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How to select a membrane distillation configuration? Process conditions and membrane influence unraveled

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HIGHLIGHTS

- Different configurations were evaluated under similar conditions.
- The order of fluxes observed in this study is VMD > DCMD > PGMD > AGMD.
- Each configuration has a different sensitivity to a specific process parameter.
- Recommendations on the selection of a configurations are given.
- Guidelines are given for the membrane depending on the configuration.

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ABSTRACT

In membrane distillation, the liquid phase including dissolved components is retained by a hydrophobic membrane, while the microporous structure allows transport of vapor through the membrane. The vapor pressure difference over the membrane is the driving force and is applied using a variety of configurations. This paper directly compares the flux and energy efficiency of a lab scale direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), permeate gap membrane distillation (PGMD) and vacuum membrane distillation (VMD) using the same bulk driving force. The highest flux was observed for VMD, followed by DCMD > PGMD > AGMD. Furthermore, it was observed that the different configurations are not equally sensitive to the applied process conditions, including temperature difference, flow velocity and salinity. For the first time, also the importance of the specific requirements for the membrane for each configuration was investigated.

1. Introduction

Membrane distillation (MD) is a thermally driven separation process, mostly applied for the separation of non-volatile dissolved substances from a diluent [1]. The process can be used in for treatment of a broad range of salinities, including seawater desalination [2], brine [3] and industrial waste water treatment [4–6] and resource recovery up to crystallization [7,8]. A hydrophobic membrane prevents the liquid phase from entering the membrane, whereas its microporous structure allows transport of water vapor [9,10]. The hot feed with high vapor pressure is in direct contact with the membrane. A variety of methods is used to apply a low vapor pressure on permeate side, distinguishing the four basic configurations described in the literature (Table 1). In direct contact membrane distillation (DCMD), a cold liquid is in direct contact with the membrane on permeate side, while an additional compartment with an air gap separates a cold condensing plate from the membrane in air gap membrane distillation (AGMD). A cold sweep gas provides the driving force in sweep gas membrane distillation (SGMD) and a vacuum pressure is applied on the permeate side in vacuum membrane distillation (VMD). Recently, also permeate gap membrane distillation (PGMD) is introduced as a hybrid configuration combining AGMD and DCMD, where the gap between membrane and cold condensing foil is filled with permeate. All these configurations have their own advantages and disadvantages, which are thoroughly described in literature and summarized in Table 1.

A proper selection of the best configuration for a certain application requires a quantitative and direct comparison including flux and energy efficiency under similar conditions. Yet, only a small fraction of the

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Nomenclature

Abbreviations

A	membrane surface area [m^2]
ANOVA	analysis of variance
AGMD	air gap membrane distillation
B	permeability [kg/(m^2·h·Pa)]
C_p	specific heat capacity [J/(kg·K)]
d	average pore diameter [μm]
DCMD	direct contact membrane distillation
EE	single pass energy efficiency [%]
F	mass flow rate [kg/s]
FS	flat sheet membrane
HF	hollow fiber membrane
GOR	gained output ratio
LEP	liquid entry pressure [Pa]
MD	membrane distillation
N	flux [kg/(m^2·h)]
P	vacuum pressure [Pa]
p	vapor pressure [Pa]
PE	polyethylene
PGMD	permeate gap membrane distillation
PGMD0	0 mm permeate gap membrane distillation
PGMD2	2 mm permeate gap membrane distillation
PP	polypropylene
PTFE	polytetrafluoroethylene
Q	heat transfer [W/m^2]
SEM	scanning electron microscope
SGMD	sweeping gas membrane distillation
T	feed temperature [°C or K]
v	flow velocity [m/s]
VMD	vacuum membrane distillation
δ	membrane thickness [μm]
ΔH	enthalpy of evaporation [J/kg]
Δp	vapor pressure difference [Pa]
ε	porosity [%]
θ	water contact angle [°]

Subscripts

ag	air gap
av.	average
b	bulk
f	feed
i	interfacial
in	inlet
m	membrane
out	outlet
p	permeate
vac	vacuum
w	water vapor

publications on membrane distillation evaluates the flux of two or three different configurations (Table 2). VMD appears to have higher fluxes than DCMD, SGMD and AGMD based on [15–18], while Koo et al. uses relatively low vacuum pressures and reports lower flux for VMD compared to DCMD [19]. Furthermore, PGMD shows a higher flux compared to AGMD [13,21,24,25]. Two studies show higher fluxes for DCMD compared to AGMD [26,27], while another study claims the opposite [28]. These 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, while only one publication considered the energy consumption [13]. Table 1 indicates a higher heat loss due to conduction through the membrane for the configurations where the membrane is in direct contact with a cold liquid (DCMD and PGMD). Nevertheless, the only comparative study including energy consumption reports the lowest single pass specific thermal energy consumption (kWh/kg distillate) for PGMD followed by VMD and AGMD [13].

At this moment, DCMD, AGMD, PGMD and VMD are already considered at commercial level [12,29–33]. However, based on the available literature, no adequate sequence for the flux or energy efficiency can be given for these configurations. Therefore, in this study DCMD, PGMD, AGMD and VMD are directly compared using similar process conditions. This contribution takes into account the effect of salinity on the performance of the MD system. This is of major importance because the focus of MD is increasingly oriented towards high salinity streams. Moreover, the choice of the configuration might depend on the availability of waste heat, limiting the driving force over the membrane. To be able to provide guidelines for a broad range of applications with variations in process conditions, a Design of Experiments is used to investigate the effect of salinity, temperature difference and flow velocity on the performance in different configurations. Finally, different types of membranes considered at commercial level are tested in this study and a recommendation is given for the selection of the most suitable membrane in each case [6,32–34]. In this study, novel insights in the operation of the different membrane distillation configurations are described and a guide for making a selection of the best configuration and membrane for a specific application is provided.

2. Materials and methods

2.1. Membrane characterization

The minimum, average and maximum pore diameter and pore size distribution were measured using a Porolux™ 1000 device (Porometer, Eke, Belgium) [35]. The method to determine the liquid entry pressure (LEP) is described by Khayet et al. [36]. The pressure is increased stepwise with 10 kPa each 30 s until a flow is detected. The porosity of the unsupported membranes was determined using a Helium pycnometer (Micromeretics, Norcross, USA) [35]. A cold field emission scanning electron microscope (SEM) type JSM6340F (JEOL, Tokyo, Japan) was used to study membrane cross-sections [35].

2.2. Membrane distillation experiments

2.2.1. Setup

The membrane distillation performance was evaluated with a lab-scale MD setup (Fig. 1). The feed and coolant were circulated counter-currently on their respective sides of the module using centrifugal pumps (Totton pumps, HPR 10/15, Florida, USA). The temperatures were kept constant using a heating bath on feed side (LAUDA-Brinkmann LP, Lauda ECO E4, New Jersey, USA) and a cooling thermostat on permeate side (LAUDA-Brinkmann LP, Lauda ECO RE 415, New Jersey, USA). These thermostats were combined with a temperature control unit (LAUDA-Brinkmann LP, Lauda ECO Silver, New Jersey, USA) and monitored using four thermocouples (Thermo Electric Company, PT100 TF, Balen, Belgium). The flux was measured by evaluating the weight variations in the feed and distillate tank, using an analytical balance (Kern & Sohn GmbH, Kern FBK, Balingen, Germany). The electrical conductivities at the feed and permeate side were monitored by portable conductivity meters (WTW GmbH, pH/Cond 340i, Weilheim, Germany).

The flat-sheet module had an effective membrane surface of 0.0108 m^2. The module built-up is presented in Fig. 2. For DCMD, the module consisted of a feed and permeate compartment, separated by the membrane. In the literature the air gap thickness in AGMD ranges from 0.5 up to 13 mm [1,5–7]. Because of the negative effect of air gap