transport through the membrane will be inefficient and lead to wasteful energy consumption. (Changyong Zhang, Jinxing Ma, Lei Wu, Jingyi Sun, Li Wang, Tianyu Li, and T. David Waite, 2021)

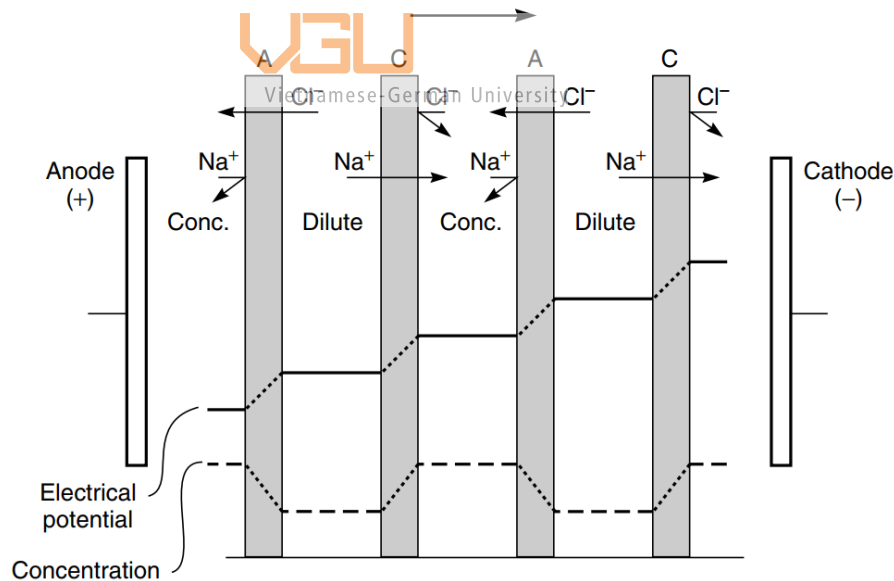


Figure 12 Ion exchange membrane working principle in FCDI cell

e) Metrics for Performance Valuation

1. Power consumption

In order to determine the general efficiency of the electrical dialysis, the energy consumed for performing the ion separation is the key factor. The expression is followed by:

$$E_v = \frac{\int_0^t IU dt}{\int_0^t v_d} \quad (2)$$

where U is the potential different between two side of the current collector, v_d is the dilute stream flow rate.

Or

$$E = I^2 R \quad (3)$$

which E is the power consumption in watts (W), I is current (A) and resistance of number of FCDI stacks R (Ω).

2. Average salt removal rate

Average salt removal rate (ASRR) is the rate that the FCDI system can eliminate the amount of the salt content in the influent stream by the unit of IEMs in an interval of time. This metric is one of the most significant properties that can evaluate the overall performance of the CDI system in general. The formula for calculate the ASRR is:

$$ASRR = \frac{\int_0^t v_d (c_f - c_d) dt}{A_{eff} t} \quad (4)$$

where the c_f and c_d is the salt concentration of the influent and effluent flow respectively. A_{eff} is the area of the membrane that contact with the flow electrode (mm^2).

3. Output rate

The amount of treated water in a unit of time can be calculate by the formular below:

$$P = \frac{\int_0^t v_d dt}{At} \quad (5)$$

In this case, the area of the membrane that contact with the flow electrode will be used. This metric can indicate the operation and maintaining cost, which for economic optimization.

4. Water Recovery

Beside the ASRR, the water recovery (WR) is also contribute to the valuation of FCDI performance. WR can be define as the proportion of the water outcome volume and the sum of the brine water and the treated water volume or the amount of water has become the deionized water.

$$WR = \frac{\int_0^t v_d dt}{\int_0^t v_d dt + \int_0^t v_b dt} \quad (6)$$

Which the v_b is the volume of brine water (ml) and v_d is the treated water (ml).

5. Salt Adsorption Capacity (SAC)

This parameter indicates the amount of salt can be adsorbed by the flow electrodes. Although SAC is used to evaluated the performance of the normal CDI system due to the static electrodes, the flow electrode might not be suitable for SAC calculation. For example, in the short-circuit cycles (SCC) operation where the electrode is shared the same reservoir that the ions is oppositely charged ions get neutralized and form a brine stream along side with the flow electrode stream. This would lead to the inaccurate for measuring the SAC value. (Changyong Zhang, Jinxing Ma, Lei Wu, Jingyi Sun, Li Wang, Tianyu Li, and T. David Waite, 2021)

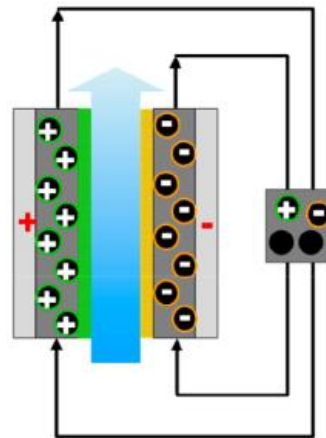


Figure 13 Short Circuit Cycle operation for FCDI desalination system

6. Average concentration reduction and salt removal efficiency

To calculate the reduction concentration of salt, the value of flow rate of the dilute stream and the concentration of the feed water input and output are taken into account. The formular is illustrated as:

$$\Delta C = \frac{\int_0^t v_d (c_i - c_o) dt}{\int_0^t v_d dt} \quad (7)$$

Which the c_i and c_o is the concentration of the intial and dilute stream of the feed water, v_d is the flow rate of the water feed into the cell, Δc is the concentration different rate.

2.2.3 FCDI development in recent years

Recently, experts have identified the FCDI method for its potential benefits in desalinating salt water, such as reducing time and being very effective. Most scientific research publications are going to concentrate on two FCDI development directions: modifying the composition of the electrode compound and modifying the FCDI system's structure and operating system.

a) Electrode development



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First, in terms of the structure of the electrode flow component, scientists have explored a variety of materials to improve the FCDI system's salt removal capabilities. In a study published by Changyong Zhang and colleagues, activated carbon was combined with Fe₃O₄ powder in the electrode combination. As a consequence, their relatively high surface area, superior electrical conductivity, moderate static adsorption capacity, and magnetization responsiveness result in an excellent choice. (Changyong Zhang et al, 2021).

In addition, there are also many scientific articles that have shown that applying battery materials to electricity will produce extremely impressive salt removal results. The results demonstrate that raising the applied voltage from 1.2 to 2.8 V improves the salt removal rate and efficiency of the developed FCDI. Furthermore, the novel FCDI based on CuHCF-AC pair outperforms conventional FCDI with AC-AC pair when operating at high voltages above 2.0 V (e.g. salt removal rate of 0.12 vs. 0.11 mg cm² min⁻¹, salt removal

efficiency of 91 vs. 84%, and current efficiency of 96 vs. 95% at 2.8 V), despite the fact that the pH of the concentrated water changes more significantly. (Junjun Chang et al, 2019).

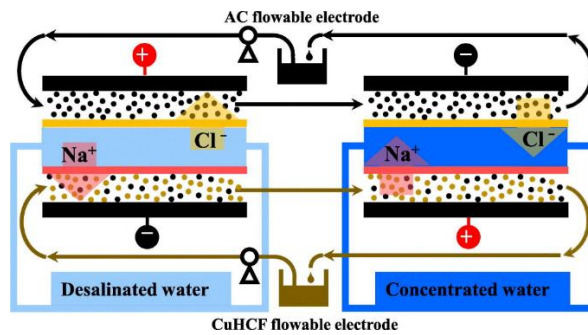


Figure 14 Battery materials based made for electrode component

In addition to removing salt ions from the initial aqueous solution, this desalination technique also removes metals. Haoyu Yin and colleagues discovered that using self-enhanced oxidation (FCDI-SEO), the FCDI system can remove Cu-organic chelate from industrial wastewater solutions. After 75 minutes of operating, the system was able to remove over 99% of the Cu in the solution with an initial salt concentration of 1mmol L^{-1} . (Haoyu Yin et al, 2022) This study is regarded a new milestone since previous studies used FCDI to remove Na^+ and Cl^- ions from solution, but very few studies have been conducted on the efficacy of metal ion removal type. In figure 15, the Cu-organic ion is adsorped onto the surface of the electrode when applied electrical difference on both side.

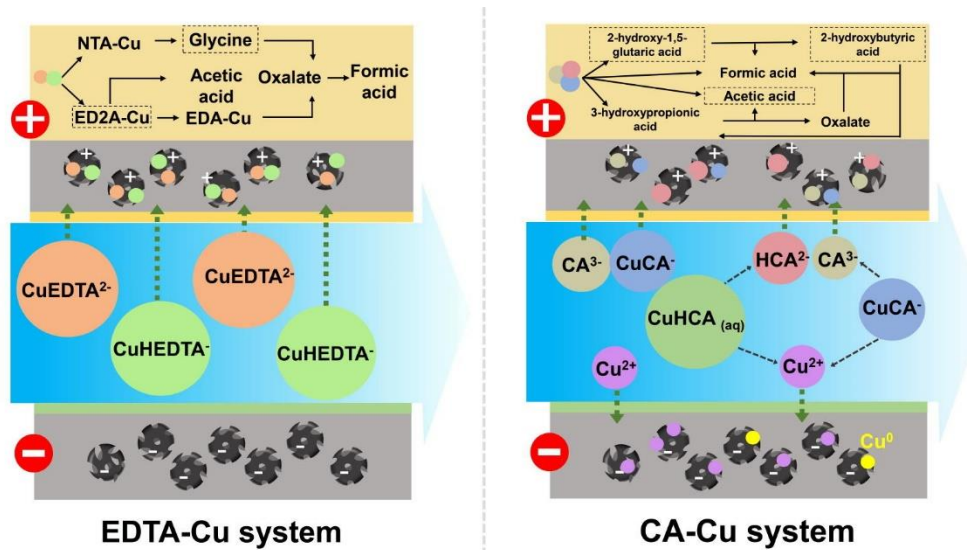


Figure 15 EDTA-Cu system and CA-Cu system operation principle

b) Cell Design Enhancement

Junjun Ma et al. developed a three-stage flow electrode capacitive deionization (FCDI) system in which the flow electrodes were linked in series and flowed between the three stages. The results demonstrate that it obtained the greatest desalination performance while saving 43.47 percent of energy, and that multi-stage FCDI devices were more energy-efficient and less expensive than standard single-stage devices. (Junjun Ma et al, 2023)

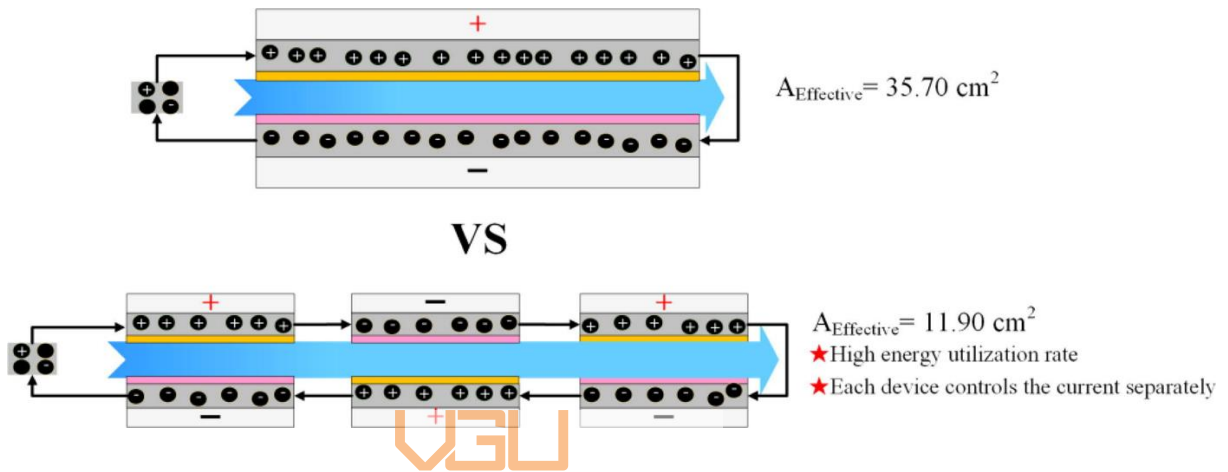


Figure 16 Junjun Ma's 3 FCDI line development compared with one stack original FCDI cell

The Xinyuan Zhang team developed a new cell design method in which three-dimensional (3D) carbon coated nickel foam was used as a current collector in a flow-electrode capacitive deionization (CF-FCDI) device to strengthen the charge transfer ability of the FCDI device, achieving distinguished desalination efficiency for real seawater. The result of this method is suprisingly high with 99.8% of the salt ions is removed from the water in the initial condition of 3.5g/L NaCl. Figure 16 is indicated the design concept of the foam current implied in this research.

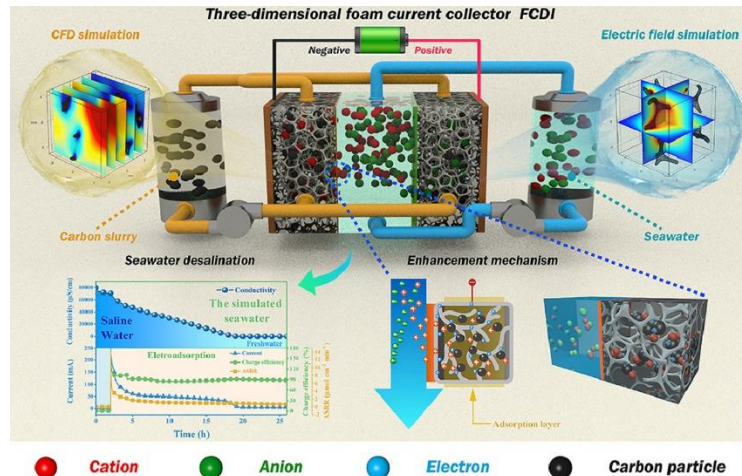


Figure 17 Three-dimensional foam current collector

These are several in many FCDI-related research publications published in the previous five years. Other research publications, when summarized, all strive towards the same goal of expanding the capability and efficiency of desalination, as well as the practical use of this sort of water filtering in everyday life.



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2.2.4 New features of this report

In this study article, various new characteristics will be reported, including:

- Testing on real brackish water condition
- Cost reduction for FCDI design and system operation
- Analysis of the system design and comparison of advantages and disadvantages with previously explored and proposed designs.
- Suggestions for design enhancements that can be adopted and investigated in the future.

3. Methodology

3.1 FCIDI Cell Components and Assembly

In this research, the Flow-electrode Capacitive Deionization (FCIDI) system is designed with the following criteria:

1. Easy to process, easy to disassemble, replaceable materials
2. The operating system must meet the requirements of electrical safety, stability and neatness
3. Minimize system operating and maintenance costs for electrode materials and equipment

The design for the FCIDI will include 5 main components, including:

3.1.1 *Electrode path flow*

The electrode path flows are constructed of Plexiglas (other designs are made of pricey metal) and measure 15mm x 15mm x 4mm to reduce the overall cost of manufacturing the design. In the center, a serpentine route was cut to smooth the carbon flow and enhance the contact face area with the ion-exchange membranes (IEMs). The overall contact surface of the placeholders and IEMs is 42 cm², which is more than the average value of prior experiment designs. This increases the probability of a greater adsorption rate. Furthermore, the surface is polished with a route length of 420mm to prevent carbon particles from becoming entangled while traveling. Due to the fact that as previously stated, this design is focused on lowering manufacturing costs, the inner surface of the placeholders is cut down around 0.8mm in order to construct the holder for IEMs and minimize the total thickness of the FCIDI cell. There are 5 drilled holes, one in the bottom centre for saltwater flow and four at each corner for assembly.

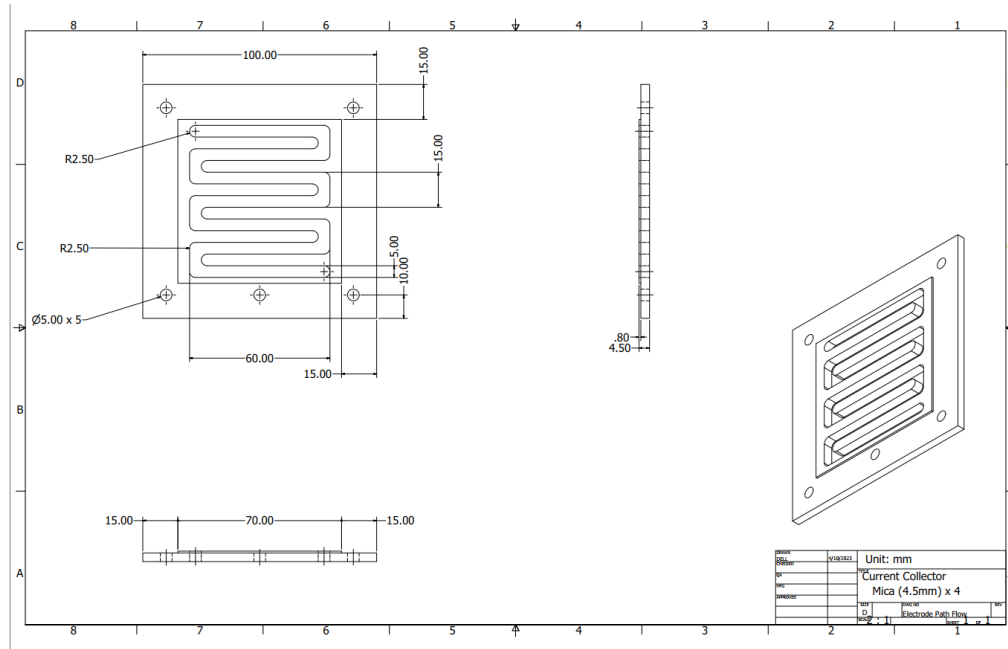


Figure 18 Design of Electrode path flow

3.1.2 Endplate

The endplates on the exterior of the FCDI cell are responsible for supporting all the parts that are positioned in their space. The dimensions of these two plates 140mm x 140mm x 8mm, as seen in Figure 19. The surface of the endplate is cut down 1.2mm in the middle to link the stainless steel for electrical conductivity to the carbon electrode flow. There are 4 bolt holes in each of the four corners and a water flow hole in the centre. There are two large circles in the centre at each corner, which are used to attach two external threaded screws. Specifically, like the electrode route flow, there is a hole for water stream into the system that is situated in the same location. Plexiglas also manufactures the endplate material.

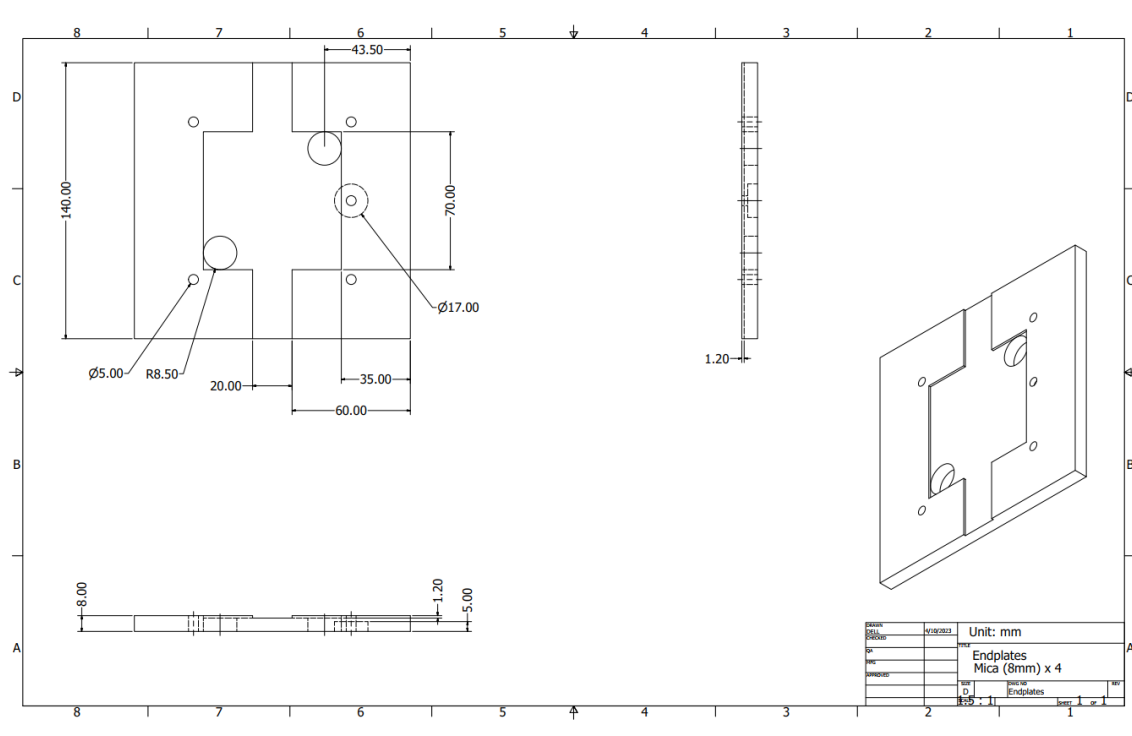


Figure 19 Endplates

3.1.3 Current collector



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In almost FCDI system, the current collector would be design with various functions as mentioned in the literature review, including current transfer, charge distribution to the electrode and direct the flow of suspension electrode. Furthermore, the current collector must include the superior electrical conductivity and anti-corrosion, lightweight and low cost. In this design, the stainless steel are choosed as the material for the current collector due to the adequated with required properties. Also, the current collector in this senarios would be in the sheet form, which is easy to replace when get damaged and low cost for manufacturing.

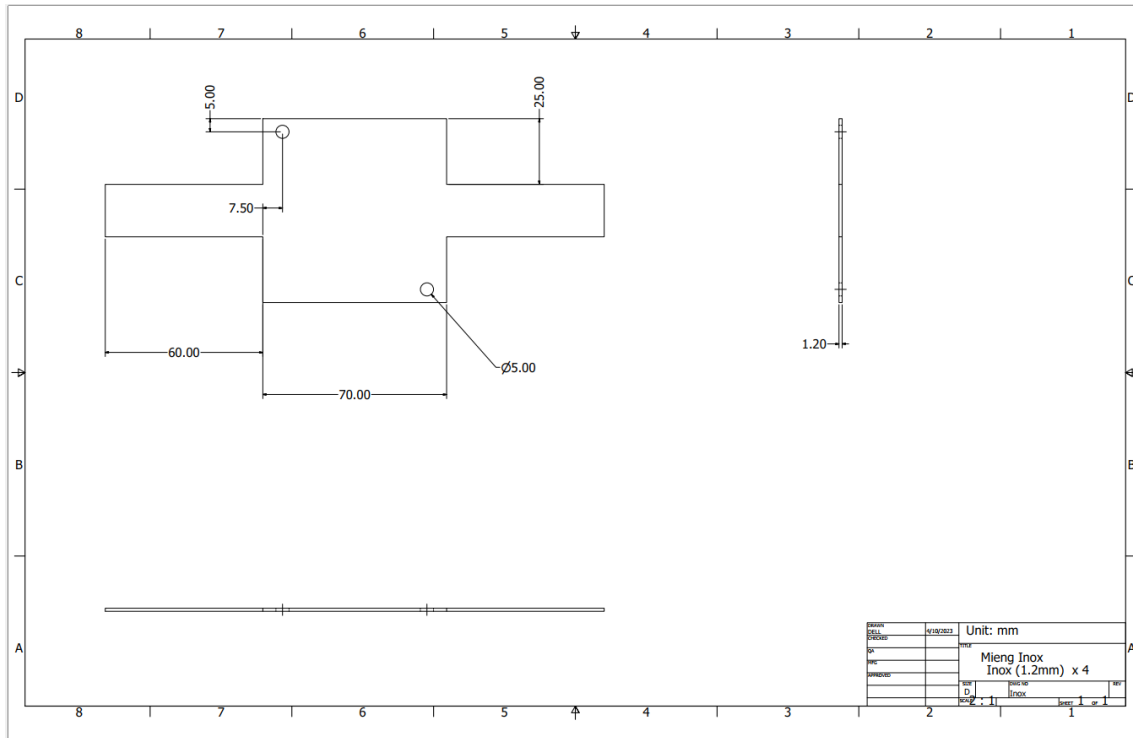


Figure 20 Stainless steel sheet current collector

3.1.4 Holder plates and Spacer Gasket

The two holding plates are utilized to hold the membrane. These parts mentioned are constructed of stainless steel and silicon. Figure 14 illustrates the dimensions and design of the plate. The surface of the electrode path flow has been reduced by 0.8 (dependent on the holder plates' thickness) to increase the contact surface with the IEMs. As a result, the membrane boundary is in direct contact with the electrode flow, culminating in increased carbon adsorption efficiency and improved conductivity.

The spacer gasket is manufactured of Plexiglas to take advantage of its low electrical conductivity and affordable cost, and its major role is to retain the spacer and direct the water flow. The design concept is basically identical with respect to the holder plates; nevertheless, the holes for water flow are constructed symmetrically on both sides for easy assembly and replacement. The design is shown in Figure 21 and 22.

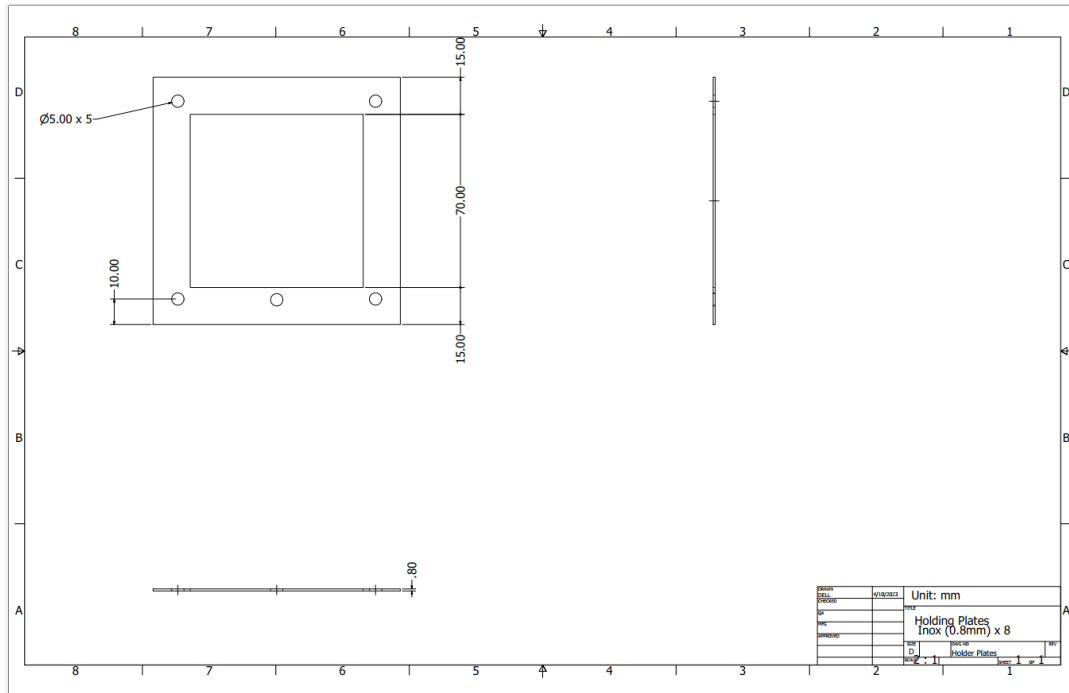


Figure 21 Holding Plates

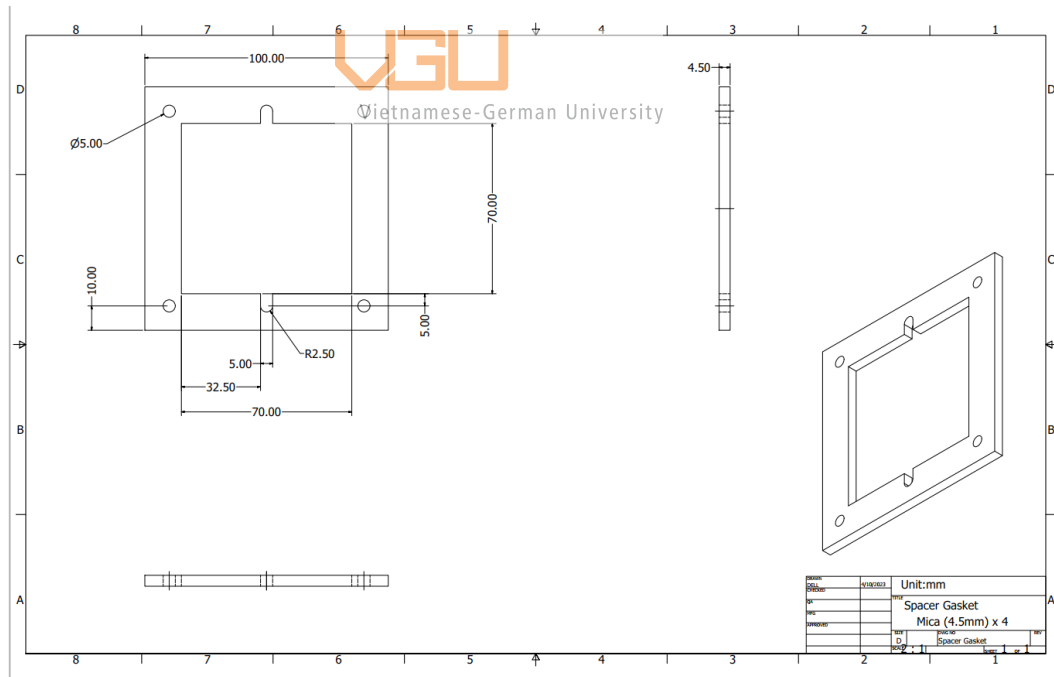


Figure 22 Spacer Gasket

3.1.5 Final Assembly

In the assembly, all the parts are combine together and the final assembly is display below:

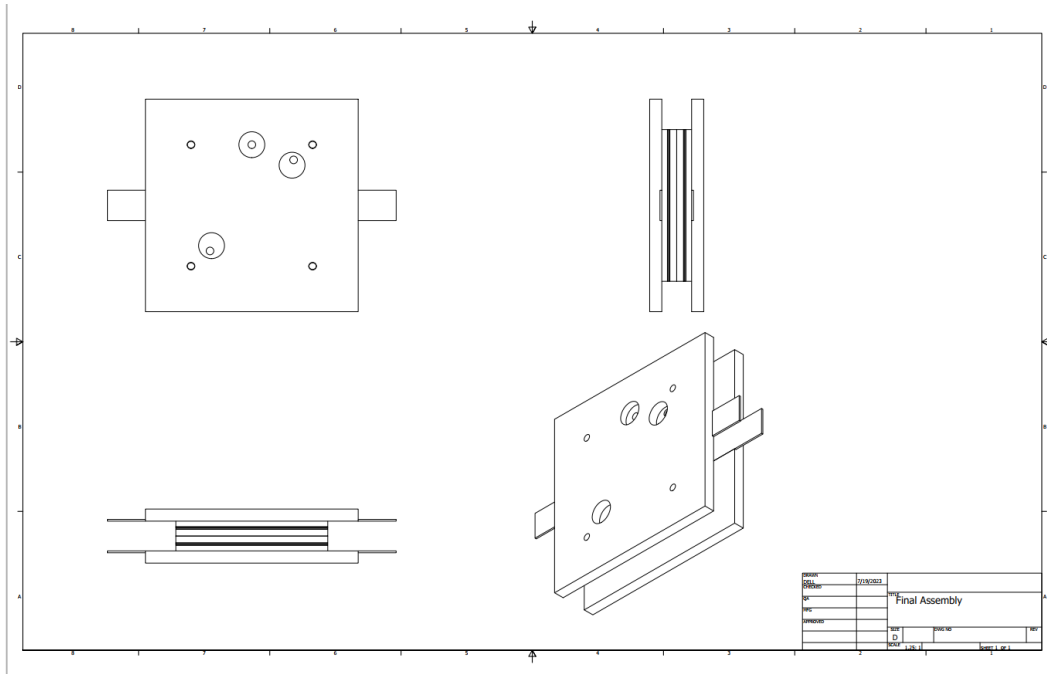


Figure 23 The Final Assembly of the FCDI cell

The specification of the FCDI cell are shown in the table below:

Parts	Value	Unit
Salt water treatment chamber	44.1	ml
Anion Exchange Membrane (HUOMATECH – China)	300	A/m ²
Cation Exchange Membrane (SIN-D117 – Sinoro - China)	0.083	S/cm
Total IEM surface area	4900	mm ²
Total contact area	2560	mm ²

Figure 24 FCDI cell specifications

After several test trials, the cell showed several problems, such as water leakages and deformation when tightening bolts. There are some solutions that are applied to fix the

problems temporarily. For the water leakages, all positions between the surface contact of solid parts are inserted by the silicon gasket. As a result, the amount of water leaked decreases dramatically over time. About the deformation, the fix for this issue is to tighten with enough turn so that the internal stress inside the materials doesn't increase and lead to the parts becoming warped and leading to liquid leakage.

The first advantage that this cell can provide is a high guarantee for safety during the operating process due to the fact that most touchable surfaces are electrically resistant materials (e.g., Plexiglas, silicon) and prevent electrical leakage. The effortless disassembly design and being able to cleanse all components with only clean water make maintenance simple as well. The best conditions for the operation are cool temperatures and avoiding dangerous chemicals. Also, the anticorrosion material is used for the current collector, and the bolts are used for the purpose of blocking the rust that can appear in the effluent of treatment water and cause harm to human health.

3.2 Material preparation

3.2.1 Feed water preparation

In this work, with the aim of reducing the salt concentration of the solution and investigate the system performance, there are mixed by only two components: deionized water and sodium chloride. The deionized water are taken from the laboratory after going through filtering steps, which has the high purity level and extremely low conductivity. The experiment will be applied in the ideal condition to observe the desalination performance result of the system. The outputs of this experiment would be used for comparing with other CDI desalination system which has been done in many experiments before by other scientists.

The feed water properties are listed in the table below:

Salt concentration (g)	Conductivity (mS/cm)	Salinity (PPT)	TDS (g/L)
1.00	1.87	0.996	0.989
2.00	3.71	1.95	1.99

5.00	9.29	5.19	5.05
8.50	10.13	8.52	8.48
10.00	11.36	9.27	9.30
15.00	12.48	14.43	14.67
25.00	33.9	25.01	24.96

Figure 25 List of initial condition for feed water

As can be seen from the table that, the value of the TDS (total dissolve solid) and salinity of the feed water is slightly lower than the input salt concentration. It can be explain by approxiamtely all the amount of the salt are dissolve into the water solution by using the magnetic agitator for stirring. The more amount of salt to be added, the more time need to spend for preparation for stirring to acquired the highest TDS. To evaluate the performance of the FCDI system, the changes of these three properties in the table are applied.

3.2.2 Flow electrode preparation

The work is aimed at optimizing the cost of the system and making it affordable for all the materials. Thus, the flow electrode components include three components: activated carbon, sodium chloride (NaCl), and water.

About the activated carbon, this is the unique material that has a vast amount of pores on its surface and possesses impressive van de Waals forces, which contribute to its properties of high adsorption ability. For preparation, the activated carbon was crushed into the power form in 30 minutes, initially in the granular form. The powder was collected after being filtered by a sieve to ensure that the hole had the required diameter. Plus, activated carbon is economical and easily accessible. The activated carbon in this cases is bought from privated business with properties included, 1mm mesh size, 5% moisture, 3% ash.

In the next step, three components are imported into a 1000-ml flask and stirred by the magnetic agitator. The percentage by weight of water, activated carbon, and NaCl is 90 wt%, 5 wt%, and 5 wt%, respectively. Especially for the activated carbon, the percentage can be varied from 5 wt% to 25 wt% depending on the demand for salt removal rate and preventing high viscosity of the liquid, which can reduce the flow rate or suspended.

For testing the quality of the flow electrodes, the electrodes must meet several conditions including

- High conductivity: NaCl is added into the flow electrodes for better conductivity. For boosting the conductivity value, conductive additives can be added into the solution (e.g carbon black or MnO₂).
- Flowable: with high viscosity, the electrodes unable to flow through the chambers and might be trapped inside. This will turn the FCDI into the casual CDI and reduce the expect salt removal rate.
- Constant concentration of activated carbon: the amount of the activated carbon particles get pumped inside and outside the system needs to approximate constant.

The table below here present each component value for each test run

Test run	Activated Carbon (g)	NaCl (g)	Water (ml)
1 & 2 g/L	40	40	720
5 g/L	43	40	700
8.5 g/L	48	40	712
10 g/L	56	40	704
15 g/L	64	40	696
25 g/L	80	40	680

Figure 26 List of fabrication materials for flow-electrode

3.2.3 Pump

In other to supply the slurry into the cell chambers, the pump selection criteria has to meet several conditions:

- Pressure: The pump generates pressure enough to push the liquid in and out of the system.
- Flow rate: a constant value that fulfills the desired amount of liquid volume in the chamber for an interval of time.

- Fluid: Select a pump that is made to manage the fluid's corrosiveness and consistency to prevent degradation or clogging from slurry or debris.

Based on these requirements, a number of pumps can be applied to this model, such as centrifuge pumps, peristaltic pumps, and air-operated diaphragm pumps. In this scenario, the peristaltic pump is selected due to its reasonable price, low energy consumption, and ability to meet all the requirements listed above.

3.3 System setup and operation process

In this system, there will include 3 main components: electrodes and water pumping system, power source, and data logger.

For the electrode pumping system, there are 4 peristaltic pumps, which are used for pumping the slurry from the electrode reservoirs into the electrode cell chambers, and 1 pressure pump for water. These pumps will cycle the flow electrode and water stream throughout the operation time. To control the flow rate of the influent, a speeder is added to vary the speed of the pumps. The maximum flow rate of the pump for flow electrode and water in this experiment is 80 ml/min and 1000 ml/min, respectively. As the amount of activated carbon expand, the speed of the pump must be increased or else the sludge would be unable to be pushed in to the chamber. In this experiment, the adjustable DC power source will supply voltage directly to the FCDI cell while it is operating to test desalination efficiency and compare the outcome.

Simultaneously, for the evaluation method, the conductivity meter rod is inserted into the water flask to check the value of the three properties mentioned on the sketch. The whole system is operated manually, and data is collected by the Horiba measuring device in real time during system performance.

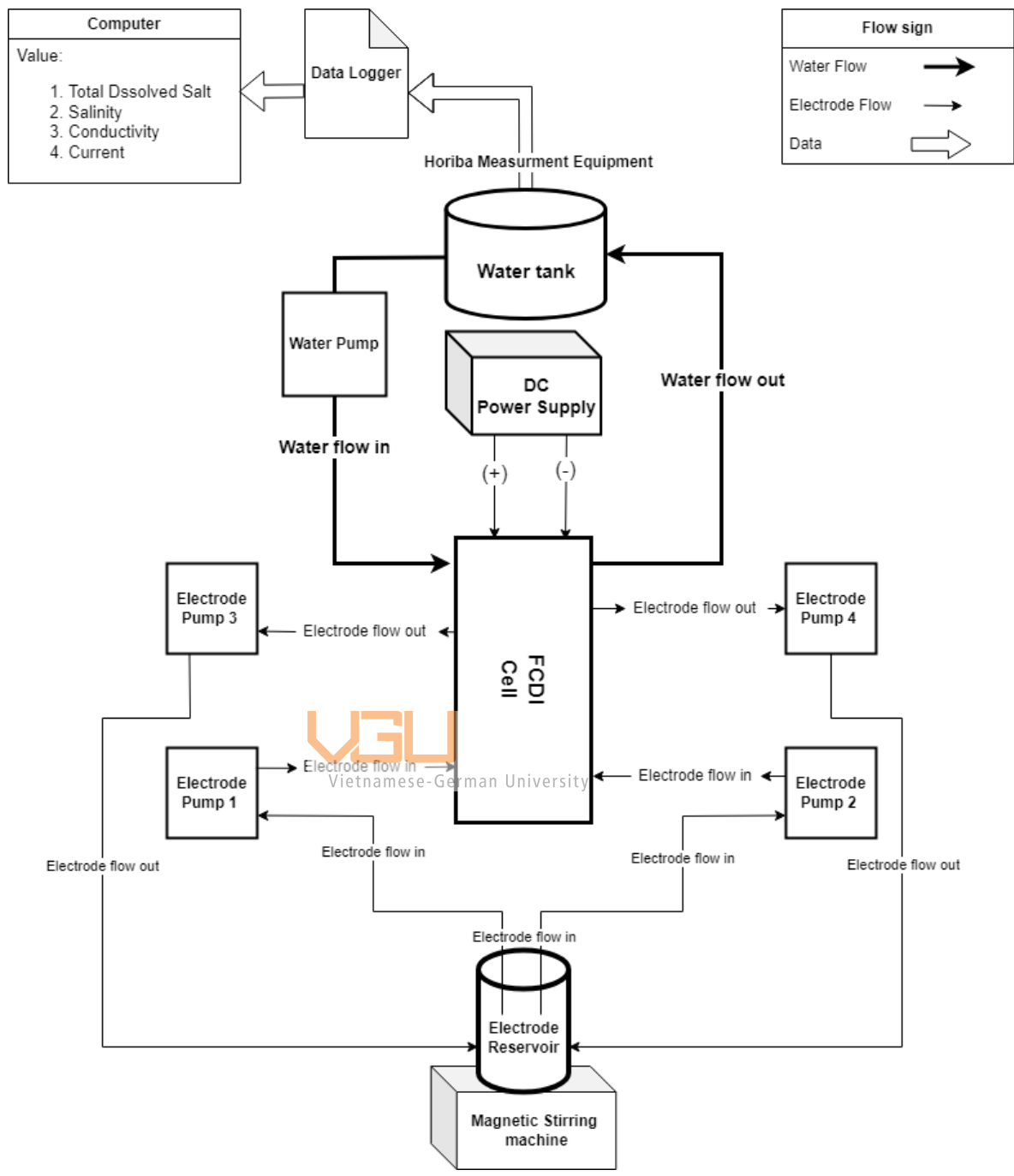


Figure 27 Flow-electrode Capacitive Deionization (FCDI) system operation setup

3.3.1 Operation process

The FCDI system is operated in accordance with electrical safety standards, which includes limiting the risk of short circuits and water contact. The following are the steps in the FCDI experimental operating procedure:

1. Turn on the pump switch:
 - a. If all the pumps operate normally then proceed to the next step.
 - b. The pumps would need to be checked with the clogged carbon in the pipes or the electrical wiring issue
2. Adjusting the pump speed: All the pumps speed will be started with the low speed and increasing the rotation after 15 seconds operation. The purpose for this is to maintain the durability of the pump. Also in this stage, all the pumps are used to push the electrode liquid and treated water into the system in order to support the next step.
3. Apply the DC voltage on both side of the FCDI cell: In this stage, the voltage is setting in the purpose of preparing for applying into the cell constantly throughout the test run in the later step. The work is only hanging one pole on each side of the cell and not yet output the voltage.
4. Stirring electrode chamber: The major goal of this procedure is to keep the activated carbon in the electrode from sinking to the bottom of the container over time. To address this issue, a magnetic stirrer is installed beneath the tank and will continually agitate throughout the experiment to enhance the stability of the quantity of coal injected into the system.
5. Set up measurement device: At this phase, a rod measuring several vital indicators such as conductivity, salinity and TDS of the solution will be dropped into the water tank for treatment. This measuring rod will be placed in the container during the entire period to examine the changes in the aforementioned indicators during the experiment over time.
6. Output the voltage: In this stage, the main task is to pressing the output button on the DC voltage source in order to make current go through the system and start to deslination task.

7. Measuring and collecting data: The measure tool will collect data and sent the value to the data logger in the computer simultaneously with the process operation.

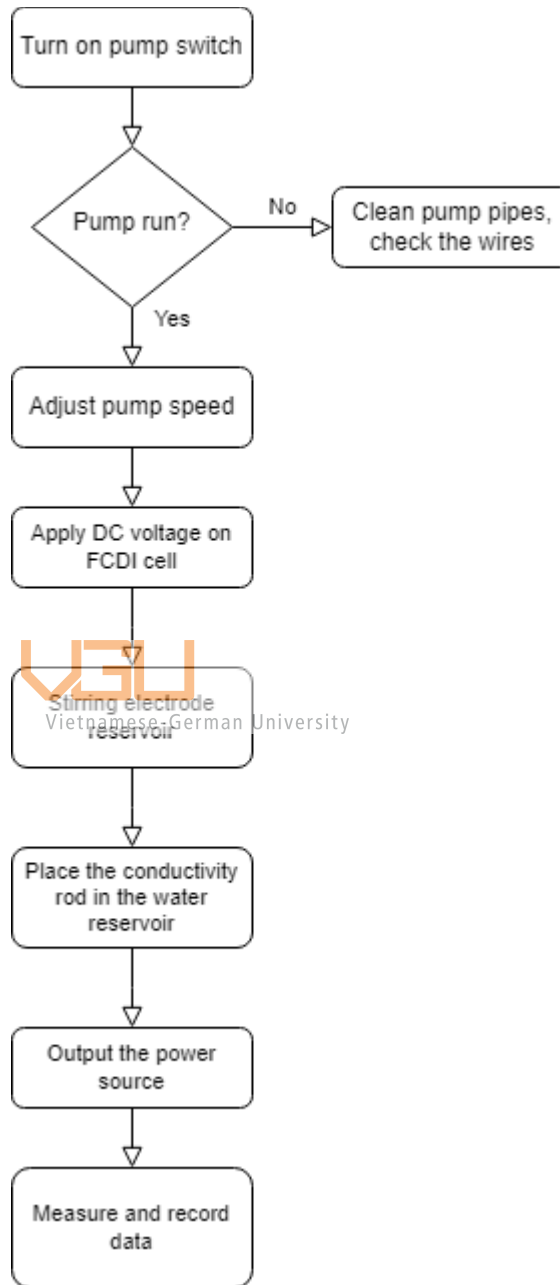


Figure 28 Procedure for FCDI system operation

4. Result and Discussion

4.1 Salt removal efficiency by FCDI desalination systems within brackish water range

4.1.1 Experiment data

Total dissolved salt (TDS), salinity, and conductivity are the three parameters of the influent that will be changed to determine the degree to which the FCDI system performs in this study. As soon as the Na^+ ions and Cl^- ions are removed from the treated water, these attributes reduce at the same pace. This can be explained by the reduction of moving ions which decrease the conductivity of the solution. In order to prevent aberrant values and erroneous findings, it is therefore more reliable to compare the data after desalination is complete.

The initial salt concentration for the treated water will range from a minimum of 1 grams to a maximum of 25 grams. The goal of the extensive testing is to identify the ideal starting concentration for the FCDI system to operate at peak efficiency. Furthermore, the voltage delivered to the FCDI device for each beginning condition will be adjusted from 1V to 1.5V for each test run and maintained for 15 minutes. This aids in determining the best strategy for utilizing the energy required for each FCDI desalination run at a low cost and energy saving.

First, the FCDI device demonstrates that its desalination capacity at low starting salt concentrations, from 1 g/L NaCl to 5 g/L NaCl, is significantly better than that at high salt concentrations. Particularly in the instance of 1 g/L when, over a 15-minute period, an average of 47 milligrams of salt were eliminated. When compared to other CDI systems, which vary from 15 to 30 mg per gram of salt, this is a very outstanding result. Additionally, this FCDI system is approximately 1.5 times superior than the standard CDI system when comparing desalination rates, with the average salt removal of FCDI being 41.3mg/L and that of CDI being approximately 20 mg/L. Additionally, the FCDI system only uses a mixture of activated carbon and brine to make electrodes in order to lower the cost of

replacing electrodes, whereas the CDI system needs to add other expensive components including titanium (Ti), MXene, etc. in order to operate better with higher desalination efficiency and preserve the electrode.

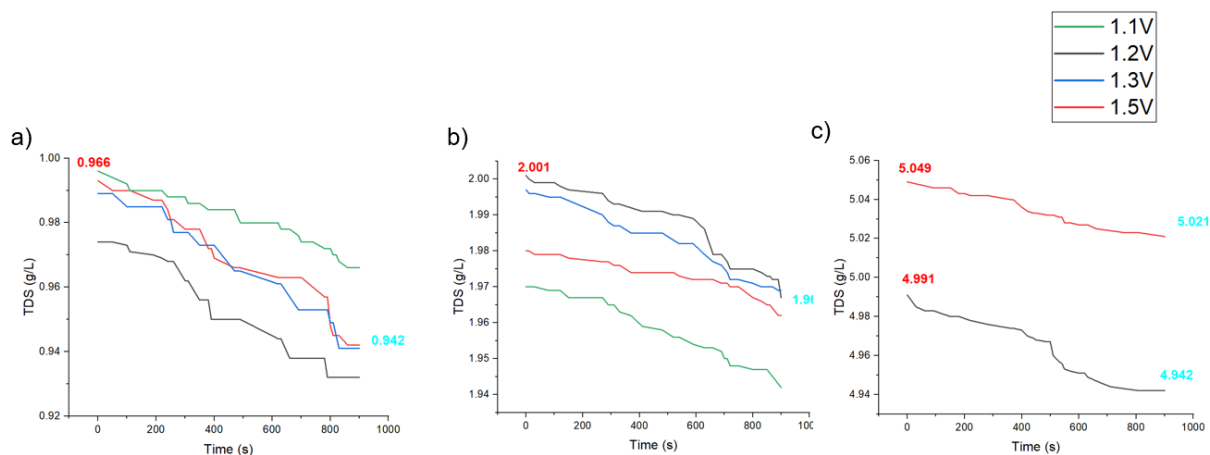


Figure 29 TDS value of NaCl concentration in the case of treated water with initial condition of 1g/L (a), 2g/L (b) and 5g/L (c) NaCl, respectively.

The experimental results show that the desalination efficiency is approximately between 20 and 40 mg for all types of beginning salt concentration settings when studies are conducted at low voltages as 1.1 V. The desalination efficiency is typically between 30mg and 60mg NaCl for voltages between 1.2 V and 1.5 V. This may be explained by the fact that the stronger the current generated by an FCDI system's higher voltage will result in more ions being absorbed onto the activated carbon's surface from the electrode.

The FCDI device can still function well and maintain consistent salt ion removal from water during conditions that involve high initial salt concentrations, ranging from 6 g/L to 25 g/L NaCl. In the further testing, the constant of 1.5V will be applied.

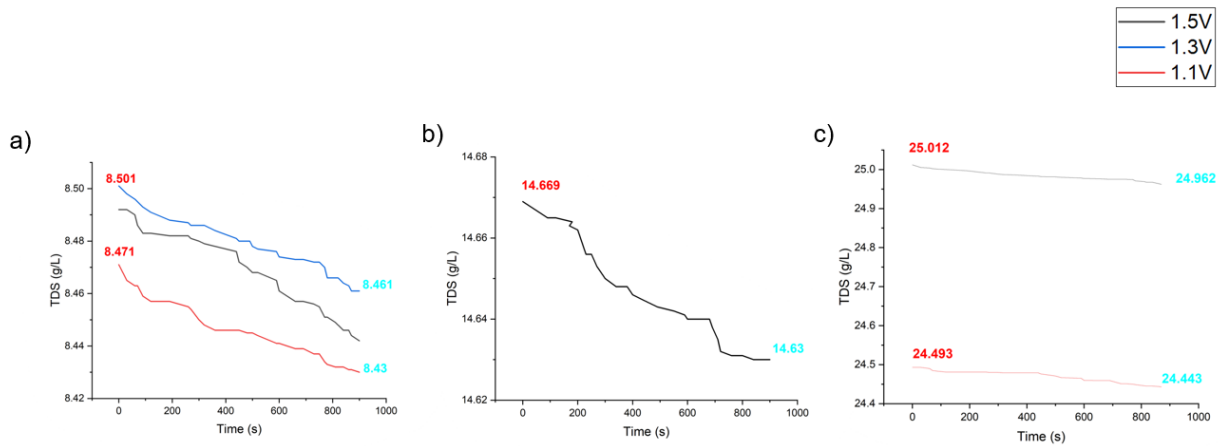


Figure 30 TDS value of operation in high NaCl initial concentration with 8.5g/L (a), 15g/L (b), 25g/L (c), respectively.

The FCDI system has a minimum desalination capacity of 18mg and a maximum desalination capability of up to 60mg for all scenarios. The result heavily depends on variables like the design of the machine, the voltage, the flow velocity, and the ion exchange membrane.



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Especially, in the 25 mg/L NaCl case, the sample is collected from the area has the issue with brackish water. The result from the experiments illustrate that the efficiency to remove the salt ions is about 0.14% in 15 minutes operation. To explain for this result, the brackish water collected has several types of ions included in the solution, might affect the quality of the couple of IEMs which were only applied for Na⁺ and Cl⁻ ions removal. The results will increase better if the higher quality IEMs are applied in this situation.

4.1.2 Average salt removal rate (ASRR)

Additionally, a significant factor in determining the efficiency with which the device performs in desalination is its average salt removal rate (ASRR). The graph shows that with a 1mm² ion exchange membrane, an average of roughly 0.00492ml of brine is entirely removed from the initial solution of Na⁺ and Cl⁻ ions in 1 second. As a result, 4200mm² of the ion exchange membrane is able to be exposed to the brine to be treated in the FCDI system in this experiment. The FCDI system may theoretically process up to 18 liters of saline in 15 minutes and can theoretically remove all Na⁺ and Cl⁻ ions from 20,664 ml of

saline in 1 second. However, this is also impacted by a variety of parameters such as the flow rate and the quality of the activated carbon.

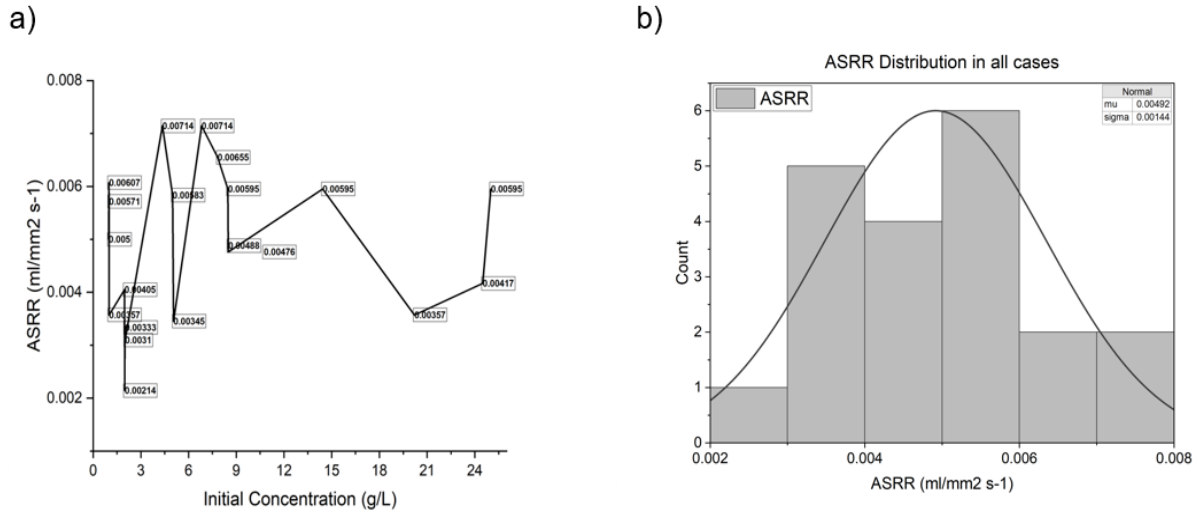


Figure 31 (a) ASSR based on initial NaCl in feed water concentration, (b) Distribution of ASRR value for all initial concentration trials

The rate of salt removal rate is unstable throughout several experimental runs because of a variety of factors, including flow rate and activated carbon quality. It is clear that the ASRR will fluctuate based on the aforementioned parameters whether the initial concentration is high or low. For instance, when the efficiency declined by nearly three times, there was a noticeable difference between the cases of 1g/L NaCl and 2g/L NaCl. Another example is the 5g/L to 10g/L range, where the chart tends to vary although the 5g/L case has a stronger capacity to remove salt than the 6.8g/L, then value increased dramatically even at 8g/L.

4.1.3 Stability

Evaluation of the machine's desalination process' operational stability is just as crucial as other parameters in addition to the FCDI system's desalination capacity. Twenty trials were carried out with variables including identical and diverse launching salt concentrations, voltages, and flow rates, with the aim of evaluating the machine's stability. A total of 16 out of 20 examinations, as well as around 80 percent of the total, reveal that

this FCDI system is capable of eliminating salt in the range of 30 mg to 50 mg. In particular, the quantity of salt removed will vary by 10% to 20% under the same beginning salt concentration conditions. An initial salt content of 8 g/L, for instance, would result in salt removal amounts of 41 mg, 50 mg, and 40 mg for each of the three trial runs. As the quantity of salt removed increased or reduced from only 0.5% to 2% compared to the original default flow rate of 500 ml/min, the desalination efficiency did not change considerably for varied flowrates. It may be inferred that this FCDI system runs remarkably steadily and has the capacity to salt out various beginning circumstances.

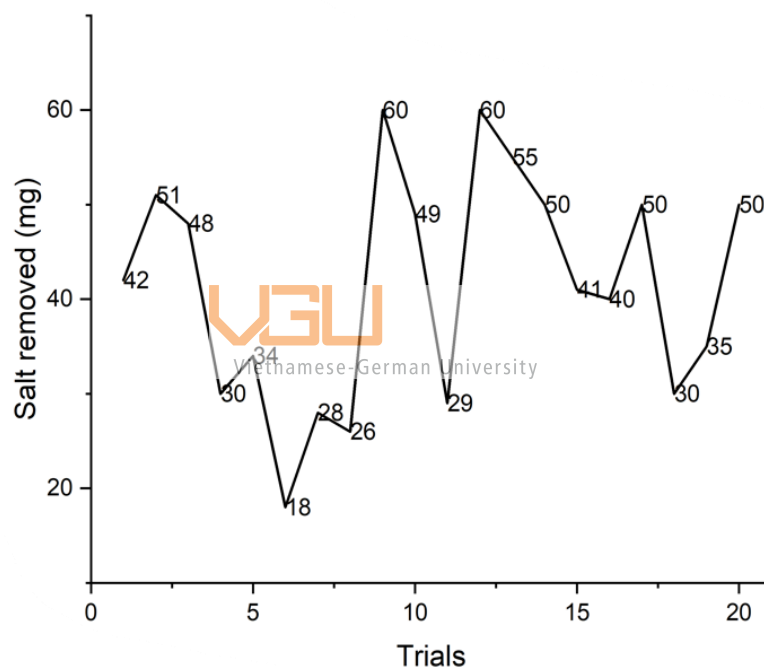


Figure 32 Desalination stability of FCDI in the various initial concentration (1g/L to 25g/L NaCl)

In another cases, the test for stability was conducted in the scenarios of 1g/L initial concentration feed water. There were 5 more experiments done in the similar condition to justify the working stability of the FCDI system. The result can be seen from the Figure 33, which is clear that the salt removal rate was 4.855% in average. From all the data is shown

in both cases, it can be concluded that this FCDI system is working stably in all initial condition within the range from 30 mg/L to 50 mg/L of salt removed from the system.

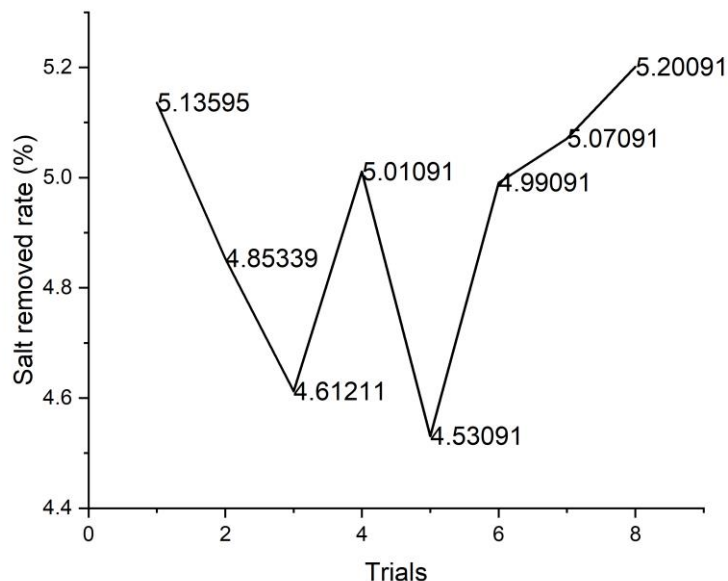


Figure 33 Stability test on salt removal rate in 1g/L initial concentration

4.1.4 Removal efficiency

According to the data retrieved from the chart, it can be presented that the desalination efficiency of FCDI achieves around 5% in 15 minutes for one working cycle with low salt concentrations between 1 g/L and 2 g/L. In the initial conditions with 25 g/L NaCl in 1 liter of water, the FCDI system is capable of eliminating about 50mg of salt out of a total of 25g (approximate 0.1429% of salt removed from the solution) in the identical time frame as before. Nevertheless, as the initial salt concentration gradually increases, the desalination efficiency does not decrease significantly compared to the initial conditions. The conclusion is that This FCDI design promises to be more efficient in terms of time, economy, and energy when utilized in circumstances in which salt removal is required at low initially concentrations and high removal rates. There are plenty of approaches to enhance the efficiency of this FCDI system, including altering the ion exchange membrane's quality and mixing the electrode with materials with more ion absorption and higher absorption

capacity. Additionally, enhance the structural design of FCDI cells by adding layers for filtering and ensuring good electrical conductivity.

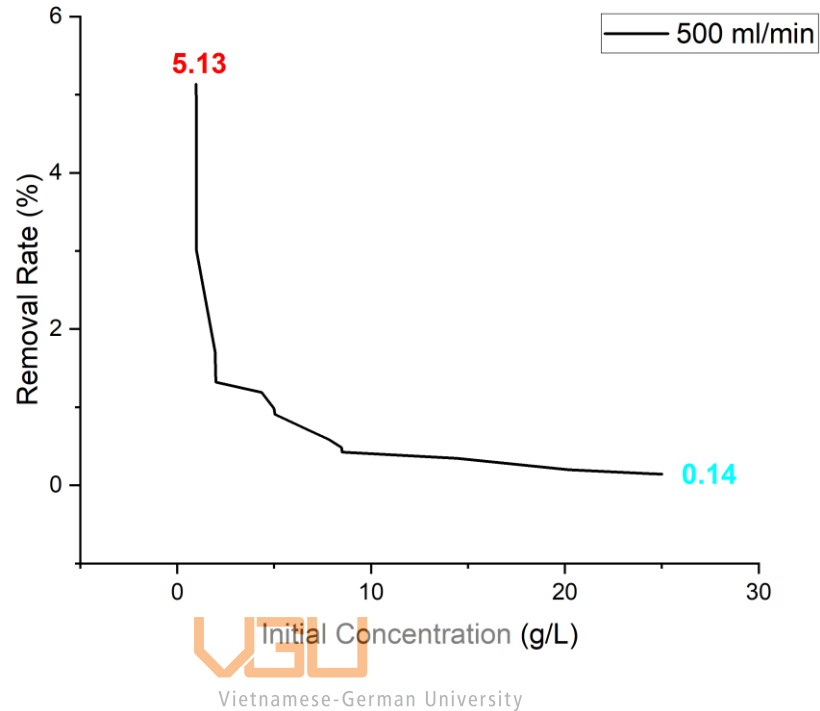


Figure 34 Removal rate of the FCDI based on the increment of initial concentration.

4.1.5 Energy consumption

When used to larger-scale systems, energy consumption for FCDI operation is also regarded as a critical element. Figure 34 shows that with a voltage of 1.5V applied in situations ranging from a minimum of 1g/L to a maximum of 25g/L, the greater the initial salt concentration, the higher the energy consumption. This is explained by the fact that when the electrical conductivity of the solvent rises, so does the current density, resulting in a large increase in the amount of electrical energy used for ions traveling to the electrodes.

Furthermore, when compared to RO water filtration systems, this can be considered as a significant benefit when using FCDI to desalination and water filtration models. This leads to additional benefit that will assist conserve power and running expenses when this FCDI system filters water with a maximum of 400W in 15 minutes and consumes 1 liter of water. costs around 0.4kWh, however using a RO water filtration system will spend

approximately 3kWh to 10kWh to filter water under same conditions. (Reverse Osmosis Filtration System's Energy Consumption, 2023). If converted into the amount of electricity consumed for this FCDI system to remove salt continuously for 1 day, this system only costs about 1.27 USD, about 1.33 USD less than RO filtration.

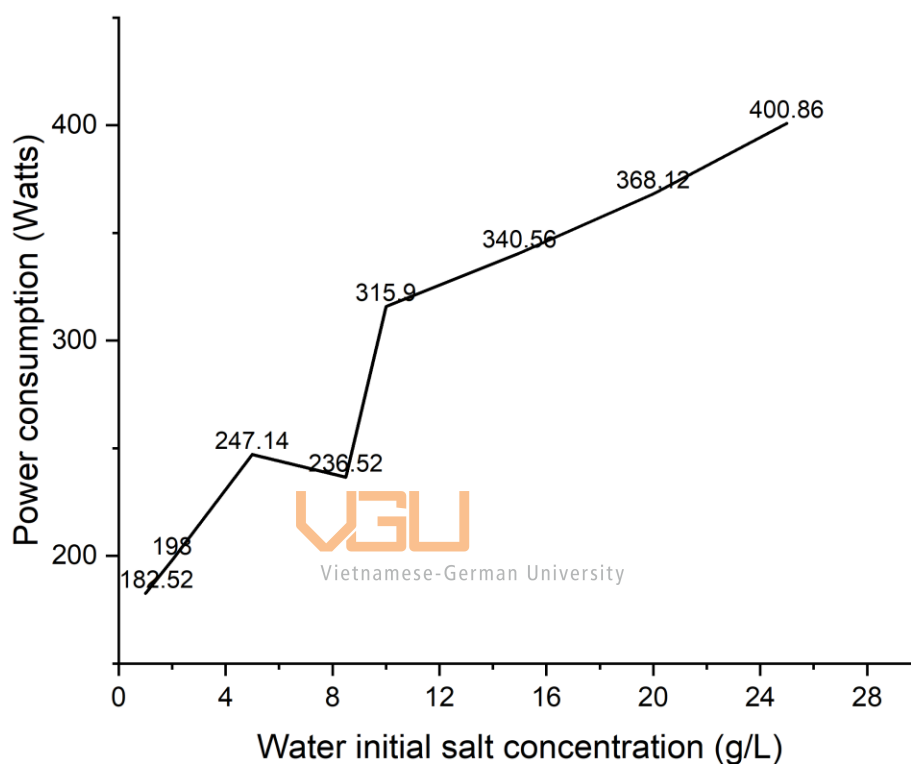


Figure 35 Energy consumption based on water initial concentration in 15 minutes operation

4.2 Effect on FCDI performance

4.2.1 Design and Materials

In this work, the design was initially implied for the commercial purpose, which means easy manufacturing, maintaining and low price cost.

a) Design of FCDI cell

The average treatment water chamber volume in earlier FCDI operations is 0.006 liters, regarding a mean flow rate of 30 ml/min. These designs may result in decreased effectiveness, higher running costs, and challenges when attempting to apply significant saltwater treatment. First, the water chamber capacity needs to be raised in order to enhance the quantity of water treatment and decrease operating time.

In this experiment, the spacer is not included in the middle of the saltwater chamber for treatment, which is distinct from other designs, as this component divides the water chamber into two sections and is only beneficial if utilized with CDI. In order to prevent increasing the quantity of salt in the water chamber, the water in this chamber will be filled and pumped out without being contaminated with activated carbon on either side of the electrode chamber. Additionally, in older versions, the spacer was used to guide the water flow within the chamber, which included two electrodes with one side at the top and the other at the bottom. The two electrodes in this FCDI version, however, are positioned parallel to one another and vertically, eliminating the need for a spacer and allowing the entire water chamber to come into contact with the two exchange membranes, where ions increase electrical conductivity and aid in better salt ion removal.

The surface of the flow electrode chamber has been contoured into a spine-line form with curves to facilitate the simple transit of the carbon particles while being affected by gravity. This is essential because, in order to maximize salt removal while additionally enhancing conductivity, the activated carbon flow must be in close proximity with the ion exchange membrane. Additionally, the electrode employed here is part of the flow process, unlike other CDI kinds with fixed electrodes. Regular equipment maintenance is therefore required while using the device to prevent damage from activated carbon and salt accumulation in the pipes. This involves cleaning the pipes and equipment after each usage.

b) Material selection

The materials that's used for FCDI cell possess the essential effect on the machine's desalination performance. In the context of design criteria for the current collector, specific

requirements for material characteristics consisting of as electrical conductivity and wear resistance are mentioned in the cell design section above.



1. Current collectors

The initially observed desalination performance with stainless steel material was quite excellent, featuring an exceptionally high removal rate of approximately two milligrams NaCl within 10 seconds of operation. However, the cell's effectiveness is drastically declined when the current passing through the device drops rapidly and then totally vanishes. The reason for this is considering the surface on that stainless steel component has been totally adsorbed by salt ions, minimizing the amount of contact with the electrode current significantly. This can greatly affect desalination performance in a process that needs to run continuously for a long time as well as the amount of energy that becomes wasted.

To solve this problem, there are two elements need to fulfill: a material with a large pore surface area as well as good electrical conductivity. In this case, a couple of the commercial's electrode pieces was added to solve this problem. This electrode pad consists of two upper and lower surfaces rolled through 2 layers of activated carbon and a middle layer of graphite. For mounting on the electrode assembly, the activated carbon layer of a surface is scraped away to reveal the graphite in direct contact with the surface of the stainless steel pad to ensure good electrical conductivity. On the other side, the activated carbon is scraped off half of the surface and the other half is graphite to conduct electric current through the electrode. With this material, by making the moisture for the electrode pad, it can be adhered to the surface of the steel plate without the need to use any adhesive. The results represent above showed a significant improvement by time as well as desalination efficiency when the time usage is increased more about 30 minutes compared to the original design if running continuously. In addition, the results presented in this report were performed with the electrode pad inserted in order to optimize the stability of the operating time as well as the performance of the FCDI cell.

2. Electrodes

Regarding the electrode, one of the most important parts that directly affects the desalination performance of an FCDI system, the selection and mixing of their components during operation is something that when designing the whole system that designing the FCDI

system needs to be taken into account. Various materials have been tested when adding electrodes such as MnO_2 , MXene, TiO_2 , etc to improve the desalination efficiency as well as the electrical conductivity (Enas Taha Sayed et al, 2021). However, in this design, the target is commercial and the selection of materials has characteristics such as cheap, easily obtainable, easy to replace and manufacture as well as non-toxic to the user. In this case, the electrode is made from activated carbon, NaCl salt and water (not necessarily pure water, clean water can be used). These three ingredients can all meet the above criteria with coal and salt that can be purchased in bulk at an affordable price, and tap water that can be used. In addition, MnO_2 can be added with higher efficiency salt deionization needs.

The materials for the design used in the FCDI cell must also exhibit significant corrosion resistance. This is critical because rusty machine parts have the potential to damage the equipment and contaminate the water after it has been cleaned.

c) System operation

If compared with conventional CDI system, the operation of FCDI system is more complicated as it requires more flow control and more number of pumps depending on the configuration of the pump system being applied.

- *Flow control*

Controlling the flow of activated carbon when injected into the system and the morphology of the flow in the reservoir affects the desalination capacity of the system and the energy required. For electrodes, since the solution contains activated carbon with different mass percent depending on the process conditions, the viscosity of the electrode solution needs to be controlled to reduce negative effects its to the desalination of the system. Experimental results show that, the higher the percentage of activated carbon in the electrode solution, the higher its viscosity, making the circulation more difficult and using more energy to increase thrust from the pump over. However, the more activated carbon is injected, the results show that the desalination capacity increases significantly because the number of ions is absorbed on the surface of the activated carbon is more. It can be seen that, with 40 grams of activated carbon in 600ml solution in the case of 20 grams of salt per liter of water, the desalination efficiency of the system increases significantly compared to 15 grams of

activated carbon in the case of 2 grams of salt per liter water. This, if applied to desalination in large quantities and in a short period of time, will be extremely effective and save operating time. The downside of this is that it can have serious effects on other components such as the pump and, importantly, its ability to handle salt in the long run.

Regarding the pump problem, unlike pumping other ordinary liquids with low viscosity, the energy that needs to be supplied to the pump must increase gradually according to the type of viscous solution that is injected into the system and causing the pump to reduce the work load. performance and cause damage to the pump. In addition, in this model, the number of pumps required is close to 4 or more, as the viscosity of the electrode solution is increasing due to the need for faster and more desalination.

- *Operation issues and solutions*

During the experimental run, there is one problem that has the potential to reduce desalination efficiency, which is that a small amount of activated carbon does not move and gets stuck in the grooves of the coal chamber. Accumulation of this activated carbon over several runs can form large clumps and impede the flow of the electrode from circulating in the cavity. Another negative point of this problem is that the amount of coal accumulated in the cavity will exhibit the same defects as conventional CDI, that when the ion is fully adsorbed on the surface, it will completely lose its ability to attract ions and then only other activated carbon particles in the electrode flow can adsorb ions. Gradually, the amount of accumulation will make FCDI become a normal CDI and reduce the advantages that this system offers in desalination.

In addition to the affected electrode compartment, pump blockage is also a rather painful problem in helping the FCDI system to work long and durable. For a small system like the one in this report, when the desalination and discharged process is completed, there will be some remaining electrode solution in the pump tubes. Because in the composition of the flow electrode includes activated carbon and salt. Therefore, after letting the device resting for a period of 1 to a few days, the water in the solution will evaporate and the coal and salt will be deposited in the pipe and pump. The type of pump used in this report is a peristaltic pump with the ability to pump liquids with high viscosity. However, the pump

will still be clogged when the deposits of the electrode flow solution harden and it will take a long time to clean them and install the equipment to continue running. So the common solution for both the electrode flow chamber and the pump is that after use, it is necessary to pump water to wash it and push all the residue out of the system. As for large systems, the recommended pumps are centrifugal pumps, gear pumps, diaphragm pumps, vane pumps, and hose pumps because they provide more power and a more even pump flow when the liquid is concentrated. high viscosity. As for the flow of brine, the experimental in the small scale device results show that increasing or decreasing the flow injected into the system does not have much effect on the desalination efficiency of the system. One possible explanation for this phenomenon is that the pumped water circulates continuously throughout the running time at a constant speed. When the water tank is full, increasing or decreasing the amount of water added does not change the salt concentration in the water tank of the FCDI cell.

Depending on the model for which FCDI is designed, the number of pumps put into use in the system will be carefully calculated to achieve criteria such as high efficiency, energy saving and operating costs. It can be seen that, with this operating model, the number of pumps that need to be used is up to 5, and the capacity of each pump type only requires about 10W to maximize its use (including pumping electrode and treated water), in total, 50W is needed for maximum desalination capability and ion discharged from electrode surface poles. However, utilizing four small pumps to push the activated carbon solution with high pressure under high-viscosity electrode circumstances would result in greater efficiency (reducing clogging in the storage compartment) and cost less money and energy than using only one large pump. Generally speaking, based on the desalination requirements and system design, the number of pumps should be carefully chosen and installed.

4.2.2 Voltage effect on FCDI performance

In order to test the impact of voltage on desalination performance, the pumping system will be maintained at a consistent flow rate of 500 ml/min for the water pump and 80 ml/min for the four electrode pumps. In addition, the FCDI system will be tested with voltage levels ranging from 1.1 volts to 1.5 volts. As can be observed from the experimental findings, with a voltage level of 1.5 V applied at both ends of the electrode, the average salt removal

result is roughly 26.7% greater than the remaining voltage levels. In addition, the component that impacts the capacity to desalinate is TDS. With the increased quantity of TDS in the water chamber that has to be treated, plus the larger voltages set at both ends of the device, according to Ohm's law for electric current, the current density tends to progressively grow, which will aid the ions flow to the electrodes. This helps boost adsorption capacity as well as remove ions from the electrode more readily.

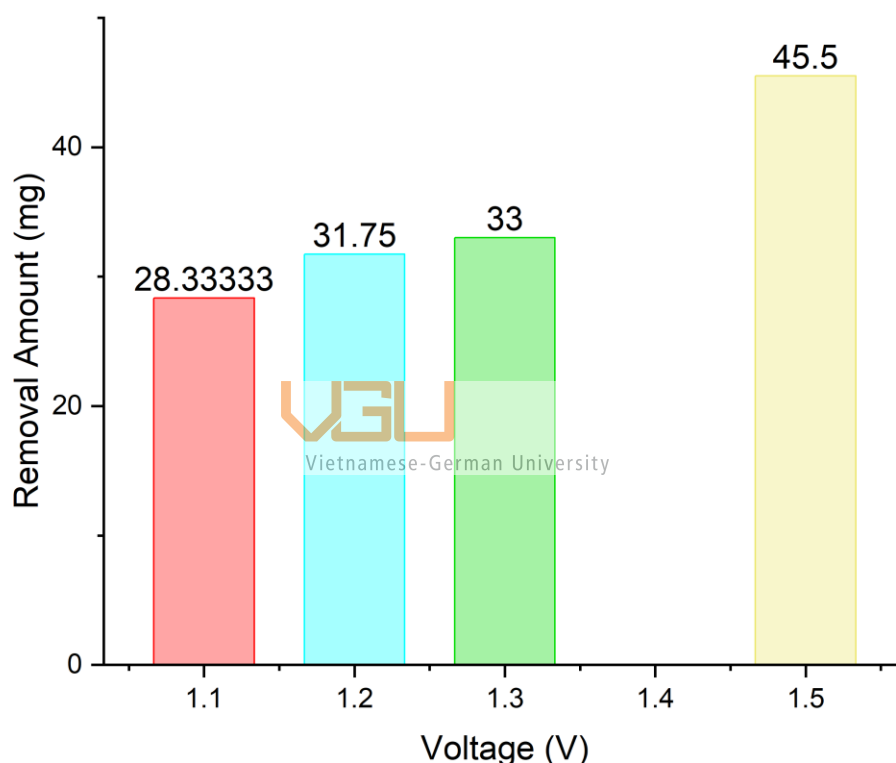


Figure 36 Average removal amount of salt based on the applied voltage on two polarizes in FCDI cell

4.2.3 Flow rate effect on FCDI performance

In addition to the influence of applied voltage on FCDI, the pump flow into the system (containing water and electrodes) also impacts salt removal. In this section of the experiment, the operating parameters include: 1.5V voltage, and the percentage of electrode solution composition is kept the same throughout the process as well as applied to analogous

tests to analyze the influence of flow rate on the FCDI system. It can be shown that at water flow rates of 300 ml/min, 500 ml/min, and 750 ml/min, there is a small variance in the quantity of salt ions removed from the original solution. This can be explained by the design of the FCDI cell.

In terms of design, the water tank of this FCDI system increases the quantity of water kept in the tank to enhance the duration and volume of water treated. This results in the fact that no matter how much water is pumped into the system, the number of absorbed ions stays the same (Figure 39) with the same operating conditions.

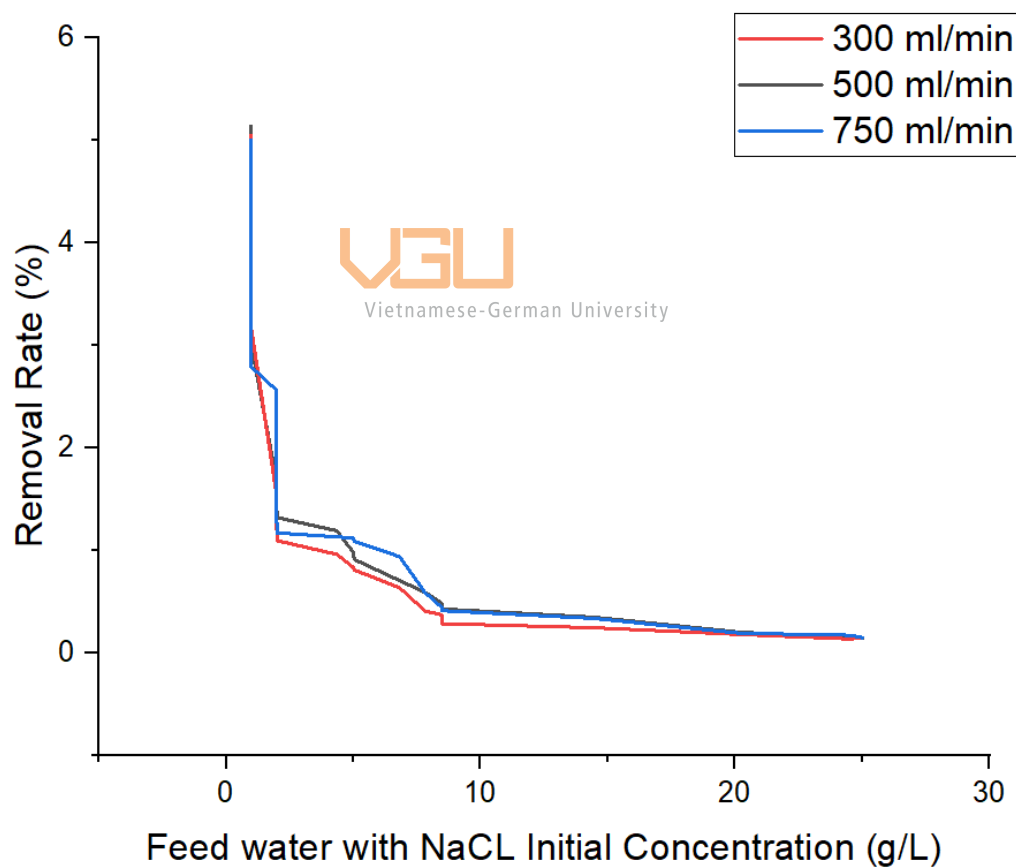


Figure 37 Impact of different mode of flow rate on FCDI desalination performance

4.2.4 Initial Concentration Effect on FCDI desalination performance

As demonstrated by the following experimental findings, with a decreased starting salt concentration (from 5g/L to 1g/L), the FCDI system exhibits strong salt removal capabilities, removing approximately 6% of the salt. Within 15 minutes of the surgery, it was gone. However, at high salt concentrations, the proportion of salt removed from the solution is relatively low in comparison to the prior condition; for example, at 25g/L NaCl, only around 0.14% of the salt is removed in similar working time. This is explained by the FCDI system's stability, since the number of salt ions that the ion exchange membrane utilized in this situation has reached its maximum level and cannot pass any more. Changing the kind of ion exchange membrane is a viable strategy in this circumstance to boost the desalination capacity since each type of IEM has independent parameters for conductivity and water permeability, as well as ion exchange constraints. Furthermore, in a capacitive environment, the conductivity factor of the ion exchange membrane adds to increased electrical conductivity in FCDI cells. However, replacing the ion exchange membrane is a pretty pricey procedure due to the high cost of the material and must be thoroughly evaluated before being applied to the system.



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4.3 Comparison with other FCDI desalination work with other study

Comparison with other forms of FCDI in other research publications will produce additional objective results in addition to the evaluation of the aforementioned FCDI markers in this article. In this investigation, a 15-minute test run of the FCDI system will be compared with other performed tests.

4.3.1 Electrode components comparison

One of the most critical aspects impacting FCDI operation is the electrode composition. In the past 5 years, there have been numerous research on enhancing the composition of electrodes by combining activated carbon with substances with superior electrical conductivity or increasing adsorption capacity.

First, a group of researchers from Beijing University released a study that improved the FCDI electrode by adding a nickel hexacyanoferrate (NiHCF) molecule which have great electrochemical properties to activated carbon to boost its capacity to conduct electricity and absorb ions through the IEMs. When this compound was used to replace traditional activated carbon electrodes, as described in this report, the electrical conductivity of salt was reduced from 16.08 mS/cm⁻¹ to 0.125 mS/cm⁻¹, with salt removal efficiency reaching 88% in 180 minutes. It is clear that this is a very high-quality improvement, since a huge volume of salt ions may be eliminated from the solution in a short period of time. The addition of NiHCF compound to the electrode flow has the benefit of increasing the current density in the compound, making salt ions migrate to the electrode surface easier. (Yang Xu, Feng Duan, Yuping Li, Hongbin Cao, Junjun Chang, Haoliang Pang, 2021)

Secondly, a team of researchers from the Institute of Process Engineering in China has introduced the other improvement for the flow electrode component. The material of Copper hexacyanoferrate (CuHCF), which has the good conductivity properties that help the ions moving better to the electrodes side is mixed with the activated carbon for the flow-electrode compound. The test result for this experiment is including: 17.45mS/cm-1 to 15.4mS/cm-1 with 1.2V constant operation in 3 hours working. (Junjun Chang, Feng Duan, Hongbin Cao, Kexin Tang, Chunlei Su, Yuping Li, 2019)

In general, all the information are include in the table below:

Type of electrode	AC-NaCl	NiHCF	CuHCF
Operation time (min)	180	180	180
Voltage (V)	1.5	2.8	1.2
Conductivity decrease	2.73 mS/cm ⁻¹	16 mS/cm ⁻¹	2.5 mS/cm ⁻¹

Figure 38 Comparison data between AC-NaCl, NiHCF and CuHCF desalination performance

The statistics show that using NiHCF materials in the flow-electrode system improves desalination substantially more than using two other materials. In comparison to the AC-NaCl electrode used in this study, NiHCF is strongly suggested as the optimum flow-electrode compound for the FCDI system. The main reason for this choice is that AC-NaCl

has only two properties: a large porous surface area and good conductivity, whereas NiHCF flow electrodes have better electrochemical performance than the electrodes used in this work and also produce better desalination results. Finally, if the objective is a laboratory experiment, NiHCF is a better choice than AC-NaCl electrodes. AC-NaCl would be chosen for large-scale desalination as an industrial or water treatment center because to the low cost of fabrication and replacement and a high probability of greater desalination efficiency when done under stronger potential applications.

4.3.2 FCDI cell configuration comparison

Cell design in FCDI systems also plays a crucial role in salt processing capabilities, such as how water and electrodes are carried through the system, conductivity, and device longevity.

The FCDI cell of the University of New South Wales research team in Australia has been modified by adding extra pairs of ion exchange membranes to the original design. Instead of employing a pair of AEM and CEM as proposed in this study report, this group's cell can contain as many pairs of IEMs as required. Furthermore, the current collector is machined using graphite material to improve the flow-electrode solution's electrical conductivity. Their investigation yielded the following experimental results: 43mg, 130 mg, and 261 mg using 1 pair, 2 pair, and 3 pair IEMs systems, respectively. (Jinxing Ma et al, 2019)

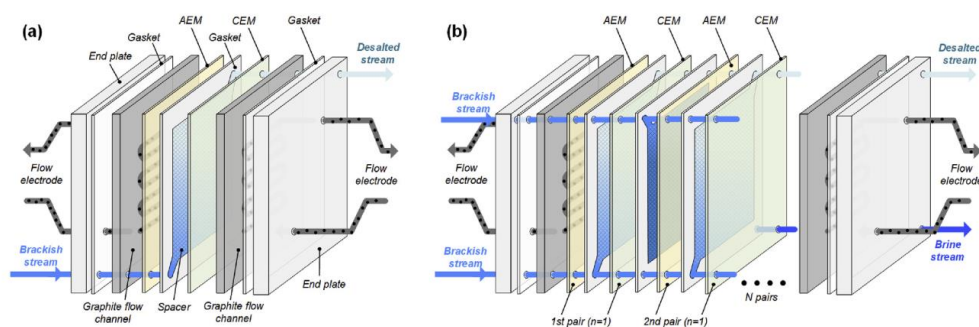


Figure 39 FCDI with ion exchange membrane stacking

When compared to the FCDI cells of the Australian research team, the technology described in this article performs significantly better at removing salt when it has been

installed several times. additional ion exchange membranes (with only three pairs of ion exchange membranes, performance is boosted fivefold). This is a noteworthy improvement since it boosts salt removal effectiveness several times without changing much about the electrode or the voltage at both ends of the electrode. In terms of economic benefits, however, their FCDI technology costs a lot of money to process cell components, as well as a considerable extra price for costly components. as an ion exchange membrane. As a result, it is feasible to mix these two designs and choose the advantages from each other to maximize and balance the strengths of desalination ability while also bringing economic benefits when adopting this model. Every design and finished product is optimized.



Conclusion


This study article examines the elements that influence desalination performance as well as the overall performance of the FCEDI system. However, FCEDI systems work best for salt removal from solutions with low initially concentrations, which will lead to a quick and highly effective salt removal process that will also save energy. 51mg of salt are swiftly eliminated within 15 minutes of performing the experiment, same as in the case of 1 g/L with a flow rate of 500 ml/min and 1.5V at both electrodes.

The FCEDI method also provides a number of other benefits, including the use of inexpensive and easily accessible materials, the ability to make electrodes with less resources, and a shorter processing time for electrode regeneration. This method provides superior economic benefits as well as convenience when the electrode can be readily replaced due to its basic ingredients but effective outcomes equivalent to complicated materials utilized in other studies. Furthermore, design adjustments such as enlarging the treated water tank, minimizing friction and boosting the thrust for the activated carbon flow, and notably the circulation system, aid the desalination system. The FCEDI salt in this study meets the objectives and is competitive with other FCEDI models throughout the world. Furthermore, this study offers some suggestions for reducing costs in the production of FCEDI cells and electrodes, as well as saving operational expenses for the existing system and being relevant to other future investigations.

When the FCEDI system outperforms CDI and MCDI in terms of desalination and operating capabilities, it demonstrates its promise. When time and high-performance standards can be reached, this FCEDI system may also be modified to expand the capacity for salt removal in industry.

References

- Brackish water*. (n.d.). Retrieved from European Environment Agency:
<https://www.eea.europa.eu/archived/archived-content-water-topic/wise-help-centre/glossary-definitions/brackish-water>
- Changyong Zhang, Jinxing Ma, Lei Wu, Jingyi Sun, Li Wang, Tianyu Li, and T. David Waite. (2021). Flow Electrode Capacitive Deionization (FCDI): Recent Developments, Environmental Applications, and Future Perspectives. *Environment Science & Technology*.
- Changyong Zhang, Min Wang, Wei Xiao, Jinxing Ma, Jingyi Sun, Hengliang Mo, T. David Waite. (2021). Phosphate selective recovery by magnetic iron oxide impregnated carbon flow-electrode capacitive deionization (FCDI). *Water Research*.
- Enas Taha Sayed, Muaz Al Radi, Aasim Ahmad, Mohammad Ali Abdelkareem, Hussain Alawadhi, Muataz Ali Atieh, A.G. Olabi. (2021). Faradic capacitive deionization (FCDI) for desalination and ion removal from wastewater. *Chemosphere*, 3.
- Haoyu Yin, Guohong Qiu, Wenfeng Tan, Jinxing Ma, Lihu Liu. (2022). Highly efficient removal of Cu-organic chelate complexes by flow-electrode capacitive deionization-self enhanced oxidation (FCDI-SEO): Dissociation, migration and degradation. *Chemical Engineering Journal*.
- Jaloliddin Eshbobaev, Adham Norkobilov, Zafar Turakulov, Bakhodir Khamidov, Orifjon Kodirov. (2003). Field Trial of Solar-Powered Ion-Exchange Resin for the Industrial Wastewater Treatment Process . *MDPI*.
- Jinxing Ma , Junjun Ma a, Changyong Zhang, Jingke Song, Wenjia Dong. (2019). Flow-electrode capacitive deionization (FCDI) scale-up using a membrane stack configuration. *ScienceDirect*.

- Junjun Chang, Feng Duan, Hongbin Cao, Kexin Tang, Chunlei Su, Yuping Li. (2019). Superiority of a novel flow-electrode capacitive deionization (FCDI) based on a battery material at high applied voltage. *ScienceDirect*.
- Junjun Chang, Feng Duan, Hongbin Cao, Kexin Tang, Chunlei Su, Yuping Li. (2019). Superiority of a novel flow-electrode capacitive deionization (FCDI) based on a battery material at high applied voltage. *Desalination*.
- Junjun Ma, Ruicheng Chen, Jiarong Gu, Jianrui Niu, Shujie Hou, Yunke Li, Jing Zhang, Chun Liu. (2023). Improving the energy utilization efficiency of flow electrode capacitive deionization (FCDI) with multiple series flow electrodes. *Separation and Purification Technology*.
- Kong, S. (2022, March 12). *VIETNAM'S WATER CRISIS THREATENS FOOD SECURITY*. Retrieved from Fair Planet: <https://www.fairplanet.org/story/vietnams-water-crisis-threatens-food-security/>
- Multi Stage Flash Distillation*. (n.d.). Retrieved from KetavConsultant: <https://ketavconsultant.com/multi-stage-flash-distillation/>

- Qasim Khan, Munjed A. Maraqa, Abdel-Mohsen O. Mohamed. (2021). Inland desalination: techniques, brine management, and environmental concerns. In Butterworth-Heinemann, *Pollution Assessment for Sustainable Practices in Applied Sciences and Engineering* (pp. 871-918).
- Reverse Osmosis Filtration System's Energy Consumption*. (2023, 1 30). Retrieved from Cruise rowater and power: <https://www.cruiserowaterandpower.com/reverse-osmosis-filtration-system/#:~:text=Since%20its%20inception%2C%20reverse%20osmosis,meter%20of%20freshwater%20from%20seawater.>
- S. Porada, R. Zhao, A. van der Wal, V. Presser, P.M. Biesheuvel. (n.d.). Review on the science and technology of water desalination by capacitive deionization. *Progress in Materials Science*, 2013.

- Scavetta, A. (n.d.). *The Pros and Cons of Reverse Osmosis Filtration*. Retrieved from Aquasana: <https://www.aquasana.com/info/the-pros-and-cons-of-reverse-osmosis-filtration-pd.html>
- SeungCheol Yang, Jiyeon Choi, Jeong-gu Yeo, Sung-il Jeon, Hong-ran Park. (2016). Flow-Electrode Capacitive Deionization Using an Aqueous Electrolyte with a High Salt Concentration. *Environment Sciences & Technology*, D.
- Toth, A. J. (2020). Modelling and Optimisation of Multi-Stage Flash Distillation and Reverse Osmosis for Desalination of Saline Process Wastewater Sources. *ResearchGate*, 2.
- VNA. (2022, February 28). *Mekong Delta faces increasing saline intrusion*. Retrieved from Vietnamplus: <https://en.vietnamplus.vn/mekong-delta-faces-increasing-saline-intrusion/222743.vnp>
- Xâm nhập mặn tại Đồng bằng sông Cửu Long - những giải pháp ứng phó hiệu quả trong điều kiện biến đổi khí hậu*. (2016, 4/22). Retrieved from Học viện Nông Nghiệp Việt Nam: <https://qlkh.vnua.edu.vn/d6/news/Xam-nhap-man-tai-Dong-bang-song-Cuu-Long-nhung-giai-phap-ung-pho-hieu-qua-trong-dieu-kien-bien-doi-khi-hau-3-3-51.aspx>
- Yang Xu, Feng Duan, Yuping Li, Hongbin Cao, Junjun Chang, Haoliang Pang. (2021). Enhanced desalination performance in asymmetric flow electrode capacitive deionization with nickel hexacyanoferrate and activated carbon electrodes. *ScienceDirect*.