Desalination 424 (2017) 122–130

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Numerical investigation of air gap membrane distillation (AGMD): Seeking optimal performance

Isam Janajreh[a,*], Khadije El Kadi[a], Raed Hashaikeh[a], Rizwan Ahmed[b]

[a] Mechanical and Materials Engineering Department, Khalifa University of Science and Technology, Masdar Institute, UAE
[b] Takreer Research Center, ADNOC, Abu Dhabi, UAE

ARTICLE INFO

Keywords:
Air gap membrane distillation
CFD
DCMD
Temperature polarization coefficient
Heat transfer

ABSTRACT

Membrane distillation (MD) is used in desalination, wastewater treatment, and medicinal application. Direct contact (DCMD) and air-gap (AGMD) membrane distillation are the most common configurations. The simplicity and high flux marks the advantages of the former while the low fouling is attributed to the latter. The air-gap integration used between the bottom surface of membrane and the permeate although adds thermal resistance it reduces membrane wetting and fouling. Researchers continue to investigate these configurations to optimize their performance. In this work, high fidelity numerical analysis is carried out to assess and quantify the performance of the AGMD and compare it with the DCMD. Different geometric and operating parameters are considered. Results are demonstrated in terms of temperature distributions, polarization-coefficient (TPC), mass-flux, heat-flux, surface heat coefficients, and thermal efficiency (η). Results reveal that the integration of a thin air-gap reduces the TPC by 38%, the total heat-flux by 37%, and nearly 22% for each of the mass-flux and the thermal efficiency. Furthermore, increasing AGMD feed temperature from 50 °C to 75 °C cause increase in the mass flux from 3.34 to 15.3 $g/m^2 \cdot s$ that corresponds to increase in the thermal efficiency from 11.5% to 52.7%. Higher temperature show much larger effect on the performance than flow velocity.

1. Introduction

Membrane distillation (MD) is a low energy and effective method for water treatment and desalination. It is a separation process driven by temperature gradient, where hot-salt water is circulated in one side of a hydrophobic porous membrane, and cold-fresh stream is circulated in the other side. Thus, creating a difference of partial pressure between the two sides of the membrane that constitutes the main driving force of the process. The MD system can be configured in four different ways. These are the conventional direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD) as depicted in Fig. 1. The DCMD and AGMD configurations are the most researched and used technology in desalination processes due to their simple configuration [1–5]. However, the main obstruction of DCMD and AGMD is the heat loss by conduction and additional thermal resistance, respectively [1]. The addition of air gap in the AGMD makes the temperature and partial pressure gradients less pronounced than the conventional DCMD, thus causing lower AGMD fluxes than in the other MD configurations as DCMD [6]. However, the indirect contact of permeate with the lower membrane surface in the AGMD gives the advantage to halt the wetting at the permeate side when volatile components are present. As such components are likely to wet the lower membrane surface due to their lower surface tension [6,7]. Introducing lower pressure at the permeate side by mean of VMD can also improve wetting problem. In AGMD, as shown in Fig. 1 the feed is directly in contact with membrane upper surface, while the permeate is condensed on a cold collection plate which is separated from the membrane surface by an air gap. This method ensures a reduction in energy loss due heat conduction through the membrane but at the same time it adds an insulation layer at the gap side [2]. This penalizes the yield production in AGMD. Air gap MD is suitable for all DCMD applications. Moreover, it can also extract other volatile substances from solutions such as alcohols [8,9]. Those substances cause the permeate side to be wet because the lower side of the membrane is considered as hydrophilic. In other words, permeate side of AGMD unit is not directly touching the membrane. This fact reduces the risk of wetting the bottom side of the membrane marking AGMD as better choice than DCMD in some application. As a quantitative comparison between the performances of these two-setups is limited in literature, this work intends to quantify this difference targeting system performance [10]. In line of past studies [11–14], this can be presented in terms of the attained temperature

* Corresponding author.
E-mail address: ijanajreh@masdar.ac.ae (I. Janajreh).

http://dx.doi.org/10.1016/j.desal.2017.10.001
Received 29 April 2017; Received in revised form 27 September 2017; Accepted 1 October 2017

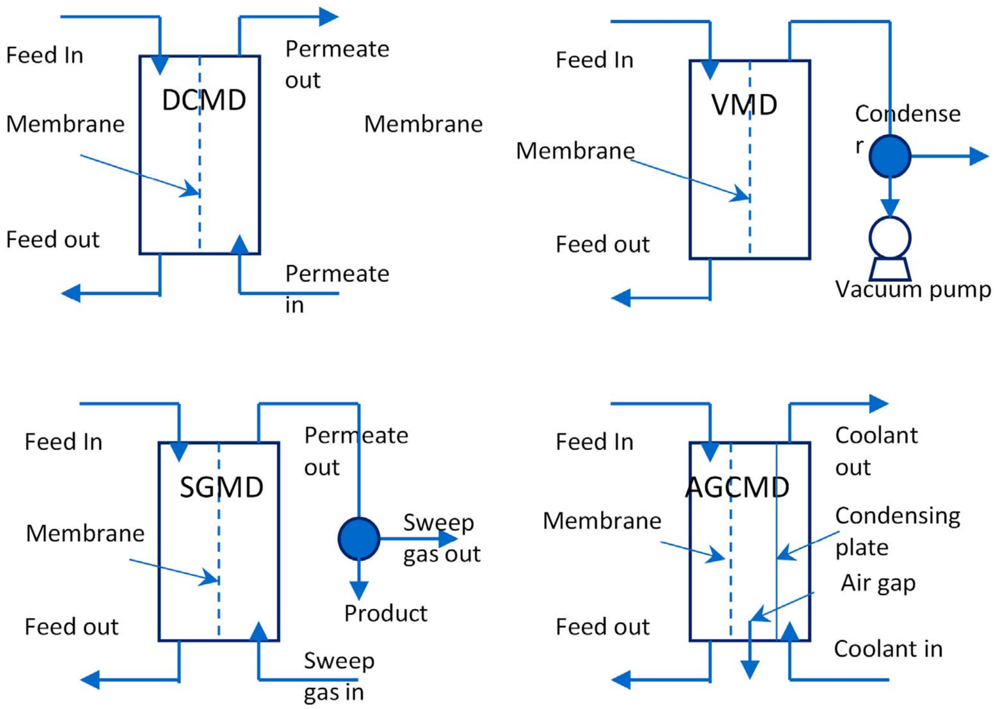

Fig. 1. Membrane distillation (MD) process configurations.

distribution, the distribution and average of TCP, mass flux as well as the attained thermal efficiency corresponding to parametrical consideration. It is worth mentioning that MD modules (i.e. flat sheet membranes) require mechanical support to prevent rupture of the thin membrane. Such strong support (i.e. spacers) is capable also to promote turbulence which as a result offers a great potential for system optimization [15–16]. The role of spacers in the MD performance is not covered in this work, however, a full study was well-illustrated in a previous work of the authors [17].

Numerical simulation of DCMD and AGMD has been sought by several researchers to gain insight of their operation [18–28]. Yu et al. [18] used Navier-Stokes flow analysis while accounted to heat and mass fluxes in a hollow fiber tube. They however used a fixed mass transfer coefficient independent of temperature or membrane properties. Empirical and coarse model that based on semi-empirical correlation or constant mass flux coefficient, one side flow, or thermal resistances analogy stack that evaluate temperature distribution are appear in several literature works [19–23]. Zhang et al. [24–25] used conjugate heat flow model while Charfi et al. [26] used Navier-stokes equations in a single chamber modeling associated with pressure drop Ergun model and membrane flux of Knudson-diffusion. Asghari et al. [27] developed conjugated heat and mass transfer numerical model for AGMD assuming a static air gap between the bottom side of the membrane and the condensing plate. Exact quantification of the system yield and extended system parameters (temperature and pressure distribution) as well as performance metrics (TPC, mass and thermal yield and efficiency) were incomplete in these models. Swaminathan et al. [28] have considered different AGMD including conductive and permeate filled they reported the thermal efficiency of the model. They however implemented lower fidelity one-dimensional model that ignores Navier-stokes based flow formulation. Nevertheless, it was successfully used in evaluating the effect of pure water flow direction, integrate the influence of conductive gap materials side to the membrane material conductivity [28]. More up to date work appears in the dissertation of Winer [15] who carried out extensive thermodynamic and economic analysis of DCMD. He coupled the heat and mass transfer in the numerical model and assessed it experimentally. In this work, conjugated heat transfer Navier-Stokes flow model for counter flow of DCMD and AGMD is developed and assessed simultaneously under range of velocity and temperature conditions. These models are validated following the previous work of the authors [14]. Strong validation of these models is incepted by the accounted conjugated heat thermal coupling, appropriate boundary conditions and accurate modeling of the considered temperature-dependent Poiseuille and Knudson-diffusion mass transfer. Parametric study is done to explore and quantify the role of velocity and temperature in the performance of the AGMD. Recommendation on the conditions that provide best system performance is also given. The developed model accounts for numerous DCMD parameters, gap thickness, membrane properties and its composite, porosity, toruisity, system geometry including membrane support and various operational conditions. Thus, it can be used in the process development of MD that pushes the technology closure for full scale deployment.

2. Methodology

2.1. Model setup and governing equations

In this work, a numerical study will be performed on air gap membrane distillation (AGMD) using non-isothermal computational fluid dynamics (CFD) and thermally conjugated/coupled with the solid porous membrane. The computational domain comprises of two channels (210 mm length by 1 mm height) sandwiching the 0.13 mm thickness membrane as shown in the baseline setup in Fig. 2. Another conjugated heat is also considered at the air gap wall to keep the problem coupled. At this wall, however a super thermal conductive layer is utilized to minimize the thermal resistance created by the gap. It should be noted that the height of the gap is directly proportional to thermal resistance and hence causing higher temperature of the bottom wall and leading to reduction in the overall performance. In this work, several gap heights are considered, i.e. starting from the no-gap baseline then sweeping from the smallest feasible air gap (0.05 mm) to 0.4 mm.

Appropriate flow conditions will be utilized for the feed and permeate flow channels with a prescribed inlet velocity/mass flow rate and temperature and insulated outer walls as well as the outlet conditions including pressures. These conditions depend on the application, for example in water desalination it appears that channel Reynolds number near 100 and 75 °C temperature lead to high thermal efficiency