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# Evaluation of air gap membrane distillation process running under sub-atmospheric conditions: Experimental and simulation studies

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ABSTRACT

The importance of removing non-condensable gases from air gap membrane distillation (AGMD) modules in improving the water vapor flux is presented in this paper. Additionally, a previously developed AGMD mathematical model is used to predict to the degree of flux enhancement under sub-atmospheric pressure conditions. Since the mathematical model prediction is expected to be very sensitive to membrane distillation (MD) membrane resistance when the mass diffusion resistance is eliminated, the permeability of the membrane was carefully measured with two different methods (gas permeance test and vacuum MD permeability test). The mathematical model prediction was found to highly agree with the experimental data, which showed that the removal of non-condensable gases increased the flux by more than three-fold when the gap pressure was maintained at the saturation pressure of the feed temperature. The importance of staging the sub-atmospheric AGMD process and how this could give better control over the gap pressure as the feed temperature decreases are also highlighted in this paper. The effect of staging on the sub-atmospheric AGMD flux and its relation to membrane capital cost are briefly discussed.



## 1. Introduction

Air gap membrane distillation (AGMD) is one of the four common configurations that became the first choice for pilot testing [1–7]. However, this configuration still suffers from producing low flux compared to direct contact membrane distillation (DCMD) or vacuum membrane distillation (VMD) configurations [8–10]. We have demonstrated in our previous work [11] that heat recovery is very essential for enhancing the thermal efficiency of the AGMD process. But, the increase in thermal efficiency does not come free and the recovered heat always results in lowering the distillate production rate through the reduction of the driving force across the membrane. This makes improving the AGMD flux at large scale very challenging. One good approach toward solving the low flux problem is to study some of the techniques that are applied in the conventional thermal-based desalination processes which have been proved over many years of operational experience to be very effective in enhancing the water vapor flux in order to adapt them for the AGMD process. Multi-Stage Flash (MSF) is one of these conventional thermal desalination technologies that shares some similarity with the AGMD configuration. In MSF process, non-condensable gases are removed from the distillation chambers through steam ejectors and the seawater feed is de-aerated before it enters the distillers. Moreover, the condenser tube bundles inside the distillers are separated from the brine pool by more than 2 m (to avoid salt carryover along with the rising vapor) without any adverse effect on the production capacity (flux). The hypothesis of such design is that as long as non-condensable gases are removed from distillers, the diffusion mass transfer resistance is negligible and the distance between the evaporation and condensation surfaces is not that important. Even though MSF is operated under small $\Delta T$ (5–10 °C) and has a gap of more than 2 m between the evaporation and condensation surfaces, the process flux reaches more than 800 kg/m$^2$ h [12–13]. As its name may suggest, each train of MSF is consisted of 18–24 stages in series to maintain the vacuum pressure inside each stage at saturation pressure of the feed that enters that specific stage.

AGMD, in contrast, introduces a thin layer of ambient air (2–10 mm) between the MD membrane and the condensation surface as a thermal insulation layer to minimize heat loss by conduction. However, the non-condensable gases in this thin layer have been reported in several AGMD studies to be the dominating mass transfer resistance of the process [14–17]. The vapor formed at the interface of the hot side of the membrane must diffuse all the way through the pores of the membrane and across the air gap before it condenses on the cold surface (Fig. 1).

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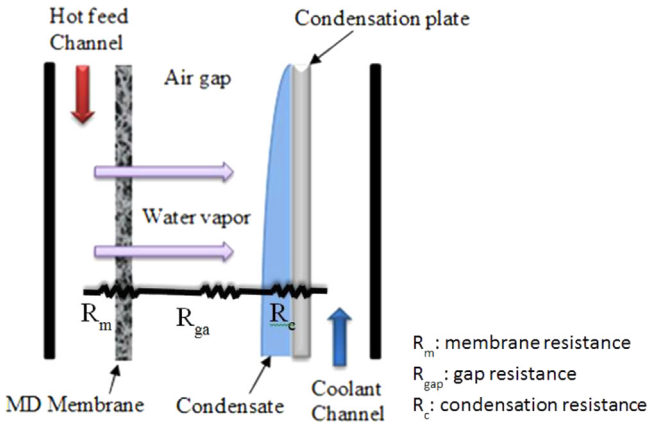


**Fig. 1.** Mass transfer resistance across the air gap in a vertical flat sheet module.

According to Fick's law, "the diffusive mass transfer is inversely proportional to the diffusion path". Jonsson's et al. [18] theoretical work and Kimura's et al. [19] experimental study demonstrated that AGMD water vapor flux decreases as the air gap thickness increases.

In other studies, Gostoli et al. [20] tested flat sheet membranes in air gap modules under different sub- atmospheric pressures and found that the flux increases as the absolute pressure of the gap pressure decreases. Similarly, Guijt et al. [21] removed the non-condensable gases from their air gap hollow fiber module and observed that the flux increased by three folds. Furthermore, the studies of steam condensers have well demonstrated that non-condensable gases shift the transport mechanism of the condensation process from being liquid-phase heat transfer controlled to a vapor-phase mass transfer controlled [22].

The presence of the non-condensable gases not only affects the mass transfer but also impair the heat transfer as well. When a vapor containing non-condensing gases condenses on a cold surface, the concentration of the gases in the immediate vicinity of the surface becomes greater than that in the bulk air–vapor mixture due to the low solubility of these gases in the liquid condensate. As a result, the partial pressure, and hence the temperature of the vapor near the surface, is reduced. This, in turn, reduces the temperature difference across the condensate film, and thereby reduces the heat flux. For instance, the studies on the effect of non-condensable gases on film type condensation on a flat vertical plate and in the absence of forced convection (i.e., under natural convection conditions), have indicated that a gas mass fraction as little as 0.5 % can cause a reduction of about 50% in heat flux [23]. Therefore, the enhanced water vapor transfer can only be seen near the saturation pressure of the hot liquid phase, which is the optimal operating condition of the MSF process.

In all thermal separation processes, the heat and mass transfer rates are always coupled and the rate at which a component is being separated from a mixture must be limited by either its heat transfer mechanism or its mass transfer mechanism. At low mass transfer resistance, the thermal separation process becomes heat transfer limited and the opposite is true when the heat transfer resistance is lower. Thus, the high mass transfer rate makes MSF a heat transfer limited process and one can infer this fact from the typical MSF design that allocates more than 60 folds of the evaporation surface area for condensation [12–13]. All the experimental findings mentioned earlier support the idea of adapting the removal of non-condensable gases applied in MSF technology for AGMD, which practically requires staging the process in series in order to maintain the feed temperature at the saturation pressure. The adaption of this technique may allow us here to refer to this technology as sub-atmospheric AGMD.

Since Guijt et al., [21], Gostoli et al., [20] and Prince et al., [24] are the only works reported for the removal of non-condensable gases and the concept of staging sub-atmospheric AGMD has not been introduced in MD literature, we believe that there is still a knowledge gap in the MD literature in this regard and the work of this paper tries to close part of it. Additionally, there is a potential enhancement in the water vapor flux of AGMD if it is operated at sub-atmospheric pressure. Therefore, this paper reports experimental and simulated fluxes predicted by our previously reported AGMD mathematical model [11] running under sub-atmospheric pressure and compare them to each other. The experiments and simulated scenarios have been conducted at different feed temperatures and different sub-atmospheric pressures using three different gap widths (5, 11, and 21 mm). The effect of the coolant temperature and staging sub-atmospheric AGMD process on water vapor flux are also discussed.

## 2. Theory

It was highlighted in previous work [11] that the mass transfer resistance across the AGMD membrane can be described as two resistances in series according to the following equation:

$$R_v = R_{mv} + R_{kv} \tag{1}$$

where $R_{mv}$ is the mass transfer resistance exerted by all non-condensable gases within the membrane pores on the water vapor molecules, and $R_{kv}$ is the mass transfer resistance due to the momentum loss during the collision of water vapor molecules with the internal walls of the membrane pores. In a flux form, the above equation can be written as:

$$\frac{1}{J_m} = \frac{1}{J_{mv}} + \frac{1}{J_{kv}} \tag{2}$$

where $J_m$ is the total flux across the membrane, $J_{mv}$ and $J_{kv}$ are the water vapor fluxes due to molecular diffusion and Knudsen diffusion, respectively. The Knudsen ($J_k$) and molecular diffusion ($J_{mv}$) fluxes are calculated by the following equations [11]:

$$J_{kv} = \frac{4}{3}\frac{d\varepsilon}{b\tau}\sqrt{\frac{M_v}{2\pi RT}}(P_{hm} - P_{ma}) \tag{3}$$

$$J_{mv} = \frac{M_v}{1-y}\frac{\varepsilon D_{AB}}{\tau b RT}(P_{hm} - P_{ma}) \tag{4}$$

where $d$, $b$, $\tau$, and $\varepsilon$ are the average diameter of pores, the membrane thickness, the tortuosity of the pores and the porosity of the membrane, respectively, $M_v$ is the molecular weight of water, $R$ is the universal gas constant, $D_{AB}$ is the mass diffusivity coefficient between air and water vapor, $y$ is the mole fraction of water vapor in the membrane pores, $T$ is the average temperature inside the membrane pores, and $P_{hm}$ and $P_{ma}$ are the water vapor pressures at the membrane interface of the feed and air gap sides, respectively.

The mass transfer across the air gap is only controlled by the molecular diffusion mechanism and can be combined also with the membrane resistance in series according to the following equation:

$$\frac{1}{J_{AGMD}} = \frac{1}{J_m} + \frac{1}{J_{gap}} \tag{5}$$

At high partial pressure of non-condensable gases, which is the typical case of an atmospheric AGMD, the mass transfer is mainly controlled by the molecular diffusion mechanism and the micro porous membrane structure resistance is negligible. Such a fact is supported by our experimental and mathematical model findings [25] as well as by Alkhudhiri et al. [26] and Kimura et al. [19] works that showed that changing the membrane pore size from