

THEORETICAL AND EXPERIMENTAL STUDY OF A MULTI-STAGE MEMBRANE DISTILLATION SYSTEM

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ABSTRACT

The rapid growth of population, particularly in the developed countries, the desire to improve the living standards and the concern for the environment (protection of natural water resources) have resulted, in the last years, in the increasing demand and supply of sufficient quantity and good quality drinking water. The common thermal desalination technologies (multi-stage flash distillation, multiple stage evaporation, vapor compression) and the separation processes (distillation, reverse osmosis), even if they are commercially available, they present significant energy consumption and high costs. Membrane distillation (MD) is a relatively new and promising technology for the desalination of brackish and seawater.

MD is a non-isothermal membrane separation process that involves the transport of water vapormolecules from a hot aqueous solution through a microporous hydrophobic membrane, due to the vapor pressure difference that is created by the temperature difference between the two sides of the membrane. This is an attractive alternative solution to the conventional desalination techniques, due to the production of high quality distillate and the possibility of operating at low temperatures. Compared to other membrane separation processes (nanofiltration, reverse osmosis), MD operates at low pressures and can treat high concentration or supersaturated solutions. Moreover, the capability of utilizing solar thermal energy or waste heat from other processes, makes MD an energy and cost efficient and environmental friendly process.

The purpose of the present study is the theoretical and experimental approach of a multi-stage MD system. In that framework a mathematical model will be developed in order to investigate the effect of the operating parameters, such as the hot feed and cold stream temperature, feed flow rate and the concentration of the feed aqueous solution, on the quality and quantity of the produced desalinated water. The influence of the vacuum pressure is also important on the water vapor flux. The study of the design parameters (eg. channel width, membrane area) will give directions for the optimization of the system. This model can be used to study the thermal flow in cases of connection with thermal solar system and the use of the recovered heat of condensation, with final aim of maximizing the productivity and the energy optimization of the process. Furthermore, the model will assist the effective design of the experimental unit that will be used to validate the model results.

Keywords: Membrane Distillation, mathematical model, experimental unit

1. Introduction

MD is a thermal membrane separation process that involves the transport of water vapor molecules from a hot aqueous solution through a microporous hydrophobic membrane, due to the vapor pressure difference that is created by the temperature difference between the two sides of the membrane. This is an attractive alternative solution to the conventional desalination techniques, due to the production of high quality distillate and the possibility of operating at low temperatures. Compared to other membrane separation processes (nanofiltration, reverse osmosis), MD operates at low pressures and can treat high concentration or supersaturated solutions. Moreover, the capability of utilizing solar thermal energy or waste heat from other processes, makes MD an energy and cost efficient and environmental friendly process.

Although the MD technology is known for several decades, its exploitation in practice remained very limited until recently [1]. However, in recent years there has been an renaissance of research interest for applications in desalination, mainly due to developments in the field of materials and in particular the membranes. The investigation presented is a part of a wider research action with aim to elaborate technologically reliable and economically viable desalination MD solutions. The specific objective is the design of a pilot plant with the possibility of integration of innovative membranes and energy design optimization solutions, in terms of improving water recovery rate, gain ratio (Gained Output Ratio - GOR) and the performance ratio (Performance Ratio - PR).

The effective design of a desalination plant requires, except the research experience from previous installations, the use of an appropriate mathematical model of the process that will allow the parametric study of the effect of various operating parameters of the installation to various conditions of use. Such a model based on the simultaneous solution of mass and heat balances, taking also into account the phenomena of concentration polarization and temperature. Finally, the theoretical results obtained from the mathematical model lead to the effective design of the experimental MD set up.

2. Model development

For the thermohydraulic optimization of multi-stage membrane distillation systems, an one dimensional (1-D) mathematical model was developed for an air gap membrane distillation system (AGMD) with a flat sheet membrane. The model is based on mass and energy balances and combines the vacuum membrane distillation (VMD) and the multi-stage distillation concept. The system was treated as three different sections, which are related to each other through simultaneous mass and heat transfer. As illustrated in Fig. 1, the sections, in order from left to right, are: i) the evaporator, ii) a stage and iii) the condenser.

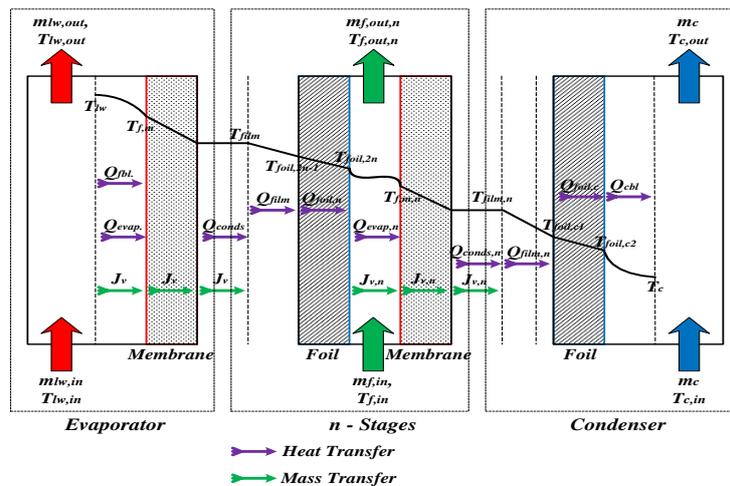


Figure 1: Schematic illustration of mass and heat transfer at a multi-stage system.

For simulation with reasonable computational expense, the model was simplified according to the following assumptions: i) the system is under steady state conditions, ii) there is no heat loss to the ambient environment, iii) the hot feed stream and cold stream flow in the x-direction only, iv) there are no mass and heat effects in the z-direction, v) the boundary layers at each stream are fully hydrodynamic and thermally developed, vi) there is a linear temperature distribution across the membrane, vii) pure water vapor is only transported through the membrane pores, viii) the concentration polarization affects (negatively) the process, ix) the physicochemical properties of the fluid (viscosity, density, etc) are only depended on the temperature. The mass balances at the evaporator and the stage can be described as follows:

Evaporator

- For the hot water stream:
$$m_{Lw,in} = m_{Lw,out} + J_{v, \text{evp}} dA_{\text{evp}} \quad (1)$$

Stage

- For the feed saline solution: $m_{f,in}^{SW} = m_{f,out}^{SW} + J_{v,n} dA_{stg}$ (2)

- For the salt: $m_{f,in}^{SW} x_{f,in}^{salt} = m_{f,out}^{SW} x_{f,out}^{salt}$ (3)

where $m_{lw,in}$, $m_{lw,out}$, $m_{f,in}^{SW}$, $m_{f,out}^{SW}$ are the mass flow rates of the hot water stream and saline water at the entrance and the exit of the evaporator and stage (kg/sec), $J_{v,evp}$, $J_{v,n}$ is the water vapor mass flux at the evaporator and stage (kg/m².sec), A_{evp} , A_{stg} is the membrane surface area of the evaporator and stage (m²) and $x_{f,in}^{salt}$, $x_{f,out}^{salt}$ are the salt mole fractions at the entrance and the exit of the stage respectively.

The energy balances at each section can be written as:

Evaporator: $Q_h dA_{evp} = m_{lw,in} C_{p,lw} T_{lw,in} - m_{lw,out} C_{p,lw} T_{lw,out}$ (4)

Stage: $Q_{foil,n} dA_{stg} = m_{f,out}^{SW} C_{p,sw} T_{f,out} - m_{f,in}^{SW} C_{p,sw} T_{f,in} + Q_{evap,n} dA_{stg}$ (5)

Condenser: $Q_c dA_{cond} = m_{c,lw} C_{p,w} (T_{c,out} - T_{c,in})$ (6)

where Q_h , $Q_{foil,n}$, Q_c is the heat flux at the hot water stream, at the foil of the stage and at the cold stream (W/m²), $Q_{evap,n}$ is latent heat of vaporization (W/m²), $C_{p,lw}$, $C_{p,sw}$ is the specific heat capacity of the liquid water and saline water (J/kg.K), A_{cond} is the condenser area (m²), $m_{c,lw}$ is the mass flow rate of the cold stream (kg/sec) and $T_{lw,in}$, $T_{lw,out}$, $T_{f,in}$, $T_{f,out}$, $T_{c,in}$, $T_{c,out}$ are the temperatures of the liquid water, saline water and cold stream at the entrance and the exit of each section correspondingly.

2.1. Mass transfer

In the MD desalination system, the mass transfer occurs in the feed boundary layer (concentration polarization) and across the porous membrane.

A mass balance across the feed side boundary layer described by the film theory, it gives a relationship between the mass flux of water vapor, J_v , the solute mass transfer coefficient, $k_{f,s}$ and the solute mole fraction:

$$x_{f,m}^{salt} = x_f^{salt} \exp\left(\frac{J_{v,n}}{\rho_f k_{f,s}}\right) \quad (7)$$

where ρ_f is the density of the feed solution (kg/m³). The solute mass transfer coefficient can be estimated from Sherwood number (Sh) via existing mass transfer correlations.

The mass transfer through the gas-phase membrane pores is typically described by the Darcy's law, whereby the water vapor mass flux is proportional to the partial pressure difference of water vapor across the membrane:

$$J_{v,n} = C_m (P_{f,m} - P_{film}) \quad (8)$$

where J_v is the water vapor mass flux through the membrane (kg/m².s), C_m is the membrane mass transfer coefficient (kg/m².s.P) and $P_{f,m}$, P_{film} are the partial pressures of water vapor at the feed – membrane interface and the condensing film surface (Pa).

The membrane mass transfer coefficient, C_m , is primarily a function of membrane structural properties (porosity, tortuosity, thickness and pore size), the physical and chemical properties of the vapour passing through the membrane (molecular weight, diffusivity) and the operating conditions (temperature and pressure). The C_m depends on the dominating mass transport mechanism within the membrane pores. The controlling diffusion mechanism in the membrane is related to the collisions between diffusing molecules and other molecules or the pore walls and can be determined by the ratio the ratio of the mean free path (λ_i) of the transported molecule to the pore size (d_p) of the membrane (Knudsen number). As the nominal membrane pore size of

the current system is 0.2 μm , close to the value of the mean free path of water vapor (0.49 μm at 70 $^{\circ}\text{C}$), Knudsen number ranges from 0.01 to 10. Therefore, it is assumed that the mass transport controlling mechanism within the membrane is a combination of Knudsen diffusion – Poiseuille flow. The membrane mass transfer coefficient is defined as:

$$C_m = \left(\frac{2}{3} \frac{\varepsilon r_p}{\tau \bar{\delta}_m} \left(\frac{8M_i}{\pi R T_m} \right)^{\frac{1}{2}} \right) + \left(\frac{1}{8\mu_i} \frac{\varepsilon r_p^2}{\tau \bar{\delta}_m} \frac{M_i P_m}{R T_m} \right) \quad (9)$$

where ε , r_p , τ , $\bar{\delta}_m$, is the porosity, the pore size (m), the tortuosity, and the thickness (m) of the membrane and M_i is the permeating specie molecular weight (kg/mol), T_m , P_m is the average temperature and pressure at the membrane.

2.2. Heat transfer

2.2.1. Evaporator

The evaporator is built from membranes and is optimized to create steam from fresh water as driving thermal energy source for the process. The heated fresh water is evaporated at the feed – membrane interface and the created vapor flows to the first stage, where is condensed. The total heat is transferred from the bulk feed through the feed boundary layer to the feed – membrane interface by convection (Eq. 10). The transferred heat at the membrane surface is consumed only by the latent heat of vaporization (Q_{evap}), assuming that the heat conduction through the membrane can be neglected (Eq. 11).

$$Q_{\text{fbl}} = h_{\text{fbl}} (T_{\text{lw}} - T_{\text{f,m}}) \quad (10)$$

$$Q_{\text{evap}} = J_{\text{v, evp}} \Delta H_v \quad (11)$$

where Q_{fbl} (W/m^2) is the heat flux across the feed boundary layer, h_{fbl} ($\text{W}/\text{m}^2 \cdot \text{K}$) is the heat transfer coefficient at the hot water stream [2], T_{lw} is the average temperature at the feed side of the steam raiser (K), $T_{\text{f,m}}$ is the temperature at the feed – membrane interface (K) and ΔH_v is the latent of vaporization.

2.2.2. Stage

A stage is comprised from foils and membranes alternating, starting with a foil. In each stage the generated vapor flows from one stage (or evaporator) through a channel and it is completely condensed at the surface of the impermeable foil (Eq. 12). As pure water vapor is condensed on the foil, a condensing film is formed at the top of the foil and flows downward under the influence of gravity. The latent heat of condensation is transferred through the condensing film and the foil by conduction (Eq. 13, 14) and is transmitted to the feed channel where it heats up the feed saline stream.

$$Q_{\text{evap}} = Q_{\text{conds}} = J_{\text{v, evp}} \Delta H_v \quad (12)$$

$$Q_{\text{film,n}} = \frac{k_{\text{film}}}{\bar{\delta}_{\text{film}}} (T_{\text{film,n}} - T_{\text{foil,2n-1}}) \quad (13)$$

$$Q_{\text{foil,n}} = \frac{k_{\text{foil}}}{\bar{\delta}_{\text{foil}}} (T_{\text{foil,2n-1}} - T_{\text{foil,2n}}) \quad (14)$$

where k_{film} , $\bar{\delta}_{\text{film}}$, k_{foil} , $\bar{\delta}_{\text{foil}}$ is the thermal conductivity ($\text{W}/\text{m} \cdot \text{K}$) and the thickness (m) of the condensing film [3] and foil, and $T_{\text{film,n}}$, $T_{\text{foil,2n-1}}$, $T_{\text{foil,2n}}$ are the temperatures (K) at the surface of the condensing film, at the vapor gap – foil interface and at the foil – feed channel interface respectively.

Considering the feed channel as a control volume and uniform surface temperature at the foil and at the membrane, the outlet temperature of the saline water from the stage, $T_{\text{f,out}}$, can be calculated from the following equation:

$$\frac{T_{\text{foil},2n}+T_{f,m,n}-2T_{f,\text{out}}}{T_{\text{foil},2n}+T_{f,m,n}-2T_{f,\text{in}}} = \exp\left(-\frac{2W_{\text{mem}}L_{\text{mem}}}{m_{f,\text{in}}C_{p,\text{sw}}}\overline{h_L}\right) \quad (15)$$

where W_{mem} , L_{mem} is the membrane width and length (m) respectively, $\overline{h_L}$ is the average value of h for the entire length of the feed channel ($\text{W}/\text{m}^2\cdot\text{K}$) and $T_{f,m,1}$ is the temperature at the feed – membrane interface at the effect (K).

At the feed – membrane interface the water is partially evaporated and new vapor is produced. The heat transferred from the feed channel to the feed – membrane interface is only consumed by the latent heat of vaporization ($Q_{\text{evap},n}$), assuming that the heat conduction through the membrane can be neglected.

$$Q_{\text{evap},n} = J_{v,n}\Delta H_v \quad (16)$$

2.2.3. Condenser

The condenser consists of foils, where the produced vapor from the last stage is condensed completely (Eq. 17). The latent heat of condensation is transferred through the condensing film and the foil by conduction (Eq. 18, 19). In the boundary layer of the cold stream the heat is transported by convection (Eq. 20).

$$Q_{\text{evap},n} = Q_{\text{condsc}} = J_{v,\text{stg}}\Delta H_v \quad (17)$$

$$Q_{\text{film},c} = \frac{k_{\text{film}}}{\delta_{\text{film}}}(T_{\text{film},c} - T_{\text{foil},c1}) \quad (18)$$

$$Q_{\text{foil},c} = \frac{k_{\text{foil}}}{\delta_{\text{foil}}}(T_{\text{foil},c1} - T_{\text{foil},c2}) \quad (19)$$

$$Q_{\text{cbl}} = h_{\text{cbl}}(T_{\text{foil},c2} - T_c) \quad (20)$$

where h_{cbl} ($\text{W}/\text{m}^2\cdot\text{K}$) is the heat transfer coefficient at the boundary layer and $T_{\text{film},c}$, $T_{\text{foil},c1}$, $T_{\text{foil},c2}$, T_c , are the temperatures (K) at the condensing film surface, the vapor gap – foil interface, the foil – cold stream interface and the average temperature at the cold stream respectively.

Based to the above mass and heat transfer relations, a set of equations comes out for the temperatures T_{fw} , $T_{f,m}$, T_{film} , $T_{\text{foil},2n-1}$, $T_{\text{foil},2n}$, $T_{f,m,n}$, $T_{\text{film},n}$, $T_{\text{film},c}$, $T_{\text{foil},c1}$, $T_{\text{foil},c2}$, T_c . For solving these equations, algorithms were developed in Matlab version 8.2.0 (R2013b), which were solved by the minimization method. They were given hypothetical initial values at the unknown temperatures and a theoretical prediction of the water flux production were performed.

3. Experimental setup

The mathematical model that was developed earlier, contributed to the effective design of an experimental multi-stage membrane distillation unit. This MD unit will be used to validate the simulation model and to test several parametric variables, such as the stage of feed water flow, heating and cooling water flow, heating and cooling water temperatures and the level of vacuum applied.



Figure 2: Schematic illustration of the experimental multi-stage system.

The experimental unit consists of 1) the main distillation unit (membranes, foils, steam production and condenser), 2) heating, cooling, feed, brine and distillate tanks, 3) sensors and transducers for temperature, flow rate, pressure and water electrical conductivity, 4) power and control cabinet and finally 5) the vacuum cycle. Currently the unit is at the final stage of construction and experimental results are planned to be ready within few weeks. This unit promises to lower the specific energy consumption and maximize Gain Output Ratio (GOR) mainly due to the application of multi-stage and vacuum design.

4. Conclusions

An experimental multi-stage vacuum membrane distillation unit has been designed and is being currently installed in order to validate several parameters of the already developed theoretical model.

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