CYCLE PERFORMANCE OF MULTI-STAGE VACUUM MEMBRANE DISTILLATION (MS-VMD) SYSTEMS

Authors: *Edward K. Summers, John H. Lienhard V*

Presenter: Edward K. Summers
Massachusetts Institute of Technology – United States
esummers@mit.edu

Abstract

In membrane distillation, a heated saline liquid stream is allowed to vaporize through a hydrophobic porous membrane. Vacuum membrane distillation (VMD) is a variation on this process in which the driving pressure difference is increased by lowering the pressure on the vapor side of the membrane. The heat of vaporization is recovered in an external condenser. This process has been applied to the desalination of seawater. However, energy recovery is limited by the saturation temperature of the pressure in the condenser. Maximizing flux by increasing the pressure difference between the saline feed and the condenser results in poor energy recovery. This paper proposes a simple cycle in which many membrane modules and condensers are cascaded at successively lower pressure as more vapor is removed from the feed, and the feed temperature decreases. By reducing the pressure step-wise over many stages, the feed can be preheated to a higher temperature in the condenser. This type of cycle is also found in multi-stage flash (MSF) desalination systems. MSF systems, however, generally require large-scale components and associated infrastructure, particularly for the flash chambers that produce vapor. By replacing the flash chambers with membrane distillation modules, a more compact system can be built, lending itself to small-scale and off-grid desalination applications. Modeling of the energy efficiency and irreversibility has shown that these MS-VMD systems can achieve performance comparable to MSF for the same operating conditions. Additionally, MS-VMD can operate at lower temperatures without the need for a steam generator, allowing the use of low temperature heat sources, such as unconcentrated solar energy.

I. INTRODUCTION

In membrane distillation, a heated saline liquid stream is allowed to vaporize through a hydrophobic porous membrane. Vacuum membrane distillation (VMD) is a variation on this process in which the driving pressure difference is increased by lowering the pressure on the vapor side of the membrane. The resulting vapor is condensed in an external condenser. In desalination systems, recovering the energy given off in condensation is essential to thermal efficiency of the system, which is strongly correlated with low water cost [1]. Some studies of VMD from an energy efficiency point of view have been conducted, but typically report low performance. Performance as measured by the Gained Output Ratio[1] (GOR) is below 1 for these systems [2, 3]. Work by the authors on the cycle performance of single stage VMD systems yielded similar results, and demonstrated that the fundamental performance limit of a single-stage VMD systems to a GOR of 1 [4].

This arises from the fact that energy recovery is limited by the saturation temperature of the pressure in the condenser. Maximizing flux by increasing the pressure difference between the saline feed and the condenser lowers the condensation temperature in the condenser, which requires high mass flow rates of colder water to condense the additional vapor, when compared to a system with a smaller pressure difference (higher saturation temperature) and lower flux. This trade-off results in poor energy recovery.

II. STAGED VMD SYSTEM

One way to maximize energy recovery is to stage the MD modules in a similar manner as that found in multi-stage flash (MSF) desalination. In MSF vapor is produced by flashing heated liquid at sequentially lower pressures. The vapor is condensed at the reduced pressure in each stage, pre-heating saline water, which acts as a coolant. MSF systems can have upwards of 40 stages with a small pressure difference between them. The simplest case is the once-through MSF system. This system achieves a GOR of 3-7 depending on the season. In winter, lower feed water temperatures reduce performance, as greater feed preheating is required [5]. Figure 1 shows a typical MSF desalination system.

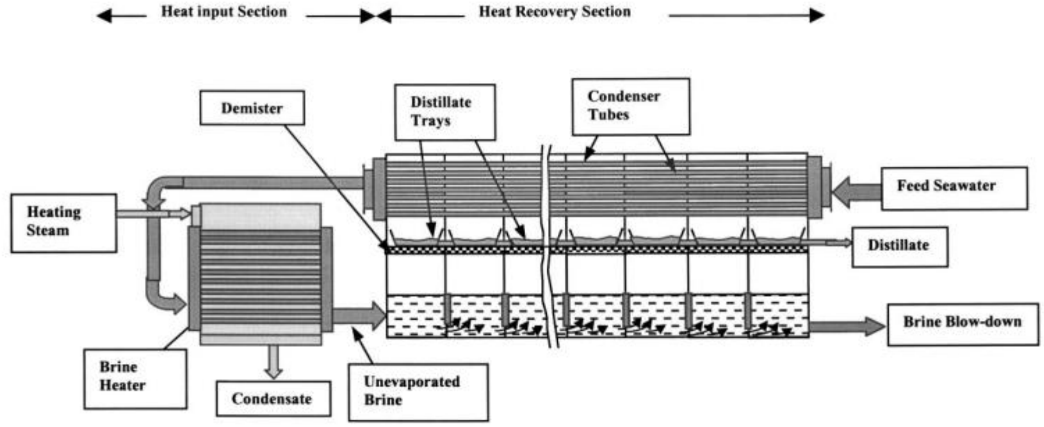

Figure 1: Process diagram for a once-through MSF system from [5].

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[1] GOR is the ratio of the latent heat of evaporation of a unit mass of product water to the amount of energy used by a desalination system to produce that unit mass of product. The higher, the GOR, the better the performance. For example, a solar still would have a GOR on the order of 1, whereas a good Multi-Effect Distillation system may have a GOR of 12.

In the proposed multistage configuration of VMD the flash chambers of MSF are replaced with membrane distillation modules. Optimal membrane sizing and flow rates were taken from results of previous work [4]. Membranes were short in the flow direction with over 300 sheets in parallel to maximize water production. Feed flow channel size was chosen to balance heat transfer coefficient (to minimize temperature polarization) and pressure drop. Figure 2 shows a multi-stage VMD system.

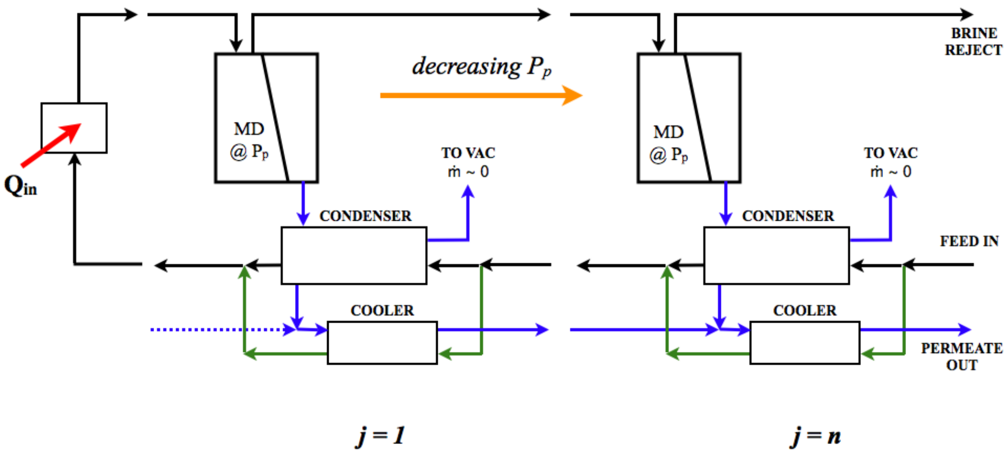

Figure 2: Multi-Stage Vacuum MD (MS-VMD) process diagram.

This configuration has several distinct advantages over MSF. MD systems are easily scalable. MSF systems are typically built into municipal water systems and desalinate hundreds of thousands of cubic meters of water per day. Flash chambers have to be large to accommodate the vapor and reduced pressure. Flash chambers also require extra hardware to keep seawater mist from contaminating the condensed vapor. MD modules can be built smaller to accommodate lower volume applications, such as off-grid water purification. In MD, spaces where the pressure is reduced are very small requiring a smaller amount of lower strength, and often cheaper, materials to support the pressure difference. Lower temperatures in MD also mean that the membrane and heat exchanger surfaces are less prone to fouling.

In cases where such a system may be used off-grid reduced pressure can be generated from a mechanical vacuum pump powered by photovoltaics. For a larger scale system a steam ejector can be used to maintain vacuum in each MD stage, as is done in a multi-effect distillation (MED) system.

III. METHODS

This paper compares MSF with Multi-Stage VMD by using a once-through configuration for each system. Models for each system were solved in using the Engineering Equation Solver simultaneous equation solver [6]. To model the heat and mass transfer processes in a MD module, an analytical model developed by the authors [4] was adapted to be solved numerically, with a flat-plate membrane module separated into differential cells along the direction of fluid flow. The membrane divided along its length, L, in the flow direction, into cells of length *dz* and width *w*, which multiplied make a differential area element, *dA* [4]. Bulk flows serve as inputs and outputs for neighboring cells. Figure 3 shows the control volume for a cell of a VMD module.

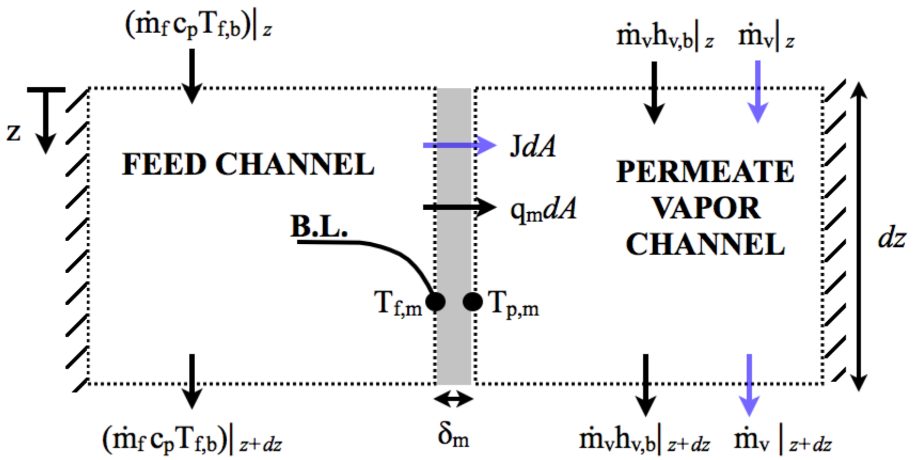

Figure 3: Control volume of a differential length of VMD module

Other components in the system are modeled based on "black box" control volume models. The condenser and permeate cooler are both modeled with an effectiveness model and energy balance. Equations 1 - 2 detail the energy balance and effectiveness model for the condenser.

$$\dot{m}_{cond} c_p \left(T_{cond,out} - T_{cond,in}\right) = m_p \left(h_{p,v}^{\cdot} - h_{p,c}\right) \tag{1}$$

$$\epsilon = \frac{h_{p,v} - h_{p,c}}{h_{p,v} - h_{p,c,max}} \tag{2a}$$

$$\frac{h_{p,max}}{c_p} = T_{cond,in} \tag{2b}$$

where the subscript *cond* denotes the coolant passing through the condenser, which is saline water being pre-heated, and p denotes permeate water passing from the vapor state, v to a condensed liquid state, c. A perfectly effective condenser ($\varepsilon = 1$) would cool the liquid permeate to the coolant inlet temperature. A model for the permeate chiller follows similarly, however instead of entering as a vapor the permeate would enter the chiller carrying an enthalpy $h_{p,c}$.

As a means of comparison with an MSF system, the component performance can be measured by the log-mean temperature difference (ΔT_{lm}). These are approximately 13 ◦C for the condenser and 10 ◦C for the permeate chiller. Similar or better component effectiveness can be found in actual large-scale MSF systems [7]. These log-mean temperature differences correspond to effectiveness, ε, values of 0.98 and 0.96 for the condenser and permeate chiller respectively. Equation 3 defines the log-mean temperature difference for the heat transfer components where the subscripts *in* and *out* represent the coolant stream and *hot* represents the inlet stream of the fluid to be cooled or condensed.

$$\Delta T_{lm} = \frac{T_{out} - T_{in}}{\ln\left(\frac{T_{hot} - T_{in}}{T_{hot} - T_{out}}\right)} \tag{3}$$

As a compromise between summer and winter performance, the seawater inlet temperature is set at 20 ◦C and seawater inlet temperature at 95 ◦C, which is near the upper limit for MD systems. For the purpose of comparison, a once-through MSF system as outlined in Figure 1 is used where the membrane modules are replaced by an isenthalpic flashing process at the same pressure. The decrease in vapor saturation temperature from stage to stage (called ΔT_{flash} in MSF systems) is 3 ◦C. Saturation temperature determines the pressure in each module, P_p.

Optimal membrane sizing and flow rates were taken from results of the parametric study of VMD systems in previous work by the authors [4]. The membrane module was designed to produce the maximum amount of vapor at a given permeate pressure. The maximum amount of vapor is produced when the feed temperature exiting the module is reduced to the saturation temperature at the given module pressure, P_p, and the driving potential for evaporation is zero. As a result, membranes were short in the flow direction with 400 sheets in parallel such that the feed reaches the saturation temperature at the end of the module and no non-productive membrane is used. If the difference in saturation pressure between each stage is equal then the optimal module design for one stage should be close to optimal for all other stages. Feed flow channel size was chosen to balance heat transfer coefficient (to minimize temperature polarization) and pressure drop. A full list of system parameters for the two modeled systems can be found in Table 1. For the model of the MD module, separating the length into 40 cells was sufficient to prevent changes in the results (within ½%) which arise from discretizing the model.

Table 1: Parameters for MS-VMD system and MSF equivalent.

Operational Parameters		**Membrane Module**	
Inlet Mass Flow Rate	3 kg/sec	Length	2 m
Top Temperature	95 ◦C	Width	0.15 m
Seawater Inlet Temperature	20 ◦C	Flow Channel Depth	2 mm
Number of Stages	20	Membrane Thickness	200 μm
ΔT_{flash}	3 ◦C	Pore Size	0.2 μm
Condenser Effectiveness	0.98	Number of Parallel Sheets	400
Cooler Effectiveness	0.96	Membrane Distillation Coefficient, B	16×10^{-7} kg/m^2 sec Pa

IV. RESULTS

4.1 Energy Efficiency - GOR

A MS-VMD system and a MSF system operating at the same top and bottom temperatures, mass flow rate, and ΔT_{flash} are compared. Both systems show very comparable thermal performance, for a membrane module that is optimally designed to produce the largest amount of vapor possible. This makes the end states of the evaporation process in MS-VMD similar to the end states of the evaporation (flashing) process in MSF, with the resulting vapor produced in MS-VMD exiting the module slightly superheated, as vapor near the feed inlet is produced at a temperature slightly above the saturation temperature for that stage (Vapor at the feed inlet is produced near the saturation temperature of the previous stage). For the operating conditions given above and the same number of stages, multi-stage VMD has very similar performance as measured by GOR as shown in Figure 4. Performance for a non-optimal membrane module, which contains a quarter of the membrane area of an optimized module, is also shown.

Performance is significantly lower, demonstrating the importance of module geometry in achieving superior system performance.

As with MSF, performance is greatest for a large number of stages. The number of stages modeled for this case is restricted by the maximum number of variables allowed in EES. Decreasing ΔT_{flash} allows a greater number of stages and higher thermal performance as the temperature gradient between the vapor and condenser is smaller, however, equipment cost would be prohibitive.

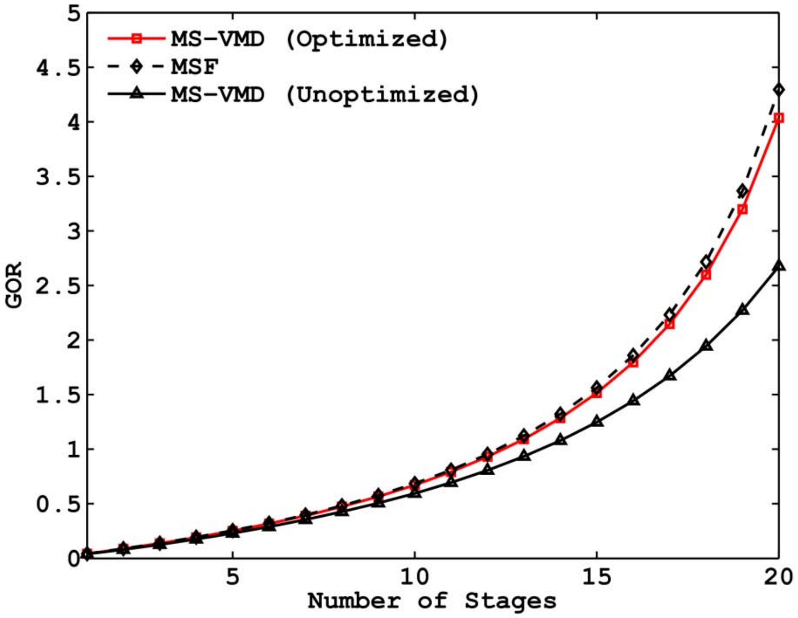

Figure 4: GOR as a function of the number of stages in an MS-VMD process

4.2. Irreversibility - Entropy Generation

Another way to evaluate the performance of the MS-VMD is to look at the rate of entropy generation compared to similar components in MSF. Here a 20-stage system for both MS-VMD and MSF with the parameters described in Table 1 will be used. Specific entropy generation in a stage is defined as the total entropy generation divided by the flowrate of fresh water permeate produced in that stage. Entropy generation is defined as the difference between the flows, *i*, of specific entropy going in and out of the control volumes shown in Figure 5.

$$\dot{s}_{gen} = \frac{\sum_i \dot{m}_{out,i} s_{out,i} - \sum_i \dot{m}_{in,i} s_{in,i}}{\dot{m}_p} \qquad (4)$$

Figure 6 shows a breakdown of specific entropy generation for each system. For MS-VMD, the evaporation of water through an MD membrane replaces the vapor flashing process in MSF. Despite the small pore sizes in an MD membrane, which would lead to a great deal of mass transfer resistance, and thus high irreversibility, the vapor flashing process is comparably irreversible. In fact, the production of vapor in and MD process is less irreversible than a flashing process, but produces superheated vapor. The greater source of irreversibility comes from the condensation and cooling process, which could be targeted for improvement; for example, by using a more effective condenser, or using more stages and decreasing ΔT_{flash} to minimize the temperature gradient between the vapor and condenser.

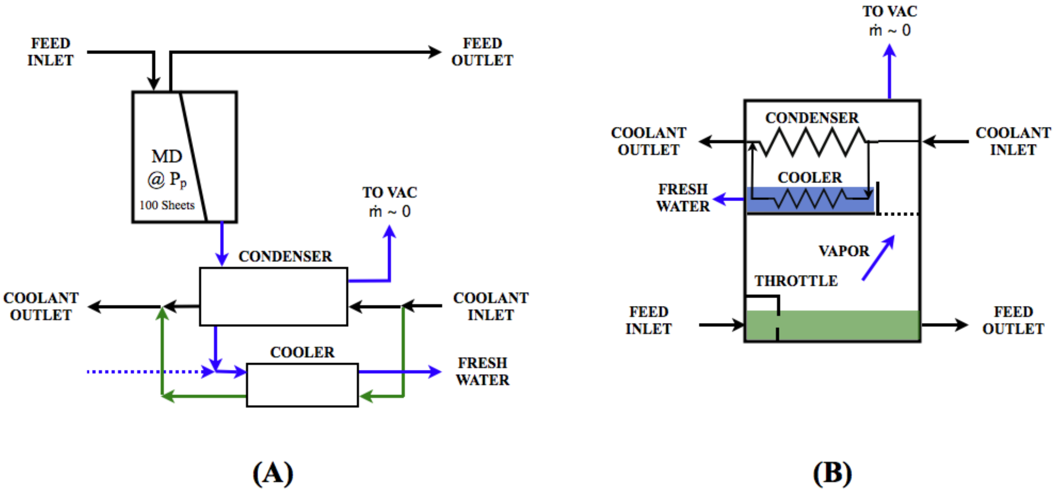

Figure 5: Control volumes for comparison of entropy generation. (A) A MS- VMD single stage, and (B) a MSF stage with the same components. Specific entropy is evaluated at the inlets and outlets shown.

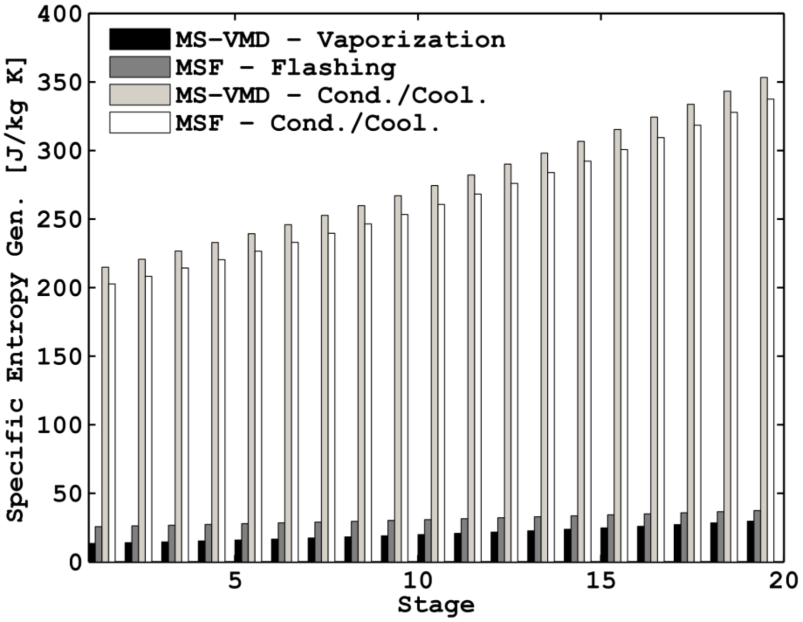

Figure 6: Irreversibility comparison between a conventional once-through MSF system and the MS-VMD process

V. CONCLUSIONS

Analysis from both energy efficiency (GOR) and irreversibly (entropy generation) perspectives clearly demonstrates the viability of MS-VMD for scalable, and potentially reduced cost, water desalination. Using entropy generation analysis it can be shown MD modules produce vapor more efficiently. However, due to the production of slightly superheated vapor in an MS-VMD systems, the temperature gradient between the vapor and condenser coolant is larger, leading to more irreversibly in the condensation and cooling steps. This balances out the more efficient production of vapor to produce a MS-VMD system that is overall very comparable in energy efficiency to MSF, with the benefits of a more scalable system, the use of inexpensive polymer materials, and the use of lower temperature heat sources, such as solar energy.

VI. REFERENCES

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