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A novel multi-stage direct contact membrane distillation module: Design, experimental and theoretical approaches

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An economic desalination system with a small scale and footprint for remote areas, which have a limited and inadequate water supply, insufficient water treatment and low infrastructure, is strongly demanded in the desalination markets. Here, a direct contact membrane distillation (DCMD) process has the simplest configuration and potentially the highest permeate flux among all of the possible MD processes. This process can also be easily instituted in a multi-stage manner for enhanced compactness, productivity, versatility and cost-effectiveness. In this study, an innovative, multi-stage, DCMD module under countercurrent-flow configuration is first designed and then investigate both theoretically and experimentally to identify its feasibility and operability for desalination application. Model predictions and measured data for mean permeate flux are compared and shown to be in good agreement. The effect of the number of module stages on the mean permeate flux, performance ratio and daily water production of the MDCMD system has been theoretically identified at inlet feed and permeate flow rates of 1.5 l/min and inlet feed and permeate temperatures of 70 °C and 25 °C, respectively. The daily water production of a three-stage DCMD module with a membrane area of 0.01 m^2 at each stage is found to be 21.5 kg.

1. Introduction

Global climate change and variability have a negative impact on water supply and quality in remote areas by diminishing both the availability of water and the dilution of contaminants, such as pollutants, sediment and salts. These effects are expected to be exacerbated by a limited and inadequate water supply, low infrastructure and insufficient water treatment. Because it is unfeasible to adopt large-scale and mature seawater desalination technologies such as multi-stage flash (MSF), multi-effect desalination (MED) and reverse osmosis (RO) in such regions, seawater desalination markets will necessarily require an economic seawater desalination system with a small scale and footprint in order to supply sufficient fresh water to isolated areas. The membrane distillation (MD) process may be an alternative for providing potable water in such areas. MD is a thermally-driven separation process using a microporous hydrophobic membrane. The transmembrane partial vapor pressure difference is the driving force of the MD process, and is generated by the temperature gradient formed between the liquid-vapor interfaces across the membrane. This MD process has many attractive features, such as low operating temperature and hydraulic pressure, low sensitivity to salt concentration, a small footprint, a near 99.9% rejection of non-volatile solutes (Alkhudhiri et al., 2012; Curcio and Drioli, 2005), independent performance of high osmotic pressure or concentration polarization (Al-Obaidani et al., 2008; Cheng et al., 2011; El-Bourawi et al., 2006; Francis et al., 2013, 2014a; Kim et al., 2013; Lawson and Lloyd, 1997; Lee and Kim, 2013, 2014; Lee et al., 2015a, 2015b; Maab et al., 2013; Shim et al., 2014), potentially low maintenance requirements (Guillén-Burrieza et al., 2011) and high permeate flux in lab-scale membrane tests (Cath et al., 2004; Francis et al., 2014b; Gilron et al., 2007; Li and Sirkar, 2004). Due to the aforementioned advantages, MD has exhibited high potential as a seawater desalination process; however, the major barriers hindering its

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commercialization, aside from the MD membrane, include module design, membrane pore wetting, low permeate flux, flux degradation with time, as well as uncertain energy and economic costs. In order to overcome these limitations, various studies on module and process design utilizing a heat recovery concept have been conducted (Blanco Gálvez et al., 2009; Duong et al., 2015; González-Bravo et al., 2015; Guan et al., 2015; Khayet et al., 2005; Kim et al., 2013, 2015; Lee et al., 2011; Maab et al., 2012; Zhao et al., 2013) and various MD membranes have been developed (Feng et al., 2006; Francis et al., 2014c; Huo et al., 2009; Khayet et al., 2005; Peng et al., 2005; Prince et al., 2013; Winter et al., 2013). A composite membrane, which has high permeability with an appropriate pore size and porosity, low thermal conductivity with a high thickness and porosity, good thermal stability and high mechanical strength, has been developed and may meet the intricate demands of MD (Khayet et al., 2005; Lee et al., 2015a).

A multi-stage MD process with various configurations such as series, parallel and series/parallel arrangements of the MD modules has been studied to efficiently increase water production and system performance (González-Bravo et al., 2015; Lee and Kim, 2014). It has been shown that the multi-stage concept for the air gap membrane distillation (AGMD) and vacuum membrane distillation (VMD) processes could reduce energy consumption by recovering the latent heat of water vapor condensation (Guillén-Burrieza et al., 2011; Zhao et al., 2013). By applying the multi-stage scheme, an improvement in MD permeate flux can be achieved with thermal entrance effects, which affects the enhancement of heat transfer coefficient near the inlet flow region of each stage as the thermal boundary layer begins to develop near the inlet region (Phattaranawik et al., 2003a; Welty et al., 2009). In addition, due to the separated module configuration, the multi-stage scheme may provide supplementary advantages, such as simple maintenance, replacements, as well as the ability to check the leaks in the module (Lee and Kim, 2014). Multi-stage MD systems have been studied by many researchers (Blanco Gálvez et al., 2009; Kim et al., 2015; Lee and Kim, 2014; Lee et al., 2015b; Zhao et al., 2013). Lee and Kim (2014) presented various configurations of multi-stage VMD systems. Among the proposed systems which have various configuration manners, an optimized multi-stage VMD system configuration was determined via cost evaluation. Kim et al. (2015) proposed a solar-assisted multi-stage VMD system with a heat recovery unit, which could increase thermal efficiency and water production. Blanco Gálvez et al. (2009) reported an innovative solar-powered AGMD desalination system. The solar powered multi-stage AGMD system was developed and experimentally determined to improve the energy efficiency and reduce water production costs. The memsys had commercialized a vacuum-multi effect membrane distillation (V-MEMD) module, which achieved highly efficient heat recovery as compared to conventional thermal desalination processes. The solar-driven memsys system showed good operating performance with a flux at approximately 7 l/m^2h on a sunny day with a seawater feed (Zhao et al., 2013).

All of the aforementioned studies have attempted to develop a commercialized MD system using a multi-stage concept due to negligible conductive heat loss through the membranes of both the AGMD and VMD processes. However, the AGMD has several drawbacks such as complex module design and low permeate flux, and the VMD has several disadvantages such as treatment of non-condensable gases, requirement of an additional vacuum pump and membrane pore wetting, which readily occurs when vacuuming the permeate side of the membrane. In contrast, the direct contact membrane distillation (DCMD) process has the simplest configuration and potentially the highest permeate flux among all of the possible MD processes. In addition, the effects of the diffusion of non-condensable gases on the permeate flux is negligible in the DCMD process due to the very small quantity, as compared with a high DCMD permeate flux (Khayet and Matsuura, 2011). Furthermore, DCMD can be configured easily in a multiple stages to achieve improvements in compactness, cost-effectiveness, productivity and versatility. However, previous experimental and theoretical studies for DCMD process with a multi-stage concept were conducted with a rather simple module configuration via external pipelines between the stages (Gilron et al., 2007; Lee et al., 2011; Song et al., 2008). It was evident that a multi-stage concept could have a higher water production due to a higher effective membrane area. The module configuration proposed in previous works, however, can lead to additional heat losses to the ambient through the external pipelines, larger footprint, more complex structure as well as higher capital cost and operating cost due to higher pumping power caused by high pressure drop. In order to ameliorate such shortcomings, completely different module configurations need to be designed and studied both theoretically and experimentally.

The ultimate objective of this work is to develop a high-performance multi-stage direct contact membrane distillation (MDCMD) process that is applicable to a small scale and footprint desalination system. In this study, therefore, an innovative MDCMD module under countercurrent-flow operation has been first designed and both theoretically and experimentally examined to demonstrate the feasibility and operability of the module design for desalination. A rigorous numerical model, which was developed in our previous work (Lee et al., 2015a), has been modified to incorporate a thermal entrance effect near the inlet flow region of each stage for the performance prediction of the MDCMD process. Further investigations have been conducted to identify the effect of the number of module stages on the mean permeate flux, performance ratio and daily water production of the MDCMD system.

2. Experimental set-up and procedure

The requirements of an ideal membrane applied for the MD process are (i) higher permeability with an optimal pore size and porosity, (ii) lower thermal conductivity with higher thickness and porosity, (iii) higher liquid entry pressure with water and smaller maximum pore size, (iv) higher mechanical strength, (v) excellent thermal stability and (vi) chemical resistance (Khayet et al., 2005; Lee et al., 2015a). However, it exhibits a conflict between the requirements of an ideal membrane such as higher mass transfer and lower conductive heat loss. It is well known that the above conflict can be resolved by using a microporous hydrophobic/hydrophilic (or hydrophobic) composite membrane (Khayet et al., 2005; Lee et al., 2015a). As shown in the SEM images (clockwise from top left: 100x, 500x, 1,000x and 10,000x magnifications) in Fig. 1 (Lee et al., 2015a), therefore, a commercial hydrophobic microporous PTFE/PP composite membrane (Sterlitech Corporation) has been used for this study. It appears that the knot-fibril net-structured PTFE active layer (dark gray in top right of Fig. 1) is partially covered by the PP scrim support layer (white gray). Here, the PTFE active layer is not covered by the PP support layer at the permeate side, indicating an effective area for diffusion that can be expressed by the surface porosity, defined as the surface area of the PTFE active layer exposed to the permeate side divided by the total membrane surface area. The surface porosity is found to be 42% using CAD software based on the SEM images. The physical properties of the PTFE/PP composite membrane are given in Table 1. Note that the composite membrane has a significantly thinner and more porous active layer than the scrim support layer, which can result in decreased mass transfer resistance and increased heat transfer resistance.

Fig. 2 represents a schematic (Fig. 2a) and picture (Fig. 2b) of the