Applied Energy 211 (2018) 997–1008

Contents lists available at ScienceDirect

Applied Energy

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

Evaluation of a solar-powered spray-assisted low-temperature desalination technology

Q. Chen[a], M. Kum Ja[a], Y. Li[b], K.J. Chua[a,*]

[a] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore
[b] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- A spray-assisted low-temperature desalination system powered by solar energy was evaluated.
- A non-steady-state mathematical model has been developed and validated using experimental data.
- The feasibility and potential of the desalination system was evaluated under tropic climatic conditions.
- Sources of energy inefficiencies inside the system have been identified.

ARTICLE INFO

Keywords:
Spray-assisted
Desalination
Solar thermal
Long-term system performance

ABSTRACT

The use of solar energy has huge potential for desalination application due to the geographical coincidence between high solar irradiance and fresh water scarcity. This paper investigates the performance of a spray-assisted low-temperature desalination system powered by solar thermal energy. The proposed system applies a spray evaporator and a coil condenser that operate under low-pressure conditions, which increases evaporation rate and promotes productivity. A numerical model was developed to predict the dynamical system performance. Concurrently, an experimental setup was designed and commissioned to demonstrate the feasibility of the spray-assisted low-temperature desalination system and to validate the model. Applying the developed model, the long-term desalination performance of the system coupled with a flat plate solar thermal collector was evaluated under Singapore's climatic conditions. Additionally, the energy flow inside the system is analyzed in order to highlight the sources of energy losses. Results revealed that the inefficiency of the system is attributed to the losses of both the solar thermal collector and the desalination unit. There exists an optimal feed flowrate that promotes the solar collector performance while minimizing the inefficiency of the desalination unit. The system is able to provide uninterrupted fresh water supply of 30 L per day with a solar collector area of 7.6 m^2 and a water storage tank of 305 L. The contributions of this paper include: (1) the development of a validated non-steady-state model via the dual experimental and numerical approach; (2) identifying the sources of inefficiencies inside the system through a detail energy flow analysis; and (3) evaluating and optimizing the system based on long-term performance calculated from annual weather data, which provides a more accurate and robust design basis for this type of standalone solar desalination system.

1. Introduction

Fresh water is one of the key resources for the evolution of human beings. However, fresh water supply on the earth is limited. Even though 71% of the earth surface is covered by water, only 3% is present as potable water. Moreover, most of the potable water is in the form of ice or resided at groundwater level, while only 1% of them is accessible to human beings. The limited water supply is made worse by the growth of human population and the development of world industry, leading to more fresh water consumption.

Desalination is the process that separates potable water from saline water. It is considered to be the most promising method to address the global water deficit. With continuous advances made in desalination technologies, the global desalination capacity has been increasing rapidly in the past decades. In 2014, the global cumulative desalination capacity reached 83.09 million m^3/day [1]. However, many of the desalination plants, including reverse osmosis (RO), multistage flash desalination (MSF) and multiple effect distillation (MED), employ fossil

* Corresponding author.
E-mail address: mpeckje@nus.edu.sg (K.J. Chua).

https://doi.org/10.1016/j.apenergy.2017.11.103
Received 28 August 2017; Received in revised form 19 October 2017; Accepted 27 November 2017
0306-2619/

Nomenclature

A	area
BPE	boiling point elevation
C	specific heat
c_p	specific heat
D	production rate
hfg	latent heat of vaporization
I	solar irradiance
M	mass
$\dot{m}$	mass flowrate
P	pumping power
p	pressure
Q	heat flux
r	recycling ratio
T	temperature
t	time
U	overall heat transfer coefficient
X	salinity

Subscripts

amb	ambient
ave	average
b	brine
c	condensation
cond	condenser
cw	cooling water
d	distillate, desalination
e	evaporation
p	pumping
evap	evaporator
f	feed water
in	inlet
loss	heat loss
o	outlet
sl	solar collector
st	storage tank

Greek letters

η	efficiency
Δ	difference
θ	dimensionless temperature difference

fuels as the energy source for operations. They are not accessible for people who live in remote areas and have a limited primary energy supply. The issues associated with primary energy depletion and greenhouse gas emissions further hinder the wider application of these desalination technologies. Therefore, it is an exacting need to develop new and sustainable energy sources for desalination.

Among all the renewable energy sources, solar energy has the highest potential for desalination applications [2]. This is due to the geographical coincidence between water shortage and high solar irradiance. Solar still is the earliest and simplest technique for distillation. Its application dates back to 1872 when C. Wilson designed the first conventional solar still in Chile [3]. A conventional solar still consists of a black painted basin and a transparent cover. Saline water is stored in the basin and gets heated up by solar irradiance passing through the transparent cover. The hot saline water partially evaporates, and the resultant vapor rises towards the cooler cover to be condensed. The condensate flows along the cover inner surface due to gravity and is duly collected in a tray. In the past decades, extensive research efforts have been conducted to improve the productivity of solar stills. Xiao et al. [4] conducted a review on solar stills for brine desalination. Based on the design guidelines, solar stills were categorized into six types. Detailed heat and mass transfer analyses were presented to evaluate each type of solar stills. Additionally, preferred design guidelines were provided under various climate conditions to enhance the productivity. Ahsan et al. [5] developed a triangular solar still using cheap and lightweight materials that are available in the coastal areas of Malaysia. Several experimental tests were conducted to evaluate the effect key parameters. The productivity was observed to be inversely proportional to the water depth, while higher solar radiation promoted the production rate. Guo et al. [6] proposed a modular desalination system composed of several arrayed tubular solar stills. An experimental tubular solar still prototype was fabricated and tested under varying pressure and temperature conditions, and the maximum solar efficiency was observed to be 0.81. Meanwhile a 5-effect modular with a capacity of 86 kg/day was analytically evaluated. Results demonstrated the applicability in remote and desert regions. Estahbanati et al. [7] investigated a single-slope solar still coupled with internal reflectors. The reflectors were placed in different positions, and installing the reflector on the back wall yielded the highest production increase of 22%. Additionally, installing the reflectors on all walls increased the annual productivity by 34%. Omara et al. [8] tested a corrugated absorber solar still with wick and reflectors. Results indicated that the productivity of the corrugated solar still with wick and reflectors were 145.5% higher than the conventional solar stills, and the daily efficiency was improved by 26%. Sharshir et al. [9] modified the conventional solar stills to enhance the productivity. The modifications included using flake graphite nanoparticles, phase change materials and film cooling. When all the three modifications were conducted, the productivity was enhanced by 73.8%. Additionally, decrease of water depth from 2 cm to 0.5 cm resulted in another 13% of productivity improvement. Despite all the research efforts, the productivity of solar stills is still low. The major reason is that the various processes, i.e. evaporation, condensation, heat recovery and solar heating, occur within a single component. Such a single-component configuration yields considerable thermal inefficiency.

To further improve the productivity, humidification–dehumidification (HDH) desalination cycle has been proposed. The HDH cycle works on the same principle as the solar stills, but the system components are separated. This allows each component to be individually designed in order to lower the inefficiencies in each process. Due to these promising features, HDH technologies have become the subjects of great research interests. McGovern et al. [10] analyzed the limits of the closed-air water-heated humidification-dehumidification cycles. The limits were calculated by considering zero pinch point temperature and concentration differences in the humidifier and dehumidifier. The theoretically maximum GOR (gained output ratio) were 3.5 and 14 for the single stage system and dual stage system, respectively. Al-Sulaiman et al. [11] conducted an exergy analysis for a high-temperature-steam-driven humidification–dehumidification system. It was revealed that 50% of the exergy destruction occurred in the thermal vapor compressor. Additionally, the performance of the system was significantly affected by the specific exergy destruction of the dehumidifier and the thermal vapor compressor. Li et al. [12] tested a membrane-based humidification–dehumidification desalination system driven by solar energy. The test rig consisted of a U-tube evacuated solar collector, a heat storage water tank, a membrane-based humidifier (hollow fiber membrane module) and a dehumidifier (a fin-and-tube heat exchanger). A specific energy consumption of 19.23 kW h/m^3 was observed, and the most significant energy loss was found to be the sensible heat losses. Rajaseenivasan et al. [13] reported a bubble column humidification