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Direct contact and air gap membrane distillation: Differences and similarities between lab and pilot scale

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ABSTRACT

Membrane distillation separates liquids and solutes using a hydrophobic microporous membrane. Different configurations have been investigated at lab scale, among which direct contact membrane distillation (DCMD) and air gap membrane distillation (AGMD). Lab scale studies comparing different configurations show higher flux for DCMD, while AGMD is more energy efficient. However, no straightforward directions are given yet on how to translate these results to pilot scale. As membrane distillation is currently shifting from lab environment towards pilot experiments, a good understanding of pilot scale modules and the differences with lab modules are important. In this study, DCMD and AGMD were compared both at lab and pilot scale using the same membrane. At lab scale, it was found that the flux of DCMD is a factor 4 higher compared to the flux of AGMD. However, at pilot scale, the AGMD modules showed a higher flux and lower energy consumption compared to DCMD. As it is important for further upscaling of the technology, this study focusses on the explanation behind these unexpected higher fluxes of AGMD modules. Since the AGMD modules showed better performance and do not require an additional recuperating heat exchanger, this configuration is preferred over DCMD for larger scale applications.

1. Introduction

Membrane distillation is an emerging technology using a hydrophobic porous membrane to separate liquid and solutes, such as salts. Different configurations are used to provide a driving force over the membrane [1,2]. The direct contact MD (DCMD) configuration is the most studied configuration at lab scale due to the simplicity in design and the high fluxes. Because both hot and cold sides are in direct contact with the membrane, this configuration suffers more from heat loss due to conduction through the membrane. Additionally, an external heat exchanger is required for heat recuperation in DCMD. To reduce the heat loss due to conduction, an air gap is introduced between the membrane and a cold surface on permeate side in air-gap membrane distillation (AGMD). Because of the separation of coolant and permeate, the cold feed can be used as coolant. The cold feed is preheated in the module in counter current flow, whereby thermal energy is recuperated internally in the module [3].

The transport mechanisms of AGMD and DCMD are compared in Fig. 1. In DCMD the driving force is the interfacial temperature difference over the membrane and the vapor transport distance is equal to the membrane. In AGMD, an additional isolating air layer strongly decreases the heat losses in this case. In an entirely dry gap, the thickness of the gap should be added to the membrane thickness to obtain the total vapor transport distance and therefore, also the vapor permeability is severely reduced by the gap. The driving force in this case is not the interfacial temperature difference over the membrane, but the temperature difference over the membrane and the gap. As shown by Hitsov et al. [4], up to 45% of the gap is flooded at pilot scale, which also should be accounted for in the interpretation of performance results.

A proper selection of the best configuration requires a quantitative and direct comparison including flux and energy efficiency under similar conditions. Yet, only a small fraction of the publications on membrane distillation evaluates the flux of different configurations at lab scale [5–10]. In general, higher fluxes are reported for DCMD compared to AGMD [10–12]. Only one study claims higher fluxes for

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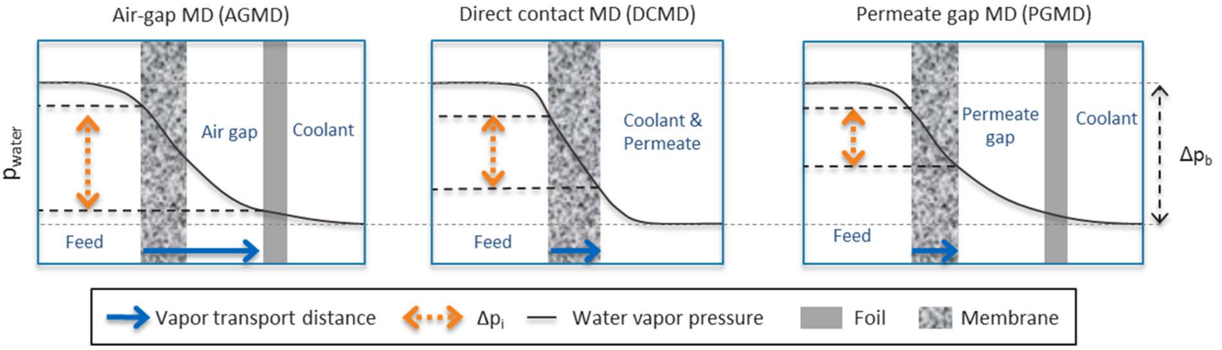

Fig. 1. Mechanism of transport for DCMD, AGMD and PGMD.

AGMD, using ceramic and hence very conductive membranes [13]. Especially for the high temperature differences of 70–90 °C that are used in this study, the effect of temperature polarization in DCMD becomes so large that the flux is severely reduced in DCMD, resulting in a higher flux for AGMD in this case [14]. These lab scale studies all used different modules, membranes and process conditions and therefore, the configurations cannot be compared among the different publications.

Besides flux, also the thermal efficiency is of major importance for the selection of a configuration. At lab scale, this efficiency is evaluated based on the ratio of the energy consumed by flux and the total energy consumed after a single pass of the liquid through the module channel. At lab scale only few publications considered the energy consumption [7,10]. At full scale however, this single pass energy efficiency is of minor importance, because both in DCMD and in AGMD, part of this energy is recuperated. Therefore at full scale, the gained output ratio (GOR) is used, which is defined as the ratio of the energy used for evaporation and the total duty of the heat exchanger. Summers et al. concluded that with both configurations high GORs are feasible based on simulations [15]. Winter showed that comparing a 8.7 m^2 AGMD module (l = 6.5 m) and a 9.8 m^2 DCMD (l = 7 m), the highest permeate output rate ($l \cdot h^{-1}$) and thermal energy efficiency was obtained for AGMD [16]. In a previous work focusing on modelling of full scale AGMD modules, it was also shown that AGMD modules can have higher fluxes than DCMD with equal channel length and membrane surface area [4]. These pilot scale observations of Winter et al. and Hitsov et al. are in contrast with the findings at lab scale.

To investigate and explain this difference in MD performance between lab and full scale, this follow-up study focusses on the flux and energy efficiency behavior of a lab scale (0.0108 m^2) and a pilot scale 7.2 m^2 DCMD and AGMD module. Both pilot scale modules were from the same provider (Aquastill) and have the same structure and dimensions. The membrane and spacers used in these modules are also equal to the ones used at lab scale making a direct comparison possible. To the best of our knowledge, this is the first that time such a direct, in-depth comparison is made between lab and pilot scale AGMD and DCMD. Different process conditions were used and the tests were compared with the results obtained from the lab scale testing, providing novel and surprising insights in the choice of a MD configuration. These insights can facilitate the transition from the small scale lab tests towards module design for industrial applications of MD. This topic is recently also indicated as a main focus area for MD by industry experts [17].

2. Materials and methods

2.1. Membranes

The PE membrane of Lydall was used both at lab and pilot scale MD test. The membrane has an average pore diameter of 0.3 µm, a porosity of 76% and a thickness of 99 µm. The LEP was 3.9 bar [18].

2.2. Setups

2.2.1. Lab scale MD

The membrane distillation performance was evaluated with a lab-scale MD setup, visualized in Fig. 2. More details on the setup can be found elsewhere [10].

The flat-sheet module with an effective membrane surface of 6x18cm (0.0108 m^2) is presented in Fig. 3. For DCMD, the module consisted of a feed and permeate compartment, separated by the membrane. The membrane was kept in place by a 2 mm PP spacer. For

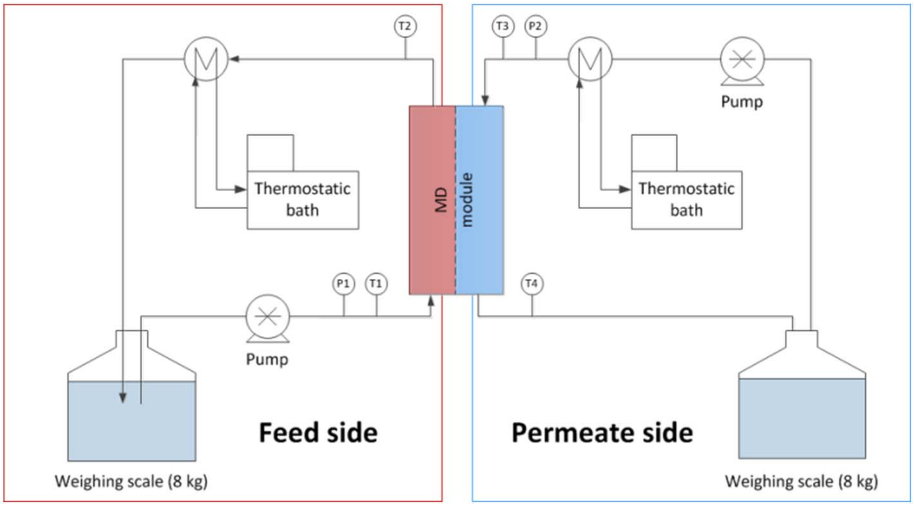

Fig. 2. Process scheme of the DCMD-lab scale setup.