ENERGY EFFICIENT DESALINATION WITH MEMBRANE CAPACITIVE DEIONIZATION (MCDI): BEST-PRACTICE RECOMMENDATIONS

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ABSTRACT

To find an energy-efficient way for desalinating water is highly necessary if the process needs to be run by renewable energy. A promising approach is the technology of membrane capacitive deionization (MCDI). To make it deployable for sustainable drinking water production, modular pilot scaled concepts and modelling strategies have been developed. Lab scale experiments demonstrate that an energy efficient desalination of brackish water is visible with commercial MCDI modules. NaCl solutions can be desalinated from 1000 mg L^{-1} below 450 mg L^{-1} with a specific energy consumption of SEC = 0.3 kWh m^{-3}, which is below state of the art technologies like reverse osmosis. Hereby, the mobility of different ions as well as the composition of the model water largely affects the removal efficiency. Ions with smaller hydrated radius as well as higher bulk concentration have a higher electrosorption potential. This has to be considered if priorities in ion selection are important. These results will be compared with real values from pilot plants installed in Vietnam, which are operating with renewable energy like photovoltaic and a wind turbine.

The developed FEM simulation model can describe experimental data sufficiently when applied voltages at the MCDI module are low. It implements Nernst-Planck-Poisson equations and is solved with a coupled direct solver. The calculation time is still too high for a practical use as a designing tool. For improving, the modified Donnan model and a RC-model will be implemented.

Keywords: Capacitive Deionisation (CDI), Desalination, Energy Efficiency, Operational Experiences, Pilot Scale, Brackish Water

1 INTRODUCTION

A trend of water shortage can be seen worldwide (Ross-Larson et al., 2006). The salinisation of groundwater does a big part to it (Schmidt-Thome et al., 2015). Well settled conventional membrane technologies as reverse osmosis (RO) give solutions to make it drinkable. The relatively low energy consumption makes the RO to one of the most common methods for seawater desalination as well (Alkaisi et al., 2017). The scarcity of drinking water will hit developing countries the hardest. Especially in rural areas, the infrastructure or the financial power is often not good enough for an electrical grid connection and technical advanced treatment plants. Therefore, energy efficient desalination processes are highly wanted so water treatment plants can be operated decentralised together with renewable energy systems like photovoltaic and wind power generators.

Research work like in (Zhao, R. et al., 2013) show that electrochemical treatment processes like the capacitive deionization (CDI) have a lower energy consumption for desalinating water with a salt concentration of $c < 2.5$ g/L than the classical RO. Therefore, for brackish water this technology becomes very attractive.

A main goal in the development of CDI modules is to make them fit for use on pilot and industrial scale. The application of ion exchange membranes (IEM) adjacent to the porous carbon electrodes already improved the system (Zhao, Y. et al., 2013). Now for the discharge phase the voltage can be reversed without ions migrating in the opposite electrodes. Furthermore, the membranes help retaining the salt inside the pores during the desalination phase. Nevertheless, extensive testing and simulation for optimisation are still highly necessary (Suss et al., 2015).

On laboratory- and pilot scale, the MCDI will be used as part of a novel modular water treatment concept for treating saline and arsenic laden water in Vietnam. One objective of the work is to implement the not yet implemented experimental technology in common water treatment plants for drinking water use on realistic field sites. The advantages of the system, being energy efficient, suitable for low pressure and low voltages set-ups and thus good for coupling with renewable energies in rural areas. Furthermore, a CDI modelling strategy to predict diluate water quality as well as energy consumption shall be developed and lab scale trials with model water are conducted, which can be validated with these theoretical findings.

For desalinating brackish water with higher concentrations of salt, a combination process of RO / NF membranes and MCDI will be tested in a pilot scale in the following months. Hereby, the MCDI module plays the role of buffering fluctuations of salt concentration, which can occur in tropical coastal regions according to raining and dry season. The low-pressure concept allows a low cost, easy to implement setup with low capital costs for the periphery and an easy operation.

2 MATERIALS AND METHODS

2.1 Laboratory Experiments

In the laboratories, wide ranged tests were operated with different model water qualities, operating parameters and boundary conditions for the performance characterization of the MCDI module. The feed water mainly consisted of a mixture of deionised water with NaCl concentrations, between 0.5 and 4.5 g L^{-1}. For evaluating the rejection of typical contaminant ions occurring in South East Asian groundwater, the model water is spiked with arsenic, ammonium or manganese in further tests.

A lab scale MCDI unit consisting of a membrane pump, a pre-filter (1 µm) and a commercial electrode module with three stacks à 25 porous electrode pairs was used. In front of each electrode, IEMs are mounted. The goal of the desalination tests is to remove sufficient salt from the feed water to achieve drinking water quality. The test duration was 5 to 8 hours for short time and 1 to 5 days for long time tests.

By varying the different operation parameters: desalination / regeneration cycle time, constant electrical current in phases and water volume flow the performance of the desalination process is highly affected and can be regulated on the needs in the application.

2.2 Pilot scale tests

MCDI modules can be very easily implemented modularly in water treatment plants. To demonatrate this advantage, several pilot plants are set up with different technologies, respective to the quality of the feed water.

In a pilot scale, MCDI modules were set up in the Mekong Delta region in Vietnam to treat brackish water for drinking water purpose. In a first pilot plant the groundwater has a TDS concentration of $c = 2$ g L^{-1}. The same module like in the laboratory tests is used. Instead of a model water (DI + NaCl), the plant has to handle a natural salt matrix. In this pilot site, the MCDI module is combined with an in-situ subsurface arsenic removal system.

In a second pilot plant, a module with five times bigger active electrode area will be installed in coastal region next to Long Tau River in between Ho Chi Minh City and Vung Tau. The TDS concentration is $c > 20\ g\ L^{-1}$ and thus very high. To handle the salt level, a low-pressure RO system will be set up upfront the MCDI system, which replaces a second stage RO treatment. The low pressure system allows a set up with low-cost periphery. As a pre-treatment, an ultrafiltration (UF) membrane is considered, which is necessary for RO and MCDI treatment, due to the high TSS values above $50\ mg\ L^{-1}$ found in the river delta.

2.3 Modelling

To design future MCDI systems, mathematical models to predict the performance of a MCDI module are required, to describe the complexity of such an electrochemical system. Therefore, 1D and 2D FEM models for electrode pairs inside a MCDI module were developed with the simulation program COMSOL. For the mass transport and the electric potential distribution, Nernst-Planck-Poisson-equations were applied. The modified Donnan model (Dykstra et al., 2016) will be used for the electrical potential inside the electrodes, which does not show the exact distribution of ions in the electrical double layer like it is according to the Gouy-Chapman Model but only the absolute numbers of ions. Furthermore, energy models (RC-models) shall calculate the specific energy consumption (Andres et al., 2017). For the IEMs, the Nernst-Planck equations will be used like in Biesheuvel et al. (2011), but differing from the spacer model, since only the part for diffusion and migration and not for convection is being included. Boundary conditions for water have to be set as zero flow.

Finally, a holistic model, which can predict the performance of the module like salt rejection and energy consumption, can be developed.

3 RESULTS AND DISCUSSION

3.1 Laboratory Experiments

The focus in the lab scale MCDI experiments is on the salt removal, the volumetric recovery and the specific energy demand, which is needed by the module to produce the pure water in drinking water quality (kWh per produced m^3 of diluate).

The experimental findings of the laboratory tests demonstrated that removal of NaCl from $1000\ mg\ L^{-1}$ to $450\ mg\ L^{-1}$ is feasible with a specific energy demand of $SEC = 0.6\ kWh\ m^{-3}$ with a recovery rate of $\Phi = 71\%$. The drinking water regulations of (WHO, 2006) state a water with $TDS < 600\ mg\ L^{-1}$ as “good” water and set thresholds for Na^+ to $200\ mg\ L^{-1}$ and Cl^- to $250\ mg\ L^{-1}$. The sum of both limits determine the removal minimum. When increasing the feed concentration on $c = 2000\ mg\ L^{-1}$, a recovery rate of $\Phi = 65\%$ can be reached. The desalination consumes $SEC = 0.97\ kWh\ m^{-3}$ and produces a permeate volume of $V = 400\ L\ d^{-1}$.

The used feed water flow $Q = 60\ L\ h^{-1}$ is relatively low due to use of a small-scale CDI test system. In contrast, by use of systems with higher capacity, higher volumetric flows can be achieved and more diluate can be produced per hour. Simultaneously, the energy consumption is increasing less, which leads to a decrease in specific energy demand. Thus it was shown by using a bigger module operated at feed flow of $Q = 660\ L\ h^{-1}$ the specific energy demand can be reduced about 50% to $0.3\ kWh\ m^{-3}$. In literature, Zhao, R. et al. (2013) reported lab scale tests of non-commercial MCDI modules showed a highly efficient desalination of brackish water up to a concentration of $c = 2.5\ g\ NaCl\ L^{-1}$ with a specific energy demand of $SEC < 1\ kWh\ m^{-3}$. In his work, he highlighted at similar boundary conditions (influent and effluent concentrations) a specific energy demand of $SEC \approx 0.25\ kWh\ m^{-3}$.

Further critical ions like arsenic(V), ammonium and manganese can be removed as well. Experiments showed that the mobility of the different ions as well as the composition of the model water largely affects the removal efficiency. Results indicate that e.g. manganese can be much better removed than arsenic and a high amount of NaCl hinder further ions to be removed.

3.2 Pilot Scale Tests

The pilot tests cannot reach the results of laboratory tests as expected. Indeed a permeate volume of V = 470 L d^{-1} can be achieved, however the recovery rate can be determined only on Φ = 33%. Hence, the SEC is higher with SEC ≈ 1.52 kWh m^{-3}. The salt matrix is more complex than in the laboratory counterpart. Furthermore, operational parameters have to be optimised again.

In the second pilot plant treating high saline brackish water, tests could not been carried out yet and results are still outstanding.

3.3 Modelling

The developed two-dimensional FEM-simulation model can calculate salt removal under different boundary conditions. Since the model for the micro pores and the IEMs are not implemented yet, a difference at higher applied voltages at the module between simulation results and measured values in the laboratory can be noticed. Hence, a higher voltage has greater influence on retention properties of ion exchange membranes inside MCDI modules.

4 CONCLUSION AND OUTLOOK

Laboratory experiments have been operated with a MCDI module and its efficiency in desalinating brackish water could be determined. The results show, that the MCDI is deployable for a pilot scale use, if TDS concentrations are low and thus can be an alternative for conventional desalination processes, due to the lower specific energy demand. Besides NaCl, other undesirable ions can be removed to a high degree. Apart from the advantage of high-energy efficiency, MCDI technology is attractive due to low maintenance effort, since no moving parts are involved. An additional feed pump is not needed and capital expenditure can be further reduced, if the system could be run under gravitational water flow. A further advantage is the simple coupling to renewable energies such as PV-systems due to the power source of MCDI needs to be low voltage DC. Power loss due to converting electricity are minimized and the security for the not trained operator is increased.

The pilot tests show a promising application in a realistic environment. Laboratory values cannot be achieved. In further tests, the SEC has to be lowered by upscaling the size of the MCDI module.

With the developed simulation model, it is possible to calculate the salt removal of a MCDI module. It is restricted to low applied voltages and a simplified geometrical design. Further models will be implemented so it can be used in future for the total operational range of different MCDI modules.

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ABBREVIATIONS

1D, 2D One-dimensional, two-dimensional
FEM Finite elements method

MCDI Membrane capacitive deionization
RC Resistor capacitor
RO Reverse osmosis
SEC Specific energy consumption
TDS Total dissolved solids
UF Ultrafiltration

REFERENCES

Alkaisi, A. et al. (2017) A Review of the Water Desalination Systems Integrated with Renewable Energy. *Energy Procedia*, 110 (268-274), doi:10.1016/j.egypro.2017.03.138

Andres, G. L. et al (2017) Simulation of an electric behavior of the CDI system. *Desalination,* 419 (211-218), doi:10.1016/j.desal.2017.06.011

Biesheuvel, P. M. et al (2011) Theory of membrane capacitive deionization including the effect of the electrode pore space. *Journal of Colloid and Interface Science*, 360 (239-248), doi:10.1016/j.jcis.2011.04.049

Dykstra, J. E. et al. (2016) Resistance identification and rational process design in Capacitive Deionization. *Water Research*, 88 (358-370), doi:10.1016/j.watres.2015.10.006

Ross-Larson, B. et al., (2006) *Human Development Report 2006*. New York: Palgrave Macmillan

Schmidt-Thome, P. et al., (2015) *Climate Change Adaption Measures in Vietnam: Development and Implementation*. Cham Heidelberg New York Dordrecht London: Springer

Suss, M.E. et al. (2015) Water desalination via capacitive deionization: what is it and what can we expect from it? *Energy Environ. Sci.*, 8 (2296-2319), doi:10.1039/C5EE00519A

WHO, (2006) *Guidelines for drinking-water quality.* Geneva: WHO press, Vol. 1 (3rd ed.)

Zhao, R. et al. (2013) Energy consumption in membrane capacitive deionization for different water recoveries and flow rates, and comparison with reverse osmosis. *Desalination*, 330 (35-41), doi:10.1016/j.desal.2013.08.017

Zhao, Y. et al. (2013) Performance comparison and energy consumption analysis of capacitive deionization and membrane capacitive deionization processes. *Desalination* 324 (127-133), doi:10.1016/j.desal.2013.06.009