Applied Energy 231 (2018) 1079–1088

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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.

ARTICLE INFO

Keywords:
Sweep-gas membrane distillation (SGMD)
Hybrid membrane process
Space cooling
Natural convection
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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https://doi.org/10.1016/j.apenergy.2018.09.196
Received 25 April 2018; Received in revised form 10 August 2018; Accepted 23 September 2018

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

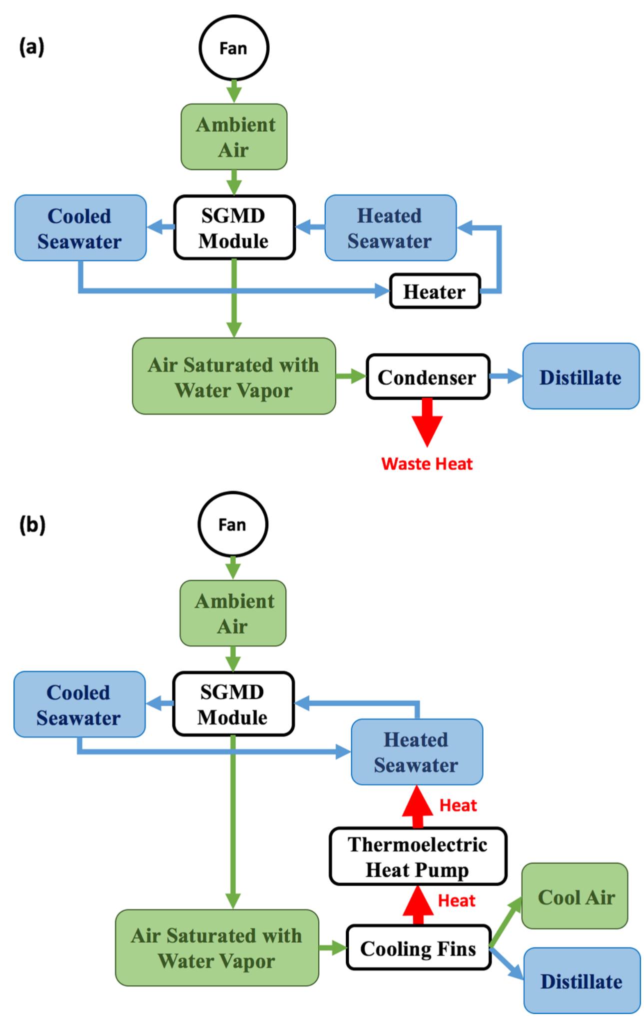

Fig. 1. Overview of (a) a typical SGMD; and (b) a T-SGMD with heat integration and cool air generation.