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Parabolic-trough plant integrated with direct-contact membrane distillation system: Concept, simulation, performance, and economic evaluation

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ABSTRACT

This paper investigates performance and economic evaluation of integrating 50 MWe parabolic-trough (PT) plant with direct-contact membrane distillation (DCMD) system for electricity and freshwater production in Abu Dhabi, United Arab Emirates. The evaluations of PT plant were performed utilizing SAM software. Maximum and minimum electrical energy generation was estimated to be 13.5 GWh and 7.71 GWh in May and December, respectively. Similarly, the cooling water requirement fluctuated from 856 m^3/day to 1440 m^3/day in December and May, respectively. The economic evaluation showed that the nominal and real levelized electricity cost was 24.54 cents per kWh and 19.3833 cents per kWh, respectively. The performance evaluation of DCMD system was performed by solving DCMD mathematical model in MATLAB® Software. An increase in feed temperature from 30 °C to 45 °C increased the permeate flux from 5.19 kg/m^2 h to 20.01 kg/m^2 h, and evaporation efficiency from 39.2% to 54.98%, respectively. Furthermore, it was assessed that proposed PT plant integrated with DCMD system could produce up to 14.33 m^3 of freshwater per day with a water production cost of \$0.64/m^3. It was revealed that the integration of DCMD system with PT plant could be a sustainable and economical approach to cope with increasing demand of freshwater and electricity.

1. Introduction

Freshwater is one of the greatest challenges of 21st century. It has been predicted that two-third of world's population will suffer from freshwater scarcity by 2025 (World Health Organization, 2018). A large proportion of the world is covered with water; however, 99.3% of all water is either saline or unapproachable (Qtaishat and Banat, 2013). The massive availability of saline water makes desalination a suitable and sustainable solution to the problem posed by the growing demand for freshwater. Desalination can be achieved by thermal or membrane processes. Thermal desalination is a phase change process in which saline water is heated, evaporated, condensed, and collected; it includes multi-effect distillation (MED), and multi-stage flash (MSF). In contrast, membrane desalination is a separation process that uses a membrane that only permits water vapors to cross through it; this process includes reverse osmosis (RO), and membrane distillation (MD).

MD is an advanced and attractive choice for water desalination (Shim et al., 2015; Kim et al., 2013; Alkhudhiri et al., 2012). The driving force of MD is the pressure gradient between hot and cold streams as they interface across a membrane (Ali et al., 2018). Direct contact membrane distillation (DCMD) is the simplest and most commonly used MD configuration (Ghaffour et al., 2015). Feed temperature in MD normally range from 60 °C to 90 °C, although temperatures as low as 30 °C have also been reported (Qtaishat and Banat, 2013). In any case, a temperature difference of 7–10 °C, between the warm and cold streams, is generally enough to produce freshwater (Alkhudhiri et al., 2012; Khayet, 2011; Curcio and Drioli, 2005). Hence, waste heat and renewable energy sources (such as solar or geothermal) could be incorporated with an MD system for a high rejection ratio and cost efficient system (Qtaishat and Banat, 2013; Alkhudhiri et al., 2012; Ghaffour et al., 2015; Khayet, 2011; Alobaidani et al., 2008; Goosen et al., 2014; Ghaffour et al., 2014).

In particular, solar powered/integrated MD has gained great consideration in the last decade (Thomas et al., 2017). MD can be coupled with both non-concentrating and concentrating solar thermal collectors. Non–concentrating collectors are generally used for small scale and remote areas. However, concentrating solar thermal collectors, commonly known as concentrating solar power (CSP), are utilized for large scale, and it could be better option for continuous energy production. At present, CSP technology has four main families: parabolic

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trough collector (PTC), solar power tower (SPT), linear Fresnel reflects (LFR), and parabolic dish systems (Ghaffour et al., 2015). PTC is the most mature CSP technology; therefore, it is widely used in commercially operating CSP plants worldwide (Ghaffour et al., 2015; Zhang et al., 2013). Commercialization of CSP has considerably increased since last decade (REN21.2016). Additionally, it has been argued that a CSP plant integrated desalination technologies could be an approach to cope with increasing demand of freshwater and electricity, especially in arid regions (Palenzuela et al., 2011).

Few attempts have been made to combine the advantages of CSP and desalination systems for the production of both electricity and freshwater (Schmitz et al., 2009; Trieb, 2007; Mohammed et al., 2017). Trieb and Müller-Steinhagen (2008) presented an assessment of different configurations of CSP plants and desalination units (MED and RO). An assessment of integrating CSP technology and desalination plants (MED and RO) for Duqum, Oman, was studied by Gastli et al. (2010). Palenzuela et al. (2011) presented an assessment of PT plant integrated desalination technologies (RO and MED) for Abu Dhabi, United Arab Emirates (UAE). Iaquaniello et al. (2014) presented an integration of CSP plant with MED-RO hybrid desalination. Valenzuela et al. (2017) presented CSP and solar photovoltaic plants for power, and integrated MED for freshwater production in northern Chile. Alhaj et al. (2018) reported an integration of LFR plant with MED for Qatar. The results of all studies showed that the integration of CSP plants with desalination technologies could be an effective way to cope with increasing demand of freshwater and electricity.

All of the previous studies examined the integration of CSP plants with MED/MSF/RO; however, no assessment have considered integrating CSP plant with DCMD system. Therefore, core objective of this research is the concept description and simulations to investigate performance and economics of a 50 MW_e PT plant integrated with DCMD system for weather conditions of Abu Dhabi, UAE. The parameters which affect the performance of the proposed system are demonstrated. Finally, economic evaluations are performed to determine unit cost of electricity and freshwater. The structure of the paper is as follows: Section 2 presents DCMD mathematical modeling, and Section 3 presents methodology including system description and evaluation. Section 4 investigates performance and economic evaluation of PT plant integrated with DCMD system, and Section 5 concludes the paper.

2. MD mathematical model

DCMD is thermally driven and one of the most commonly used MD configurations (Eleiwi et al., 2016). Feed flows through one side while permeate flows on the other side of a hydrophobic membrane. The evaporation heat for the feed side is supplied by a hot liquid phase, and the condensation heat at the permeate side is removed by a cold liquid phase. A temperature difference is created between the membrane surfaces on the feed (T_{mf}) and permeate (T_{mp}) sides, and thermal boundary layers are formed on the both (feed and permeate) sides (Andrjesdóttir et al., 2013). Formation of layers that correspond to the bulk feed and permeate temperatures (T_{bf} and T_{bp}) differ from the T_{mf} and T_{mp}, as shown in Fig. 1. This temperature gradient leads to a reduction in the hypothetical driving force—which is the difference between T_{bf} and T_{bp}. This phenomenon is known as *temperature polarization*. The temperature polarization coefficient (TPC) is the ratio of the actual driving force and the theoretical driving force; mathematically TPC is expressed as follows (Qtaishat et al., 2008):

$$TPC = \frac{T_{mf} - T_{mp}}{T_{bf} - T_{bp}} \tag{1}$$

Experimentally, it is not possible to measure T_{mf} and T_{mp}, so those temperatures are typically calculated by carrying out a heat balance that relates them to the bulk temperatures. Solving the heat balance for T_{mf} and T_{mp} includes an assessment of the heat transfer coefficients in the fluid boundary layers of the membrane. The boundary-layer heat transfer coefficients can be estimated using empirical correlations of the Nusselt number (Nu) (Qtaishat et al., 2008). For comprehensive the analysis of the MD system, a mathematical model based on mass and heat transfer equations has been adapted.

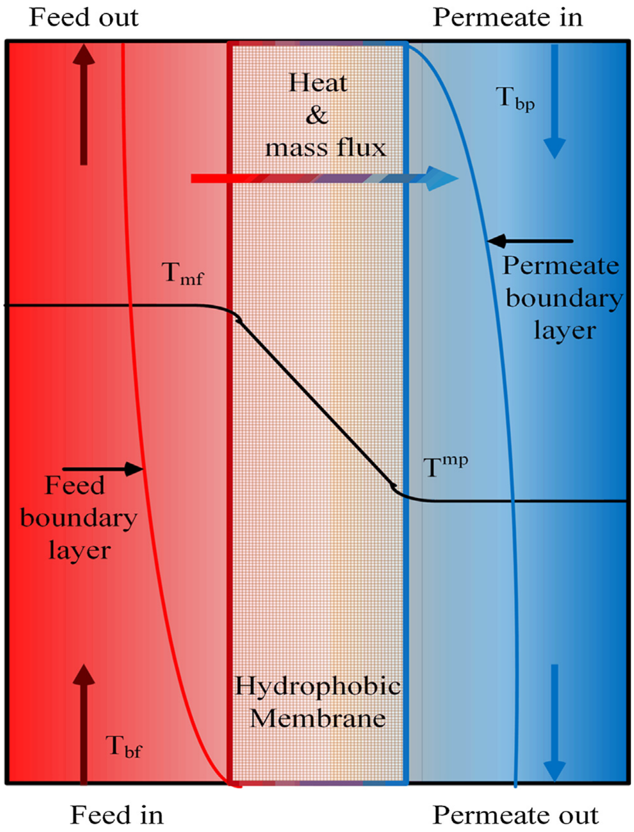

Fig. 1. DCMD process.

2.1. Mass transfer

In MD, the membrane pore size is an important parameter for determining the mass transfer mechanism. Generally, a large pore size is essential for high permeate flux, although it must be small enough to prevent penetration. Therefore, an optimum pore size should be selected for maximum vapor flux without saturation. Depending on the pore size of the membrane, three basic mechanisms for mass transfer are generally considered: (i) Knudsen diffusion, (ii) molecular diffusion, and (iii) Poiseuille (viscous) flow, as illustrated in Fig. 2 (Khalifa et al., 2017). A governing equation that provides a guideline to determine the suitable mechanism is known as the Knudsen number (K_n). It can be determined from the expression:

$$K_n = \lambda/d \tag{2}$$

where λ represents mean free path, and d is mean diameter of a membrane pore.

λ can be calculated by

$$\lambda = \frac{K_B * T}{\sqrt{2} * \pi * P_{avg} * {d_e}^2} \tag{3}$$

where K_B, T, and P_{avg} are the Boltzmann constant, absolute temperature, and average pressure inside the membrane pores, respectively. d_e is the collision diameter, which is in the range of 2.64×10^{-10} and 3.66×10^{-10} for water vapor and air, respectively (Sperati and DuPont de Nemours, 1975). The mass transfer mechanisms inside membrane pores for different K_n are summarized in Table 1.

The permeate flux (J_m) depends mainly on the vapor pressure difference of the water on the feed and permeate sides. The equation for