Mineral Scale Prevention on Electrically Conducting Membrane Distillation Membranes using Induced Electrophoretic Mixing

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Supporting information

Table S1: Calcium sulfate scaling solution recipe

Salt	Concentration (mM)
Na_2SO_4	10.500
$MgSO_4$	14.500
$CaCl_2$	16.400
pH	6.9

Table S2: Silicate scaling solution recipe

Salt	Concentration (mM)
$Na_2SiO_3,5H_2O$	8.985
$AlCl_3,6H_2O$	0.051
$BaCl_2,2H_2O$	0.010
$FeCl_3,6H_2O$	0.026
$CaCl_2,2H_2O$	1.439
KCl	1.372
$MgCl_2,6H_2O$	0.605
Na_2SO_4	0.774
pH	10
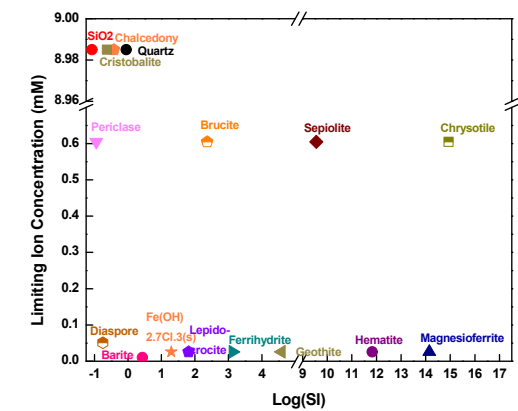
Figure S1: Saturation indices of minerals that could potentially precipitate in the feed during the desalination of silicate solution.
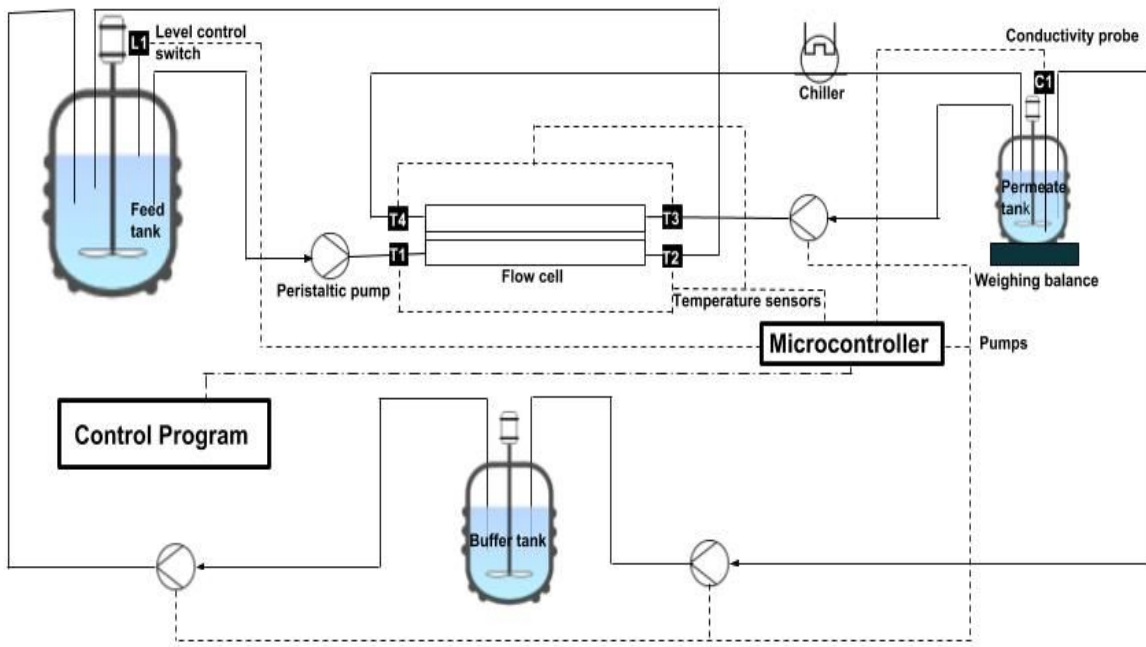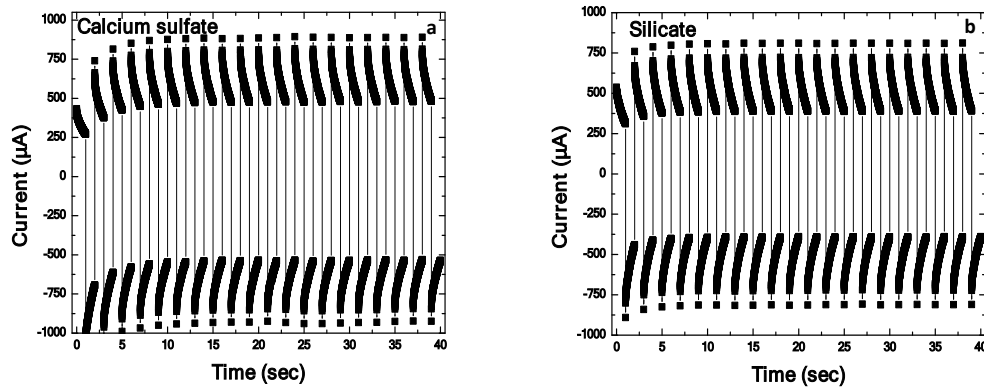
Figure S2: System process diagram

Figure S3. Chronoamperometry curves with CNT membrane and metal plate (Pt-Ti) as electrodes for (a) CaSO$_4$, and (b) silicate solution.

Calculation of saturation index along the membrane surface[1]

$$c_m = c_b * exp \, (J/\rho K) \qquad\qquad Equation \; S1$$

Where, c_m is the salt concentration at the membrane surface, c_b the salt concentration in the bulk, J the flux of water across the membrane, ρ the density of water, and K the solute mass transfer coefficient. The solute mass transfer coefficient can be calculated using the Graetz-Leveque mass transfer analogy:

$$Sh = 1.86(Re * Sc * \frac{d_h}{L})^{0.33} \qquad\qquad Equation\ S2$$

where L is the length of the channel, d_h is the hydraulic diameter, and Sh and Sc are Sherwood and Schmidt numbers respectively, which can be calculated using:

$$Sh = \frac{K * d_h}{D} \qquad\qquad Equation\ S3$$

$$Sc = \frac{\mu}{\rho * D} \qquad\qquad Equation\ S4$$

where μ is the viscosity of water, and D the diffusion coefficient of the solute.

The flux (J) in equation 2 is calculated by iteratively solving for the membrane surface temperatures on the feed and permeate side using eq. 7-15. Temperature difference in MD system leads to heat transfer from the hot feed to cold permeate. In addition to heat transfer, vaporization of water at the feed side leads to a further decline in temperature due to loss of latent heat. To account for the polarization effect, we assume steady state conditions with heat transfer (Q) in the bulk of the feed and permeate to be equal to the heat transferred across the membrane:

$$Q = h_f(T_{bf} - T_c) = h_c(T_c - T_{mp}) + J\lambda = h_m(T_{mf} - T_{mp}) = h_p(T_{mp} - T_{bp}) \quad Equation\ S5$$

$$T_{mp} = T_{bp} + \frac{(T_{bf} - T_{bp})}{h_p}\left[\frac{1}{(1/h_m) + (1/(h_c + h_v)) + (1/h_f) + (1/h_p)}\right] \qquad Equation\ S6$$

$$T_c = T_{bf} - \frac{(T_{bf} - T_{bp})}{h_f}\left[\frac{1}{(1/h_m) + (1/(h_c + h_v)) + (1/h_f) + (1/h_p)}\right] \qquad Equation\ S7$$

where T_{bp} and T_{bf} are the bulk permeate and feed temperatures respectively, T_c, T_{mf}, T_{mp} are the temperatures of the CNT surface, PP membrane surface, and PP back side (i.e., permeate side), and h_f, h_p, h_m, h_v, $and\ h_c$ are the heat transfer coefficients on the feed side, permeate side, membrane, vapor and the CNT layer respectively (calculated from equations 9-15). $h_f\ and\ h_p$ are calculated using the Nusselt equation:

$$h_x = \frac{Nu_x k_x}{d_h} \qquad\qquad Equation\ S8$$

where, k_x is the fluid thermal conductivity.

Nu_x in equation 9 is the Nusselt number, obtained using the equation:

$$Nu = 1.86(Re\ Pr\frac{d_h}{L})^{0.33} \qquad\qquad Equation\ S9$$

$$Where,\ Reynolds\ number,\ Re = \frac{d_h\ v\ \rho}{\mu} \qquad\qquad Equation\ S10$$

$$And\ Prandtl\ number,\ Pr = \frac{c_p\ \mu}{k} \qquad\qquad Equation\ S11$$

where v is the velocity, c_p is the specific heat capacity, and k is the thermal conductivity of the fluid.

$h_m, h_v,\ and\ h_c$ are determined as:

$$h_m = \frac{k_m}{\delta_m} \qquad\qquad \textit{Equation S12}$$

$$h_v = \frac{J\lambda}{T_c - T_{mp}} \qquad\qquad \textit{Equation S13}$$

$$h_c = \frac{k_c}{\delta_c} \qquad\qquad \textit{Equation S14}$$

Where, k_m, k_c and δ_m, δ_c are the thermal conductivity and thickness of membrane and the CNT layer respectively, and λ is the latent heat of vaporization.

Modeling surface pH under the influence of applied potential

Equation S15 was solved to estimate surface pH which was found to be 10.02

$$j = \frac{F}{\delta} * [D_H^+ * \left(C_H^{+s} - C_H^{+b}\right) - D_{\overline{OH}} * K_{OW} * \left(\frac{1}{C_H^{+s}} - \frac{1}{C_H^{+b}}\right)] \qquad \textit{Equation S15}$$

Here, j signifies current density, D_H^+ is proton diffusion coefficient, C_H^{+s} is the surface proton concentration to be calculated, C_H^{+b} is the bulk proton concentration, $D_{\overline{OH}}$ is the diffusion coefficient of the hydroxide ion, K_{OW} is the ionic product of water, F is Faraday's constant and δ is the boundary layer thickness.
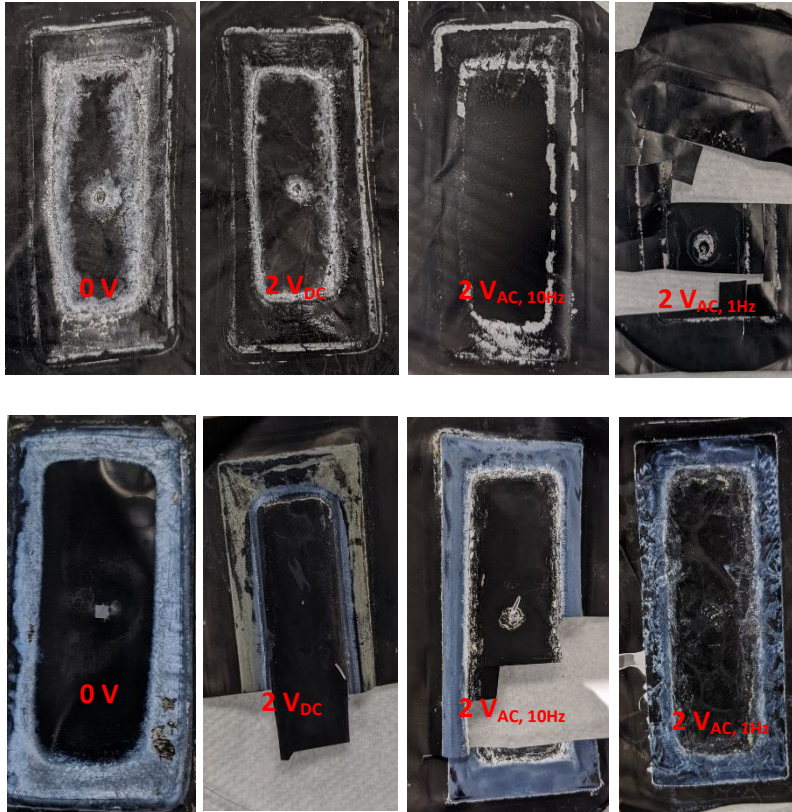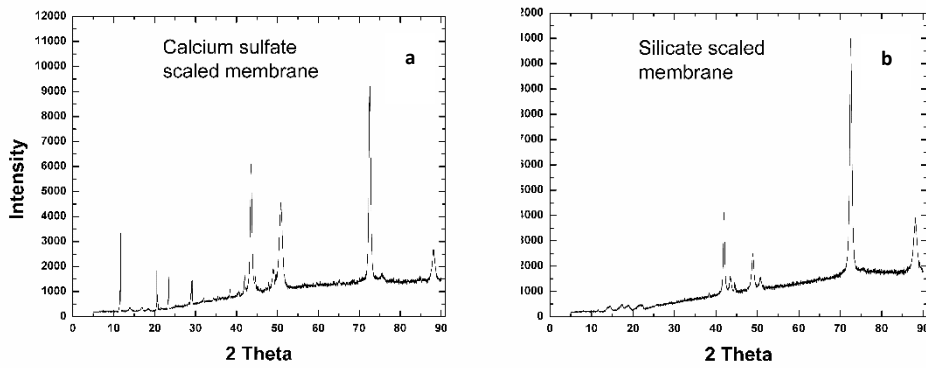

Figure S4. Pictures of the (a) CaSO$_4$ and (b) silicate scaled membranes under different operating conditions

Calculating EDL thickness

EDL thickness was calculated by using equation S16

$$\lambda_D = \left(\frac{\varepsilon k_B T}{e^2 \sum n_i z_i^2} \right)^{0.5}$$

Equation S16

Where, λ_D is the Debye length which is a measure of EDL thickness, ε, k_B, and T are the permittivity, Boltzmann constant and temperature respectively, e is the charge on one electron, n_i and z_i are the ionic concentration and charge of individual ions in the solution.

Figure S5. X-ray diffractogram of the (a) CaSO$_4$ and (b) silicate scaled membranes.
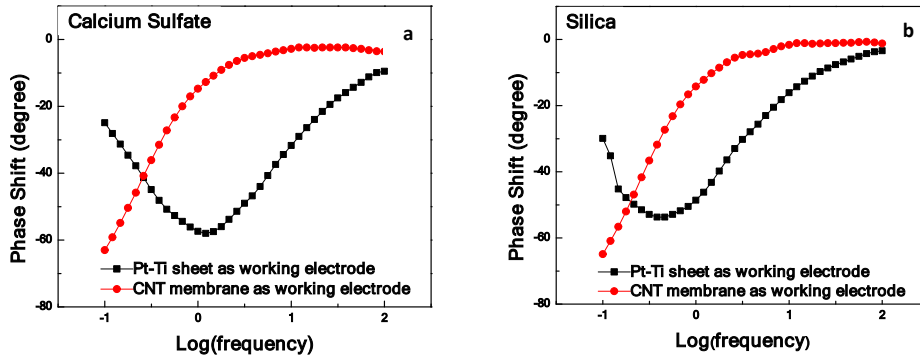
Figure S6. Phase shift versus frequency with a highly conductive metal plate (Pt-Ti) as the working electrode (black) and CNT membrane as the working electrode (red) for (a) CaSO$_4$, and (b) silicate solution.

Economic analysis

The proposed ECMD system has the potential to enhance membrane lifetime (by scaling mitigation), reduce membrane cleaning frequency, minimize pretreatment requirements, and reduce the volume of brine that requires disposal (by enhancing water recovery). The additional costs of this process (over conventional MD processes) are associated with fabricating the conductive CNT/PVA composite (cost of materials and fabrication), and energy requirements for the application of the electrical potential. In this section, we consider only the additional capital and operating costs incurred, and potential savings offered, by our process, without considering costs associated with membrane system design, heating of the feed solution, or pumping and cooling of the permeate stream, as these are expected to be comparable with conventional MD processes.

The cost of COOH-functionalized multi-wall CNTs used here is $0.6 g^{-1}. A single piece of membrane being coated (16 cm X 30 cm or 0.048 m^2) requires 0.2 g (200 ml of 1 g L^{-1} CNT solution), resulting in a requirement of 4.17 g CNT m^{-2}, which translates to a cost of $2.5 m^{-2}. A mathematical model for the design and fabrication of polymer solar cells by spray coating has been used to estimate the thermal cost of spray coating a CNT solution on to the membrane.[69] With an assumed substrate speed of 0.15 m s^{-1} and a nozzle-substrate distance of 0.3 m, for a 1 g L^{-1} solution of CNT, the thermal cost of spray coating (which dominates over other electric costs) was $2 m^{-2} per layer. The total additional cost of membrane fabrication is therefore $2 + $2.5 = $4.5 m^{-2}. Assuming a flux of 30 LMH and an operation time of 20 hours a day and 360 days a year, the water treated over this five-year period is 1080 m^3 m^{-2}. This results in an additional cost of $0.004 m^{-3}.

The power required to apply 2 V$_{AC, 1 Hz}$ was calculated using Equation 2:[70]

$$P = \frac{V^2}{Z}cos\theta \qquad\qquad Equation\ S17$$

where V is the voltage applied (2 V), Z is the impedance measured from EIS data and θ is the phase shift.

The impedance of the system was determined to be 191 Ω for the $CaSO_4$ solution and 182 Ω for the silicate

solution. Using Equation 2, it was determined that the power requirements were 0.02 W for both solutions

(for the 0.004 m^2 piece of membrane). This results in a power requirement of 5 W m^{-2}. Over the five-year

period being considered, power requirements are 180 kWh m^{-2}. Assuming electricity to cost $0.12 per

kWh, the resulting cost is $21.6 per m^2, which for 1080 m^3 of treated water results in $0.02 per m^3. Thus,

the total additional costs incurred are $0.004 per m^3 (membrane fabrication) + $0.02 per m^3 (electrical

potential applied) = $0.024 per m^3 water produced. In terms of savings, these costs need to be compared

to the cost of anti-scalants and brine disposal, which vary depending on the physical location and the

chemical composition of the water requiring treatment.

References

[1]   L. Martínez-Díez, M. I. Vazquez-Gonzalez, Journal of membrane science 1999, 156, 265.