4-2020

Fabrication of Composite Membranes for Solar-thermal Desalination

Andrew Mason

Mahdi Mohammadighaleni

Siamak Nejati

Fabrication of Composite Membranes for Solar-thermal Desalination

Andy Mason, Mahdi Mohammadi Ghaleni, and Siamak Nejati
Department of Chemical and Biomolecular Engineering, University of Nebraska-Lincoln

Motivation

With rising human populations, the demand for freshwater is an ever-growing problem. One emerging technology to combat this problem is membrane distillation (MD). MD has several advantages for water desalination such as:

- 100% rejection of solute (salt, heavy metals, etc.)
- Mergeable with other affordable energy sources (solar heat, electric resistance, etc.)

However, at the moment the specific energy consumption (SEC) of MD is very high due to low water production rates and large energy inputs to heat water. In a solar-assisted design for MD, the high cost of solar collectors (~$200/m^2) inhibits low cost of water production in comparison to reverse osmosis (RO).[1] Low water production rates for MD designs can be addressed with high-performance membranes and distillation modules. Solar-integrated devices will improve MD efficiencies and make it a marketable technology for desalination processes. This research poster shows great improvement upon current MD efficiencies.

MEMBRANE DISTILLATION (MD)

In membrane distillation (MD), water vapor diffuses through a hydrophobic membrane from the hot feed stream to the cold exit stream. [1]

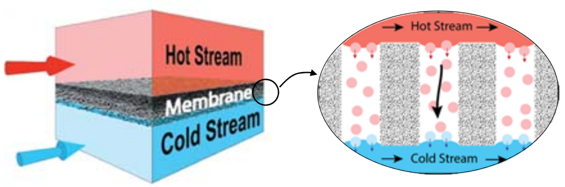

Figure 1. Schematic of MD process, where a hydrophobic membrane acts as a physical barrier between hot and cold streams but allows water vapor to diffuse through its pore channels.

MD THERMODYNAMIC LIMITATIONS

1st Law: $\dot{Q}_{sep} + \dot{m}_s h_s = \dot{m}_b h_b + \dot{m}_p h_p$

2nd Law: $\frac{\dot{Q}_{sep}}{T_0} + \dot{m}_s s_s + \dot{S}_{gen} = \dot{m}_b s_b + \dot{m}_p s_p$

Carnot: $\dot{Q}_{sep} = \dot{Q} + \dot{W}_{sep}$

Gibbs free energy: $g = h - Ts$

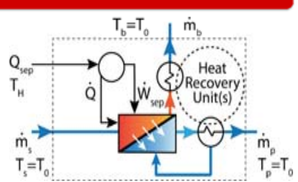

Figure 2. MD control volume[2]

1st law + 2nd law: ⇨ $\dot{W}_{sep} = \dot{m}_p g_p + \dot{m}_b g_b - \dot{m}_s g_s + T_0 \dot{S}_{gen}$

Reversible: $\dot{S}_{gen} = 0$ ⇨ $\dot{W}_{sep,least} = \dot{m}_p g_p + \dot{m}_b g_b - \dot{m}_s g_s$

For the Carnot Cycle: $\frac{\dot{Q}_{sep}}{\dot{m}_p} = \frac{\dot{W}_{sep}}{\dot{m}_p \left(1 - \frac{T_0}{T_H}\right)} = \frac{\dot{W}_{sep}^{rev} + T_0 \dot{S}_{gen}}{\dot{m}_p \left(1 - \frac{T_0}{T_H}\right)}$

MD efficiency factors:[2]

- ❑ Recovery ratio: $r = \frac{\dot{m}_p}{\dot{m}_s}$
- ❑ Specific energy consumption (SEC): $SEC \equiv \frac{\dot{Q}_{sep}}{\dot{m}_p}$
- ❑ Gain output ratio (GOR): $GOR \equiv \frac{\dot{m}_p h_{fg}}{\dot{Q}_{sep}}$

Solar-Thermal Composite Membrane

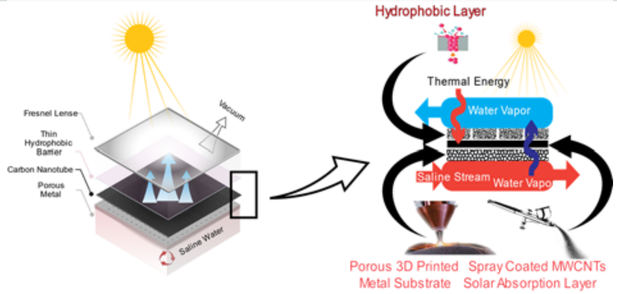

Figure 3. Three-dimensional (3D)[1] and two-dimensional (2D) schematics of a solar-integrated device. The composite membrane consists of four parts: a Fresnel lens, a thin porous hydrophobic barrier, a solar absorption layer, and a porous metal substrate produced from additive manufacturing methods.

Solar Absorption Layer

Method 1: Spray Coating MWCNT Process

Step 1. Spray Coat

- Mix Solutions of Multiwalled Carbon Nanotubes (MWCNTs), Polyvinyl-Acetylene (PVA), and Styrene (STY)
- Apply with Air Brush to Heated Polyvinyl Difluoride (PVDF) or Metal Substrate

Step 2. Crosslink

- Submerged in Glycolaldehyde (GA) and HCl Solution at 70°C for 1 hour
- Chemically Bonds MWCNT and PVA; Rendering PVA insoluble and Fixing Permeability of Films
- Permeability of Film Mainly Controlled by PVA composition
- Wash with Toluene to Remove STY

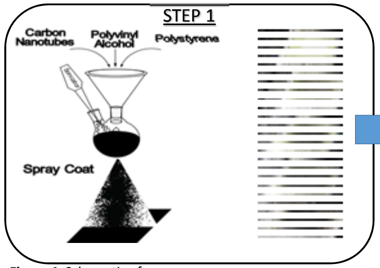

Figure 4. Schematic of synthesizing steps for spray coating MWCNT Process

Figure 5. Progression of spray coating a PVDF film with MWCNT solution

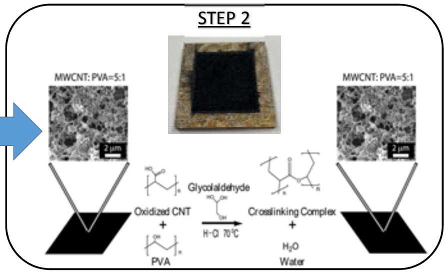

Figure 6. Crosslinking reaction with starting and ending products in addition to SEM images of film surfaces before and after crosslinking. Image of metal substrate with surface spray coated (Top Center).

Method 2: Femtosecond Laser Process[2]

- Femtosecond Laser Processing of Top Surface to Create Solar Absorber
- Properties of Surface can be Adjusted by Manipulating Rastering speed and Laser Power

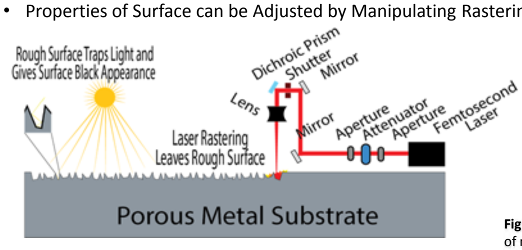

Figure 7. Schematic of femtosecond laser processing and light trapping geometry

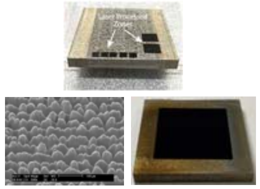

Figure 8. SEM image of rastered metal surface (Left).[2] Image of metal substrate with laser processed zones (Top).[2] Image of metal substrate with entire surface laser processed (Right). [2]

Testing and Analysis

Method 1: Gas Permeation

Solar Absorption Layer Needs to be Highly Permeable to Gas/Vapor

- PVA is Used to Control Film Permeability
  - PVA bonds MWCNTs together to Strengthen Film
  - Too much PVA Block Pores and Reduces Permeability
- Film Ratios of 1:4, 1:7, and 1:10 [PVA : MWCNTs]
- Nitrogen Flow was Measured through Films at Different Pressures

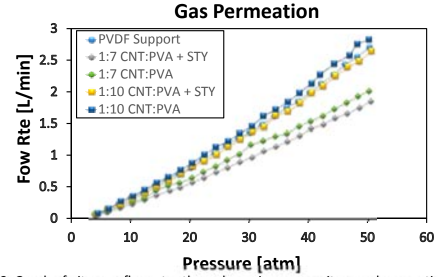

Figure 9. Graph of nitrogen flowrates through varying composite membrane ratios at different pressures

Methods 1 and 2: Reflectance Data

Solar Absorption Layer Needs to be Highly Nonreflective

- Femtosecond Laser Process (FLSP) had Lower Reflectance and thus Higher Absorption in Comparison to MWCNT-PVA Films

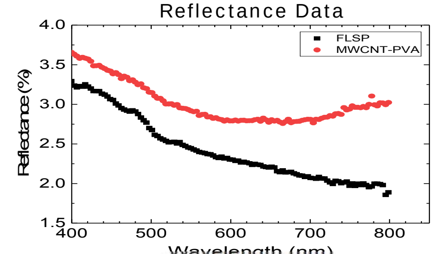

Figure 10. Graph of light reflectance percentages for spray coated and laser processed solar absorption layers across different wavelengths

CONCLUSIONS

Composite Solar Distillation Membranes are a viable separation module for desalination. The solar absorption layer can be produced by several different methods. It appears that Femtosecond Laser Processing is a fast and reliable way to produce a solar absorption layer. However, the gas permeation of the spray coated layer has more desirable flow rates for evaporation of water. Both methods are viable options of pursing to enhance solar-thermal desalination for fresh water production.

ACKNOWLEDGEMENTS

[1] Ghaleni, Mahdi Mohammadi, et al. "Model-Guided Design of High-Performance Membrane Distillation Modules for Water Desalination." Journal of Membrane Science, Elsevier, 28 June 2018, www.sciencedirect.com/science/article/abs/pii/S0376738818306835.

[2] Mahdi Mohammadi Ghaleni, Design, Synthesis, and Fabrication of Membranes and Modules for Water Desalination: Porous Materials with Special Wettability for Membrane Distillation, Ph.D. Dissertation, University of Nebraska-Lincoln, 2020.