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Membrane distillation hybridized with a thermoelectric heat pump for energy-efficient water treatment and space cooling

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HIGHLIGHTS

- Novel thermoelectric coupled sweeping gas membrane distillation (T-SGMD) hybrid.
- Hybrid membrane distillation for decentralized water treatment, dehumidification and space cooling.
- Latent heat cooling provides for water treatment simultaneously.
- Impact of membrane area, cool air recycle and module orientation on T-SGMD efficiency.
- Interplay among power consumption, space cooling capacity and condensate rate.

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Sweep-gas membrane distillation (SGMD)
Hybrid membrane process
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Module orientation

ABSTRACT

The current concept for cooling the indoors is far from ideal with respect to the total energy consumed and waste discharged. A novel concept for improving the energy efficiency is proposed via hybridizing the heat pump with a membrane distillation (MD) unit for simultaneous space cooling and water treatment. MD is well-acknowledged for utilizing low-quality waste heat for water treatment, which makes it feasible for coupling with a heat pump to make use of both the hot and cold reservoirs of the pump. Accordingly, the objective of the current effort was to investigate via experiments the efficacy of a thermoelectric heat pump coupled with a sweep-gas MD system (T-SGMD) by measuring the cooling capacity, condensate production and power consumption. The results from this study can be extended to other heat pumps. Three key highlights emanated from this study. Firstly, condensate production per unit energy consumed can be doubled with the T-SGMD system relative to thermoelectric dehumidification alone. Secondly, cool air recycle affected the condensate flux the most without a drastic loss of cooling compared to other tested parameters during the operation of the T-SGMD. Lastly, the T-SGMD system was able to provide an increase in condensate produced per unit energy without a loss in cooling capacity per unit energy input. These advantages of coupling heat pumps with MD, leveraging on the current advancements in MD, is promising for a hybridized system for decentralized water treatment, dehumidification and space cooling.

1. Introduction

The severity of energy and water issues escalates as the population continues to grow exponentially, which has correspondingly attracted much research efforts towards mitigation. The focus here is on the space cooling of the indoors. In order to cope with the high temperature and humidity throughout the year, the building sector in tropical countries accounts for approximately 30% of primary energy demand, with space cooling for the interior accounting for over 50% of total energy consumption in buildings and increasing to 80% during peak periods [1]. A significant portion of this cooling load consumed is in the form of latent heat to dehumidify air. In some systems, air dehumidification is achieved by reducing the ambient air temperature below its dew point, which is far lower than the required comfort conditions in buildings,

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causing more energy waste for air reheating. In addition to the energy wastage, the heat being pumped into the surrounding environment adds to the cooling load required characterized by the well-known urban heat island effect [3]. In other systems, desiccants or novel polymeric electrolyte membranes [2] are utilized for dehumidification, but energy has to be expended to regenerate these desiccants or new materials to recover the water.

This inefficient use of energy results in not only the wastage of resources used to generate the energy, but also the rejection of more heat into the environment, which is the very heat we need to remove to maintain a comfortable living and working environment. Water-cooled air-conditioning systems that are often found in commercial buildings with centralized cooling systems have better thermal efficiency. Chen et al. [4] showed that by using water-cooled condensers for split-type air conditioners in residential buildings in Hong Kong, annual electricity consumption can be reduced by 8%. However, when a cooling tower is used, evaporative cooling increases the humidity of the environment outside which in turn has to be dehumidified for space cooling. To further improve the energy efficiency, this vicious cycle can be broken by coupling the heat pump used with a membrane distillation (MD) unit to provide a system for simultaneous space cooling and water treatment.

Aside from the waste heat generated, most space-cooling systems to date dispose of the condensate produced to the sanitary drain, due to the small amount of condensate produced [5] and the concern of contamination with organic and inorganic contaminants [3,4]. However, a recent research highlighted through theoretical calculations that the condensate recovery system in a typical hotel on the Arab Emirates coast can produce a significant amount of water that can mitigate the water requirements of the hotel [6]. Furthermore, the inorganic contaminants in the condensate from contact with the metal condenser surface was reported to be inconsequential [7]. The possibility of increasing the condensate recovered through the coupling of a heat-pump and MD could improve the feasibility of condensate recovery, which was evaluated in this study.

Many studies have been carried out on coupling MD with different processes such as forward osmosis-membrane distillation (FO-MD) [8], membrane distillation-crystallizer (MD-C) [9,10] and membrane distillation-bioreactor (MDBR) [11], which suggests that MD is a promising process for hybrid separation technologies [12]. This is because MD confers advantages including the ability to treat highly concentrated feed [13–15], lower membrane fouling propensity [16] and lower energy consumption, as well as ease of integration due to the relatively mild operating conditions [17,18]. Another attractive feature of MD is the ability to make use of low-quality waste heat, although the thermal efficiency is lower than multi-stage flash [19]. In some cases, heat-loss through conduction to the permeate could even be used to pre-heat the cool feed [20–22]. Most energy-conversion processes produce primarily thermal energy, most of which could be reused if the waste heat is of high enough temperature [23], while the low-temperature waste heat are simply released into the environment [24]. An example of such low-temperature waste heat generation is the membrane bioreactors that contain microorganisms that metabolize organic compounds and produce heat while doing so, thus can be coupled with MD for further water treatment [25]. Another example is in vapor compression cycle cooling. Heat integration of heat pumps with conventional distillation is well-studied, spanning the comparison of different configurations [26], energy efficiency [27], and heat integration to the overall process [28], with a recent review summarizing the various state-of-the-art configurations [29]. However, published work related to the coupling of MD with heat pumps only include a patent of a thermoelectric-integrated membrane evaporation system filed in 1982 [30], and also a research article on the study of a heat pump for simultaneous cooling and desalination [31]. Conceivably, the condensate from the MD system can be condensed on the cold surface of the heat pump, which releases latent heat back to the heat pump to negate some of the energy required. The feasibility of this has not been proven to date, which formed the goal of the current study.

In this study, a sweeping gas membrane distillation (SGMD) process, which combines a relatively low conductive heat loss with a reduced mass transfer resistance [32,33], was hybridized with a thermoelectric cooler to partially relief the cooling load of the radiator in the system. Specifically, the condensate from the membrane was directed towards the cold fins of the thermoelectric cooler to be condensed and collected. A thermoelectric heat pump is used in this experiment to drastically improve the ease of integration and reduce the footprint of this lab-scale proof-of-concept. However, the system is versatile and can be modified to accommodate other heat pumps in the future. Other than evaluating the feasibility of coupling MD with heat pumps to improve energy efficiency and also extend the use of SGMD for space-cooling applications, this study also explored means to improve the condensate flux along with reducing the power consumption. This study aims to provide a platform for sustainability in space-cooling means through reducing waste heat rejection and also in water supply.

2. Experimental setup

2.1. Experimental study

Typically, in a SGMD system used for desalination (Fig. 1a), an external heat source is used to heat up the seawater feed, whereas the heat generated during the condensation is fully rejected to the

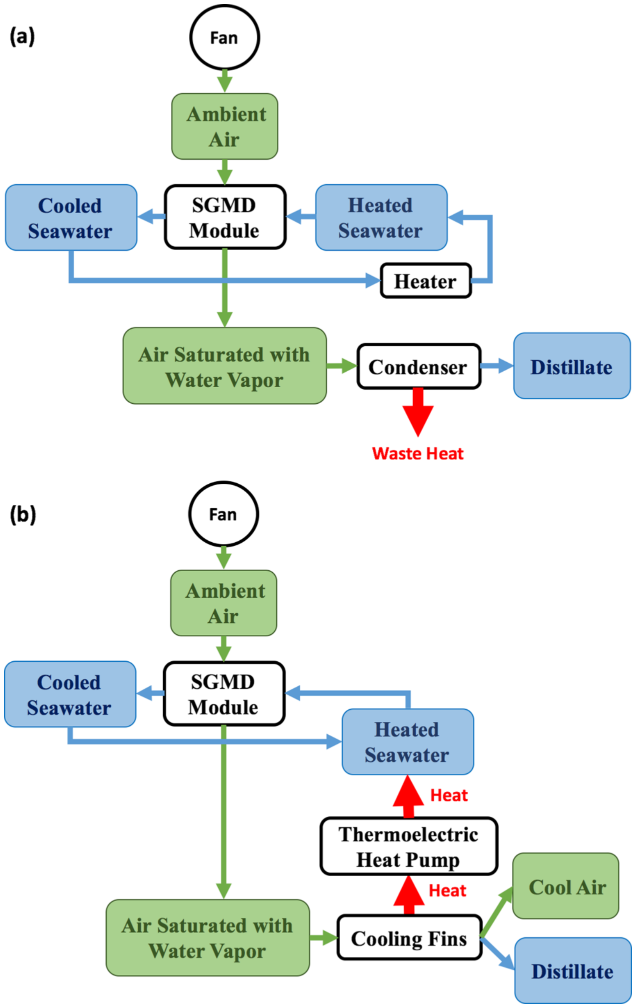

Fig. 1. Overview of (a) a typical SGMD; and (b) a T-SGMD with heat integration and cool air generation.

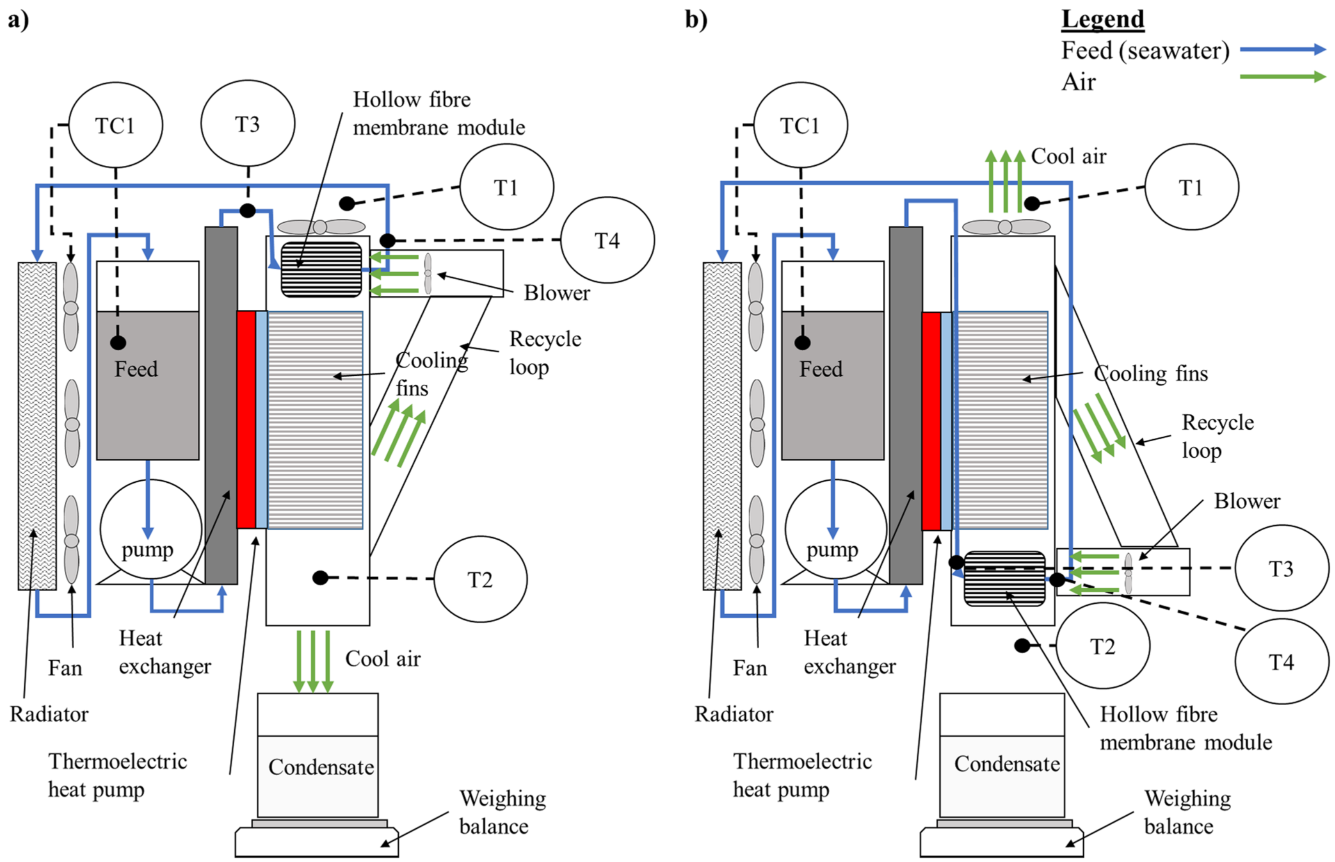

Fig. 2. Schematic of the experimental T-SGMD setup with the membrane module in two different orientations: (a) upright, and (b) inverse. T1-4 represent the PT100 temperature sensors and TC1 the temperature controller used to maintain the feed temperature.

environment, which is a waste considering one of the prime advantages of MD is its capability to make use of low-grade waste heat for water purification. To address this, a thermoelectric heat pump can be integrated into a SGMD system (T-SGMD) to reduce the energy cost and also extend the use of SGMD for space cooling, as shown in Fig. 1b. Specifically, the heat released from the condensation of the condensate is used by a thermoelectric heat pump to heat up the seawater feed, thereby negating the need for an external heater while additionally providing for space cooling as the cool air is directed outwards by the fan.

2.2. Experimental setup of the thermoelectric coupled membrane distillation (T-SGMD)

The experimental setup was designed to realize Fig. 1. Fig. 2 displays the schematic diagram of the experimental T-SGMD setups with the membrane module oriented in two different orientations, in view of earlier studies that convection plays a non-negligible role in the MD performance [34,35]. The two thermoelectric plates (Thermonamic TEC 12715; dimensions of 50 mm length × 50 mm width × 4 mm height) used were each rated at 12 V and 15 A. When an electrical potential was applied through the semiconductor in the plates, a temperature difference was generated across the plate, creating a cold and a hot surface on the two faces of the plates. The feed was continuously recirculated using a peristaltic pump (Masterflex L/S Economy Variable-Speed Console Drive) at 250 mL/min between the membrane module and the feed tank (a 3-L polypropylene beaker) via Masterflex Norprene tubing. A temperature controller (WILLHI WK7016C1) TC1 was used to control the temperature of the feed in the tank by switching the three fans (120 mm blade-diameter) of the radiator on and off. Air was circulated through the thermoelectric cooler at 1.25 m^3/min with a fan (Nidec D08T-12PU; 80 mm blade-diameter). This air can be recirculated through the cooling fins using a horizontal blower fan (Delta electronics BFB1012H; 90 mm blade-diameter). PT100 temperature sensors (HYXC TM6-1003) T1 and T2 were used to measure respectively the cold air inlet and outlet, while T3 and T4 respectively the hot water inlet and outlet of the hollow fiber membrane (PVDF; nominal pore diameter of 0.02 µm) module. The temperature sensors are connected to a Data Acquisition module (NI-DAQ; National Instruments) for temperature data acquisition every 10 min. A mass balance (Mettler-Toledo ME4002) was used to measure the condensate flux. The conductivity of the collected condensate was measured using a conductivity meter (Mettler-Toledo SevenGo) at the end of each experiment to check for membrane pore-wetting (results will be discarded and membranes replaced if pore-wetting occurs), and the energy consumption of the entire system except for the balance was measured using Voltcraft 3000 energy consumption meter (which is a plug load meter used to measure the total energy consumption from the main power outlet before it is split to power the difference devices used in the experiments) to compare the energy consumption at different experimental conditions. The effects of the feed recirculation temperature (namely, either 30 °C or 40 °C in this study), the membrane area (namely, bypass membrane module totally, 0.00849 m^2 or 0.0151 m^2), the activation of the recycle and the module orientation were investigated. The membrane module was flushed with DI water after every run and dried in a forced convection oven set at 40 °C for 16 h before reusing. The experiments and the respective operating parameters investigated in this study are summarized in Table 1.

2.3. Materials

The feed solution prepared for each experiment was 3 L of 35 g/L

Table 1
Experiments carried out using the T-SGMD system.

Experiments		Feed recirculating temperature (°C)	SGMD coupling	Membrane area	Module orientation	Recycle flow
1	Thermoelectric only	30	No	–	Upright	Off
2	Small area T-SGMD + recycle (upright)	30	Yes	Small	Upright	On
3	Small area T-SGMD (upright)	30	Yes	Small	Upright	Off
4	Small area T-SGMD + recycle(inverse)	30	Yes	Small	Inverse	On
5	Small area T-SGMD (inverse)	30	Yes	Small	Inverse	Off
6	Large area T-SGMD + recycle (upright)	30	Yes	Large	Upright	On
7	Large area T-SGMD (upright)	30	Yes	Large	Upright	Off
8	Large area T-SGMD + recycle (inverse)	30	Yes	Large	Inverse	On
9	Large area T-SGMD (inverse)	30	Yes	Large	Inverse	Off
10	Thermoelectric only	40	No	–	Upright	Off
11	Small area T-SGMD + recycle (upright)	40	Yes	Small	Upright	On
12	Small area T-SGMD (upright)	40	Yes	Small	Upright	Off
13	Small area T-SGMD + recycle (inverse)	40	Yes	Small	Inverse	On
14	Small area T-SGMD (inverse)	40	Yes	Small	Inverse	Off
15	Large area T-SGMD + recycle (upright)	40	Yes	Large	Upright	On
16	Large area T-SGMD (upright)	40	Yes	Large	Upright	Off
17	Large area T-SGMD + recycle (inverse)	40	Yes	Large	Inverse	On
18	Large area T-SGMD (inverse)	40	Yes	Large	Inverse	Off

sodium chloride (NaCl; Merck-Millipore CAS No. 7647–14-5) in DI water. PVDF hollow fiber membranes used had a nominal pore size of 0.022 µm; details on the membrane properties are given in Table A1. The lab-scale membrane module consisted of a PTFE tube (OD: 12.7 mm, ID: 9.4 mm) with a bundle of hollow fibers membranes within, with active membrane areas of either 0.00849 m^2 (made up of 10 hollow fibers each 31 cm long) or 0.0151 m^2 (made up of 12 hollow fibers each 46 cm long).

2.4. Experimental protocol

The same protocol was used for each experiment. The feed of 35 g/L NaCl solution was firstly circulated through the feed loop from the 3 L feed tank at 250 mL/min for 2 min to remove air bubbles in the system and ensure that the thermoelectric plates do not overheat, after which the direct-current power supply to the thermoelectric heat pump was switched on and the temperature controller set to the required feed temperature (namely, either 30 °C or 40 °C). Note that the feed temperatures were intentionally kept low to ensure the thermoelectric plates provided sufficient cooling of the air to demonstrate space cooling purposes, and also highlight the very low-quality waste heat required by this coupling. The system was given an hour for the temperature to stabilize before the temperature measurement started. Temperature readings were recorded every 10 min, while the condensate mass, conductivity and energy consumption readings were recorded at the end of each 3-h long experiment. It should be noted that the conductivity of the condensate was only measured at the end of every experiment, because it was consistently found that the values remained within 10 µS/cm, which is indicative that wetting did not occur during the course of the experiments.

2.5. Analysis of results

The three main parameters used to compare the efficacy of T-SGMD in cooling and desalination are power consumption (kW), cooling capacity per unit energy consumed (dimensionless) and the volume of water produced per unit energy consumed (mL/kWh). The power consumption was calculated by averaging the product of energy consumption and experimental duration (kWh). The cooling capacity per unit energy input was calculated by:

$$\text{Cooling capcity per unit energy input } (-) = \frac{Q_L}{W} = \frac{|\rho_a \dot{V} C_p (T_{ai} - T_{ao})|}{W} \tag{1}$$

where Q_L is cooling capacity (kW), W is power consumption (kW), ρ_a is the density of air (kg/m^3), $\dot{V}$ is the volumetric flow rate of air (m^3/s), T_{ai} and T_{ao} are respectively the air inlet and outlet temperatures (K). The volume of water produced per unit energy input can be derived by:

$$\text{Volume water produced per unit energy input } (-) = \frac{\text{Mass of water}}{\rho_w t W} \tag{2}$$

where ρ_w is the density of water and t is the time in hours.

3. Results and discussion

3.1. Effect of membrane area and recirculating feed temperature

The effects of membrane area and recirculating feed temperature on the performance of the T-SGMD were investigated with the module in the upright position. Fig. 3 compares the power consumption (Fig. 3a), cooling capacity per unit energy input (Fig. 3b) and condensate produced per unit energy (Fig. 3c) among the three different T-SGMD configurations (namely, without a membrane module, and with small

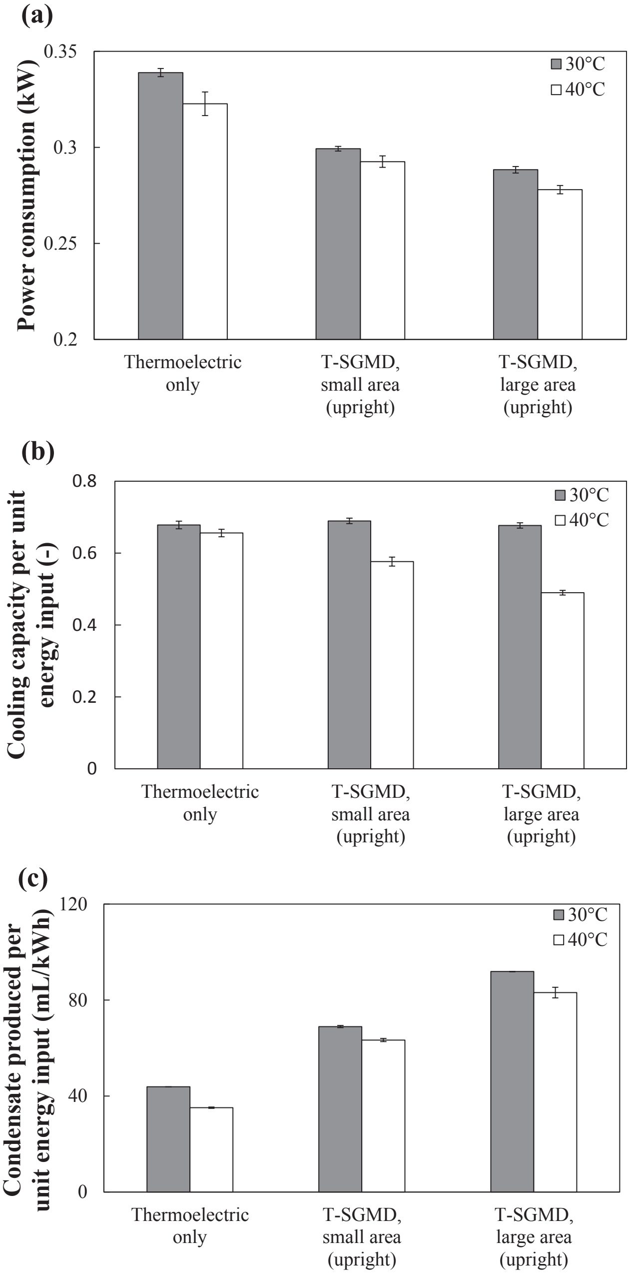

Fig. 3. Effect of membrane area at two different feed temperatures on (a) power consumption, (b) cooling capacity per unit energy input, and (c) volume of condensate per unit energy input. 'Thermoelectric only' denotes the configuration without the membrane module, while 'small area' and 'large area' indicate membrane areas respectively of 0.00849 m^2 and 0.0151 m^2. The module orientation was upright.

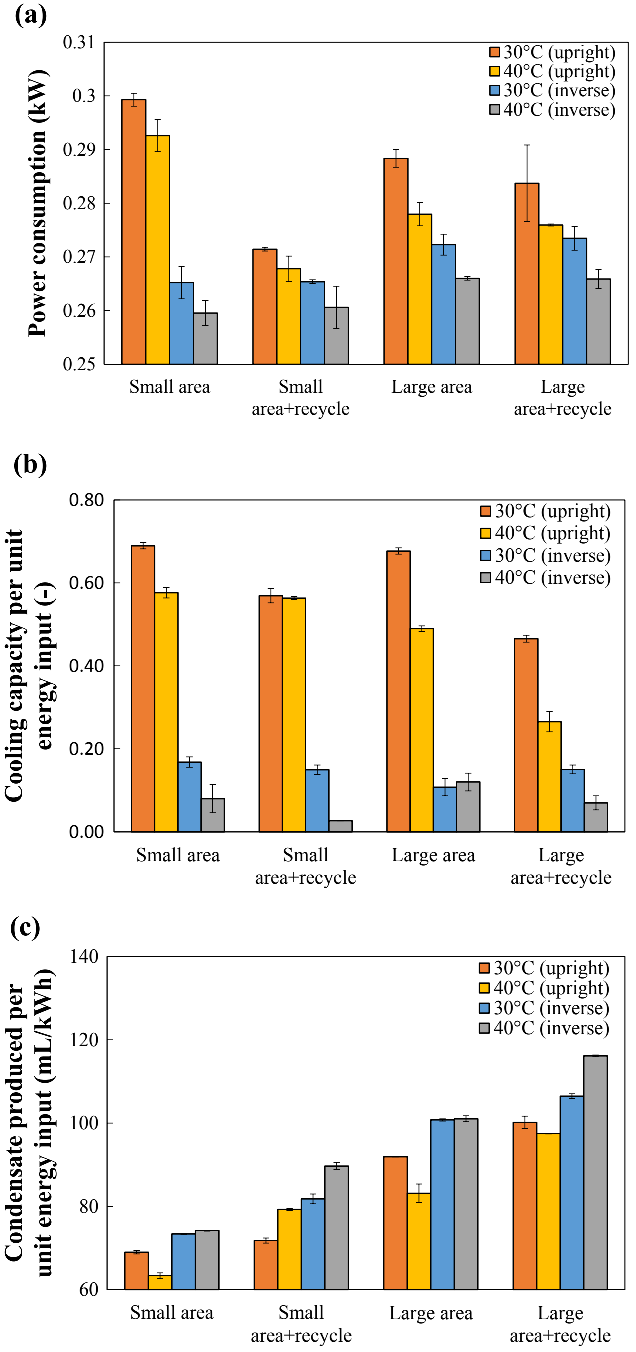

Fig. 4. Effect of membrane area (0.00849 m^2 or 0.0151 m^2), feed temperature (30 °C or 40 °C), presence of air recycle and module orientation (upright or inverse) on (a) power consumption, (b) cooling capacity per unit energy input, and (c) volume of condensate per unit energy input.

and large membrane areas). Three conclusions can be drawn. Firstly, the effect of feed temperature was such that the power consumed, the cooling capacity per unit energy input and the condensate produced per unit energy were all lower for the higher temperature of 40 °C, which indicate that operation efficiency was improved at the lower feed temperature. In particular, the higher temperature is a result of lesser heat being removed from the feed by the radiator, and hence lesser power consumed. The decrease in cooling efficiency of the T-SGMD at the higher temperature (Fig. 3c) suggests that a critical temperature exist above which the extent of cooling became compromised by the returning heat; this will be discussed more in Section 3.4. Secondly, regarding whether the T-SGMD hybrid conferred superior performance, Fig. 3 shows clearly that the T-SGMD hybrids consistently outperformed with respect to lower power consumption (Fig. 3a) and more condensate produced per unit energy (Fig. 3c). On the other hand, the T-SGMD hybrids performed similarly and poorer respectively at the lower and higher temperatures with regards to the cooling capacity per unit energy input due to the heat returning to the thermoelectric cooler reducing the cooling of the air. Thirdly, the T-SGMD hybrid with the larger membrane area generally performed better than that with a smaller area, which indicates that the performance can be better enhanced with more membrane fibers.

3.2. Effect of cool air recycling in T-SGMD

The effect of cool air recycling in the T-SGMD was investigated by comparing the system performance via switching on or off the recycle blower as shown in Fig. 2. Fig. 4a shows that cool air recycling reduced power consumption significantly for the upright module orientation but not for the inverse module orientation. This observation can be explained by referring to Fig. 4b, which shows that the inverse modules required drastically lower cooling capacities per unit energy input, resulting in less heat being removed from the membrane module, which translates into a reduction in power consumption. Furthermore, Fig. 4c shows that the recycling of cool air blowing towards the membrane modules improved the condensate produced per unit energy input by approximately 14.9 to 25.4%.

3.3. Effect of module orientation

The effect of module orientation on T-SGMD performance was investigated, since convection effects have been reported to play a non-negligible role [34,35]. In the inverse orientation (Fig. 2b), natural convection would move the warm air saturated with water vapor (which is less dense than cool dry air) upwards, while forced convection was through the suction pressure provided by the 80 mm fan to cause low air flow across the condenser fins. Hence, the effect seen in this section is the combination of both natural convection as well as forced convection. Fig. 5a shows that the small-area T-SGMD without cool air recycle showed the greatest reduction in power consumption when the module orientation was changed from upright to inverse. This is because of the drastic decrease in cooling capacity per unit energy input resulting from low air flow across the cooling fins, which led to lesser heat transferred to the cooling fins, which in turn reduced the power consumption. This low air flow across the cooling fins also reduced the temperature of the cooling fins, allowing more water vapor to condense, and thus improving the clean water produced per unit energy input by approximately 17.1–19.1%.

3.4. Feasibility of coupling heat pumps with membrane distillation

The experimental results collectively indicate that the coupling of heat pumps with membrane distillation is promising for both space cooling and water treatment. However, for this hybrid MD to be useful in space cooling and water treatment, there should be little or no decrease in cooling capacity per energy input while providing an increase in condensate produced per unit energy input. In this section, the results will be summarized to gauge the feasibility of this hybrid T-SGMD system, while providing recommendations to further improve the coupled system.

In order to be beneficial in space cooling as well as water-treatment applications, this coupled system have to provide an increase in condensate produced per energy input while maintaining its cooling capacity per unit energy input. Fig. 6a and b display respectively the cooling capacity per unit energy input and the condensate produced per unit energy input. High values in both cases indicate better energy efficiency. Fig. 6a indicates that the cooling capacities per unit energy input were similarly high for all four cases in the absence of the MD module (i.e., 'thermoelectric only'), whereas the cooling was significantly more energy-efficient with the inverse module orientation vis-à-vis the upright one, and generally slightly more energy-efficient for the larger membrane area vis-à-vis the smaller one and for the lower temperature vis-à-vis the higher one. As for the condensate produced per unit energy input, Fig. 6b shows that the most energy-efficient configuration involved the combination of higher temperature, larger membrane area, recycle, and the inverse module orientation, which gave a more than 3-fold increase in the condensate produced per unit energy input relative to the least energy-efficient system (i.e., thermoelectric only and at the higher temperature). Clearly, the opposite trends in Fig. 6a and b indicate that optimization is necessary.

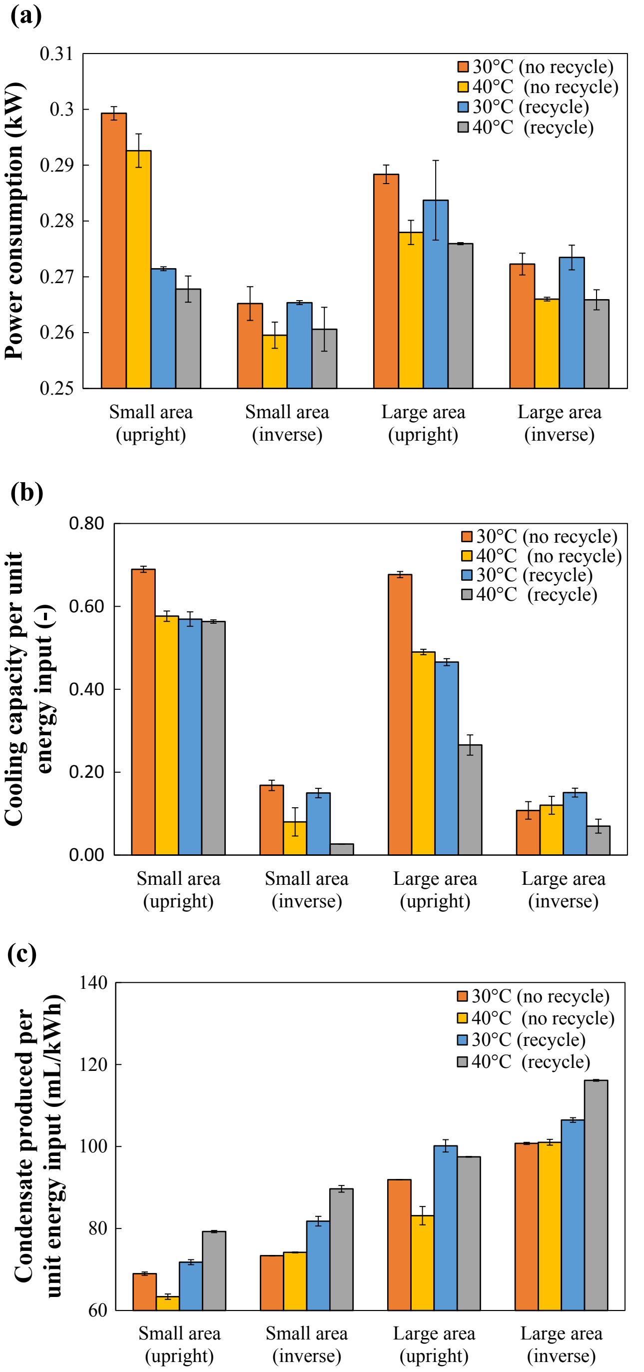

Fig. 5. Effect of module orientation on T-SGMD performance: (a) power consumption; (b) cooling capacity per unit energy consumed, and (c) the volume of condensate produced per unit energy consumed.

This coupled system, besides being able to simultaneously cool and carry out water treatment without the need of an additional condenser and at no additional power, is able to switch between maximizing clean water production or maximizing cooling capacity. This is potentially useful for example in vapor compression cycle coolers, with inverters that produce waste heat constantly, to reduce the energy consumption by switching the compressor on or off as necessary. This will result in over-cooling of the space, which would provide just the heat removal solution for condensing the condensate produced from this hybrid MD system. Vapor compression cycle coolers are susceptible to outdoor temperature changes which could result in drastic temperature

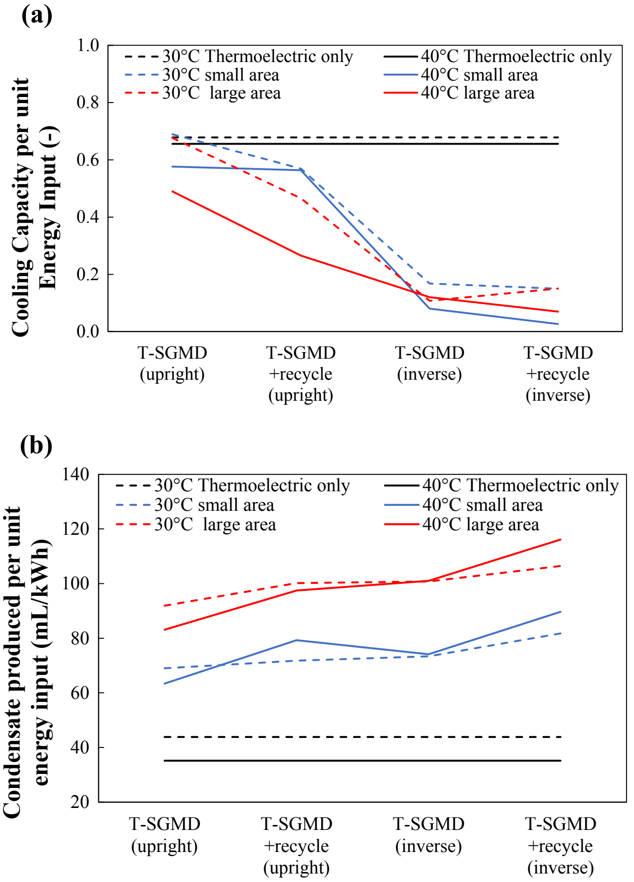

Fig. 6. Summary of T-SGMD experimental results: (a) cooling capacity per unit energy consumed, and (b) condensate produced per unit energy consumed.

fluctuations in cooled spaces, which results in discomfort for occupants in the space; this coupled with the feed can act as a buffer against sudden outdoor temperature changes, thereby dampening such drastic temperature fluctuations in the cooled space as well.

4. Implications and future research directions

In this study, experimental results show how the waste heat from a thermoelectric heat pump can be integrated into a SGMD system to treat a salt water feed mimicking seawater. The results obtained confirms the feasibility of the coupling SGMD with any system with a heat pump, which may find use also in the membrane distillation bioreactor and membrane distillation crystallizer. For example, in a common vapor compression heat pump, the heat from the compression of refrigerant can be extracted by a recirculating non-potable water before the excess is rejected to the environment through the condenser. Coupling with vapor compression heat pumps will then extend the possibility of its use in many commercially available electrical appliances beyond air-conditioning systems, such as dehumidifiers and air coolers, to refrigerators and water cooler dispensers, making decentralized commercial building or household water treatment possible. Even though a salt water feed was used here, the use of this coupled system is not limited to desalination, since MD is used for other water treatment too. For the use of such a system in households for example, the feed could be wastewater from the wash basin.

4.1. Case study

Putting this into perspective, a household with 3 rooms and 3 air-conditioning units with a total cooling capacity of 8.2 kW could potentially produce a theoretical maximum of 2.35 kg/h of water from coupling with an SGMD that could reduce the condensing temperature by 7 °C of a vapor compression cycle utilizing a R134a refrigerant. Al-Rashed [36] presented a theoretical coefficient of performance (COP) increase from 3.13 at 38 °C to 3.99 at 45 °C for a vapor compression system using an R134a refrigerant. Since the COP is the ratio of the cooling capacity to the power input, this would correspond to a 8.2 kW cooling capacity system providing an additional cooling capacity of 1.77 kW using the same amount of power. In an ideal case, with sufficient air flow across the SGMD membrane modules, evaporative cooling will saturate the air in a typical tropical country with 80–100% relative humidity (RH). Assuming dehumidification by cooling occurs at 25 °C, the psychrometric chart in Fig. 7 shows that the enthalpy change for dehumidification by the cooling of the coupled system will require 42.5 kJ/kg dry air. Fully utilizing the additional cooling capacity of 1.77 kW from the improved COP from coupling with an SGMD, $\frac{1.77\ \text{kW}}{23.5\frac{\text{kJ}}{\text{kg dry air}}} = 0.075$ kg dry air/s can be cooled to 25 °C. Multiplied by the difference in moisture content of 0.0274 kg/kg dry air – 0.02 kg/kg dry air = 0.0074 kg/kg dry air after dehumidification by cooling, a condensate production rate of 5.55×10^{-4} kg/s or 2.00 kg/h can be obtained. Since the moisture content of air at 30 °C at 80% RH is 0.0214 kg/kg dry air, the amount of moisture added to air by the evaporative cooling process is 0.0274 kg/kg dry air – 0.0214 kg/kg dry air = 0.006 kg/kg dry air, which when multiplied by the same flow rate of air into the air cooler calculated above at 0.075 kg dry air/s, 1.62 kg/h of wastewater can be treated.

4.2. Economic assessment

Since the above case only consists of the SGMD unit, similar calculations were made to include the condensate from the other indoor air conditioning units assuming 30% fresh air circulation [38] and a total average air flow rate of 6.4 m^3/min. This amounts to an additional 5.81 kg/h of condensate from the individual indoor air conditioning units. Using the case study in Section 4.1, the membrane area required to treat 1.62 kg/h of wastewater based on the average flux data at a feed temperature of 40.5 °C obtained by Khayet et al. [39] is 0.45 m^2. With these additional information and based on the calculations carried out in the supporting information SI.1, the condensate recovery cost (CRC) was determined to be 4.11 $/$m^3$ of condensate, which is approximately 4 times the cost of tap-water in Singapore [40]. This is due to the fact that the condensing unit was over-designed for the small amount of condensate. Understanding that a single indoor air-conditioning unit can provide up to 2.7 kW, designing the condensate recovery system to maximize the use of a single indoor air-conditioning unit leads to a CRC of 3.17 $/$m^3$, which is still 3 times the cost of clean water [40] and thereby cost-wise not attractive for households with smaller space-cooling requirements. However, large commercial buildings such as shopping malls or hotels which have larger space cooling requirements and wastewater production would have more incentives to adopt this additional technology to improve condensate recovery, reduce wastewater treatment costs and recycle the waste heat to mitigate energy cost.

This simplified economic assessment did not account for the economic savings on the dehumidification required before cooling, and the environmental benefits from reduced waste heat generation (e.g., reduction of urban heat island effect) and water treatment.

4.3. Future research

Further research can be carried out to incorporate current advancements in different areas of research, mainly MD and humidification/dehumidification (HDH) to improve flux as well as the effectiveness and efficiency of the coupled system. For example, Wu et al. [41] bubbled air into the feed in a hollow-fiber MD system to improve flux

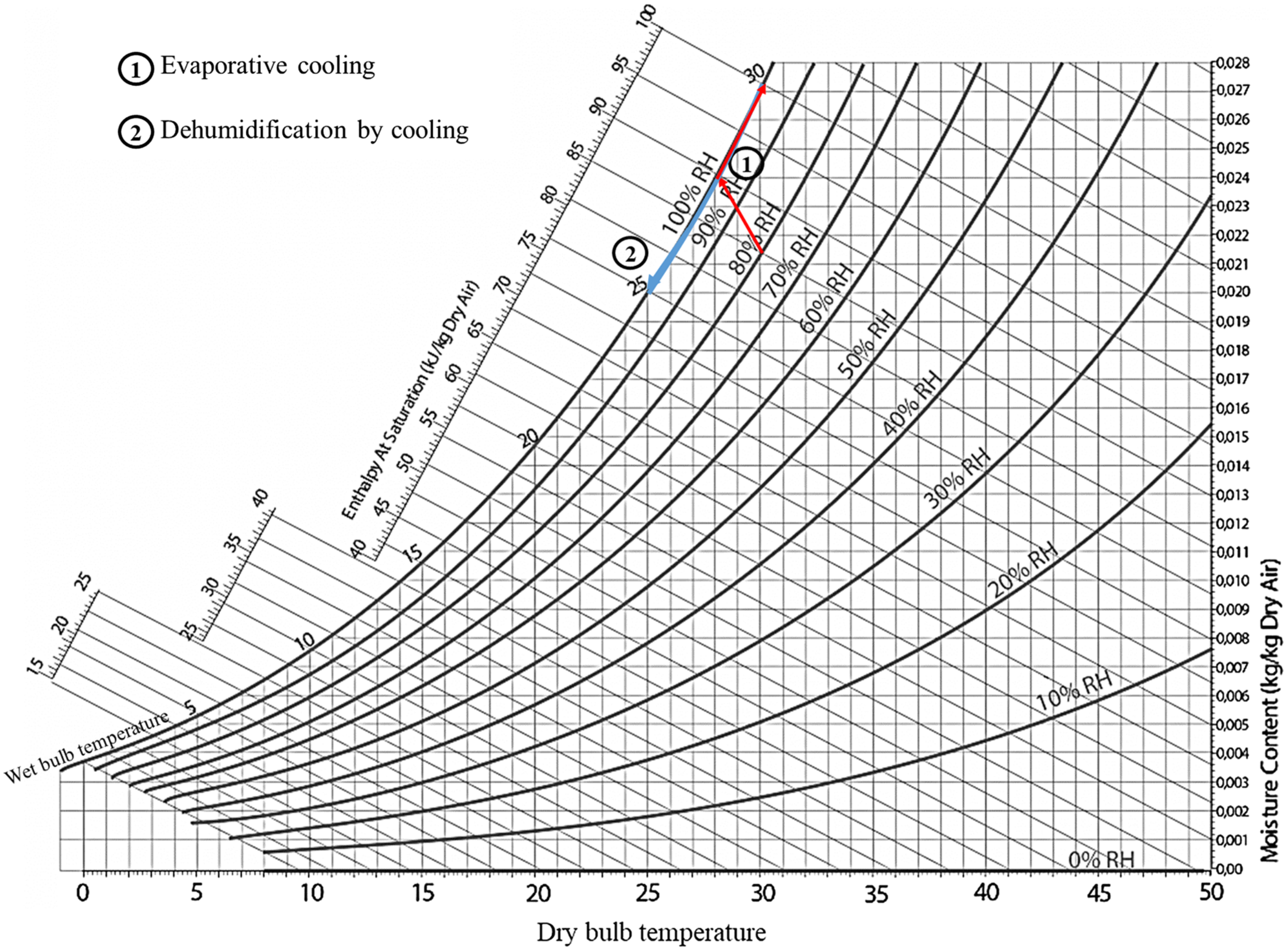

Fig. 7. Psychrometric chart [37] illustration of the SGMD hybridized with a household air conditioning unit in a typical tropical country.

by about 50% in the bubbly flow regime, which was attributed to the humidification of the air and the higher humid air flux across the membrane. Further coupling with new membrane dehumidification system such as those designed and used by Zhao et al. [42,43], which aims to supersaturate the air with water vapor at elevated temperature before condensing the water vapor at the condenser may prove to be very advantageous as well. This is because the heat from the membranes can help to supersaturate the air with water vapor due the elevated temperature surrounding the membrane fibers. The potential for such a system can be extended to larger MD-HDH systems [44] for large-scale water treatment and space cooling applications, essentially making full use of energy which will anyway be used for space cooling in tropical regions for concurrent potable water generation.

Issues and challenges which needs to be addressed includes (1) the optimization of the condensate recovery system to improve cost effectiveness by changing parameters such as air flow rate across the membrane and the balance between radiator cooling and SGMD cooling, (2) the removal of the already low levels of organic and inorganic contaminants from the condensate to meet the stringent standards of drinking water, and (3) the design of easily incorporated and economically affordable heat exchanger system to integrate with current HDH and/or space-cooling solutions to further reduce the CRC. This study along with research advances made in areas of water treatment, MD and HDH systems, progressively mitigate these issues and challenges to enhance the practical feasibility.

5. Conclusions

The impact of feed temperature, membrane area, presence of recycle and module orientation on the operation of a thermoelectric coupled sweeping gas membrane distillation (T-SGMD) was investigated experimentally.

The experimental results are summarized as follows. When coupled to membrane distillation (MD), the thermoelectric cooler consumed less energy and produced more condensate due to both the increase in thermoelectric efficiency because of the cooling provided by the MD, as well as the additional condensate produced by the MD process. Condensate production can be improved by increasing the membrane area, recycling cool air back to the membrane module and/or reducing the air flow across the cooling fins.

The two key highlights here provide more understandings for the design of such hybrid MD systems. Firstly, it is possible to couple SGMD to a heat pump for space cooling without the use of an external condenser, and yet be able to produce more condensate per unit energy without a decrease in cooling capacity per unit energy. This is made possible through the improvement in thermoelectric efficiency from the evaporative cooling occurring at the MD modules. Secondly, the increase in condensate production comes at the expense of a reduction in cooling capacity. Hence, there is a need to first optimize the membrane area for a particular cooling capacity to minimize the decrease in cooling capacity per energy while providing an increase in condensate produced per unit energy and using cool air recycle to switch between maximizing condensate production or maximizing cooling capacity per unit energy consumed. Controlling the cool air recycle to switch between maximizing clean water production or maximizing cooling capacity per unit energy input would be more feasible compared to changing the orientation in terms of implementation.

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Appendix A

Table A1 summarizes properties of the PVDF hollow-fiber membrane used in this study.

Table A1

Properties of polymeric membranes.

Membrane material	PVDF
Outer diameter (mm)	1.531
Inner diameter (mm)	0.872
Nominal pore size (µm)	0.022
Maximum pore size (µm)	0.183
Water contact angle (°)	116
Porosity (%)	83
Water liquid entry pressure, LEP_w (bar)	3.14
Tensile modulus (MPa)	26.4
Strain (%)	126.6
Zeta-potential (mV)[a]	-52.5

Summarizes properties of the PVDF hollow-fiber membrane used in this study.

[a] Surface zeta-potential was measured in NaCl solution at pH 7.

References

[1] Katili AR, Boukhanouf R, Wilson R. Space cooling in buildings in hot and humid climates—a review of the effect of humidity on the applicability of existing cooling techniques. In: Proceedings of 14th international conference on Sustainable Energy Technologies (SET), Nottingham, UK; 2015. p. 25–7.

[2] Qi R, Li D, Zhang L-Z. Performance investigation on polymeric electrolyte membrane-based electrochemical air dehumidification system. Appl Energy 2017;208:1174–83.

[3] Yang L, Qian F, Song D-X, Zheng K-J. Research on urban heat-island effect. Procedia Eng 2016;169:11–8.

[4] Chen H, Lee W, Yik F. Applying water cooled air conditioners in residential buildings in Hong Kong. Energy Convers Manage 2008;49:1416–23.

[5] Liu N, Li Z. The feasibility on the case that the air conditioning condensate water is used as the make-up water of cooling tower. Procedia Eng 2017;205:3557–62.

[6] Magrini A, Cattani L, Cartesegna M, Magnani L. Water production from air conditioning systems: some evaluations about a sustainable use of resources. Sustainability 2017;9:1309.

[7] Algarni S, Saleel CA, Mujeebu MA. Air-conditioning condensate recovery and applications—current developments and challenges ahead. Sustain Cities Soc 2018;37:263–74.

[8] Wang KY, Teoh MM, Nugroho A, Chung T-S. Integrated forward osmosis–membrane distillation (FO–MD) hybrid system for the concentration of protein solutions. Chem Eng Sci 2011;66:2421–30.

[9] Tun CM, Fane AG, Matheickal JT, Sheikholeslami R. Membrane distillation crystallization of concentrated salts—flux and crystal formation. J Membr Sci 2005;257:144–55.

[10] Jiang X, Tuo L, Lu D, Hou B, Chen W, He G. Progress in membrane distillation crystallization: process models, crystallization control and innovative applications. Front Chem Sci Eng 2017;11:647–62.

[11] Goh S, Zhang J, Liu Y, Fane AG. Membrane Distillation Bioreactor (MDBR) – a lower Green-House-Gas (GHG) option for industrial wastewater reclamation. Chemosphere 2015;140:129–42.

[12] Wang P, Chung T-S. Recent advances in membrane distillation processes: Membrane development, configuration design and application exploring. J Membr Sci 2015;474:39–56.

[13] Edwie F, Chung T-S. Development of simultaneous membrane distillation–crystallization (SMDC) technology for treatment of saturated brine. Chem Eng Sci 2013;98:160–72.

[14] Ji X, Curcio E, Al Obaidani S, Di Profio G, Fontananova E, Drioli E. Membrane distillation-crystallization of seawater reverse osmosis brines. Sep Purif Technol 2010;71:76–82.

[15] Onsekizoglu Bagci P. Potential of membrane distillation for production of high quality fruit juice concentrate. Crit Rev Food Sci Nutr 2015;55:1098–113.

[16] Warsinger DM, Swaminathan J, Guillen-Burrieza E, Arafat HA, Lienhard VJH. Scaling and fouling in membrane distillation for desalination applications: a review. Desalination 2015;356:294–313.

[17] Alkhudhiri A, Darwish N, Hilal N. Membrane distillation: a comprehensive review. Desalination 2012;287:2–18.

[18] Lawson KW, Lloyd DR. Membrane distillation. J Membr Sci 1997;124:1–25.

[19] Zhang YG, Peng YL, Ji SL, Li ZH, Chen P. Review of thermal efficiency and heat recycling in membrane distillation processes. Desalination 2015;367:223–39.

[20] Swaminathan J, Chung HW, Warsinger DM, AlMarzooqi FA, Arafat HA, Lienhard VJH. Energy efficiency of permeate gap and novel conductive gap membrane distillation. J Membr Sci 2016;502:171–8.

[21] Swaminathan J, Chung HW, Warsinger DM, Lienhard VJH. Membrane distillation model based on heat exchanger theory and configuration comparison. Appl Energy 2016;184:491–505.

[22] Swaminathan J, Chung HW, Warsinger DM, Lienhard VJH. Energy efficiency of membrane distillation up to high salinity: evaluating critical system size and optimal membrane thickness. Appl Energy 2018;211:715–34.

[23] Brückner S, Liu S, Miró L, Radspieler M, Cabeza LF, Lävemann E. Industrial waste heat recovery technologies: an economic analysis of heat transformation technologies. Appl Energy 2015;151:157–67.

[24] Varga Z, Palotai B. Comparison of low temperature waste heat recovery methods. Energy 2017;137:1286–92.

[25] Fane AG, Phattaranawik J, Wong F-S. Contaminated inflow treatment with membrane distillation bioreactor. US20100072130A1; 2012.

[26] Fonyo Z, Benkö N. Comparison of various heat pump assisted distillation configurations. Chem Eng Res Des 1998;76:348–60.

[27] Palenzuela P, Roca L, Zaragoza G, Alarcón-Padilla DC, García-Rodríguez L, de la Calle A. Operational improvements to increase the efficiency of an absorption heat pump connected to a multi-effect distillation unit. Appl Therm Eng 2014;63:84–96.

[28] Yang M, Feng X, Liu G. Heat integration of heat pump assisted distillation into the overall process. Appl Energy 2016;162:1–10.

[29] Kazemi A, Mehrabani-Zeinabad A, Beheshti M. Recently developed heat pump assisted distillation configurations: a comparative study. Appl Energy 2018;211:1261–81.

[30] Trusch RB. Thermoelectric integrated membrane evaporation system US4316774A; 1982.

[31] Byrne P, Oumeziane YA, Serres L, Maré T. Study of a heat pump for simultaneous cooling and desalination. Appl Mech Mater 2016;819:152–9.

[32] Khayet M, Godino P, Mengual JI. Theory and experiments on sweeping gas membrane distillation. J Membr Sci 2000;165:261–72.

[33] Basini L, Dangelo G, Gobbi M, Sarti GC, Gostoli C. A desalination process through sweeping gas membrane distillation. Desalination 1987;64:245–57.

[34] Warsinger DE, Swaminathan J, Lienhard V JH. Effect of module inclination angle on air gap membrane distillation. In: Proceedings of the 15th international heat transfer conference; 2014.

[35] Tan YZ, Han L, Chow WH, Fane AG, Chew JW. Influence of module orientation and geometry in the membrane distillation of oily seawater. Desalination 2017;423:111–23.

[36] Al-Rashed AAAA. Effect of evaporator temperature on vapor compression

refrigeration system. Alexandria Eng J 2011;50:283–90.

[37] Psychrometric Charts. Available online: (accessed on 15 Feb 2018) https://sustainabilityworkshop.autodesk.com/buildings/psychrometric-charts.

[38] Hassan NM, Bakry AS. Feasibility of condensate recovery in humid climates. Int J Arch Eng Constr 2:271–9.

[39] Khayet M, Godino P, Mengual JI. Nature of flow on sweeping gas membrane distillation. J Membr Sci 2000;170:243–55.

[40] Singapore utilities tariff rates (accessed on 3 Aug 2018) https://www.spgroup.com.sg/what-we-do/billing.

[41] Wu C, Li Z, Zhang J, Jia Y, Gao Q, Lu X. Study on the heat and mass transfer in air-bubbling enhanced vacuum membrane distillation. Desalination 2015;373:16–26.

[42] Zhao B, Peng N, Liang C, Yong W, Chung T-S. Hollow fiber membrane dehumidification device for air conditioning system. Membranes 2015;5:722.

[43] Zhao B, Yong WF, Chung T-S. Haze particles removal and thermally induced membrane dehumidification system. Sep Purif Technol 2017;185:24–32.

[44] Minier-Matar J, Sharma R, Hussain A, Janson A, Adham S. Field evaluation of membrane distillation followed by humidification/dehumidification crystallizer for inland desalination of saline groundwater. Desalination 2016;398:12–21.