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Design and construction of an integrated electrodeionization system with automated control for brackish water treatment

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INTRODUCTION & AIM

[The increasing pressure on water resources is one of the most critical challenges of the 21st century. Demographic, industrial and climatic factors are drastically reducing the availability of fresh water, with particular evidence in arid regions and the Mediterranean basin. Agriculture, which absorbs about 70% of global water withdrawals, is at the center of this crisis, making it essential to explore unconventional sources such as brackish water. Desalination emerges as a key technology to address this challenge. Traditional methods such as reverse osmosis, while effective, have significant limitations in terms of energy consumption and plant complexity. Electrodialysis offers an attractive alternative, particularly suitable for moderately salty water (1000-5000 mg/L of total dissolved solids), thanks to its energy efficiency within specific salinity ranges and the ability to precisely control the quality of the produced water. At the same time, agrivoltaic systems that integrate energy production and agriculture are spreading, requiring compact, modular treatment devices that can be integrated with renewable sources.

Research objectives:

1. Design and build an affordable and reproducible electrodeionizer (ED) prototype
2. Equip the system with automated sensor-based control
3. Validate device performance on brackish water
4. Analyze the feasibility of integration in agrivoltaic contexts.

The prototype has been sized with the following specifications:

Design Flow Rate: 10-50 L/h (Lab Scale)

Salt removal efficiency: to be evaluated experimentally, without a predetermined value

Target energy consumption: < 2 kWh/m³

Inlet water: 1000-5000 mg/L (moderately brackish water)

Configuration: Recirculating Batch

Current Density: 70-80% of Limit Current Density (LCD)

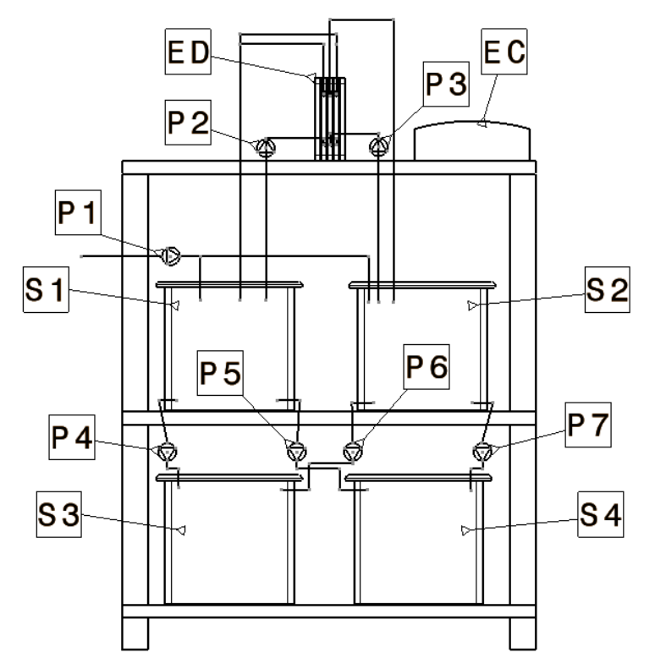
Stack configuration: 5-10 pairs of cells with commercial membranes.

METHOD

Desalination unit design and construction

General system architecture

The physical system was conceived as a compact, self-contained unit operating in a recirculating batch configuration. The architecture includes four identical tanks arranged in two overlapping pairs, a centrally positioned electrodeionizer (ED), and seven pumps for handling fluids according to a specific layout scheme.

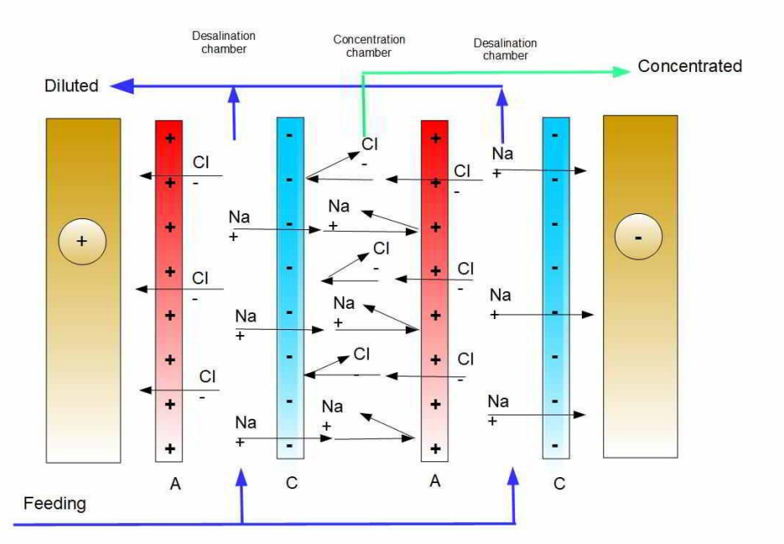


The operating cycle includes:

- Filling of the upper tanks (S1-S2) with brackish water
- Power supply of the ED channels via dedicated pumps (P2-P3)
- Ion separation by electric field
- Diluted and concentrated flow recirculation until desired thresholds are reached
- Transfer of desalinated water and brine to lower.

A key feature is periodic polarity reversal, which helps to regenerate membranes and maintain system efficiency.

ED cell: general operating principle



Operating principle

- Ion separation using selective membranes and an electric field

Generation of:

- Desalinated flow (desalinated water)
- Concentrated flow (brine)
- Normal and reverse polarity operating cycles

RESULTS & DISCUSSION

The diluted and concentrated compartments have been sized with a thickness of 6 mm, an optimal compromise between reduced electrical resistance and ease of construction.

Materials and construction technologies:

- Structural components: 3D printed with FDM technology with PLA (polylactic acid) filament, chosen for the balance between mechanical properties, ease of printing and sustainability
- Fill pattern: 20% cubic with three perimeter loops for robustness
- Sealing system: Manually cut silicone rubber sheet gaskets and silicone sealant for waterproofing the molded parts
- Pressing: Self-built metal frame for uniform force distribution
- Plumbing connections: Clear PVC pipes and barbette fittings

Electrochemical components

Ion exchange membranes:

- Cationic membranes (EMFs): allow the selective passage of positive ions
- Anionic membranes (AEM): allow the selective passage of negative ions

The alternation of these membranes creates the dilution and concentration chambers.

Electrodes:

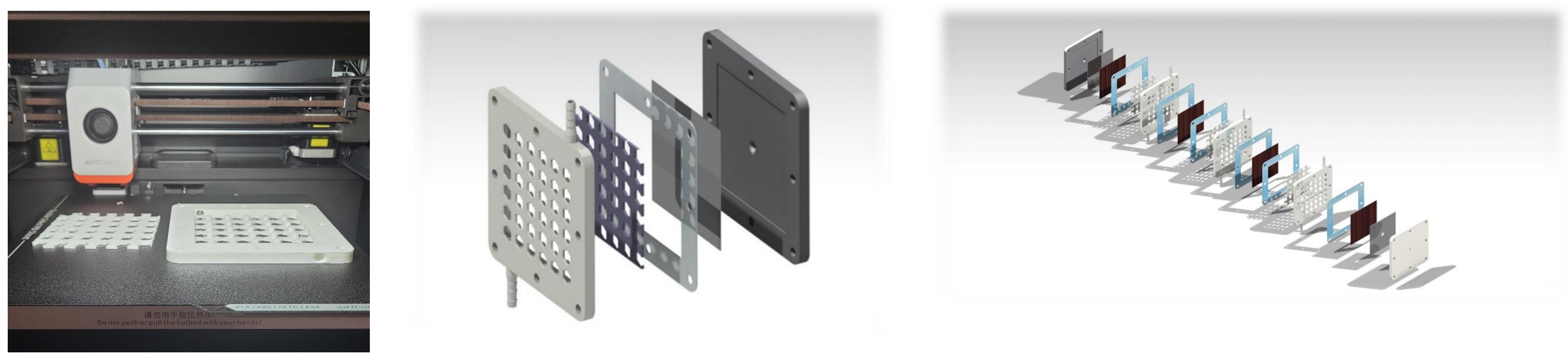
Made of galvanized steel foil, cut into a square shape (dimensions defined by the stack geometry). The zinc coating was removed locally to allow the welding of a copper wire, which was subsequently protected with resin. The electrodes are housed in separate compartments to prevent direct contact with the brackish solution and the consequent formation of unwanted gases.

Prototype Assembly

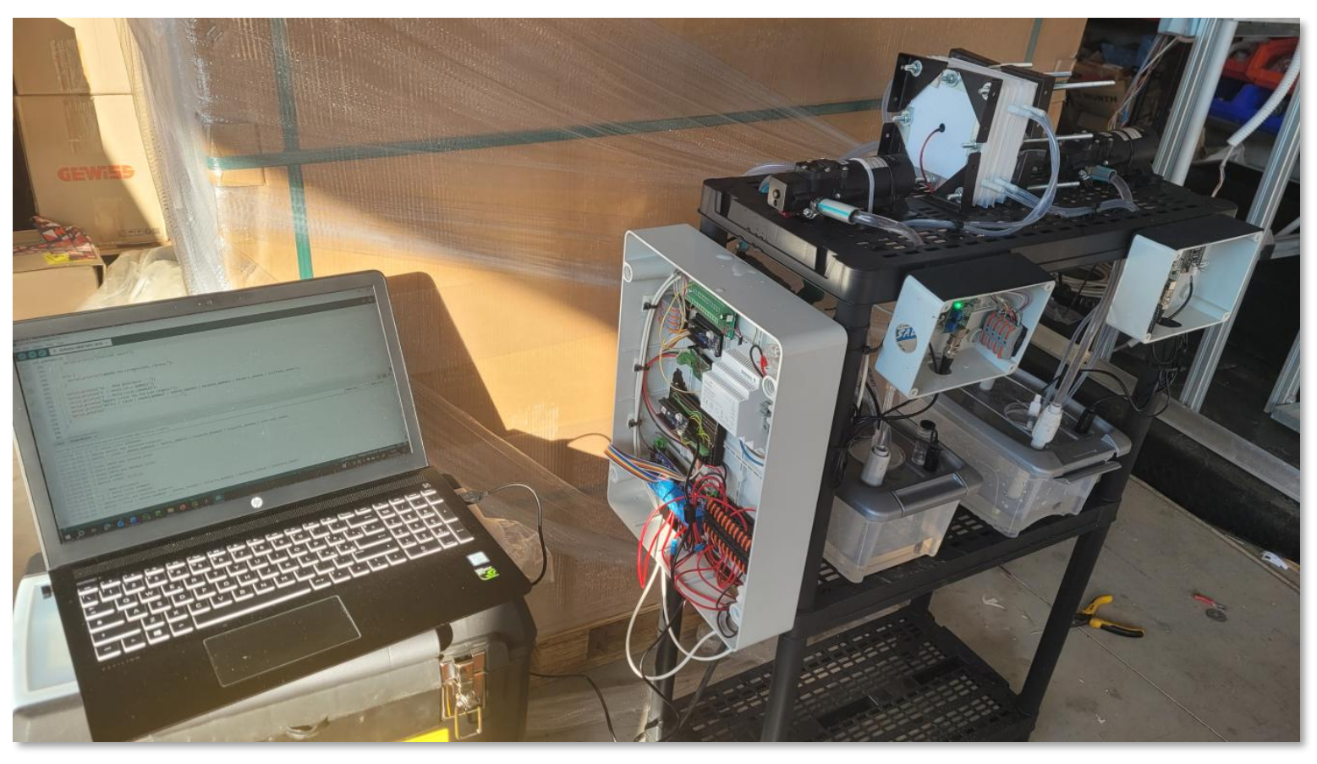
The assembly followed a precise sequence:

1. Installation of the terminal body and first electrode
2. First membrane placement (anionic or cationic based on the polarity of the adjacent electrode)
3. Alternation of membranes, gaskets and spacers according to the sequence: electrode → diaphragm → gasket → spacer
4. Completion of the battery with the opposite electrode and the end body
5. Compression by means of eight threaded rods with nuts and washers
6. Installing the outer metal frame to stabilize the assembly

The final stack includes 4 stages in total: two for the passage of desalinated water and two for brackish water.


a) b) c)

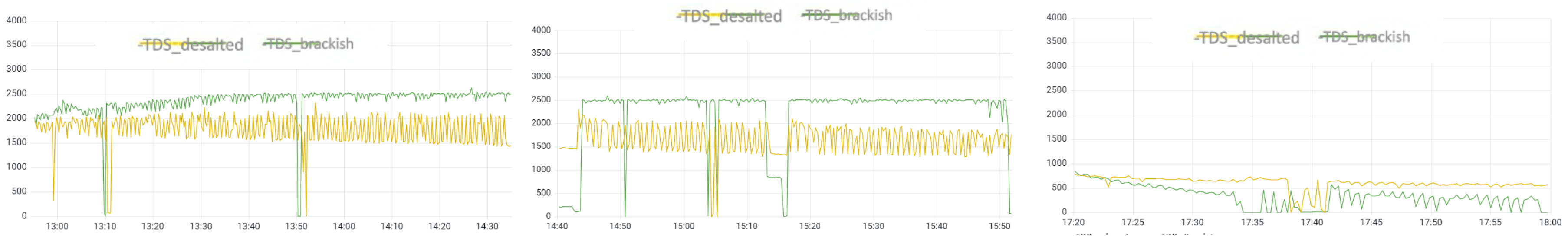
a) 3D printed components. b) channel layer detail. c) rendering of the stratigraphy of the final ED prototype.



The experimental setup adopted for the laboratory tests was configured using an electrodeionization cell, two storage tanks, and two recirculation pumps. At the beginning of each test, the two tanks are filled with equal volumes of the model saline solution, prepared at a known concentration, thus establishing controlled initial conditions that are perfectly comparable between the two branches of the system.

Once the experiment is started, the pumps are activated, and the fluid contained in the two tanks is sent to the respective channels of the electrodialysis cell, creating a recirculation batch configuration. Inside the cell, the electric field applied to the electrodes induces the selective migration of ions through the ion-exchange membranes, determining the progressive differentiation of the two flows: in one of the two channels, the solution tends to reduce its salt content, while in the other, a corresponding salt enrichment occurs. The two flows exiting the cell are then returned to their respective tanks, thus establishing a closed circuit in which ion separation evolves. In this way, starting from two identical initial conditions, it is possible to experimentally observe the effect of the electrodeionization process and monitor the progressive decrease in salinity in the dilute compartment and the simultaneous increase in the concentrated compartment. This configuration was chosen because it allows for a clear analysis of the system's behavior, isolating the main operating variables and facilitating the experimental evaluation of the prototype's performance.

To monitor the electrodeionization process, the two tanks of the prototype were equipped with essential sensors, consisting of a pH sensor, a Total Dissolved Solids (TDS) sensor, and a voltage divider to measure the voltage applied to the electrodes. The pH sensor was used to monitor the acidity or basicity of the solutions; specifically, an analogue pH sensor compatible with Arduino’s analogue readout was used. A CQRobot TDS sensor was used to measure salinity, based on the indirect measurement of the electrical conductivity of the solution. The experimental setup was completed with the remote visualization of the operating parameters and the recording of the process data and sending them to the IoT cloud platform (AWS) using graphs for remote consultation (Grafana). The TDS summary graphs of 2 experimental tests (Test1 and Test2) are shown in the figures below. About Test1, the first part, lasting approximately two hours, shows the effect of the desalination plant, which differentiates the TDS between the two mixtures. In the second part, after two hours, the TDS values stabilize, likely due to fouling of the membranes or electrodes, resulting in the accumulation of ions or substances during prolonged operation. Test2 was conducted to evaluate desalination performance, using a lower starting concentration.



a) Test1: First part b) Test1: Second part c) Test2: TDS values

CONCLUSIONS

The work demonstrated the feasibility of a self-built electrodeionization system with automated control for the treatment of brackish water, validating the operating principle through an experimental campaign.

Results achieved:

1. Prototype realization: A laboratory-scale electrodeionizer with a modular structure was designed and assembled, using accessible materials (PLA 3D printing, commercial membranes, galvanized steel electrodes) and reproducible technologies.
2. Control system: A two-level automated system based on Arduino MKR WiFi 1010 has been developed, with a user interface for manual management and automatic cycles (normal/wash). Integration with AWS IoT Core and the MQTT protocol enabled real-time remote monitoring of pH, TDS, and voltage via Grafana dashboards.
3. Experimental validation: The device demonstrated salinity reduction capabilities on 2400 ppm and 1400 ppm NaCl solutions, with desalination rates of 10 ppm/min and 5 ppm/min respectively. The measured specific energy consumption (3.2 kWh/m³) exceeds the target of 2 kWh/m³, highlighting the need for scale-up.
4. Critical analysis: Post-experimental inspection revealed electrode oxidation, membrane deposits and structural failures in PLA spacers, providing valuable insights for future developments.

FUTURE WORK/ REFERENCES/ACKNOWLEDGMENT

- Material replacement (MMO titanium electrodes, engineering polymers)
- Redesign of the sealing and compression system
- Implementation of adaptive control based on sensor feedback
- Scale-up to reduce specific consumption
- Integration with renewable sources in an agrivoltaic context..

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