Integration of Crossflow DCMD modules in a cascade for energy efficient high recovery desalination

J. Gilron, H.Fei, L. Song and K. Sirkar
Dept. of Chem. Eng., New Jersey Inst. of Tech., Newark, NJ, 07102

Introduction

DCMD presents an opportunity to achieve desalination using low-grade waste heat and highly saline feed waters, where it may be economically competitive with RO, besides providing a very high quality product that could be used for boiler feed water and without the corrosion problems associated with metal based evaporators. Combined with high packing density polymeric heat exchangers, DCMD may allow large capacity desalination in a very small footprint, which is attractive for urban locations.

Crossflow DCMD modules developed by Li and Sirkar [1] show much promise in reducing temperature polarization, maximizing flux for a given temperature difference between hot and cold streams. The realization of this promise requires integration of the DCMD with heat exchangers to recover the heat from the hot distillate stream to heat the brine recycle and feed stream in order to re-use the heat input as many times as possible, so that a given amount of waste heat can produce a maximum amount of water. This requires that in a cascade of crossflow modules the temperature difference between the inlet and exit brine stream temperature ($\Delta T_{cascade}$) be as large as possible and that the temperature difference between brine inlet and distillate exit streams of the DCMD (ΔT_{end}) and the brine exit and distillate inlet streams of the heat recovery heat exchanger, be as small as possible:

$$\frac{\dot{m}_V}{Q_{in}} \approx \frac{\eta \Delta T_{cascade}}{(\Delta T_{end} + \Delta T_{HX})\Delta H_V} \text{ and } GOR \equiv \frac{\text{mt distillate}}{\text{heat equiv. of mt steam}} = \frac{\dot{m}_V \Delta H_V}{Q_{in}} \approx \frac{\eta \Delta T_{cascade}}{(\Delta T_{end} + \Delta T_{HX})} \quad (1)$$

where η is the thermal efficiency of the DCMD cascade (fraction of heat transferred from hot to cold stream due to vapor transport).

Results are presented of simulating a crossflow DCMD cascade with integrated heat recovery. These will help illustrate sizing the stages of crossflow DCMD modules to maximize energy recovery for a given water recovery.

Method

A series of crossflow DCMD stages were placed in series as shown in Figure 1. The model developed by Song et al. [2] was used to simulate the distillate production rate and the exit temperatures for a variety of brine and distillate inlet temperatures for a given specific feed low rate (kg/h feed per m^2 membrane). Preliminary heat balance arguments showed that the most efficient arrangement would be to have the brine inlet mass flow rate equal to the distillate exit mass flow rate. Regressions were carried out to relate stage brine temperature drop (ΔT_{stage}) to the temperature of closest approach ($\Delta T_{end,j}$) and this relationship was found to be nearly linear over significant ranges of ΔT_{stage} with the linear coefficients being functions of the brine inlet temperature to the stage.

A simple heat balance shows that the brine-distillate temperature difference at the brine exit of each crossflow DCMD stage is nearly equal to the temperature difference at the brine entrance. This allows the temperature difference at the brine exit of one stage to be set equal to the temperature difference at the inlet to the next stage:

$$\Delta T_{end,j} \equiv \left(T_{b,o} - T_{d,i}\right)_j \approx \left(T_{b,i} - T_{d,o}\right)_{j+1} \tag{2}$$

and this will be almost constant throughout the cascade and equal to the top ΔT_{end}.

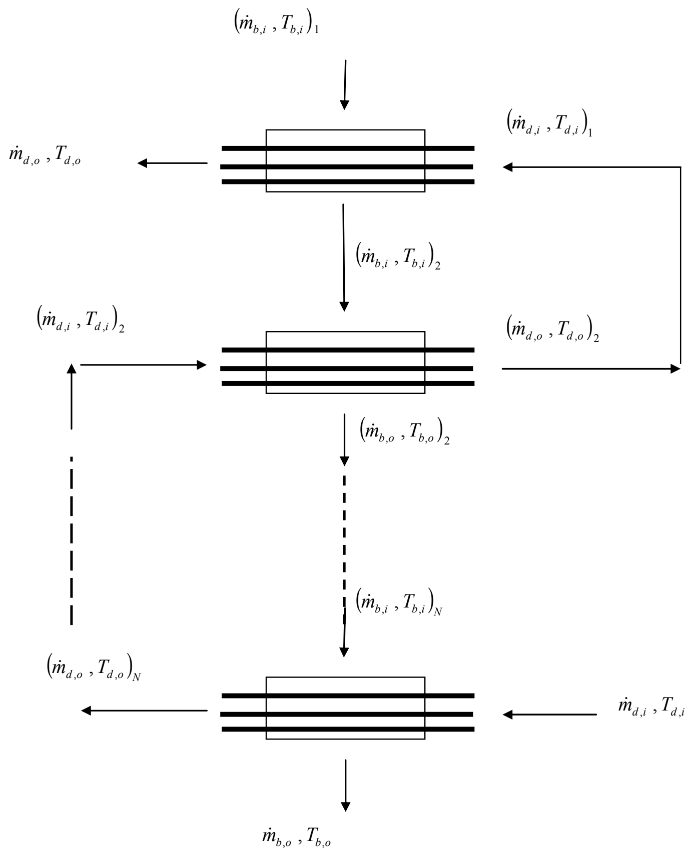


Figure 1.Column of crossflow modules.

The relationship between the ΔT_{stage} and $\Delta T_{end,j}$ for each stage can then be used to calculate the brine temperature drop per stage for a given ΔT_{end} and from this the number of stages can be figured. This can be represented graphically by a McCabe-Thiele type plot showing the number of crossflow stages obtained for a given brine inlet and exit temperature and given temperature of closest approach. This is illustrated in Figure 2 for a temperature of closest approach of 4 °C, and brine inlet and exit temperature of 95 and 33 °C respectively. The tie lines become steeper because at lower inlet brine temperatures the temperature of closest approach required for a given brine temperature drop is greater. This is because for a given flux a higher temperature difference is required to generate the same driving force to generate the flux, and the brine stage temperature drop is directly related to the flux.

Since each column of modules with its heat recovery heat exchanger has a limited recovery, a series of columns can be used to get high recovery in an once-through operation. The performance of such a series was evaluated with and without intercolumn heating. With intercolumn heating the brine was returned to the temperature of the brine to the first column. Without intercolumn heating, the brine was returned to the second column at its exit temperature from the heat recovery heat exchanger of the first column.

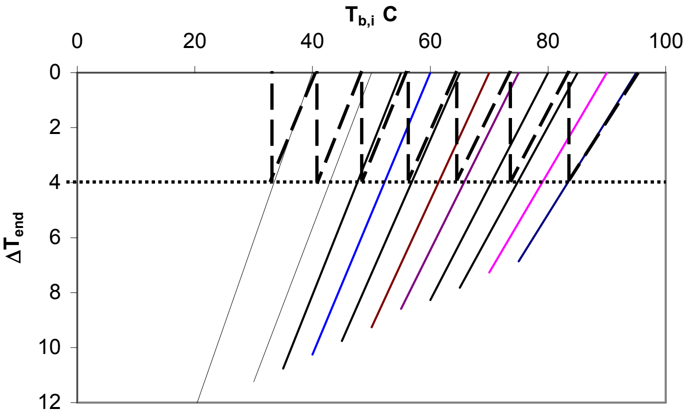


Figure 2. Calculating the number of crossflow DCMD stages needed for a given drop between brine inlet (95 °C) and outlet (~33 °C) and temperature of closest approach of 4 °C.

Results

Experiments conducted with four crossflow DCMD modules in series containing 250 cm^2 of internal area each and a brine flow rate of ~500 ml/minute, showed that the temperature of closest approach was indeed constant through the series of modules.

Figure 3 illustrates the tradeoff between GOR and number of stages for a brine inlet temperature of 95 C, which is the same kind of tradeoff found in all thermal desalination processes. The average flux will be inversely proportional to the number of stages as shown.

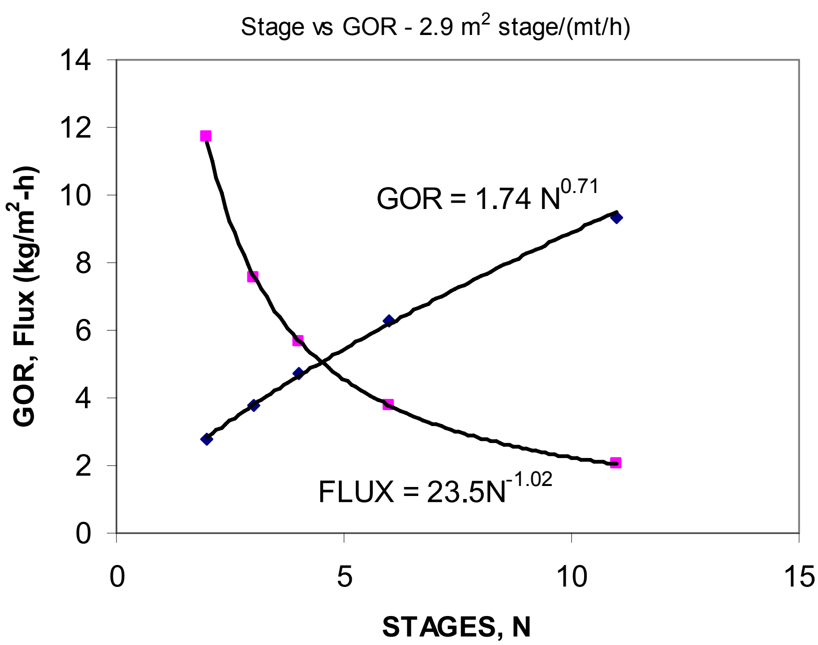
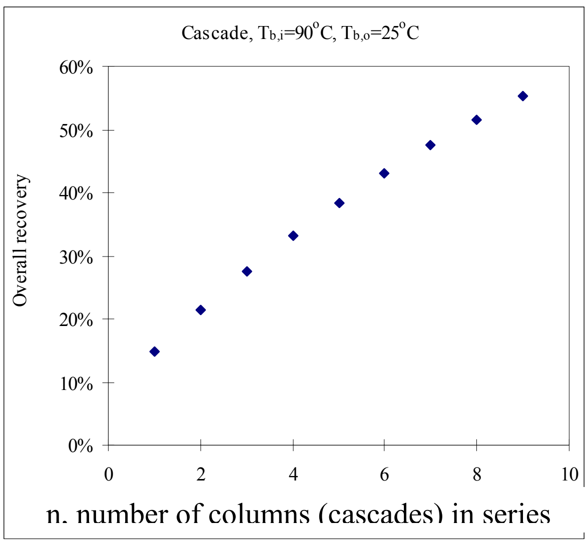


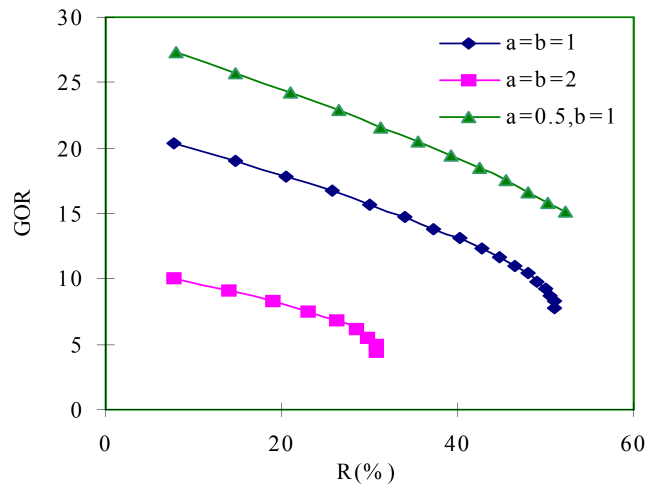
Figure 3.Tradeoff between GOR, flux and number of stages in cascades with $T_{b,i}$ = 95 °C.

Simulation varying the fiber layers (area) per crossflow stage for the same feed conditions showed that with crossflow stages with fewer fiber layers per stage, the same overall flux could be obtained with a closer temperature of approach (ΔT_{end}) allowing more water production per unit energy input for the same overall amount of membrane area.

The results with a series of columns showed that intercolumn heating allowed for greater overall recovery than using a series of columns without intercolumn heating. This is illustrated in Figure 4. With intercolumn heating of the brine, each individual column had the same productivity per unit heat input (same GOR) and so the overall GOR was also the same. Looking at the case without intercolumn heating and $\Delta T_{end}=\Delta T_{HX}=2$ we see that the maximum recovery possible is only 30%, whereas with intercolumn heating the recovery exceeds 50% for the same number of columns.



a)



b

Figure 4.GOR and recovery possible with a series of columns of crossflow modules. $T_{b,i}=90$ °C and $T_{d,i} = 25$ °C and 90% efficiency. a) series of columns with intercolumn heating of the brine $\Delta T_{end}=\Delta T_{HX}=2$. b) series of columns without interstage heating, each point is another column in the series $a=\Delta T_{DCMD}$, $b=\Delta T_{HX}$.

References:

1. Li, B., and K.K. Sirkar, Novel membrane and device for direct contact membrane distillation – based desalination process, *I&EC Research*, **2004,** *43*, 5300-5309.
2. Song, L, B. Li, K.K. Sirkar and J. Gilron, Direct contact membrane distillation-based desalination: Novel membranes, devices, larger-scale studies and a model, submitted, I&EC Research (2006).