TECHNICAL PAPER

Heat calculation inside spacer filled channels

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Abstract

The principle of membrane distillation is easy to explain and to understand, It describes a natural process of evaporation and condensation over a hydrophobic membrane. However the mathematical description of this process used for quantifying mass -and heat transfer can be very useful for the optimization of membrane distillation modules. Another purpose is the use of modelling for prediction of CAPEX and OPEX costs. These costs are mainly determined by flux and energy performance of the process. Aquastill describes in a set of technical papers the different aspects of the MD process to give a deeper understanding in this complex matter. This article describes the first step in a series of sub-processes in heat transfer inside modules which describes the calculation of the heat transfer coefficient (α_{ch}).

Solution(s)/ conclusions.

In membrane processes in general spacers are used to simply create an open channel and to promote turbulence. Turbulence promotion increase mass and heat transfer and is strongly depending on the design of a spacer making this a challenging area for deeper understanding.

Focusing on the heat transfer inside channels requires a set of physical data, description of the channel characteristics and process parameters. The calculation involves the determination of the hydraulic diameter which basically describes basically the spacer characteristics. This part of the modelling is later also used to optimize the spacer design for the channel to maximize heat transfer inside channel, with minimal pressure drop.

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The set of physical data are specific density (ρ_w), evaporation heat (ΔH_v), specific heat (Cp_w), dynamic viscosity (η_w) and heat conductivity coefficient (λw) of water:

$$\rho_w = -0{,}0036 \cdot T_{avg}^2 - 0{,}0697 \cdot T_{avg} + 1000{,}5 \; [kg/m^3]$$

$$\Delta H_v = \frac{3168{,}1 - 2{,}437 \cdot (T_{avg} + 273{,}15)}{\frac{1000}{18} * 1000} \; [J/mol]$$

$$Cp_w = 3 \cdot 10^{-6} \cdot T_{avg}^4 - 9 \cdot 10^{-4} \cdot T_{avg}^3 + 0{,}0911 \cdot T_{avg}^2 - 3{,}686 \cdot T_{avg} + 4225{,}3 \; [kJ/(kg{\cdot}K)]$$

$$\eta_w = 3 \cdot 10^{-9} \cdot T_{avg}^3 + 6 \cdot 10^{-7} \cdot T_{avg}^2 - 5 \cdot 10^{-5} \cdot T_{avg} + 0{,}018 \; [Pa{\cdot}s]$$

$$\lambda_w = 1 \cdot 10^{-5} \cdot T_{avg}^2 + 0{,}0023 \cdot T_{avg} + 0{,}5565 \; [W/(m{\cdot}K)]$$

With:

T_{avg}= average mean temperature in a specific part of channel [˚C]

In a larger membrane distillation modules temperatures in the feed channel will decrease due to evaporation. At the condensing side temperatures will increase due to condensation. These phenomena are causing a temperature profiles over the modules. The parameters shown above are all temperature depending meaning that the calculation describes the heat transfer at a specific temperature existing in a small part along the length of the channel.

For calculating the hydraulic diameter of a spacer filled channel we first need to characterize the geometry of the spacer with the porosity (free flow space) and the specific surface area (causing wall friction).

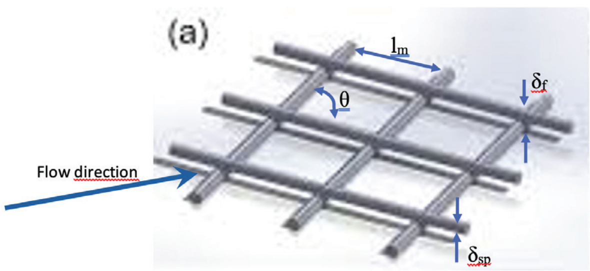

Figure 1: Illustration of a non-woven diamond spacer

The porosity of a spacer is described by using the formula from an article of Da Costa, Fane & Wiley:

$$\varepsilon_{sp} = 1 - \frac{\pi \cdot d_f}{2 \cdot l_m \cdot \delta_{sp} \cdot \sin(\theta)} \quad [-] \qquad (6)$$

With:

ε_{sp}= porosity spacer [-]
d_f= filament spacer thickness [m]
l_m= distance between two filaments [m]
δ_{sp}= spacer thickness [m]
θ= angle between filaments [-]

For the specific surface area another formula is used from the same article:

$$S_{vsp} = \frac{A_{sp}}{V_{sp}} = \frac{4}{d_f} \; [m^{-1}] \qquad (7)$$

With:

S_{vsp}= specific surface area [m-1]
A_{sp}= spacer surface area [m²]
V_{sp}= spacer volume [m³]
d_f= filament spacer thickness [m]

The spacer can now be descripted with a single number called the hydraulic diameter of the channel:

$$d_{h|sp} = \frac{4 \cdot \varepsilon_{sp}}{\left(\frac{2}{\delta_{sp}}\right) + (1 - \varepsilon_{sp}) \cdot S_{vsp}} \; [m] \qquad (3.8)$$

With:

$d_{h|sp}$= spacer hydraulc diameter [m]
ε_{sp}= spacer porosity [-]
δ_{sp}= spacer thickness [m]
S_{vsp}= spacer specific surface area [m¹]

Heat transfer inside a channel is also depending on the flow velocity through a channel. In our case we have a spacer filled channel meaning the effective flow will be increase due to the presence of extra material (the spacer). Using the spacer porosity (empty void of the spacer) is a easy method for the correction of the effective flow velocity:

$$v_{eff} = \frac{v}{\varepsilon_{sp}} \text{ [m/s]} \qquad (3.11)$$

With:

v_{eff}= effective velocity [m/s]
v= velocity in empty channel [m/s]
ε_{sp}= spacer porosity [-]

In general the numbers of Reynolds (Re) and Prandtl (Pr) are used for further calculations:

$$Re = \frac{\rho_w \cdot v_{eff} \cdot d_{h|sp}}{\eta_w} \text{ [-]} \qquad (3.12)$$

With:

Re= Reynolds number [-]
ρw= density water [kg/m³]
veff= effective velocity water [m/s]
dh|sp= spacer hydraulic diameter [m]
ηw= dynamic viscosity water [Pa·s]

$$Pr = \frac{C_p \cdot \eta_w}{\lambda_w} \text{ [-]} \qquad (3.13)$$

With:

Pr= Prandtl number [-]
$C_{p|w}$= specific heat capacity water [J/(kg·K)]
w= dynamic viscosity water [kg·m-1·s-1]
λw= thermal heat conductivity water [W/m·K]

Academical research involving heat transfer inside spacer filled channels was conducted for a number of spacers resulting in a number of formulas which can be used to describe the heat transfer. (Gryta, Tomaszewska, & Morawi, 1997)

By building a series of heat exchanger modules based on our MD design and leaving some materials out, a big dataset of measurements was generated for validation purposes.

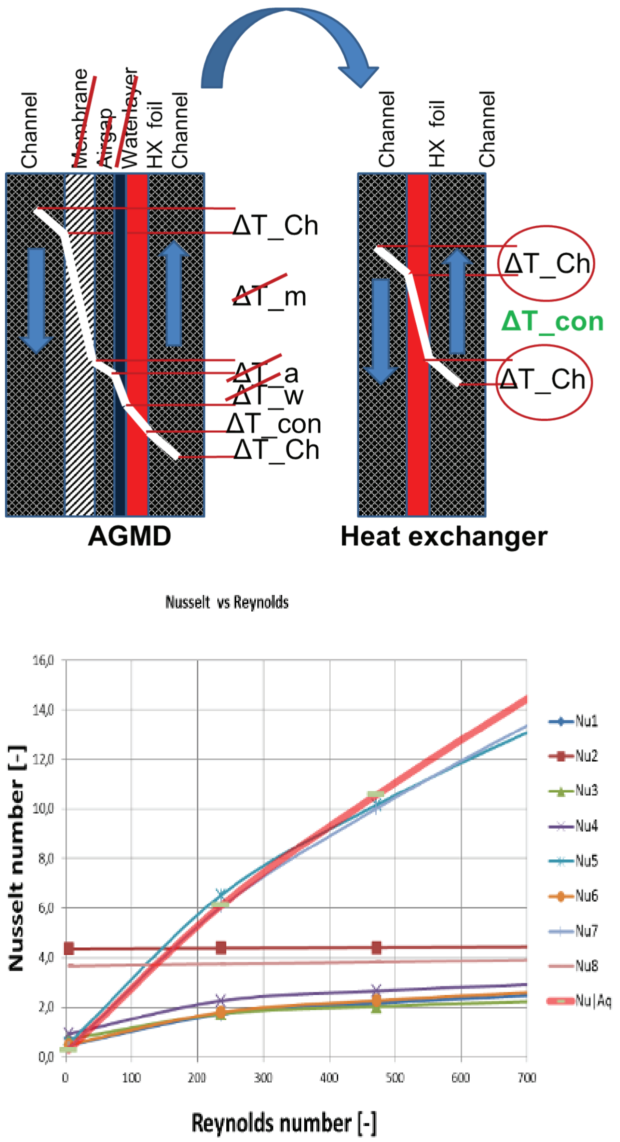

Figure 2: Generating a heat exchanger from a AGMD module & fitting mathematical relationship with the dataset

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The range for Reynolds numbers is limited due to pressure limitation inside modules. Typically a Reynolds number of 500 matches effective crossflow velocity inside spacer of approx. 0.1 m/s. This working window resulted in a formula that optimally describes the Nusselt number for spacer typically used at Aquastill:

$$\mathbf{Nu} = \mathbf{0{,}097} \cdot \mathbf{Re}^{\mathbf{0.73}} \cdot \mathbf{Pr}^{\mathbf{0{,}13}} \; [-] \qquad (3.14)$$

With:

Nu= Nusselt number [-]
Re= Reynolds number [-]
Pr= Prandtl number [-]

The heat transfer coefficient (αch) can now be easily calculated:

$$\alpha_{ch} = \frac{Nu \cdot \lambda_w}{d_{h|sp}} \; [W/(m^2 \cdot K)] \qquad (3.15)$$

With:

α_{ch}= heat transfer coefficient of the channel [W/(m²·K)]
Nu= Nusselt number [-]
λ_w= thermal heat conductivity of water [W/(m·K)]
$d_{h|sp}$= spacer hydraulic diameter [m]