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Economic modelling and model-based process optimization of membrane distillation

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ABSTRACT

Membrane distillation (MD) is a thermally driven separation process, operated at moderate temperature, allowing for the use of waste heat as driving force. While the literature is saturated with lab-scale models, almost none exist for designing a complete MD system. Based on previously published and thoroughly validated models, this work demonstrates a graphical user interface tool, capable of designing a complete membrane distillation system, including all of the supporting equipment and able to predict the price of the obtained distillate for the most commonly studied and used membrane distillation configurations. The user can also optimize the module geometry based on specific requirements. Four different case studies are discussed, ranging from 2 to 1000 m^3 of distillate per day, with final brine salinity up to 20 wt%, feed temperature up to 80 °C. The optimal system design for each case is demonstrated. The distillate price varied from 25 €/m^3 of distillate for the smallest scale to 2.1 €/m^3 for the largest scale. Finally, the reader is presented with a simplified cost model that can be used to quickly estimate the price of the produced distillate at different production scales and concentration factors.

1. Introduction

Membrane distillation can be performed in various configurations [1]. The three most widely discussed configurations in the literature are direct contact (DCMD), air gap (AGMD) and permeate gap membrane distillation (PGMD) [2] — Fig. 1.

The DCMD configuration has the simplest design where two loops (hot feed and a cold permeate) are contacted directly via a porous hydrophobic membrane [1,3,4]. In order to improve the thermal efficiency of the process, an external recuperating heat exchanger recovers the heat of the permeate outlet to the cooled feed outlet. In the AGMD and the PGMD configurations, an extra gap compartment is formed by adding an impermeable foil between the hot feed and the permeate compartments [5,6]. The AGMD and the PGMD configurations are identical in their designs, however the AGMD modules are assumed to have a gap, which is completely evacuated of distillate, while the PGMD modules are considered to have a completely flooded gap [7]. The PGMD and the AGMD configurations have the advantage of an inherited internal heat recuperation, since the cold feed gets preheated while it flows through the coolant compartment.

In order to fully utilize the performance of MD, modelling can be applied to intensify the performance of the modules and to design tailor made complete MD systems. Models developed for lab-scale configurations push the theoretical knowledge of heat and mass transfer in MD further and can be found in abundance of references [5,6,8-16]. However, much less full-scale modelling can be found in the literature [7,17-19]. It is important to notice that membrane distillation can behave completely different at lab- and full-scale. As commonly known, at lab-scale AGMD exhibits much lower fluxes than DCMD [1,2,20,21]. However, at full-scale the modules are commonly limited by inflow energy and the channel velocities are much lower. This leads to peculiar experimental observations where AGMD modules have not only higher thermal efficiencies, but also higher fluxes, when compared to DCMD from the same manufacturer and the same area [19,22].

Moreover, to date there are only a few studies aimed at module optimization and even less studies where the economics of the process are discussed [4,7,17]. While the price of water produced using RO at different production scales and feed salinity is well known [23], the price of distillate produced using MD is fairly unknown. Ali et al. [17] performed an optimization of the membrane thickness and module length of a DCMD module and performed an economic calculation for a multistage DCMD system with extremely high operational capacity

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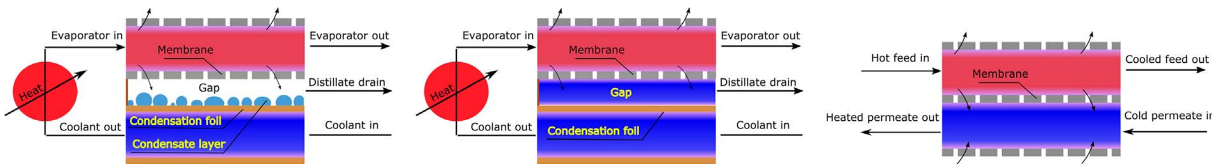

(a) Air gap membrane distillation (AGMD) (b) Permeate gap membrane distillation (PGMD) (c) Direct contact membrane distillation (DCMD)

Fig. 1. The most widely used membrane distillation configurations.

(1000 m^3/h), used an in-house developed hollow fibre module and the price is calculated only on one production scale. Winter et al. [7] performed a thorough economic analysis of systems with different modules and configurations using commercially available modules from Solarspring GMBH (Germany), but no multiple stages were considered.

In the first part of this work, we are presenting a tool with a graphical user interface which is able to optimize the geometry an AGMD, PGMD or DCMD module, starting from the design of a commercially available modules from Aquastill BV (The Netherlands). The model can optimize the geometry (e.g. channel length and module height) for yielding higher flux, thermal efficiency or combination of both, based on a user defined function. The simulation of the commercially available modules is shown in previous works for DCMD [18] and AGMD [19], including a methodology that avoids calibration on full-scale. The major equations describing the heat and mass transport in the system are summarized in Appendix E.

The second part of this work deals with four case scenarios at different distillate production scales where complete systems MD systems are designed. The systems are simulated using the standard Aquastill modules, followed by a simulation using the optimized modules from the first part, validating the optimized module designs and demonstrating the potential gains of a system that uses optimized modules. The model can also simulate a system with up to three salinity stages, operated in feed and bleed, where the brine output of each stage is the input of the following stage, similarly to RO systems [23]. This increases the efficiency of the system at the expense of higher capital cost.

Finally, a simplified cost model is presented that allows the reader to quickly estimate the price of the distillate and the investment cost of a system, depending on the configuration, concentration factor, feed temperature and production scale. The use of this model does not require prior modelling experience, therefore it can be used easily in future cost estimation studies.

2. Materials and methods

The graphical user interface (GUI) allowing interaction with the model is developed in Matlab and then exported as a Microsoft Windows executable file. The GUI consists of two parts. The first part deals with module-specific design optimization, where different number of parallel channels, module geometry, membranes and membrane properties can be tested. The second part of the GUI deals with designing a complete MD system. The model fit for AGMD and DCMD is shown in Fig. 2.

The conditions studied in Fig. 2a and b a combination of 60, 120 and 200 g/l salinity, feed temperature of 50 or 70 ° C, permeate temperature of 20 ° C. The flow rates are 500, 1000 and 1500 l/ h for the DCMD module and 300, 600 and 900 l/ h for the AGMD modules. The equations that describe the AGMD and DCMD systems are listed in Appendix E [18,19].

2.1. GUI for module optimization

The GUI dealing with module design (Fig. 3) is composed of user-definable inputs in the first two columns, output in the middle section and graphical outputs at the right hand side. First, the user can select the recirculation flow rate and temperatures of both the feed and the permeate, as well as the salinity of the feed.

In the section dealing with membrane and spacer, the user has the choice to select a calibration for a different membrane and spacer from drop-down menus. The choice of spacer affects the heat and mass transfer in the channels by employing a different Nusselt and Sherwood equation in each case as described in Ref. [24]. However, each spacer will affect the pressure drop of the module, which is modelled by employing different coefficients in the polynomial fit for the pressure drop as a function of the mean channel velocity.

If the check box *kappa memb = 0* is selected, the model considers a membrane, having the thermal conductivity of air, i.e. one can study the maximum obtainable gain from reducing the thermal conductivity of the membrane and, hence, the thermal losses through the polymer matrix of the membrane. Further, the user can set a custom thickness of the membrane by directly setting its value in the editable box, or alternatively, leaving it to 0, will make the model use the default membrane thickness for the currently selected membrane. The membrane thickness affects both the heat and mass transfer in the membrane, while the model assumes that the membrane structure remains the same. This means that a two times thinner membrane will be twice as thermally conductive, but also two times more permeable. For the case of direct contact membrane distillation, the membrane is considered to compress, or compact as a function of pressure as shown in Hitsov et al. [18]. While this effect was studied only for the PE1 membrane, if another membrane is used, the same percentage of compaction is considered as a function of pressure. Therefore, care should be taken when analyzing the results in this case, unless the calibration for membrane compaction as a function of pressure is also updated [24].

For the case of a DCMD module, a recuperating heat exchanger (RX) is also simulated if the corresponding check box is enabled. The heat exchanger is simulated using the DCMD model, in which an impermeable titanium plate is simulated, instead of a membrane. The heat exchangers in the system are plate and frame with a height and width of 0.76 and 0.29 m, respectively, and a channel thickness of 5 mm. The user can change the number of plates in the heat exchanger in order to study how this would affect the overall performance of the DCMD system. It should be noted that by adding plates, both the area and the hydrodynamics of the RX are affected.

The type of MD module can be selected from a radio button. Three configurations are considered — 0 direct contact membrane distillation, permeate gap and air gap membrane distillation. The direct contact and the air gap are thoroughly described in previous works [18,19]. The permeate gap membrane distillation is considered here only theoretically as the model was never validated. However, the permeate gap configuration is a logical extension since the configuration is identical to the air gap, but the gap is completely flooded with water, while in air gap the flooding is only partial and a function of the flux as previously demonstrated [19].

When either air gap or permeate gap configuration is selected, the gap parameters such as gap thickness, thermal conductivity and thickness of the condensation foil can be changed, to evaluate their influence.

The parameters related to the module geometry can also be changed. The module height, area and total number of parallel channels