Aspen Plus® and CFD Coupled Simulation for the Optimisation of Vacuum Membrane Distillation Process

Boyue Lian, Yuan Wang, Pierre Le-Clech, Vicki Chen and Greg Leslie

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Introduction

Submerged Module

Cross-flow Module

- Thermal driven membrane separation process, such as Vacuum Membrane Distillation (VMD) has been developed for recovery of volatile compounds from food and pharmaceutical streams, now considered for desalination of brine water .
- Numerous lab studies on new membranes and materials have been conducted; but limited work on module design and process scale up for water application and no development of design tools.

Knowledge gaps:

- What is a good design for VMD?
- Systematic evaluation of submerged and cross-flow module
- How process changes can improve the energy efficiency of VMD

Challenge:

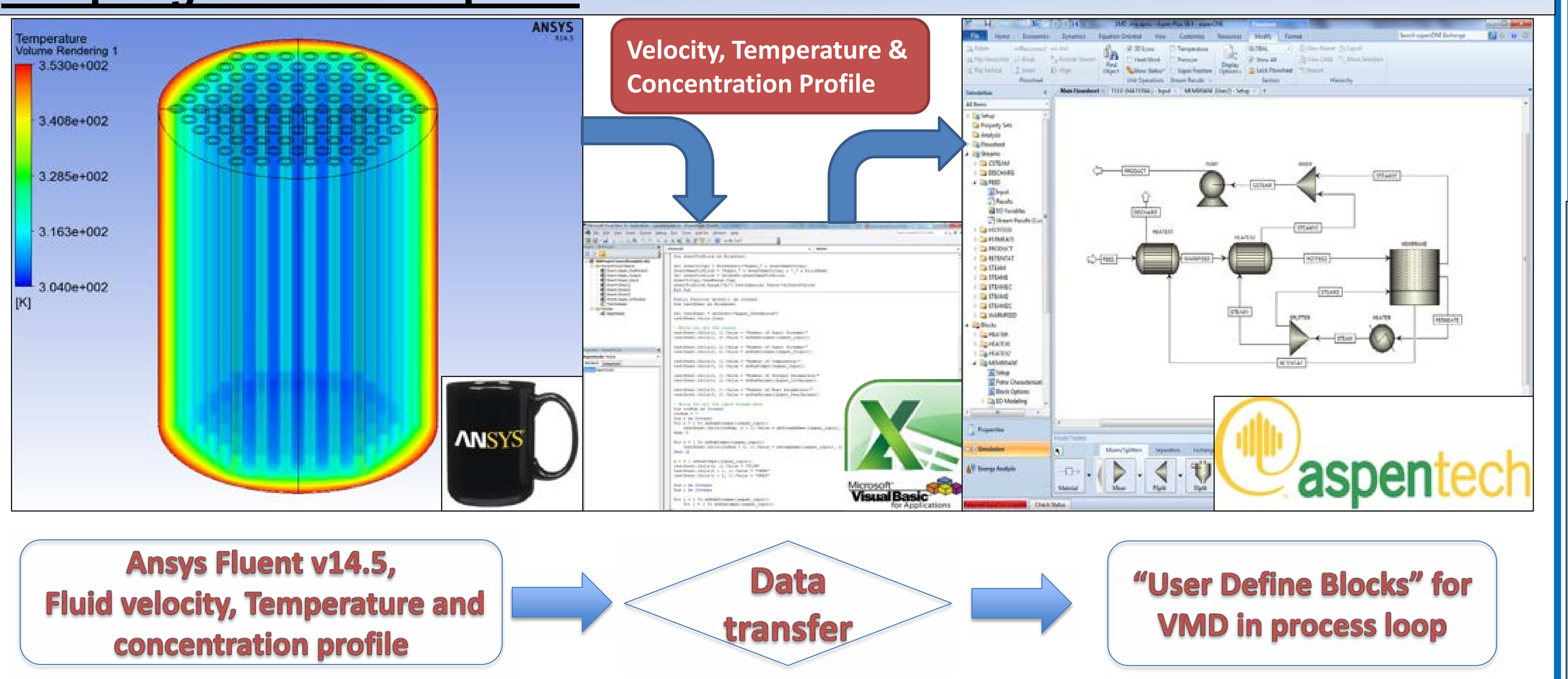
- Limited tools to simulate VMD and incorporate data on permeability

Objective

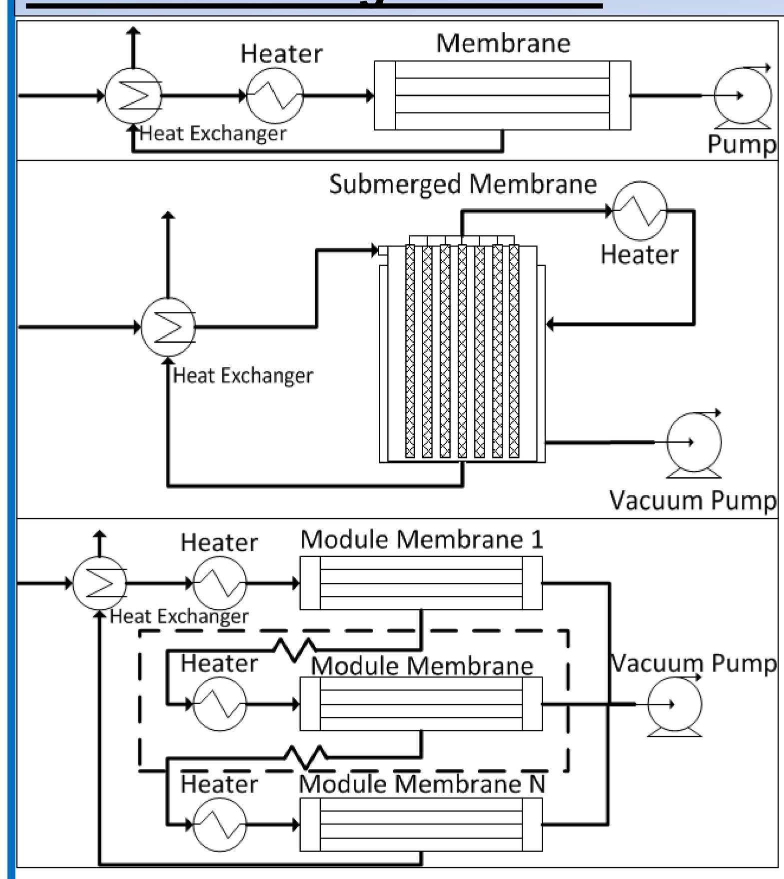
- To develop a CFD and Aspen® Coupling method to design VMD configuration with respect to fluid flow, mass and heat transfer and evaluate the overall system performance.
- To investigate the effects of module and process configurations on the production and energy consumption of VMD.

Approaches

Coupling CFD and Aspen®:



Process configurations:



Normal VMD (Pre-heating/OneUnit):

- Energy is recycled from retentate stream.

Alternative submerged VMD(Post-heating):

- Additional energy is required for submerge VMD to provide heat for evaporation.
- The alternative process utilizes heat from permeate by further heating up to 100 °C and re-direct back to the submerged VMD.

Alternative Cross-flow VMD (FourUnit):

- Cross-flow VMD relies heat from high inlet feed flowrate to support evaporation, which limits the water recovery level.
- The alternative process mimics the RO process design ideology for increasing water recovery by putting several units in series.

Aspen® Settings:

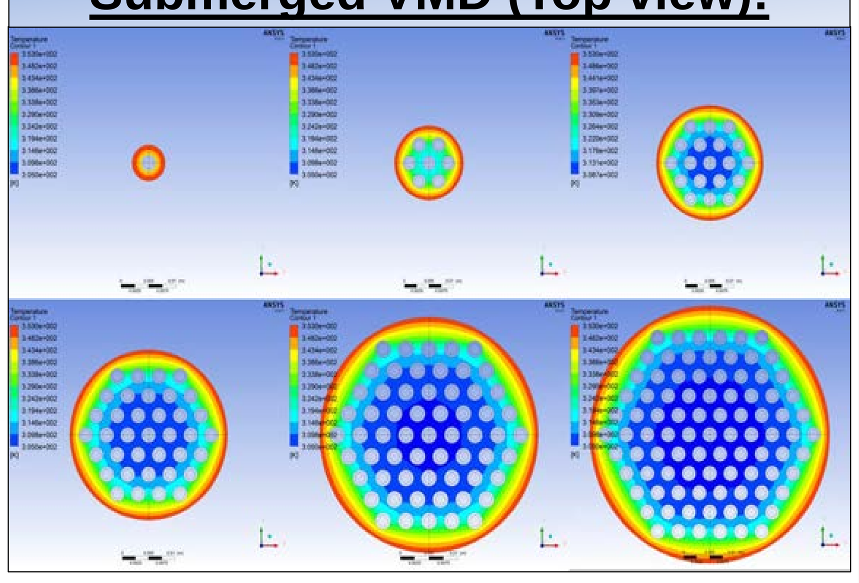
Submerged VMD					
Operating temperature, °C	80	70	60	50	40
Feed concentration, kg/L	0.4				
Number of membrane layers	6	5	4	3	2
Inlet flowrate, kg/hr	2.24	1.76	1.28	0.84	0.42
Membrane area, m²	0.81	0.52	0.31	0.16	0.06
Cross-flow VMD					
Operating temperature, °C	80	70	60	50	40
Inlet salt concentration, kg/L	0.2				
Inlet flowrate, kg/hr	2492.6				
Total number of module(s)	1	4			
Module diameter, m	0.456	0.228			
Membrane area, m²	100	25			
Inlet velocity, m/s	0.0072	0.0288			

Ideology of variables selection:

- **Temperature:** Both mass and heat transfers of VMD system are significantly affected by temperature.
- **Membrane Layers:** Higher layers of membrane causes higher production but lower the heat transfer across the bundle.
- **Units in series:** Divide one cross-flow VMD unit to four units requires three additional heating elements placed between each units.

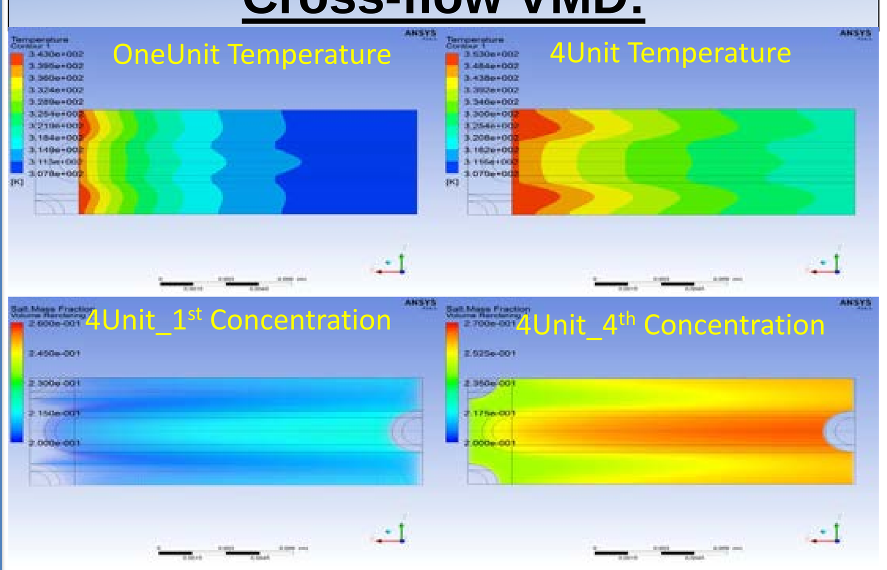
Visualization

Submerged VMD (Top view):



- Temperature dropped significantly from an average of 52°C at the outer layer to 31°C at the center, leading to a mass flux drop from 5.0LMH to 0.07LMH.
- The average mass flux per membrane fibre decreased from 6.61LMH for 2-layers module to 1.4LMH for 6-layers module

Cross-flow VMD:

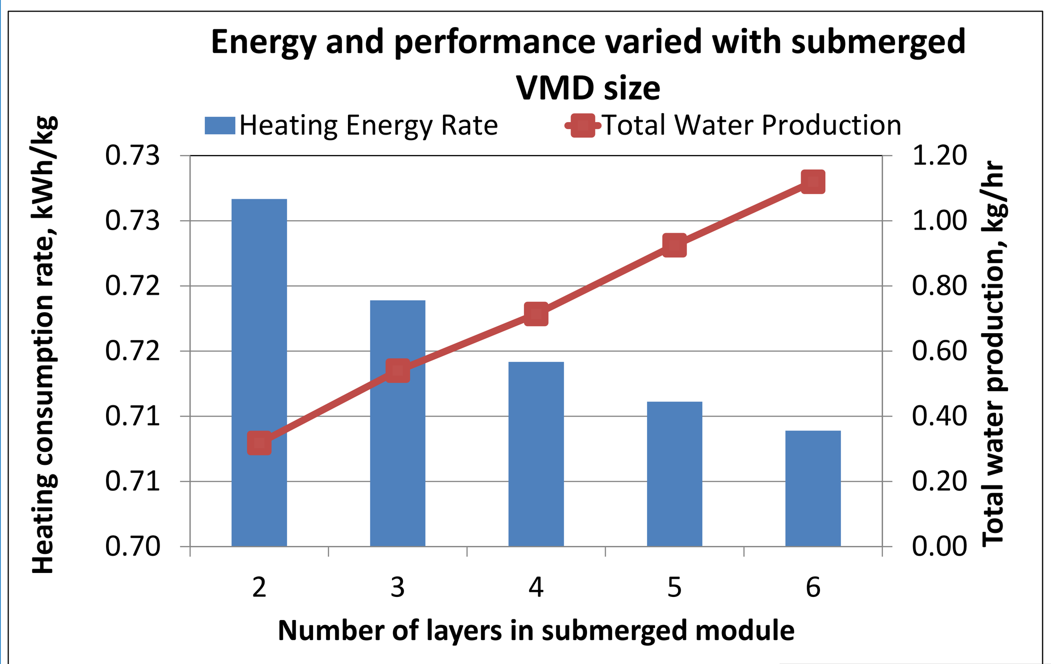


- A 13°C lower outlet temperature was observed for OneUnit configuration due to low inlet feed velocity.
- A 33% increase of salt concentration was found between the first and last unit of FourUnit configuration, due to high water flux.

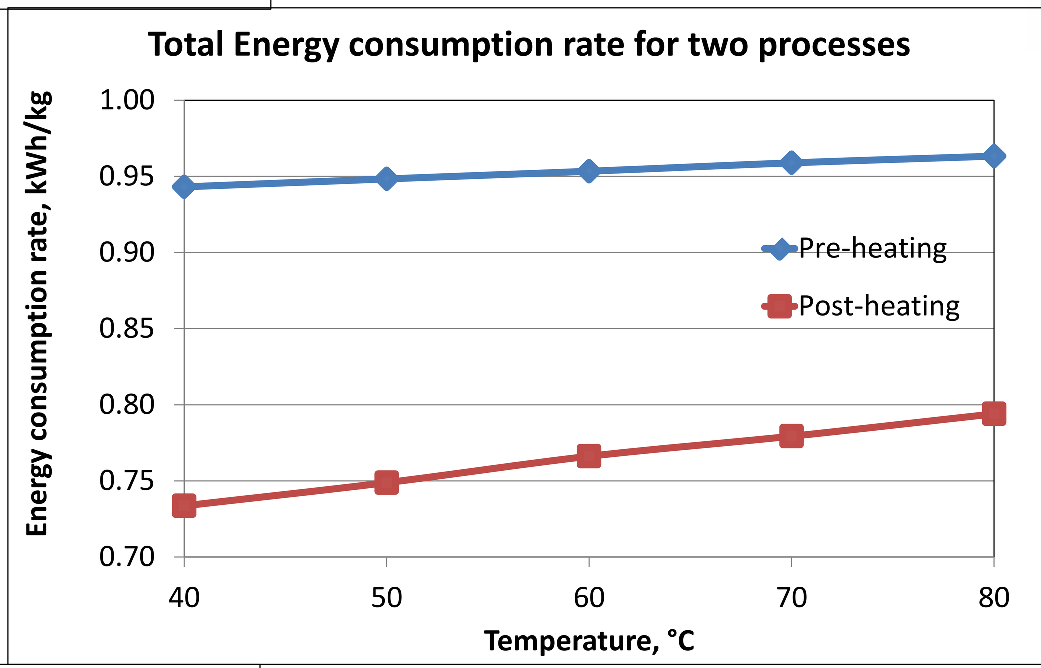
Boyue Lian; Tel: 02 9385 5373; Address: Room 912, Building M10, UNSW, Sydney NSW 2052

Results & Discussions

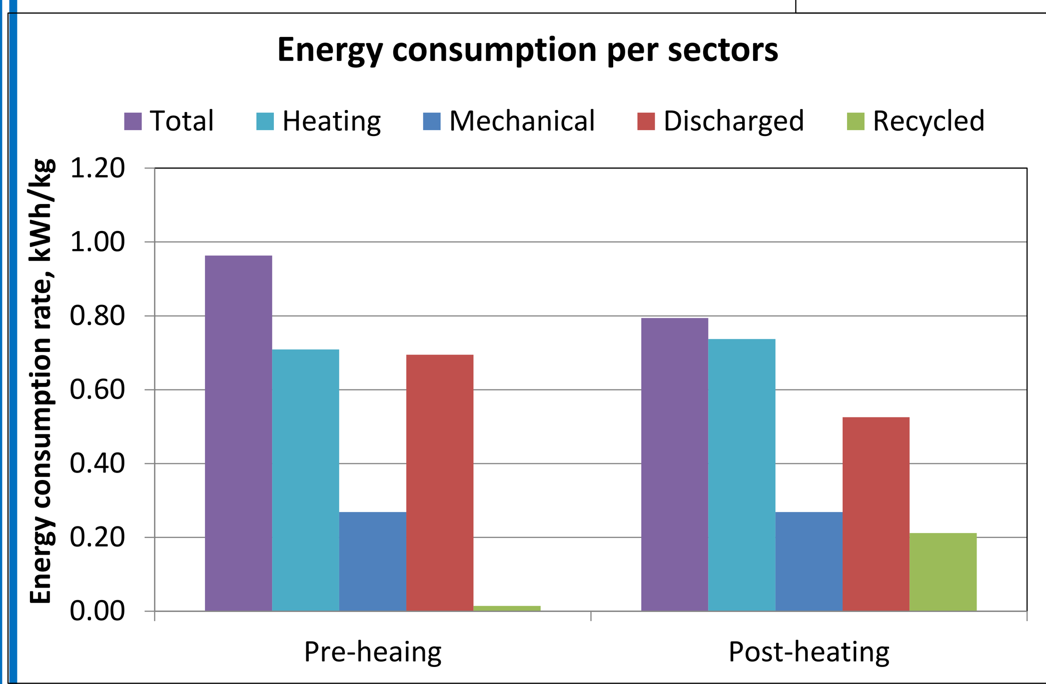
Submerged VMD:



- A linear increase in total water production was observed when numbers of membrane fibre layers increased
- An exponential decrease of heat consumption rate with maximum 1st order derivative of 7.78×10^{-3}kWh/kg per layer was detected.
- This suggested that increasing numbers of membrane layers resulted in higher total water production and higher energy efficiency

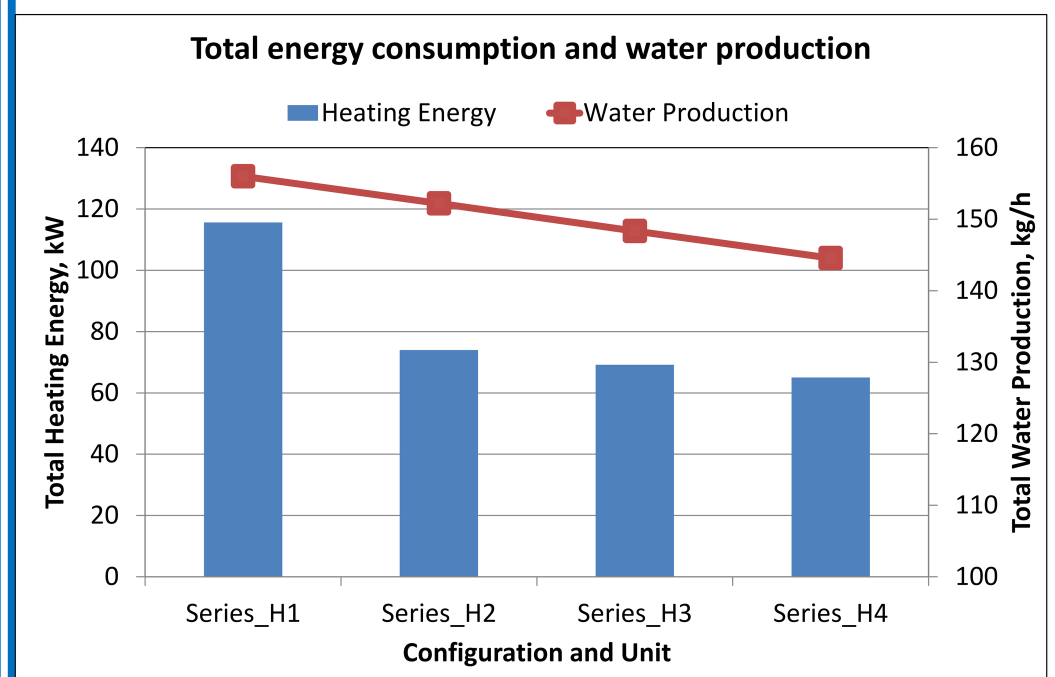


- An significant 24.7% total energy consumption rate deduction (0.19kWh/kg) was found for submerged VMD by changing the process from pre-heating to post-heating configuration.
- The increase of operating temperature caused an increase in total energy consumption for both pre-heating and post-heating processes

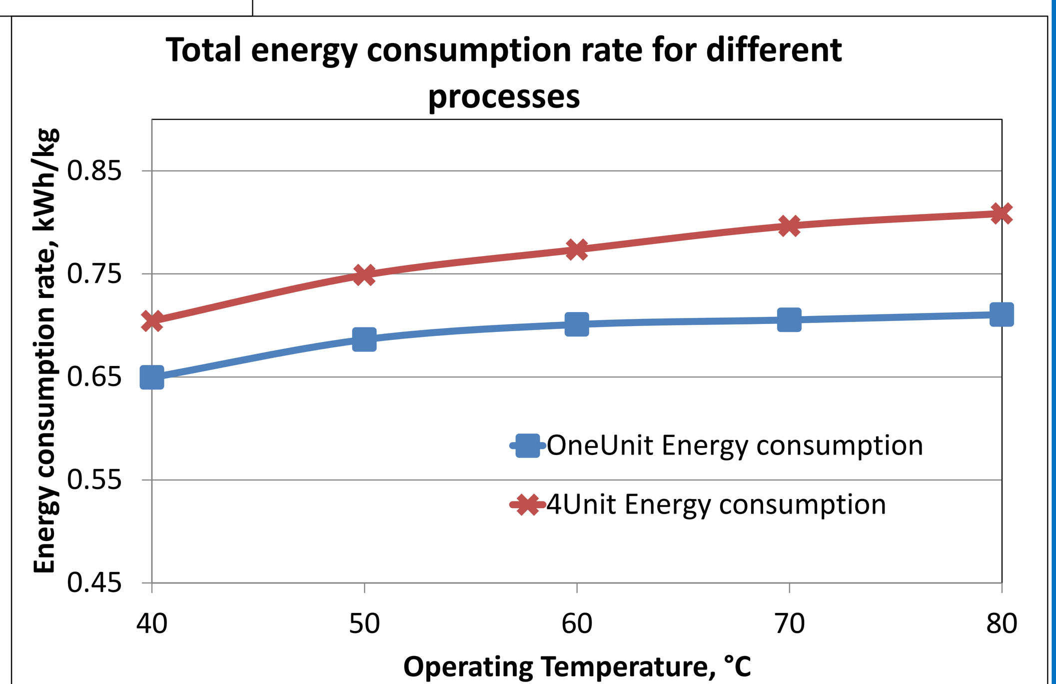


- 2.8×10^{-2}kWh/kg higher heating energy was observed at post-heating process due to greater heat requirement for re-heating the permeate stream to 100°C.
- Higher energy efficiency was achieved by the higher heat recovery of post-heating process (increased from 0.01 to 0.21 kWh/kg).

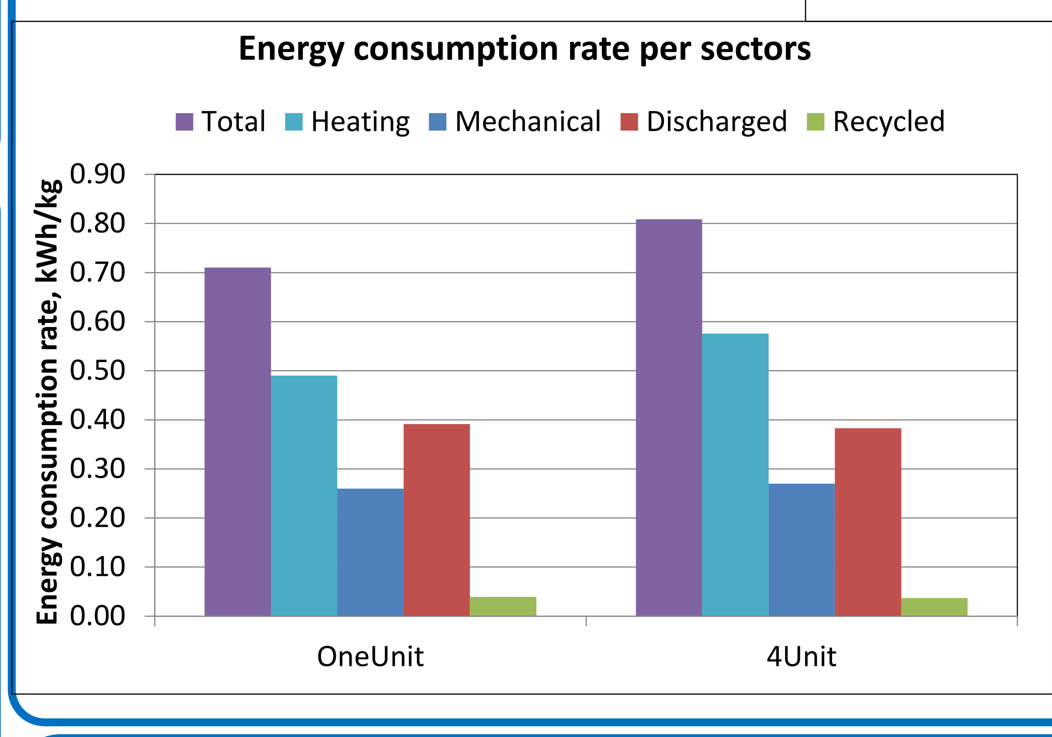
Cross-flow VMD:



- Total water production decreased linearly for each modules further away from the feed stream. This is due to the increase of inlet salt concentration from 0.2kg/L at the first module to 0.27kg/L at the last module.
- 41.7kW energy was consumed by initial heating for the first unit. The decrease of heat consumption from 74kW to 64kW for the other units was due to the decline of water production.



- The total energy consumption rate for both processes increased with higher temperature, due to the heat recovery decreased from 24.3% to 7.2%.
- The lower rate of increase in energy consumption rate at high temperature was due to the exponential increase of water flux from 1.1LMH at 40°C to 6.0LMH at 80°C.



- An average 0.098kWh/kg difference in total energy consumption rate was observed between these two processes indicating a lower energy efficiency of the FourUnit process, due to most of its units operated at higher salt concentration.
- However, the increase of total energy consumption rate led to an increase of mass recovery from 11.34% for OneUnit process to 24.12% for FourUnit process.

Conclusion

- Higher number of membrane layers in a bundle increases the total water production and energy efficiency of submerged VMD.
- More significant decrease of energy consumption rate can be found by changing the heater position in the process to recycle more heat from the permeate stream.
- Divide one Cross-Flow VMD unit into several units in series was proved to be efficient in water recovery. However, it increased the energy consumption rate due to the requirement of reheating.

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