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Visualization of droplet condensation in membrane distillation desalination with surface modification: hydrophilicity, hydrophobicity, and wicking spacers

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ABSTRACT

Condensation performance is a key target for improving the energy efficiency of thermal desalination technologies such as air gap membrane distillation (AGMD). This study includes the first visualization of condensation in AGMD, through the use of a high conductivity, transparent sapphire condenser surface. The study examines how flow patterns are affected by several novel modifications, including varied surface hydrophobicity, module tilt angle, and gap spacer design. The experimental results were analyzed with numerical modeling. While the orientation of the mesh spacer, which holds the air gap apart, was found to have no substantial effect on the permeate production rate, the surface's hydrophobicity or hydrophilicity did result in different rates. The hydrophobic surface exhibited fewer droplets bridging the gap, more spherical droplets, and better droplet shedding. For gap sizes less than ~3 mm, the hydrophilic surface frequently had regions of water pinned around the surface itself and the plastic spacer. While the flow patterns observed were more complex than the film condensation typically used to model the process, the simplified numerical modelling yielded good agreement with the data when an adjustment factor was used to account for the gap size.

KEY WORDS: Membrane distillation, desalination, condensation, hydrophobic surfaces,

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1. INTRODUCTION

Membrane distillation (MD) is an emerging thermally-driven desalination technology with acceptable energy efficiency, scalability to small sizes, simplicity of operation, and effectiveness with low temperature heat sources [1-4]. MD membranes are permeable to water vapor, but not liquid water; a warm saline feed on one side of the membrane evaporates into the membrane pores and the pure water vapor is condensed by a cool surface on the other side of the membrane [5-7]. The performance of most membrane distillation configurations is dominated by heat and mass transfer resistances in a gap between the membrane and condensing surface [8]. The process itself is essentially a flat-plate counter-current heat exchanger of the same feed fluid, where in between the two channels is a membrane and surface for condensation [9-12]. The gap between the membrane and condensation surface is filled with air in the case of air-gap membrane distillation, which is one of the most common configurations and the most efficient at high salinities [1, 13].

In the gap between the membrane and condensing surface, various flow regimes of condensation can occur (Figure 1). The modeling literature on MD is almost entirely focused on either simple film condensation behind an air gap or a fully flooded condition in the gap (so-called permeate gap MD) [6, 13, 14]. However, hydrophobic and superhydrophobic surfaces can be used to create dropwise and jumping droplet condensation conditions [15]. Additionally, as this work shows, other regimes, such as partially plugged flow, may occur.

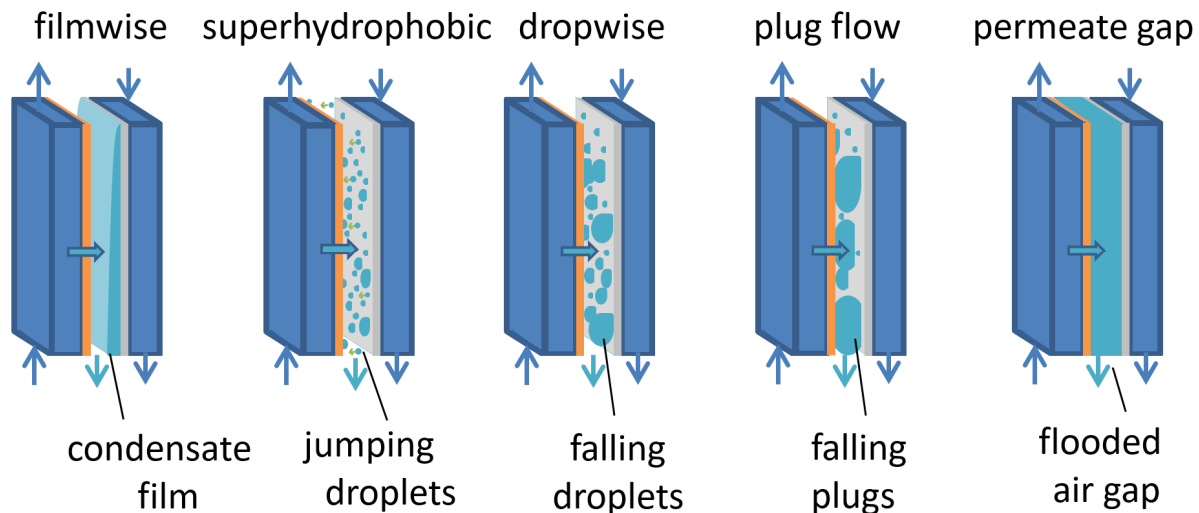


Figure 1. Droplet condensation regimes seen in AGMD. In each example, the channel on the far left is the feed (dark blue), followed by the membrane (orange), air gap with condensate (aqua), condensing plate (grey), and cooling channel for feed preheating (dark blue) [16].

2. METHODOLOGY

An AGMD module was used for this study, as shown in Figure 2, with details in Table 1. This system was capable of attaining all flow regimes shown in Figure 1.

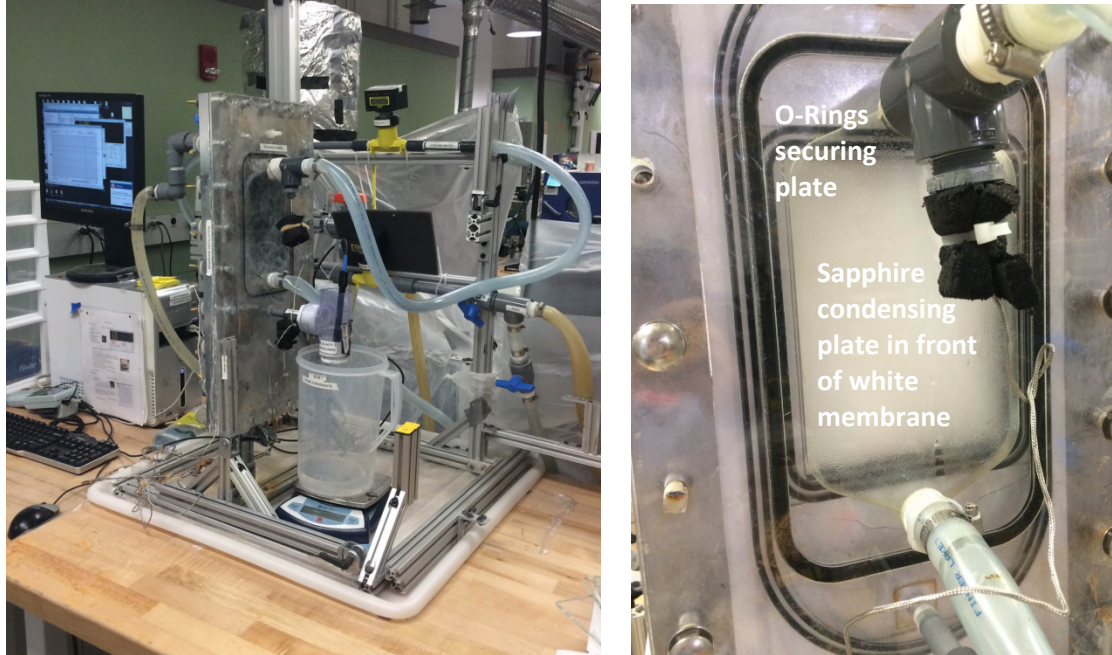


Figure 2. MD apparatus used in study. Left: full system including module, piping, PC for data recording, and condensate tank. Right: Sapphire plate condensing surface viewed from condensate channel. Plate is held between CNC machined polycarbonate plates with channels for fluid flow.

Table 1. Experimental conditions used for AGMD module

Parameter	Value	Units
Active Area	192	cm ²
Feed Depth	4	mm
Effective Air Gap Depth	0.5-2.0	mm
Feed Temperature	40-70	°C
Coolant Temperature	20-55	°C
Flux	150-250	L/m ² day

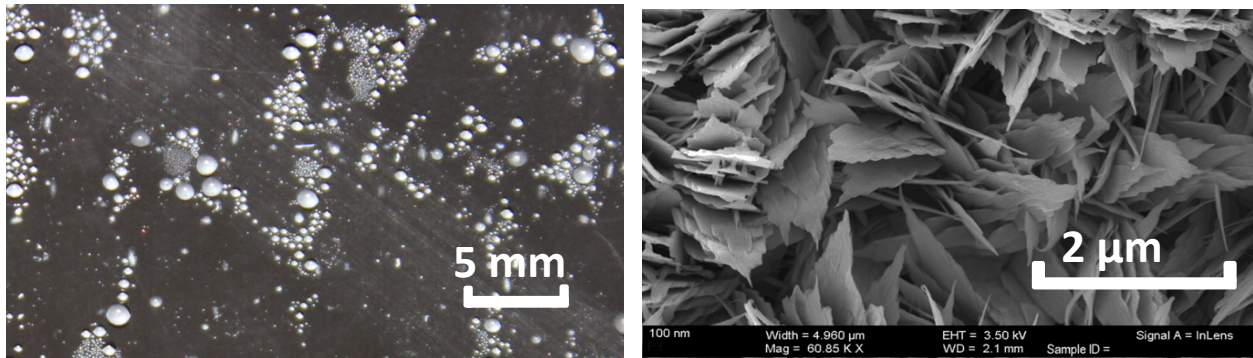


Figure 3. Copper oxide superhydrophobic MD condensing surface used in setup. Left: photograph of surface after experiment operation at $\sim 70^{\circ}\text{C}$. Right: surface under SEM before applying the silane coating, showing the fine copper oxide blade like structures that increase surface roughness [15].

Sapphire has a thermal conductivity of about $32 \text{ W/m}\cdot\text{K}$, which is two orders of magnitude higher than that of clear polymers, and roughly 50 times higher than that of a typical glass. The custom sapphire crystal plate was manufactured by the company Swiss Jewel (Figure 2). A transparent condensing plate has not been used in MD before, as the condensing surface must have low thermal resistance. Acceptable plastic or glass films would need to be $<50 \mu\text{m}$ thick and would not have adequate mechanical integrity.

Experimental uncertainty was analyzed with an EES code that used a 1-D discretized model to calculate heat and mass flow across many different elements. More detail of this modelling is provided in past studies [15] and in currently submitted work [16]. Temperature fluctuations were the largest cause of uncertainty, but the maximum uncertainty in permeate flux remained within $\pm 5\%$, while in most cases the uncertainty was smaller.

3. RESULTS & CONCLUSIONS

Numerous trials were performed that varied the surface hydrophobicity [15, 16], spacer type [15, 16], spacer orientation, spacer hydrophobicity [15], and module inclination angle [16, 17].

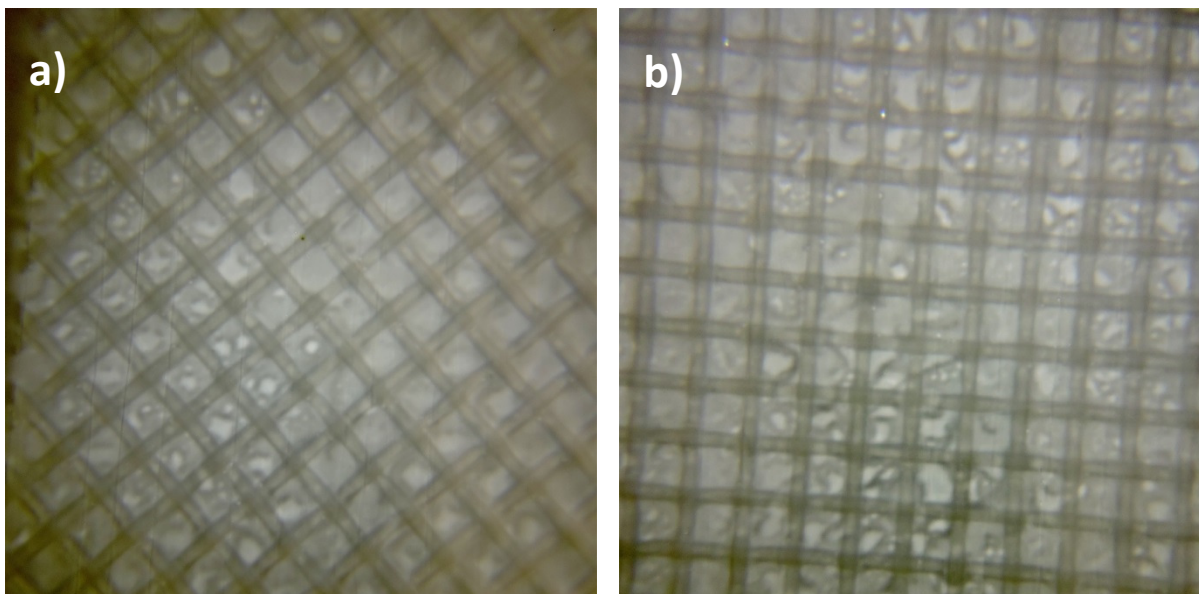


Figure 4. Condensing images taken through the sapphire plate. a) diagonal orientation, and b) horizontal orientation, for a square mesh, $T_{f,in} = 50^{\circ}\text{C}$, $T_{c,in} = 35^{\circ}\text{C}$

As seen in Figure 4, the mesh spacers that keep the membrane from collapsing into the gap can trap water. Water also tends to flow down the mesh spacers. However, the mesh supports, although rather hydrophilic, act more to slow the exit of droplets than to enable it. In the images, the light colored regions are droplets of water.

Table 2. summarizes the results from the changes to the gap across multiple studies by the authors.

Table 2. Summary of the influence of gap and configuration changes on permeate flux

parameter	Spacer Orientation	Surface Hydrophobicity	Spacer Hydrophobicity	Mesh Thermal Conductivity	Tilt Angle
range/details	horizontal & diagonal	Contact angle of $<20^{\circ}$ to 164°	Contact angle of $\sim 80^{\circ}$ to $\sim 150^{\circ}$	~ 0.3 to 400 $\text{W/m}^2\text{K}$	Module tilt of 60° to 85°
source	-	[15, 16]	[15]	[15, 18]	[16, 17]
Flux Increase	$<5\%$	0-110%	-22-2%	21-119%	0-54%

This study has reached several important conclusions by varying the parameters and visualizing fluid flow. Notably, surface hydrophobicity made a tremendous difference to permeate flux, largely with sufficient hydrophobicity for jumping droplets and low enough temperature differences to avoid flooding. Support mesh thermal conductivity also played a large role in improving flux. Moderate tilt angles ($<15^\circ$ from vertical), hydrophilic and hydrophobic spacers, and spacer orientation had minimal impact on performance.

These impacts can be understood in a framework of influence on heat and mass transfer on the air gap. Strategies which improved mixing through the air gap, such as jumping droplets, decreased mass transfer resistances, and thus improved flux. Strategies which improved conduction in the gap increased the temperature gradient across the MD membrane, also improving flux (but at the cost of increased conduction losses). Overall, both high condensing surface hydrophobicity and high gap support mesh thermal conductivity provided rather exceptional improvements and should be thought of as improved configurations in most cases. Future work should focus on minimizing temperature gradients and mass transfer resistances in all parts of the MD module, in order to maintain a large driving force across the MD membrane.

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