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Air gap and water gap multistage membrane distillation for water desalination

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ABSTRACT

The performances of multistage air gap membrane distillation (MS-AGMD) and water gap membrane distillation (MS-WGMD) systems are experimentally investigated and compared using three-stages systems for different operating conditions. Parallel, series, and mixed stage-connections are considered. The flux of MS-WGMD is more than double the flux of MS-AGMD. The parallel stages-flow connections produced higher output flux than series connections (15% on average for MS-WGMD and 10% on average for MS-AGMD). The MS-AGMD system is found to be more sensitive to changes in the feed temperature and gap width than the MS-WGMD system. The effect of feed flow rate on permeate flux is higher than the coolant flow rate. The series stage connections are more sensitive to the change in hot and cold flow rates than the parallel connection; particularly the feed flow rate. The productivity of the three-stages system is almost three times the single stage system. The calculated specific electric energy consumption ranged from 5 to 10 kWh/m^3 and it values for MS-WGMD system are lower than that of MS-AGMD system, and decreases with increasing the feed temperature.

1. Introduction

Water scarcity is a worldwide challenging problem which is increasing sharply with the industrial development and population expansion [1]. More than one-third of population in the world lives in water-stressed areas. Many people do not have access to freshwater because of the low amount of renewable resources of freshwater. In addition, many current freshwater resources are contaminated with waste water comes from the industry, cultivation, and human beings [2]. Nevertheless, there are many seawater resources in the earth. As a result, researchers have used different types of desalination processes to overcome this water scarcity problem. The industrial desalination processes are mainly classified into two groups: thermal processes and membrane processes [3–5]. The multi-stage flash (MSF) distillation and multiple-effect distillation (MED) are the common thermal desalination processes while the reverse osmosis (RO) process is the common industrial membrane desalination technique separating fresh water from the feed solution.

Membrane distillation (MD) is an evolving and promising technique for water desalination and treatment. It is a thermally-based membrane separation process used to separate water vapor from the salty water stream using a micro-porous hydrophobic membrane [6]. In MD process, the vapor passes through the membrane due to the vapor pressure difference across the membrane, which is a result of temperature difference across the membrane. Different configurations for MD module have been used for different application. The four basic configurations mainly used in MD processes are [6,7]: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD). MD technology has many features over other desalination processes such as lower operating pressure and temperature, higher salt rejection factor, lower energy consumption, insignificant or no pretreatment is needed, the construction of membrane is simple, and lower sensitivity to the concentration of salt [8–12]. Hydrophobic membranes are mostly made of poly-ethylene (PE), poly-propylene (PP), poly-vinylidene-fluoride (PVDF), and poly-tetra-fluoroethylene (PTFE). The membrane used in the MD process should have lower mass transfer resistance and lower thermal conductivity to avoid heat loss through the membrane. Furthermore, the membrane should have higher resistance to chemicals and high thermal stability with higher feed temperatures [13].

The air gap membrane distillation is one of the common MD configurations. In AGMD there is a direct contact between feed water and hot surface of membrane. A gap is placed between the membrane cold surface and the condensation surface and is filled by a stagnant air. Vapor permeated from the membrane pores passes across the air gap and condenses on the condensation surface. Due to the existence of the air gap, the resistance of vapor transfer increases and the permeate flux

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is reduced, which is considered a drawback of AGMD [14]. One modification of the air gap design is the water gap membrane distillation (WGMD) design where the stagnant air inside the gap is replaced by stagnant distilled water. The WGMD design is also known in literature as Liquid gap MD (LGMD) and Permeate gap MD (PGMD), and in reality, only liquid water can be used in the gap of the module to avoid distillate contamination. In WGMD, the evaporation process in the feed side is the same as in AGMD while the vapor permeated through the membrane pores and condenses inside the water gap directly and extra permeate is then collected from the gap.

Khalifa [15] experimentally studied and compared the performances of AGMD and WGMD systems. He showed that the permeate flux of the WGMD module is 90% to 140% higher than the AGMD module tested under the same conditions. AGMD has higher gap temperature than WGMD and for both systems the permeate flux increases when the gap width decreases. He reported that the WGMD system is less sensitive to gap thickness compared to AGMD system. Essalhi and Khayet [16] compared the air gap and liquid (water) gap MD modules. They found that although the resistance of mass transfer in liquid water gap module is greater, its permeate flux is slightly higher (from 2.2 to 6.5%) compared to that of air gap MD module. The salt rejection factors for both MD configurations are almost the same, higher than 99.61%, and the thermal efficiency of the water gap MD system is higher compared to air gap system. They reported that the liquid water MD system has slightly higher concentration polarization coefficient compared to air gap MD system, whereas the temperature polarization coefficient for air gap system is slightly higher than that for the water gap system. Kataeva and Ugrozov [17] studied the power consumption a liquid water gap membrane distillation with heat exchanger. The value of power consumption increases proportionally with the productivity and the temperature variance between the inlet and exit of MD module, and decreases with increasing the membrane surface. Ghaffour et al. [18] proposed and tested a material gap membrane distillation (MGMD). They used three different materials (air, sand, and DI water) to fill the gap between the condensation plate and the membrane. They found that, the permeate flux increases by about 200% and 800% when the gap is filled by sand and DI water, respectively. They also studied the effect of material thickness and characteristics and found that increasing the water gap width from 9 mm to 13 mm increases the water vapor flux. Their conclusion of the effect of gap width on the flux of the water gap module was found to be opposing the conclusion of Khalifa [14], who showed that increasing the water gap width decreases the flux. They reported that WGMD system has higher values of the permeate flux compared with AGMD.

The problem of low permeate flux of MD processes (compared to conventional desalination processes like RO) can be solved by using multistage design for MD systems. The main advantages of the multistage membrane distillation (MS-MD) process over the single-stage MD process include better energy recovery, efficient utilization of low-grade energy, more water vapor flux due to the number of stages if placed in a single module, low cooling energy consumption, higher stability of the process, highly reliable and easy to operate, and low maintenance cost. Zhao et al. [19] performed an experimental study of the memsys vacuum-multi-effect membrane distillation (V-MEMD) module. They studied the optimization of number of module stages and size of each stage with flux and GOR values. Boutikos et al. [20] developed a detailed mathematical model, based on energy and mass balances in order to provide guidelines for the optimum design and operating condition of a multi-effect vacuum membrane distillation system. They used two different case-studies for the feed and made a comparison between experimental and theoretical values of distillate flux. The deviations were 1.9%–11.1% when tap water was used, and 2%–23% when saline water was used as feed solution. The average value of the specific thermal energy consumption (STEC) was found to be 255 kWh/m^3. The study showed that increasing the number of effects from 2 to 4 decreases the specific thermal energy consumption significantly. Xing et al. [21] integrated a multi-effect vacuum membrane distillation (MEMD) with 2 ton/day desalination plant by using PTFE hollow fiber membranes. They analyzed the effect of operating conditions on the performance of the plant. They found that the gained output ratio (GOR) and water production are affected by temperature difference between effects and operating temperature. Results showed that the plant GOR is 2.76. When the operating temperature increases from 60 °C to 80 °C the productivity increasing by 12.7%. The vacuum degree and the feed temperature have strong effects on the productivity, the productivity increased linearly by 25% as vacuum degree increases from 70 kPa to 82 kPa. The feed salinity and feed flow have lower effects on performance. Lee et al. [22] presented a theoretical analysis of the monthly average, daily and hourly performances of a solar powered multistage direct contact membrane distillation (MS-DCMD) system. The number of module stages used by the dynamic operating scheme changes dynamically based on the inlet feed temperature of the successive modules. They found that the monthly average daily water production increases from 0.37 m^3/day to 0.4 m^3/day and thermal efficiency increases from 31% to 45% when comparing systems both without and with dynamic operation.

A multi-stage air gap membrane distillation (MS-AGMD) module for water treatment was developed by Pangarkar and Deshmukh [23]. They used the single stage AGMD mathematical model to evaluate the performance of four stages AGMD. They presented the performance of the single effect AGMD and multi effect -AGMD process at various operating conditions such as temperature and flow rate for feed and coolant solutions, also the air gap thickness. The results showed that, (1) The maximum permeate flux of ME-AGMD is about 166.38 L/m2 h at 80oC feed temperature, 1.5 L/min feed flow rate, 20 °C cold water temperature, cold water flow rate in each cooling channel of 0.75 L/min and 5 mm air gap thickness, (2) The flux of ME-AGMD module is about 3.2–3.6 times the flux of single stage AGMD module, (3) The efficiency of the ME-AGMD system is higher than efficiency of the single effect AGMD system. The performance of a multi-stage air gap membrane distillation system was investigated by Li et al. [24]. The system was used for more concentrating reverse osmosis brine gaining a higher water recovery. They performed one-stage air gap membrane distillation system by utilizing the reverse osmosis brine as feed. They found that, the maximum value of the gained output ratio and the permeate flux could reach 7.1 and 6.8 kg/m^2 h respectively. The output flux of the 4-stage AGMD process decreased by 22.2% from 5.4 kg/m^2 h of the first stage to 4.2 kg/m^2 h of the fourth stage.

In this study, the performances of multistage air gap membrane distillation (MS-AGMD) and multistage water gap membrane distillation (MS-WGMD) systems are experimentally investigated using three MD connected modules (stages). The effects of main operating and design conditions are examined and compared. Different flow arrangements between stages (series, parallel, and mixed) are examined. In addition, the specific energy consumption and distillate productivity of single and multistage system are calculated and compared.

2. Experimental work

Details of the experimental setup of the multistage water gap and the multistage air gap membrane distillation systems are presented by describing the components, assembly of the module, the instrumentation, and connecting the stages of the system. The multistage system consists of three MD modules. Different type of connections- parallel, series, and mixed- for the stages are tested. A photo of the multistage MD system experimental setup is illustrated in Fig. 1. The system consists of two water closed cycles, hot feed water and cold coolant water, connected the MD modules (stages). An electric circulating heater is used to deliver the desired temperature and flow rate for the feed water. A water circulating chiller is used to deliver the desired temperature and flow rate for the coolant stream. Each cycle has valves for additional control of the water flow and to set the required flow