



TECHNICAL PAPER

Enhancing performance of AGMD by applying Vacuum

Author (s): N. Brand, BSc
Version 1.0

Abstract

The application of vacuum is found to improve the performance MD. There are some questions or misconceptions on the application and the actual effect of the applied vacuum on the process of MD. Why does it even improve performance? what improvement is to be expected? What are the risks of applying vacuum?

Summary

Vacuum is applied to the distillate channel only, not the brine channel(s) to prevent issues resulting from brine boiling inside channels. Changing the pressure inside the airgap directly influences the mass diffusivity of the water vapour molecules. Applying vacuum on membrane and airgap via distillate channel increases mass transfer, evaporation rate and thermal efficiency. The application of vacuum has increased Flux, (membrane) efficiency and GOR.

The amount of improvement is directly related to the vacuum pressure. Experimental results are shown to display the effect. High flux modules improves most on flux with application of vacuum where-as high GOR modules improve most on GOR. The application of vacuum is not without risk. Applying a too strong vacuum for the situation will reduce salt rejection. Adjustable vacuum pressure according to application is desirable..

Where to apply Vacuum?

Before the answer as to why it improves performance can be answered the different ways to apply vacuum are to be discussed. Looking at the schematic of AGMD one can see there are 3 channels; condenser(cold brine), membrane(hot brine) and distillate.

Applying vacuum on the brine channel(s) (condenser and/or membrane) implies that the entire channel including circulation pumps, heat exchangers, brine tanks and all sensors are under vacuum. This is not how to apply vacuum in AGMD.

Why not? Applying vacuum on the brine channel(s) lowers the boiling point of the water inside the channel. Depending on the brine temperature and the applied vacuum the brine will boil as a result. When a solution boils it will try to evaporate water in an instant until the resulting heat of vaporisation lowers the temperature below boiling point. This could certainly result in a higher flux i.e. production yield however when boiling pockets of water vapour travel towards the surface i.e. membrane and due to the instantaneous manner of vaporisation these vapour pockets (bubbles) will be pushing supersaturated brine towards the membrane leading to crystallization/scaling problems on the membrane resulting in a variety of problems including low salt rejection.

Not applying vacuum on brine channels only leaves the distillate channel to apply vacuum. This is where vacuum is applied in AGMD. A vacuum generator is connected to the distillate channel. The membrane acts as a physical barrier keeping fluids on the brine side only allowing gasses .i.e. vapour to pass through the membrane.

In this configuration only the distillate channel is under vacuum, both brine channels are entering and exiting to atmospheric pressures.

What Happens when vacuum is applied?

Applying only vacuum on the distillate channel does not change anything in the brine channels, then how can it improve performance? to answer this question the working principles of MD and it's affecting parameters are discussed.

The working principle in MD is the natural process of diffusion i.e. any substance travels from a high to a low concentration. In MD the concentration difference is a difference in water vapour density, a higher temperature yields a higher density of water vapour and vice versa. As a result applying a temperature difference across 2 channels with a membrane (and distillate channel) in between creates a concentration difference, this is the driving force in MD. Then, how are we helping nature by means of applying vacuum on the distillate channel?

In MD resistance to mass transfer (diffusion) consist of 2 major components; molecular diffusion J_m and Knudsen diffusion J_k . To quantify this we will take the formulas for diffusion from Alsaadi et.al.

Used these correlations to describe the mass transfer (flux):

Vapour pressure:

$$P_v = \exp \left(A - \frac{B}{C+T_{air}} \right) \text{ [Pa]}$$

P_v = vapour pressure [Pa]

T_{air} = temperature for which vapour pressure should be calculated [K]

A = antoine coefficient A = 23,238 [-]

B = antoine coefficient B = 3841,276 [-]

C = antoine coefficient C = -45 [-]

Molecular diffusion:

$$J_m = \frac{M_v}{1-y} * \frac{\varepsilon * D_{ab}}{\tau * b * R * T} * V_p \text{ [Kg/m}^2\text{*s]}$$

J_m = flux as a result of molecular diffusion [Kg/m²*s]

M_v = molecular weight of water vapour [kg/K*mol]

y = molar fraction water vapour [-]

ε = membrane porosity [-]

D_{ab} = mass diffusivity

b = thickness of the membrane [m]

τ = membrane tortuosity [-]

T = temperature [K]

Knudsen diffusion:

$$J_k = \frac{4}{3} * \frac{d\varepsilon}{b\tau} * \sqrt{\frac{M_v}{2\pi * R * T}} * V_p \text{ [Kg/m}^2\text{*s]}$$

J_k = flux Knudsen diffusion [Kg/m²*s]

T = temperature [K]

d = diameter of the pores [m]

ε = membrane porosity [-]

b = thickness of membrane [m]

τ = membrane tortuosity [-]

M_v = molecular weight of water vapour [kg/K*mol]

V_p = vapour pressure difference across the membrane [Pa]

R = Ideal gas constant 8,314 [J*K⁻¹*mol⁻¹]

Total diffusion rate: $\frac{1}{J_t} = \frac{1}{J_k} + \frac{1}{J_m}$ [Kg/m²*s]

Parameters that are changing with pressure inside the airgap are:

Mass diffusivity: $D_{ab} = \frac{1,895 \cdot 10^{-5} \cdot T^{2,072}}{P}$ [m²/s]

P = pressure [Pa]

T = Temperature [K]

Molar fraction of water vapor: $y = \frac{P_v}{P}$ [-]

P = pressure [Pa]

P_v = vapour pressure [Pa]

As the pressure in the airgap is lowered the partial pressure of water vapour constitutes a larger part of tot total pressure, the amount of non-condensable gases is reduced, which is beneficial for mass transport. Removing these stagnant air particles increases the Mean Free Path i.e. the averaged length each particle travels before collision with another particle.

Mean Free Path: $\ell = \frac{k_B T}{\sqrt{2} \pi d^2 p}$ [m]

k_B = Boltzmann constant [1,3806488*10⁻²³ J/K]

T = temperature [K]

d = diameter of gas particles [m]

P = pressure [Pa]

ℓ = Mean free Path [m]

Removing non condensable gases reduces the amount of resistance to diffusion inside the membrane (80-85% porosity) and airgap.

Stagnant air particles are like people standing still in the middle of a busy train station hallway, they are not going anywhere only slowing down the people trying to pass the hallway and catch a train.

Does applying vacuum on the distillate channel have an insulating effect just like vacuum glazing?

While it is true that with a lower mean free path the amount of collision between particles is reduced. the amount of energy transferred per collision is increased nullifying this effect.

To reach a thermal insulation effect from vacuum the pressure should be reduced to the extent that the mean free path is larger than the airgap. This is not the case for MD.

Then why is exactly is the vacuum performance improving? Changing the pressure inside the airgap directly influences the mass diffusivity of the water vapour molecules.

Improved mass diffusion then equates to the fact that the process of diffusion is occurring at a greater pace i.e. higher flux. This greater pace then consumes more heat of evaporation to establish mass transport, which means that along the same length of membrane more heat is consumed in the same time frame, more heat consumed for evaporation with the same amount of thermal losses (same time frame) equates to a higher % (membrane) efficiency. More heat consumed/ transferred along the same surface area also means that the temperature difference (driving force), as a result will be smaller further lowering thermal losses. A smaller temperature difference on the membrane side equates to less energy to be added to the process resulting in a higher GOR. To summarise: the application of vacuum has increased productivity i.e. flux, (membrane) efficiency and GOR. The amount of improvement is directly related to the applied vacuum pressure, which will be discussed in the next paragraph.

Quantifying the performance improvement.

Now that the effect of the applied vacuum is established the characteristics of improvement on different modules can be discussed. It is observed that Aquastill's modules designed for high Flux i.e. with large(r) temperature difference improve the most on Flux, correspondingly modules designed for high GOR i.e. small(er) temperature differences improve the most on thermal efficiency. This then leaves the 'normal' modules somewhere in between. This is only natural as the flux is directly related to the amount of available energy for evaporation, as available energy is set for a given temperature and flow setting the only way to produce more water is to use available energy more efficient. Table 1 displays experimental results to show the characteristics for different modules under different vacuum pressures. All experiments were run with a heating temperature of 80-82 °C (optimal), the same coolant temperature and a brine circulation flow of 600 l/hr.

Table 1 Flux and GOR of different modules under different vacuum pressures

	Flow [l/hr]	Vacuum [mbar]	Flux [kg/m ² ·hr ⁻¹]	GO R [-]
Pura 7 (1.5m)	600	-400	5.3	2.8
	600	-600	6	3.2
	600	-800	6.3	3.5
Pura 13 / 26 (2.7m)	600	-400	3.5	5.25
	600	-600	3.8	6.4
	600	-800	4.1	7.4
Pura 24 (5m)	600	-400	2	8.4
	600	-600	2.2	10.3
	600	-800	2.3	12.2

membrane channels of 1.5, 2.7 and 5 meters in length's (the longer being more thermally efficient) were used, each with the same amount of channels (same internal velocity). Experimental graph's for each module can be found in the appendages.

Risks of vacuum enhancement

The application of vacuum is not suited for every application and/or type of membrane, the liquid entry pressure (hydrophobicity, contact angle) should be high enough to ensure good salt rejection. Furthermore the application of vacuum will put additional mechanical strain on membranes and modules.

Modules and membranes should be designed to cope with the added stress of vacuum while at operational temperatures up to 80-90 °C, combining that thin membranes with high porosity perform best for MD all while most membranes and modules are built using polymer / plastic. This is a challenge not to be underestimated.

$$LEP = \frac{2B\gamma_l \cos(\theta)}{r}$$

- LEP = Pressure at which wetting of membrane occurs [bar]
- B = Geometrical factor derived from the Laplace equation [-]
- γ_l = Surface tension of liquid [N/m]
- θ = Contact angle between the solution and the membrane [degrees]
- r = Pore size [m]

Applying a vacuum that is (too) strong for the operational situation and/or membrane will reduce salt rejection. Therefore an adjustable vacuum pressure according to application is desirable.

Appendages Literature:

Alsaadi, A.S., Ghaffour, N., Li, J.-D., Gray, S., Francis, L., Maab, H., Amy, G.L. (2013) *Modeling of air gap membrane distillation process: A theoretical and experimental study.*

Experiment graph's

