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

To investigate the effects of module and process configurations on the production and energy consumption of VMD.

**Approaches**
- Coupling CFD and Aspen+®

**Visualization**
- Submerged Module
- Cross-flow Module

**Aspen® Settings:**
- **Submerged Module**
  - Operating temperature, °C: 80
  - Feed concentration, kg/L: 0.4
  - Area of membranes (m²): 6
  - Inlet flowrate, kg/hr: 2.24
  - Membrane area, m²: 0.81
  - Number of membrane layers: 6
  - Total number of module(s): 1
  - Inlet velocity, m/s: 0.0072

- **Cross-flow Module**
  - Operating temperature, °C: 80
  - Inlet salt concentration, kg/L: 0.2
  - Membrane area, m²: 100
  - Heat flux, W/m²: 2492.6
  - Module diameter, m: 0.456
  - Membrane area, m²: 0.0072

**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.
  - Energy is recycled from retentate stream.
- Alternative Cross-flow VMD (FourUnit):
  - Cross-flow VMD relies heat from high feed inlet 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.

**Conclusion**
- 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 7.78×10^4 kWh/kg per layer was detected.
- This suggested that increasing numbers of membrane layers resulted in higher total water production and higher energy efficiency.

**Energy consumption per sectors**
- A 2.8×10^4 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).

**Energy consumption rate per sectors**
- Total energy consumption rate for different processes:
  - 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.

**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 in salt concentration was found between the first and last unit of FourUnit configuration, due to high water flux.

**Visualization**
- Submerged VMD:
  - A 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.

- 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.

**Results & Discussions**

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