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Importance of feed recirculation for the overall energy consumption in membrane distillation systems

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ABSTRACT

Membrane distillation (MD) has received significant interest for treating high salinity wastewaters, particularly when reverse osmosis is not feasible. MD has low single pass water recovery, which necessitates feed recirculation to achieve a desired overall water recovery. Feed recirculation increases turbulence in the feed channel to reduce polarization effects and membrane fouling. However, it increases the thermal and electrical energy requirements of the system. This study emphasizes the importance of recirculation and demonstrates its impact on the energy consumption of MD, which can be an order of magnitude greater when compared with calculations based on a single pass recovery. For instance, an increase in water recovery in a DCMD module from 10 to 50% for a feed solution containing 100 g/L of NaCl would increase the required recycle ratio by 633% (i.e., from 3 to 22) with a corresponding increase in thermal energy required to heat the recycle stream by 556% (i.e., from 39 to 256 kWh/m^3 of feed). While the electrical energy required for feed recirculation is only a few percent of thermal energy requirements, it may be a significant factor when considering the overall life cycle impacts of the MD process.

1. Introduction

Separation processes based on membrane technology have become an integral part of present day industries. Membrane distillation (MD) is one such technology that has the potential to become a cost effective approach for treating saline water to recover high-quality water. Unlike other membrane technologies, MD is a non-isothermal process which is driven by the vapor pressure difference across a hydrophobic membrane. Although the first MD patent was filed in 1963 [1], research on MD only received significant interest in early 1980s due to availability of membranes with improved characteristics [2]. This process is still in the early stages of the development for large scale applications. MD has been studied on a laboratory scale for the removal of heavy metals from wastewater [3], radioactive contaminants from aqueous solutions [4], desalination of sea water [5–7], fruit juice concentration [8–10] and acid recovery [11]. Pilot scale studies have been conducted for desalination of sea water and produced water from unconventional resources as well as treatment of groundwater and reverse osmosis concentrates [12–16].

1.1. Energy requirements in membrane distillation

Like all thermal separation processes, the major energy requirement of MD arises from the latent heat required to evaporate water on the feed side of the membrane. In addition, there are inherent process inefficiencies that result in additional energy requirements of MD. In direct contact membrane distillation (DCMD), these inefficiencies result from the sensible heat loss through conduction by the membrane from the feed side to the permeate side. The energy loss due to conduction can account for 30 to 80% [17–19] of the total thermal energy consumption of the process [20]. The conduction heat losses can be reduced by appropriate design of the MD module and membrane selection, and by optimizing the operating parameters of DCMD [18,21]. Significantly lower conduction losses can be achieved in vacuum membrane distillation (VMD) and air gap membrane distillation (AGMD) due to low thermal conductivity of gas phase on the permeate side [17,22].

1.2. The need for recirculation

Unlike pressure driven membrane separation processes like reverse osmosis and nanofiltration, which can have a single pass water recovery in the range of 50–84% [23–25] depending on the feed chemistries and the driving force, MD has significantly lower single pass water recovery [26,27]. A single pass MD system can be employed for desalination of sea water, where the objective is to provide fresh water. In such a case,

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sea water could be fed to the MD unit and the concentrate can be discharged because a large volume of saline water is available as feed for continuous operation. However, when the MD system is used to treat wastewater, an overall recovery factor much greater than that attained in a single pass system would be required. To attain a desired recovery factor, the concentrate (reject) stream leaving the MD system has to be reheated, recycled, and mixed with fresh feed. Concentrate recycling that is required for high recoveries in MD systems [14,28–30] will substantially increase the amount of thermal energy for reheating the concentrate stream and electrical energy for pumping it back to the inlet of an MD system. In addition, high recovery factors lead to increase in the feed salt concentration, which lowers the water vapor pressure at the feed side and decreases the evaporation efficiency [31–33]. While several studies estimated the maximum single pass permeate recovery [12,26,27,30,34–39] of an MD system, only two previous studies [30,40] provided the operating details needed to calculate the recycle ratio. A recycle ratio of 11.8 was estimated using the flow rates reported for the pilot scale DCMD sea water desalination system [30], while the recycle ratio of 10.6 was needed to achieve 66.7% water recovery when treating produced water from unconventional gas extraction [40]. In this study, an ASPEN Plus based model developed previously [40] was used to study the impact of recycle ratio on energy consumption of DCMD without heat recovery. The results from this study highlight the importance of feed recirculation in DCMD and its effect on thermal and electrical energy requirements in a continuous DCMD system used for concentrating high salinity brine.

2. Theory and methodology

2.1. Impact of evaporation efficiency on single pass permeate recovery and recycle ratio

For an MD system, the permeate flow across the membrane can be calculated as follows:

$$\text{Permeate flow}\left(\frac{\text{kg}}{\text{s}}\right) = \frac{\text{Evaporation efficiency*Enthalpy change in the feed}\left(\frac{\text{kJ}}{\text{s}}\right)}{\text{Latent heat of vaporization}\left(\frac{\text{kJ}}{\text{kg}}\right)}$$

or,

$$mx = \frac{\eta[mC_pT_{in} - m(1-x)C_pT_{out}]}{100{*}L} \quad (1)$$

where, m is the feed flow rate (kg/s), x is the fraction of feed that is recovered on the permeate side, η is the evaporation efficiency of the system, which is equal to the ratio of thermal energy utilized in evaporating the feed to total energy lost to the feed side [41–43], C_p is the specific heat capacity of water, which is assumed to be constant (4.184 kJ/kg/K), T_{in} and T_{out} are feed inlet and exit temperatures (°C), respectively, and L is the latent heat of vaporization of water (2260 kJ/kg). The above equation can be simplified as follows:

$$x = \frac{T_{in} - T_{out}}{\frac{100{*}L}{\eta C_p} - T_{out}} \quad (2)$$

Hence, the maximum amount of permeate that could be recovered from the feed in a single pass (i.e., single pass permeate recovery) can be calculated if the evaporation efficiency of a system is known.

2.2. DCMD simulation in ASPEN Plus platform

An ASPEN Plus (Version 8.8) model developed and validated in a previous study [40] was employed to study the impact of feed recirculation on energy requirements of a DCMD system. The model included fundamental equations of heat and mass transfer to simulate the operation of a countercurrent DCMD system and was used to calculate temperature, concentration and flow profiles of the feed and permeate streams. The equations and algorithm used for simulating DCMD is presented elsewhere [40]. In short, a step-wise modeling approach where the membrane module is divided into sections and energy and mass balance calculations were used to determine temperature and flow rates of feed and permeate streams for each section.

In DCMD, permeate flux can be calculated as follows:

$$J = C(p_{m,f} - p_{m,p}) \quad (3)$$

where, J is the permeate flux (kg/m^2/h), C is the membrane distillation coefficient (kg/m^2/h/Pa) and $p_{m,f}$ and $p_{m,p}$ are vapor pressures (Pa) at the feed-membrane and permeate-membrane interfaces, which correspond to membrane surface temperatures $T_{m,f}$ and $T_{m,p}$, respectively. Temperatures of the feed and permeate streams entering the DCMD system were used as the initial guesses of the membrane surface temperatures ($T_{m,\ f}$ and $T_{m,\ p}$) and the initial value of the flux (J) was calculated using Eq. 3 with a membrane distillation coefficient (C) of 5.6 kg/m^2/h/kPa determined in a previous laboratory-scale study [33]. Properties of the membrane and the spacer used in these experiments are available elsewhere [33,40] while heat transfer coefficients on the feed and permeate sides were calculated using Nusselt number correlations and used to determine the membrane surface temperatures [40]. These new values for membrane surface temperatures were used to determine the new permeate flux (J') corresponding to the adjusted membrane surface temperatures and this iterative procedure was repeated until the relative difference between two successive iterations reached a relative difference of 0.1%. The resulting permeate flux was used to determine the thermal energy transferred across the membrane, which is comprised of the latent heat lost with evaporated water and the heat transferred by conduction through the membrane. These results were combined with permeate flux values to calculate mass flow rates and temperatures of the feed and permeate streams leaving the module section. Lastly, the average feed and permeate temperatures in a module segment were determined and the initial guesses of membrane surface temperatures were updated with these values. The whole procedure, from updating the initial values of membrane surface temperatures to obtaining the average feed and permeate temperatures, was repeated until the relative difference between the average feed and permeate temperature estimated in successive iterations was below 0.1%.

Model calibration and validation using the experimental results from a DCMD system operated at different feed temperatures, flow rates and salt concentrations are presented elsewhere [40]. The following assumptions were used in the simulations performed in this study:

1- Process is at steady state.
2- Heat energy lost to the surroundings is assumed to be negligible.
3- Membrane wetting does not occur.
4- Salt rejection is assumed to be 100%.
5- Sodium chloride is the only dissolved constituent in the feed.
6- Membrane area is 0.2 m^2.
7- Membrane distillation coefficient is 5.6 LMH/kPa.

3. Results and discussion

The evaporation efficiency depends on membrane characteristics, hydrodynamic conditions in the feed and permeate channels, feed salinity and feed and permeate vapor pressures and varies significantly for different MD configurations. As demonstrated in Eq. 2, evaporation efficiency is a key factor governing single pass permeate recovery of an MD system and it was considered as an independent variable in this study to obtain a general trend in single pass permeate recovery. Fig. 1(a) shows the effect of evaporation efficiency on the single pass permeate recovery in an MD system with the feed inlet and exit