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A novel integrated thermal-/membrane-based solar energy-driven hybrid desalination system: Concept description and simulation results

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ABSTRACT

In this paper, a hybrid desalination system consisting of vacuum membrane distillation (VMD) and adsorption desalination (AD) units, designated as VMD-AD cycle, is proposed. The synergetic integration of the VMD and AD is demonstrated where a useful effect of the AD cycle is channelled to boost the operation of the VMD process, namely the low vacuum environment to maintain the high pressure gradient across the microporous hydrophobic membrane. A solar-assisted multi-stage VMD-AD hybrid desalination system with temperature modulating unit is first designed, and its performance is then examined with a mathematical model of each component in the system and compared with the VMD-only system with temperature modulating and heat recovery units. The total water production and water recovery ratio of a solar-assisted 24-stage VMD-AD hybrid system are found to be about 21% and 23% higher, respectively, as compared to the VMD-only system. For the solar-assisted 24-stage VMD-AD desalination system having 150 m^2 of evacuated-tube collectors and 10 m^3 seawater storage tanks, both annual collector efficiency and solar fraction are close to 60%.

1. Introduction

Desalination capacity is rapidly increasing worldwide, particularly in the Middle East and North Africa (MENA) region. Despite tremendous technology improvements in the conventional thermal-based and membrane-based desalination processes, its wide use is still limited to energy-rich countries due to the high energy requirements since these technologies involve high throughput volumes (Ghaffour et al., 2013). Currently, these energy requirements are met with the burning of fossil fuels either at power or boiler plants which greatly contribute to global warming and the discharge of concentrated brine laden with chemicals causing much deterioration of the marine environment (Höpner and Lattemann, 2002; Lattemann and Höpner, 2008). Thus, it is essential for engineers and scientists to search for alternative processes that are either more energy efficient or utilize waste and low-grade heat sources to meet the growing demand for desalinated water (Ghaffour et al., 2014). Renewable energy such as solar, and to some extent geothermal, is the obvious choice in several regions, especially where there is a severe shortage of fresh water; for example, the Kingdom of Saudi Arabia has an abundant supply of such low grade energy where decentralized small-scale solar-driven impaired water quality treatment plants have been installed supplying potable water in remote (off grid) locations (Ghaffour et al., 2015). However, the question of reliability and maintenance has cast doubt on the operation of these conventional renewable energy-driven desalination systems, e.g., reverse osmosis (RO), which require connection to the grid (compensation) and skilled manpower to operate them efficiently (Ghaffour, 2009). In this respect, this paper presents a novel hybrid desalination system utilizing a low-temperature heat source derived from solar energy,

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consisting of integrating two emerging thermal-/membrane-based desalination technologies, namely vacuum membrane distillation (VMD) and adsorption desalination (AD).

It can be argued that the main advantages of these emerging technologies, compared to conventional processes, such as RO, multi-stage flash (MSF) and multi-effect distillation (MED), are that they are simple, compact, operate at low temperatures and low pressures, and can function with variable loads (intermittent energy supply) without additional operating modifications (Ghaffour et al., 2015). Detailed descriptions of the AD and MD processes have been widely reported elsewhere (Alkhudhiri et al., 2012; Alsaadi et al., 2015; Curcio and Drioli, 2005; Francis et al., 2014; Khayet, 2011; Kim et al., 2014; Lee et al., 2015; Ng et al., 2012; Thu et al., 2009, 2013a, 2013b). In this paper, a brief description of these processes is presented highlighting their potential integration in a hybrid system.

Over the past decade, AD has been reported as an emerging and yet efficient heat-driven adsorption/desorption cycle for desalination. A detailed description and pros and cons of the AD process have been reported elsewhere (Ghaffour et al., 2015; Kim et al., 2014; Ng et al., 2012; Thu et al., 2009, 2013a, 2013b). In this novel process an adsorbent is used to adsorb the vapor generated from the evaporator at very low pressure and temperature, under low pressure environment, caused by the double-bond surface forces that exist between a mesoporous absorbent (silica gel) and an adsorbate (water vapor). The pore diameters of the adsorbent range from 10 to 40 nm and the total pore surface area ranges from 600 to 800 m^2/g. The main advantage of using an adsorbent like silica gel is its ability to be re-generated by a low temperature heat source (for desorption), typically from 55 to 85 °C, which is very suitable for solar energy use, and the high uptake rate of water vapor when exposed. In this process raw seawater is fed to the evaporator at its ambient temperature, which means there is no need to heat feed water as it is the case for other thermally-driven processes. When saturated, the adsorbent is heated to release the vapor (desorption process) and is then condensed inside an external condenser. Silica get is available at low-cost and could be filled in beds of different geometries, such as in vertical silos reducing its footprint especially for large scale units.

During a batch-operated operation, the reactor beds can be linked to the evaporator or the condenser during the half-cycle periods via a series of valves for the control of vapor and water flows. Consequently, an AD cycle comprises two half-cycles (intervals vary from 200 to 700 s) and a switching interval (from 20 to 40 s) in between which handles either the pre-heating or cooling of the exchangers (Kim et al., 2014; Ghaffour et al., 2014). Besides energy efficient, the AD cycle is inherently low in maintenance by design because it has almost no major moving components.

MD is a thermally driven process that utilizes a hydrophobic, microporous membrane as a contactor to achieve separation by liquid-vapor equilibrium. The driving force of MD is the partial vapor pressure difference maintained at the two interfaces of the membrane (hot feed and cold permeate). The hot feed solution is brought into contact with the membrane which allows only the vapor to pass through its dry pores so that it condenses on the coolant side (Alkhudhiri et al., 2012; Khayet, 2011).

As it is the case for the AD process some of the main advantages of MD are that the process performance is negligibly affected by high feed salinity (Adham et al., 2013; Alkhudhiri et al., 2012; Alsaadi et al., 2015; Curcio and Drioli, 2005; Francis et al., 2014; Lee et al., 2015), and it holds the potential of being efficient and cost effective separation process that can utilize low-grade waste heat or renewable energy such as low-enthalpy geothermal or solar energies (Alsaadi et al., 2014; Bundschuh et al., 2015; Goosen et al., 2014; Sarbatly and Chiam, 2013; Zaragoza et al., 2014).

Different MD module configurations have been proposed, mainly direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and VMD. More recently, other new MD configurations aiming to enhance the flux have been developed, such as liquid-gap MD and material-gap MD (Alkhudhiri et al., 2012; Alsaadi et al., 2013; Francis et al., 2013; Khayet, 2011). VMD is considered to possess a great potential for scale-up as it offers the highest flux and efficient heat recovery compared to the other configurations (Khayet, 2011), though that AGMD may offer similar of better internal heat recovery as condensation takes place inside the module. However, in the VMD configuration the condensation of water vapor takes place outside the module using a vacuum pump, which is considered as the main disadvantage of this configuration compared to others, e.g. AGMD, due to the vacuum energy required. However, the vacuum pressure of the AD process naturally created by adsorbents is a perfect environment to run the VMD process in an integrated configuration (VMD-AD) without the need for a vacuum pump, which represents the novel hybrid process combining the AD vacuum environment to the permeate side of the VMD module as proposed in this paper. A detailed description of this hybrid cycle is presented in the next sections.

2. System description

A schematic of the solar-assisted multi-stage VMD-only and VMD-AD hybrid desalination systems is illustrated in Figs. 1 and 2, respectively. The system comprises mainly the solar-thermal system with temperature modulating (TM) scheme, the heat recovery unit (HRU), the shell-and-tube type VMD modules and the AD unit which consists of three heat exchangers: a condenser and a pair of adsorber/desorber heat exchangers (sorption elements). As shown in bottom of Fig. 2, a pair of adsorber beds of the AD cycle containing highly porous hydrophilic adsorbent, i.e. silica gel, is connected to the VMD modules (permeate side) at each stage for a low vacuum environment to maintain the high pressure gradient across the pores of the membrane surface. Therefore, the vacuum provided by the beds of the AD cycle is employed to create the partial vapor pressure difference to drive the VMD process. After saturation, the desorption cycle is applied to release the water vapor collected from VMD modules by the adsorbents (adsorption process) and flows into the condenser through desorption process, which then get collected as final water product.

The solar-thermal system consists mainly of two circuits, namely, the solar energy collection circuit (ECC) and the energy storage circuit (ESC) that supplies the hot seawater to the VMD modules through the four storage tanks and the TM unit. When the storage tank-4 temperature is greater than the desired feed temperature during the mid-day hours, the hot seawater supply to the VMD modules is regulated by TM unit, which results in energy savings for application in the late-afternoon and night-time hours. That is, the hot seawater drawn from storage tank-4 is mixed with the relatively cold makeup seawater to achieve the desired feed temperature by controlling valve (CV1, CV2 and CV3). More details on the flow rate control scheme of the system are described elsewhere (Kim et al., 2012, 2013, 2015). These ECC and ESC are thermally connected via a plate heat exchanger (PHE), as shown in Figs. 1 and 2. The four storage tanks are built in a top-to-bottom configuration to attain thermal stratification yet fulfilling the load demand in terms of hot seawater supply. Whenever the storage tank-4 temperature drops below the desired feed temperature, the maximum possible portion of the thermal demand is supplied by keeping the discharge mass flow rate equal to the desired feed flow rate and the rest of the thermal demand is supplemented by the auxiliary heat.