TECHNICAL PAPER

Influence of dissolved salts

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Abstract
In this technical paper the effect of different type of salts are discussed. For example, an increase in concentration of NaCl will reduce the water activity. A reduction in water activity reduces the distillate production and increases the thermal energy consumption of the installation. In this technical paper the effects of concentration and different type of salts is discussed.

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Introduction

Membrane distillation can be used to produce drinking water from seawater. Furthermore, membrane distillation can also be used to treat other types of water. For example, waters containing lithium or other types of salts can be treated. It is also possible to recover acids from the treated fluids [1].

In this technical paper the effect of different salts and concentrations will be explained, and an example will be given. Membrane distillation is dependent on the heat transfer and the vapour pressure difference over the membrane. The concentration of salts will have an impact on these two.

Explanation of membrane distillation process, and its effect on the process

Membrane distillation is dependent on the mass and heat transfer, both will be explained in the following two sections. Furthermore, in each section the effect of an increase in concentration will be shown.

1. Heat transfer

Seawater consists mostly of sodium chloride (NaCl). Therefore, seawater can be modelled as water with a certain concentration of NaCl. The effects of increasing salinity can be noted by the following two equations:

$$h = \frac{Nuk_f}{d_h}$$

$$Nu = 0.19Re^{0.68}$$

Equation 1

The second equation gives the effect on the heat transfer coefficient of the spacer filled brine channels. The Reynolds number can be calculated by using the following equation:

$$Re = \frac{\rho v L}{\mu}$$

Equation 2

The density (ρ) and viscosity (μ) of the brine changes when the concentration of NaCl increases. This will influence the Nusselt's number and will decrease it. The effect is shown in Figure 1. As can be seen, the Nusselt's number will reduce, and therefore also the heat transfer of the brine channel. This will reduce the temperature near the membrane and reduce the driving force of the distillate flux.

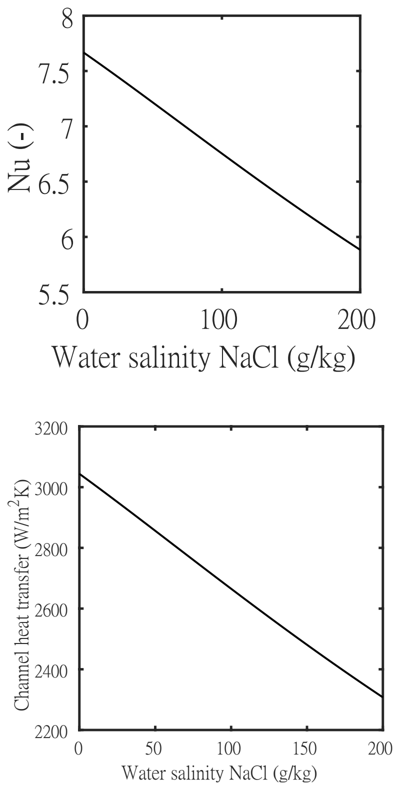

Figure 1 Influence of salinity of seawater, the effect on the Nusselts number (on the left) and heat transfer coefficient (on the right).

Another way to visualize the effect of the increase in salinity is shown in Figure 2. At higher salinities the temperature at the membrane is lower, leading to lower distillate flux due to the lower vapour pressure. More information will be given in the next section.

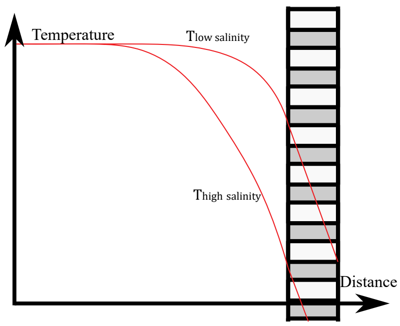

Figure 2 Effect of salinity on the temperature profile.

2. Mass transfer

Membrane distillation is a pressure driven process, which can be shown by the following equation:

$$J = C_m(P^*_{m,1} - P^*_{m,2})$$

Equation 3

Where C_m is the permeability of the membrane. $P*_{m,1}$ and $P*_{m,2}$ are the vapour pressures of the water on both sides of the membrane. The above equation can be transformed into an equation with a temperature difference by using the Clause-Clapeyron equation [2]:

$$J = C_m \frac{dP^*}{dT}(T_{m,1} - T_{m,2})$$

$$\frac{dP^*}{dT} = \frac{P^* h_v}{RT_m^2}$$

$$T_m = \frac{T_{m,1} + T_{m,2}}{2}$$

$$P_{m,1}^* = a_w P^{*,0}$$

Equation 4

Where the third equation denotes the effect of the vapour pressure, with water activity factor a_w. The vapour pressure on the distillate side of the membrane is equal to the vapour pressure of pure water, and is a function of the air gap temperature.

$$P_{m,2}^* = P^{*,0}(T_{air\ gap})$$

Equation 5

Resulting in the following equation:

$$J = C_m(a_w P^{*,0}(T_{mem}) - P^{*,0}(T_{air\ gap}))$$

Equation 6

In Figure 3 the effect of the concentration of NaCl is shown. As can be seen, an increase of concentration reduces the water activity, and thus reduces the distillate flux.

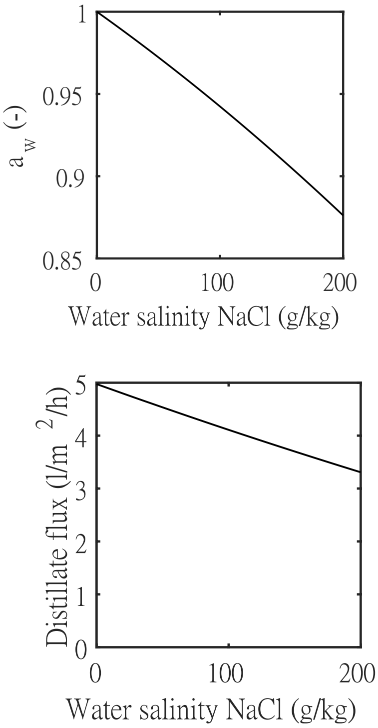

Figure 3 Water activity and distillate flux as a function of concentration of NaCl. Graph is based on a module with a channel length of 2.7 m.

Overall, an increase in concentration will lead to a reduction of distillate flux and an increase in thermal energy consumption. In this case only NaCl is used as a salt. However, more salts can be dissolved and NaCl might not always be the major component in the water. The influence of different salts will be treated in the following section.

Effect of different salts

As discussed in the introduction, not only seawater can be treated with membrane distillation, but also waters contaminated with other salts or impurities. The thermophysical properties of the treated water are needed to model the membrane distillation process. For most single salts the properties are available. However, water activity equations are not always available. In those situations, the Van't Hoff factor (i) can be used. Combining the following two equations of osmotic pressure leads to the third equation. M and V_m are the molality of the solution and the partial molar volume of water [3].

$$\Pi = -\frac{RT}{V_m}\ln(a_w)$$

$$\Pi = iMRT$$

Equation 7

Combining the two equations above leads to:

$$a_w = \exp(-iMV_m)$$

Equation 8

The last equation can then be used to estimate the water activity of each component. If thermophysical properties (density, heat coefficient, etc) are not available, they should be experimentally determined, or looked up in literature. Retaking the equation from the previous section, shows that a reduction in vapour pressure reduces the amount of distillate flux.

$$J = C_m(a_w P^{*,0}(T_{mem}) - P^{*,0}(T_{air\ gap}))$$

Equation 9

Example

In Table 1 the dissociation factor and molar mass for each salt is shown. For simplification the dissociation factor is simplified. The real dissociation factor might be different.

Salt name	Dissociation factor	Molar mass (g)
$NaCl$	2	58.44
$CaCl_2$	3	110.98
$CaCO_3$	2	100.09
$NaSO_4$	3	119.05
$LiCl$	2	42.39

Table 1 Salts treated in this example.

In Figure 4 the water activity is shown for various salts. As can be seen, the water activity reduces for all the salts, which is to be expected. LiCl has more effect on the water activity than NaCl. The effect on the heat transfer coefficient is omitted here for brevity but can be calculated when the thermophysical properties are known.

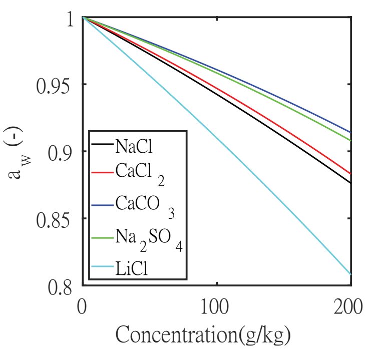

Figure 2 Effects of the concentration of several salts on the water activity

Conclusion

The types of water that can be treated with membrane distillation can vary widely in composition. In this technical paper an overview is given on how to calculate the different types of water. The succent overview given here shows the methods that can be used to calculate the performance for dissolved salts.

Nomenclature

Symbol	Meaning
L	Characteristic length
i	Dissociation factor
J	Distillate flux
ρ	Density
k_f	Fluid conductivity
R	Gas constant
h	Heat transfer coefficient
d_h	Hydraulic diameter
h_v	Latent heat of evaporation
C_m	Membrane permeability
M	Molality
Nu	Nusselt's number
Π	Osmotic pressure
V_m	Partial molar volume
Re	Reynolds number
T	Temperature
T_m	Temperature near one of the membrane sides
$P^*{}_m$	Vapour pressure at a side of the membrane
v	Velocity
μ	Viscosity

Table 2 Nomenclature

References

[1] M. Tomaszewska, M. Gryta, A.W. Morawski, The influence of salt in solutions on hydrochloric acid recovery by membrane distillation, Sep. Purif. Technol. 14 (1998) 183–188. doi:10.1016/S1383-5866(98)00073-2.

[2] M. Bindels, N. Brand, B. Nelemans, Modeling of semibatch air gap membrane distillation, Desalination. 430 (2018) 98–106. doi:10.1016/j.desal.2017.12.036.

[3] V. Gekas, C. Gonzalez, A. Sereno, A. Chiralt, F. Fito, Mass transfer properties of osmotic solutions. I. Water activity and osmotic pressure, Int. J. Food Prop. 1 (1998) 95–112. doi:10.1080/10942919809524570.