Designing and simulation of continuous direct contact membrane distillation process in Aspen HYSYS

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Abstract

Recently, the interest of membrane distillation (MD) process is increasing worldwide for desalination plants due to treat highly concentrated solutions. In current study, a continuous direct contact MD process to achieve desired recovery factor by using PVDF membrane is simulated. the design of the plant comprises multiple MD stages connected in series to achieve the set recovery factor of 40%. The simulation of this plant was performed by linking MATLAB and Aspen HYSYS software. The effect of operating and design conditions such as feed temperature and number of fiber, respectively, on key performance parameters including energy consumption, membrane area requirements, thermal efficiency, pressure drop, transmembrane flux and number of stages has been investigated. In this study, three different cases were investigated and the result indicated that by increasing the feed temperature from 70 to 80 °C , the total required membrane area and the thermal energy decreased from 370 to 266 m^2 and from 44.937×10^6 to 42×10^6 kJ/h, respectively. Also as the number of fibers increased from 3800 to 400, the total required membrane area and the thermal energy decreased to 364 m^2 and 42.856×10^6 kJ/h, respectively.

Keywords: Desalination process, Continuous Direct Contact MD, MATLAB and Aspen HYSYS

Introduction

Membrane Distillation (MD) is a membrane based thermal driven separation process with the principle of vapor–liquid equilibrium.Typically, MD is operated at moderate feed temperature (60–90 °C), which is significantly lower than thermal-based processes, such as multi-stage flash (MSF). Thus, recently, the MD process has been focused for desalination and many applications due to the attractive features and especially the relatively low operating feed temperature, which is suitable to apply the solar energy or utilizing low-grade heat source [1]. The advantages of MD compared to the conventional desalination processes are as follows: (i) lower operating conditions, such as temperature and pressure compared to MSF and multi effect distillation (MED), and reverse osmosis (RO), respectively, (ii) theoretically high rejection efficiency (100%) of non-volatile solute, and (iii) low effect of high osmotic pressure or concentration to vapor flux [1]. Depending on the process configurations, four different systems of MD have been identified: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Vaccum Membrane Distillation (VMD) and Sweep Gas Membrane Distillation (SGMD). The most common configuration of MD is DCMD.

In this study, a continuous DCMD process to achieve a particular recovery factor has been studied and simulated in commercial software Aspen HYSYS. The effect of operating and design condition such as temperatures of feed and permeate and number of fiber (in other words, velocity of streams), respectively, on key performance parameters including energy consumption, membrane area requirements and number of stages has been investigated.

process description

Bach or recirculation process requires feed tank with volume much bigger than installation yield. Similarly, the once through processes are limited to maximum single pass recovery rate (RR) of 10% [2]. In current study, MD stages connected in series to achieve a certain recovery factor has been considered as illustrated in Fig.(1). Each stages consists of the certain number of fibers to achieve certain membrane area. The specification of desired membrane and module design parameter were listed in Table 1.

Table 1.Design parameters of modules and main process parameters used in the modeling.

parameters	0.58 packing density	0.61 packing density
Module length (cm)	100	100
Fiber inner diameter (mm)	1	1
Fiber outer diameter (mm)	1.24	1.24
Membrane prosity	0.75	0.75
Module Inner Diameter(cm)	10	10
Number of fiber	3800	4000
Feed inlet temperature (°C)	70-80	70
Permeate inlet temperature (°C)	20	20
Membrane area (m^2)	14.80	15.58
Stream configuration	Counter current	Counter current
Stream allocation	Feed in lumen side	Feed in lumen side
Feed and permeate mass flowrate (kg/s)	7	7

The process description is as follows:

The feed solution, heated initially at the desired feed inlet temperature (T_{fin}) as Eq.(1), will enter the first module where some part will be yielded as the permeate. Due to conduction and convection through the membrane, the feed temperature will decrease along the module. Upon exit from the module, relatively cold stream has been reheated from T_{fout} to T_{fin} before introducing it into the next stage(Eq.(2)). This procedure will be carried out till the required recovery factor is achieved. Permeate will be introduced in counter-current mode to the feed solution. Thus the permeate stream temperature will increase along the module [3]. The number of stages connected will depend upon the required recovery factor and operating condition applied. Total thermal energy consumed has been calculated by summing up the corresponding values of all stages i as expressed in Eq.(3).

$$Q_{r-in} = \dot{m}_f \left(C_{p,in} T_{f,in} - C_{p,r} T_r\right) \tag{1}$$

$$Q_{out-in} = \dot{m}_f \left(C_{p,in} T_{f,in} - C_{p,out} T_{fout}\right) \tag{2}$$

$$Q_{total} = Q_{r-in} + \sum_{i-1} Q_{out-in} \tag{3}$$

The thermal efficiency of the DCMD process defined as the ratio of the vaporization heat associated with the transmembrane water flux (q_v) over the total heat flux and was expressed as Eq (4):

$$\eta = \frac{q_v}{q_v + q_c} \tag{4}$$

The pressure drop along the module was determined by following equation:

$$\Delta P_L = f\,\frac{L}{D_H}\,\frac{\rho v_{avg}^2}{2} \tag{5}$$

where f is the Darcy friction factor that is $f = 64/Re$, L is the length of the membrane module, ρ is the density of the feed solution, v_{avg} is the average feed velocity (v_f) and D_H is the hydraulic diameter [3].

The Recovery Rate (RR) based on feed volume intering into each stage was calculated by Eq. (6).

$$RR = \frac{J.A_m}{m_f} \tag{6}$$

The flowsheet simulation was developed using commercial software Aspen HYSYS V.10. The physicochemical properties for NaCl solution were correlated by the " NRTL" model. The simulation of the MD module was developed based on a coupled "tanks-in-series" and "black-box" approach that presented by Dong et al. [4].

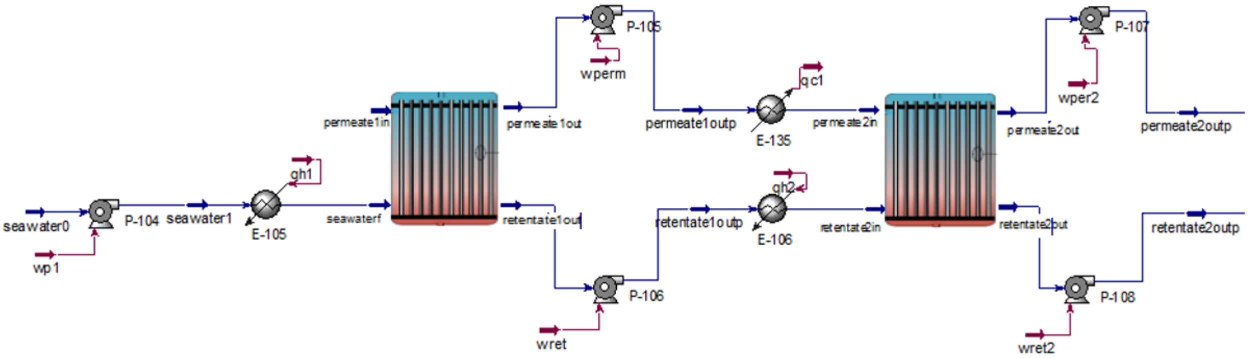

Figure 1. The schematic of MD process proposed for the larg scale application.

Results and discussion

In the present process simulation, three cases were simulated and the effect of increasing feed temperature as an operational variable and increasing the number of fibers as a design variable on key performance parameters such as energy consumption, membrane area requirements and number of stages has been investigated. In order to investigation of model validation, the modelling result have been compared with the result of literature [5], that confirming a good agreement between this model and literature results.

As shown in Fig.(2), when the feed side temperature increases from 70 to 80°C , the water flux increases as a consequence of the increase in the thermal driving force, as predicted by the Clausius - Clapeyron equation which describes the dependence of water vapor pressure on temperature. In the other case, the water flux increased with increasing packing density (as a result of increasing the number of fibers) at the same feed temperature. At a given feed flowrate, by increasing the packing density of a hollow fiber module while holding the module ID constant leads to increased feed velocity and decreased permeate velocity. Thus, the hydrodynamic condition and heat transfer behavior in hollow fiber modules were improved. In all cases, the water flux decreased from the first stage to the last stage. This is because low v_f exhibit more temperature depreciation along the length due to high residence time of feed inside the module that causes the required driving force for mass transfer to be gradually reduced in the later stages.

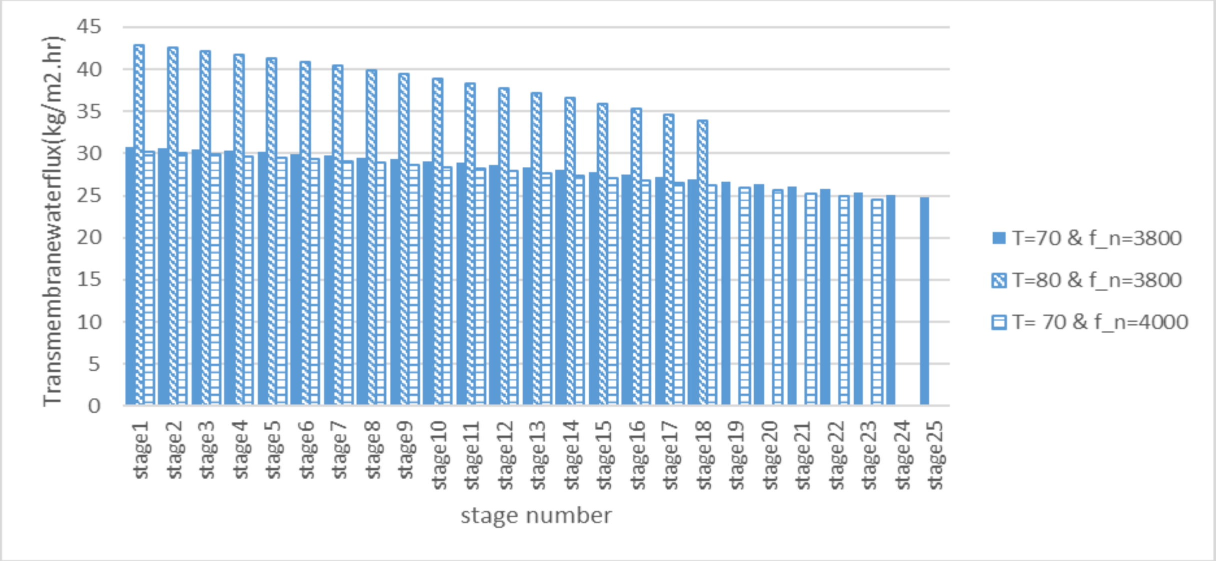

Figure 2. Transmembrane waterflux of MD module stages in three different cases.

The simulation results reported in Fig.(3) indicate that the thermal efficiency significantly improves at the higher feed temperature. However, as the packing density increases, the thermal efficiency does not change significantly, even they have exactly the same efficiency in some stages. The observed decreasing trend corresponding to the thermal efficiency from the first stage to the last one can be associated to reduction of water flux in the next stages.

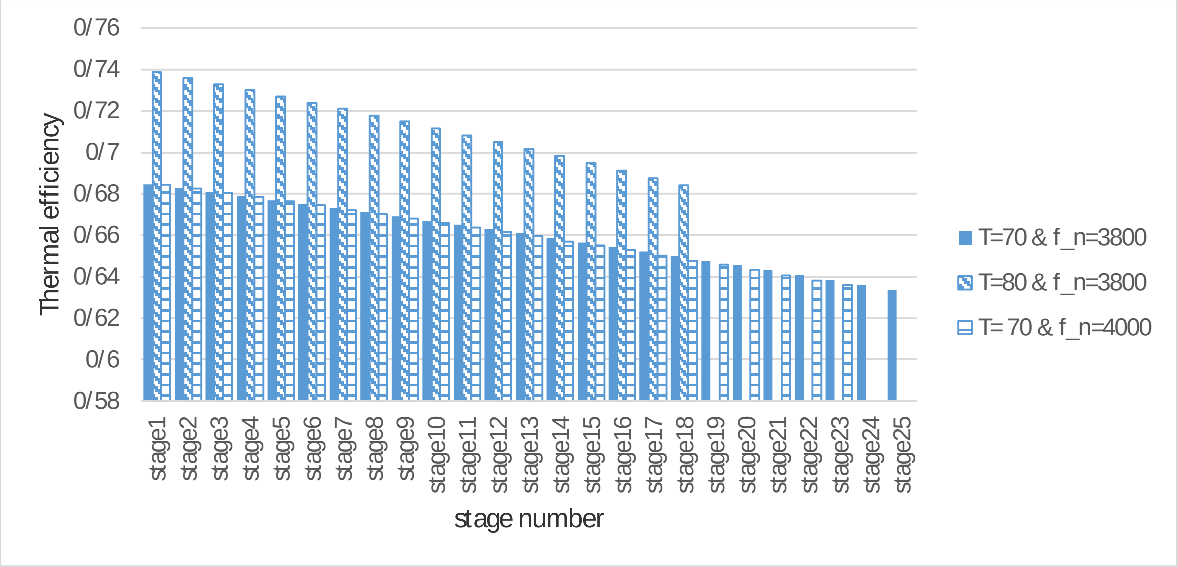

Figure 3. Thermal efficiency of MD module stages in three different cases.

As shown in Fig.(4), the RR increases by increasing feed temperature and packing density. A direct consequence of high RR is the reduction in feed flow rate entering into the next stage that will decrease net feed flow rate entering into subsequent stages. on the other hand according to Eq.(6) the entering feed flow rate into each stage is at the denominator, so an increasing trend of the RR is observed from the first stage to the last stage.

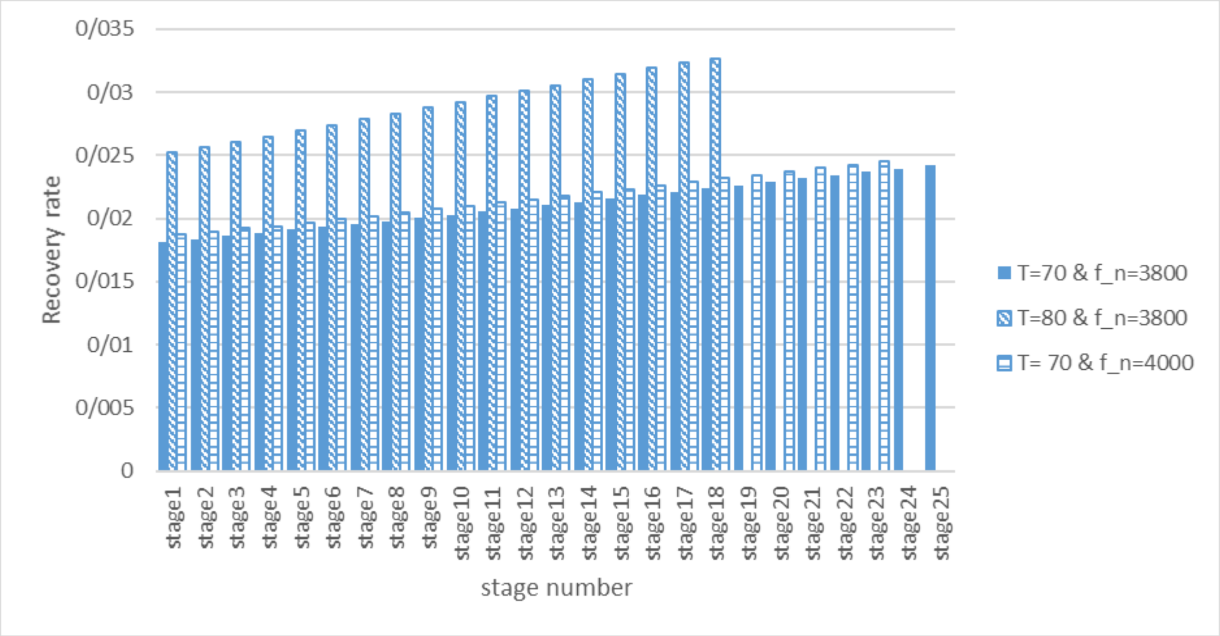

Figure 4. Recovery Rate of MD module stages in three different cases.

For successful operation of MD process, the criteria of non-wettability of membrane pores must be fulfilled. It implies that the fibers should not be exposed to the pressure exceeding the liquid entry pressure (LEP). LEP reported for PVDF membrane considered in current study is 138 KPa [5]. Pressure drop (PD) of all stages for the three simulated cases is shown in Fig.(5). It is clear from the figure that PD increases by increasing velocity of feed stream as a consequence of increasing the packing density. As the feed temperature rises, its density and viscosity increase. This effect results into increase in Re and decrease in pressure drop. The decreasing trend of PD observed in Fig.(5) from the first stage to the last one is due to reduction of feed velocity in the next stages. However, importantly, the pressure drop of all stages for the three cases, does not exceed the LEP reported for PVFD membranes used in current study.

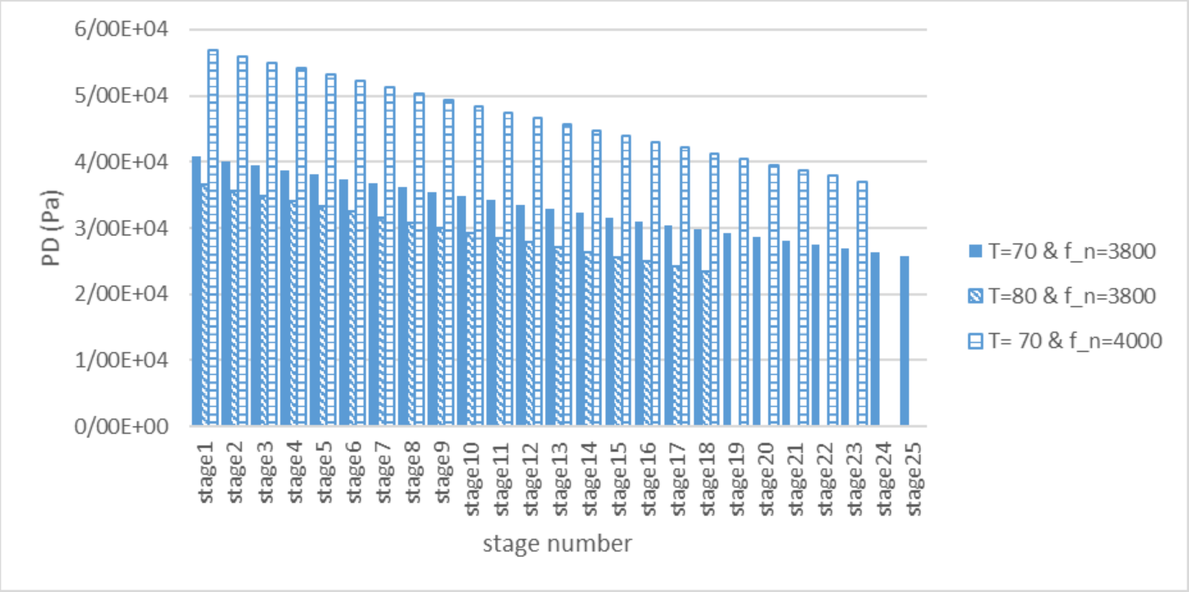

Figure 5. The pressure drop of MD module stages in three different cases .

Conclusions

A continuous DCMD process comprised multiple stages has been proposed to achieve overall recovery factor of 40%. Three different cases in term of feed temperature and number of fiber (in other word, packing density) has been simulated by linking MATLAB and Aspen HYSYS software. the result of simulated seawater desalination process showed that by increasing the feed temperature from 70 to 80 °C , the total required membrane area and the thermal energy decreased from 370 to 266 m^2 and from 44.937×10^6 to 42×10^6 kJ/h, respectively. Also as the number of fibers increased from 3800 to 400, the total required membrane area and the thermal energy decreased to 364 m^2 and 42.856×10^6 kJ/h, respectively. From the obtained result, it can be seen that if the energy is more expensive than the equipment, membrane distillation process for desalination of seawater by increasing the membrane area can be operated at a lower temperature and conversely.

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