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Modeling of semibatch air gap membrane distillation

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ABSTRACT

Membrane distillation is used to separate non-volatile components from an aqueous solution. This is particularly useful in the production of potable water from seawater. A major challenge to the latter is the high thermal energy consumption. By using a semibatch process (salinity rises during the process) or multistage process (several steady states after each other) instead of a steady state process (salinity remains constant during the process) thermal energy can be saved and more distillate can be produced. Furthermore, using semibatch processes reduce the risk of bio fouling and scaling compared to steady state or multistage processes due to salinity shocking and rinsing.

In this report, the thermal energy consumption of a steady state, multistage and semibatch membrane distillation process are measured using a AGDM membrane module from Aqua|Still. In addition a theoretical model is developed and validated using the experimental results.

The theoretical model shows good correlation with the test results and can be used to compute a steady state, multistage or semibatch process. Furthermore, experimental results confirmed that by using multistage or semibatch membrane distillation processes instead of steady state processes, the thermal energy consumption can be reduced.

1. Introduction

Membrane distillation relies on a temperature difference between two fluids separated by a hydrophobic membrane to realize mass transfer of the vapor phase. The separation is driven by the vapor pressure difference between the two surfaces of the hydrophobic, micro-porous membrane and only vapor molecules are allowed to pass the membrane [1].

Membrane distillation gained attention in the recent years because it is a promising solution to reduce the water scarcity. There are around 1.2 billion people living in areas of physical water scarcity [2]. Moreover, there are 500 million people approaching the situation of physical scarcity and another 1.6 billion people are facing economic water shortage. The situation is worsened by the high population growth rate of 80 million people a year [2]. An example of the growing water shortage is the Arabian Peninsula, where the fresh water demand increases at a rate of at least 3% annually [3]. Another benefit of membrane distillation is that is can be used with alternative energy sources such as solar energy to reduce water scarcity in remote areas [4,5].

There are four major membrane distillation configurations which are: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweep gas membrane distillation (SGMD) and vacuum membrane distillation (VMD) [6,7]. In the DCMD configuration the hot solution is in direct contact with the membrane. The water vapor condenses on the other side of the membrane. DCMD is the simplest MD configuration. However, the main drawback is heat loss due to conduction [8]. The AGMD configuration does not have this drawback as there is an air gap between the membrane and the condensation surface. The main disadvantage of AGMD system is the added resistance to the mass transfer [8]. In SGMD, the water vapor is swept by an inert gas to condense outside the MD module. This results in an enhanced mass transfer coefficient due to the non-stationary gas barrier [8]. On the other hand, in VMD there is negligible heat loss by conduction due to the vacuum at the permeate membrane side. In VMD and SGMD, the condensation takes place outside the MD module and results in a more difficult setup.

The thermal efficiency of MD is often described by the Gained Output Ratio [9], GOR:

$$GOR = \frac{h_f}{q_{in}} \tag{1}$$

MD processes can be steady state, multistage with elevating salinity brine or semibatch. Summers et al. [7] made a comparative study that showed that steady state MD system typically have a low GOR. Lu and Chen [39] modeled a multistage AGMD system for analyzing the optimal path for the cold stream. However, there was no conclusion on the

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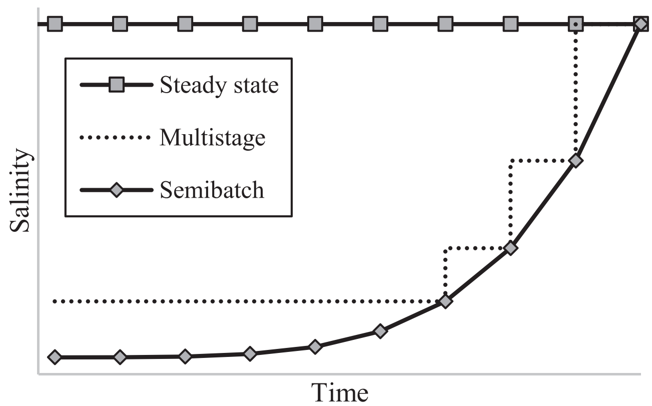

Fig. 1. Schematic graph of the salinity during the steady state, multistage and semibatch process.

GOR or other efficiency analyses. Chung et al. [9] concluded that increasing the number of stages increased the GOR with VMD.

An infinite multistage MD can be described as a semibatch process where the salinity of the brine increases during the process. The salinity during the process in steady state, multistage and semibatch is shown schematically in Fig. 1. A schematic graph of the total thermal energy needed to produce the same amount of distillate for the steady state and semibatch processes is shown in Fig. 2.

A possible advantage of using semibatch instead of steady state or multistage is the reduction of bio-fouling and scaling during the process. Bio-fouling can occur at low feed temperatures and low salinity and can be a problem at the cooling channel of an AGMD module or at the cold heat exchanger. However, at higher salinity scaling may occur. Furthermore, in commercial MD-systems bio fouling is likely to be a concern as it has been a critical issue in RO membranes [10]. Bacterial growth can be hindered by using higher salinity, elevated temperatures [3] and low pH values [10]. However, the risk of scaling increases with higher salinity and higher temperatures [10]. In a semibatch process the periodically lower salinity is used to reduce scaling and the periodically higher salinity is used to reduce bacterial growth. This results in less scaling at the beginning of the cycle and less bacterial growth at the end of the cycle compared to steady state processes.

Other advantages are the simplicity of the semibatch setup, which means it is a cheaper option compared to steady state or multistage processes and that less feed water is required for the same amount of distillate compared to one pass through system thanks to a higher concentration factor.

For several reasons, the AGMD configuration is tested in this report. As explained earlier, DCMD loses more heat by conduction than AGMD

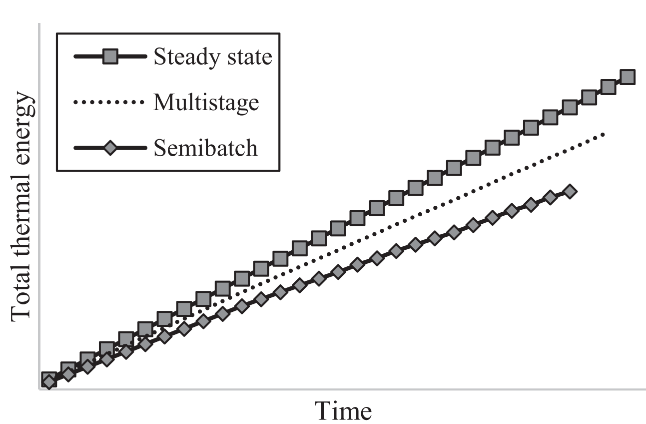

Fig. 2. Schematic graph of the total thermal energy needed to produce the same amount of distillate.

and DCMD has therefore the lowest thermal efficiency. SGMD and VMD are more complicated to test and the practical applications are limited. Besides, if a semibatch process is more efficient compared to a steady state process on an AGMD module, it should also be more efficient on a DCMD, SGMD or VMD configuration.

Generally, after the water treatment the feedwater is usually collected in a tank before entering the modules. When concentrating it in a steady state or multistage manner, the feed water will be added gradually to keep the salinity constant at each stage. However, when operating in a semibatch process a large amount of the feedwater will be added to the tank, and the latter will be refilled once the desirable salinity has been reached. This means that all three processes are fed feedwater from a tank at the same salinity; however the salinity of the water at the input of the module is different. Examples of brine concentrations can be found in [11,12]. This report will use salt (NaCl) water as a concentrating medium. The reasons for this are that scaling and biofouling is low and will therefore not influence the test results.

In this work, a mathematical model is being presented to calculate the flux and energy consumption of a spiral wound AGMD module with a semibatch process. Furthermore, an experimental study is employed to evaluate the model and to investigate the saved thermal energy of semibatch AGMD with a salinity between 4% and 10%. 4% is chosen as standard seawater has a salinity of 3.5% [13], more seawater concentrations can be found in [14]. To prevent the risk of scaling the maximum salinity for the semibatch test is 10% to 12%. A commercially available AS-7 AGMD module from Aqua|Still is used in the experiments.

2. Theoretical background

The performance of a MD-module depends on the heat and mass transfer. With the equations that were found in literature a theoretical model is developed to theoretically compute the distillate flux of a spiral wound MD-module and to evaluate the thermal energy consumption. The model will calculate a steady state process. The semibatch process can be calculated by using several steady states with increasing salinity. The following assumptions were made:

1. The system operates at steady state.
2. The module operates in a counter current flow direction.
3. The distillate is trapped inside the mesh of the spacer and no liquid film is present. Furthermore, the amount of stagnant distillate inside the module does not change.
4. The water vapor has to travel from the membrane to the condenser and cannot condense on the spacer or on the trapped water in the air gap spacer.
5. No heat is exchanged with the surroundings as it is a self-isolating system.
6. Membrane compaction effects as reported in [15] are ignored.
7. The temperature that is measured in front of the module is the same as that at the entrance of the envelope.

The envelope is divided into 25 sections of equal temperatures difference. The sections are discussed further down in the paper. In the following two sections the heat and mass transfer is discussed. The thermophysical properties can be computed from [16,17] and the latent heat can be computed from [18–20]. The velocity of the spacer filled channel can be computed from [21]. The formula from [21] is adapted to include the removal of distillate, the number of channels and the unit conversion which results in the following two equations:

$$v^{i}_{ch,c} = \frac{F^{i}_{c,in}}{3600 n_{ch} H_{ch} h_{sp} \epsilon_{sp}} \quad (2)$$