Energy Conversion and Management 148 (2017) 1306–1316

Contents lists available at ScienceDirect

Energy Conversion and Management

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

On the second law analysis of a multi-stage spray-assisted low-temperature desalination system

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

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 5 June 2017
Accepted 28 June 2017

Keywords:
Entropy generation
Second law efficiency
Spray-assisted low-temperature desalination

ABSTRACT

High energy consumption is one of the major barriers that hinder the wide application of various desalination technologies. The energy intensity of the desalination process is further increased as a result of the irreversibilities within the system components. Second law analysis is an essential tool for highlighting the imperfections within the system. This paper specially conducts a second law analysis for a spray-assisted low-temperature desalination technology. The entropy generation rates of each component are computed through a judiciously developed mathematical model. The rates of entropy generation under varying design and operating conditions are also investigated. Key results revealed that the heat exchangers are the dominating sources of entropy generation during almost all operating conditions. The specific entropy generation of the system could be minimized with lower top brine temperatures, higher operating stages, high completion level of evaporation/condensation processes and lower feed water salinities. In addition, a cooling water flowrate close to the feed flowrate resulted in the least amount of entropy generation. The specific entropy generation was computed to be 253 J/kg-K for a 10-stage system operating at a top brine temperature of 70 °C, with a corresponding second law efficiency of 3.47%.

1. Introduction

Fresh water is the key resource to sustain human evolution. However, world water deficit is becoming more and more pervasive due to the ever increase of water consumption [1] as well as the depletion and degradation of traditional sources of fresh water supply [2]. Therefore, it is essential to develop new and sustainable sources of fresh water supply. Desalination has proven to be one of the most promising methods that addresses the issues associated with water scarcity [3]. Over the last decades, many advances have been made in desalination technologies, resulting in the world desalination capacity being dramatically increased. In 2015, the global desalination capacity has reached 86.5 million m^3/day, with more than 16,000 desalination plants being installed in nearly 150 countries [4].

Currently, desalination is hugely limited to the more affluent countries due to its energy-intensive nature [5]. The membrane-based reverse osmosis (RO) technology requires a steady supply of electricity, while the thermally-driven processes, such as the multistage flash desalination (MSF) and multi-effect distillation (MED), consume a huge amount of thermal energy. Depletion of fossil-based energy sources and issues related to greenhouse gas emissions further hinder the wide deployment of desalination technologies [6].

Great efforts are presently being made at both research and industrial levels to enable the energy consumption of desalination technologies to be lowered, favoring wider deployment and applications. One of the promising approaches is to integrate desalination plants with renewable energy sources, such as solar energy [7,8], geothermal energy [5,9] and industry waste heat [10,11]. Besides introducing new energy sources, researchers are also studying how existing desalination technologies can be further improved. Theoretical analysis [12] has revealed that most of the desalination plants are operating at energy efficiencies that are far below the thermodynamic limit. The gap can be attributed to the imperfection of the system components. Accordingly, thermodynamic optimization of the components yields great potential to significantly reduce the energy consumption.

The first law analysis is unable to capture the essence and causes of the thermodynamic imperfection of the desalination process. It is the second law analysis that accounts for the sources of irreversibilities within a system [13]. The second law efficiency indicates how much the desalination system deviates from the thermodynamic limit, while the entropy generation rates determine the sources of inefficiencies and pinpoint specific targets

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

http://dx.doi.org/10.1016/j.enconman.2017.06.080
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Nomenclature

A	area
BPE	boiling point elevation
c_p	specific heat
D	production rate
GOR	gained output ratio
g	Gibb's free energy
$\dot{m}$	mass flowrate
N_{total}	total number of stages
p	pressure
PR	production ratio
Q	heat flux
r	recovery ratio
S	specific entropy generation
s	specific entropy
T	temperature
TBT	top brine temperature
X	salinity

Subscripts

0	ambient
c	condenser
$chem$	chemical disequilibrium
cl	liquid in condenser
cv	vapor in condenser
cw	cooling water
d	distillate
e	evaporator
el	liquid in evaporator
ev	vapor in evaporator
g	generation
H	heating
HEX	heat exchanger
i	ith stage, inside
in	inlet
l	liquid
$loss$	temperature loss in demister
out	outlet
R	heat recovery
sep	separation
sw	seawater
T	thermal disequilibrium
v	vapor
II	second law

Greek letters

Δ	difference
θ	dimensionless temperature difference
η	efficiency

Superscript

min	minimal

for optimization. The second law analysis has been applied to various desalination technologies, e.g. MED plant [6], RO plants [14,15] and HDH cycles [16,17]. The second law efficiencies are calculated and the major sources of entropy generation have been identified. A comparison of the second law efficiency and entropy generation rate among various desalination technologies, namely, MED, MSF, HDH, RO, MVC (mechanical vapor compression) and DCMD (direct contact membrane distillation), has also been conducted [18]. Results revealed that the thermally driven systems had higher entropy generation rates and lower second law efficiencies.

The focus of this paper is on a novel desalination technology: the spray-assisted low-temperature desalination technology. It is a very recently proposed technology that enables efficient utilization of various low grade heat sources for desalination. Differing from traditional thermally driven technologies that rely on metallic surfaces for heat transfer, it employs spray evaporators and spray condensers for evaporation and condensation. The direct contact heat transfer mechanism markedly promotes the heat transfer rates while simplifying the system design. The elimination of metallic surfaces inside the system further helps to reduce scaling and fouling potentials and lowers the initial cost.

Previous studies on the spray-assisted low-temperature desalination technology fall into two categories, namely, (1) heat and mass transfer analysis of the system components and (2) desalination performance of the whole system. Mutair and Ikegami [19,20] measured the temperature profiles of the seawater in an upward spray evaporator. The temperature variation was observed to follow the Boltzmann sigmoid equation. Chen et al. [21] modelled the droplet evaporation process in a downward spray evaporator, and key considerations were given to the variation of droplet diameter and droplet velocity. Araghi el al. [22] developed a 3D model for the spray evaporator which is capable of predicting the profiles of the droplet size, velocity, temperature and concentration. For the desalination performance analysis, Chen et al. [23] conducted a thermodynamic analysis on a multi-stage spray-assisted low-temperature desalination system. The production rate and thermal efficiency were observed to be affected by the operating stages, the top brine temperature and the cooling water flowrate. El-Agouz et al. [24] experimentally investigated the performance of a spray desalinator driven by solar energy. The production rate and the thermal efficiency were strongly affected by the solar intensity, and the maximum daily production rate was observed to be 9 L/m^2. Araghi et al. [25,26] theoretically evaluated the desalination performance of a spray desalinator driven by waste heat rejected from a power plant. Integration of the desalination system enhanced the exergy efficiency of the power plant by 28%. Wellmann et al. [27] simulated a multi-stage spray-assisted low-temperature desalination system integrated with a concentrating solar power plant. The combined system was able to produce 2.2 MW electricity and 520 m^3/day fresh water.

A second law analysis provides key information to understand the irreversibility within the system so that the thermal efficiency can be further improved. The second law efficiency evaluates the system performance, and the entropy generation analysis quantifies the thermodynamic irreversibilities and identifies key components that should be optimized. However, thus far, to the best of our knowledge, no second law analysis has been carried out for a spray-assisted low-temperature desalination system. The insufficient coverage of this subject has encouraged us to fill the existing knowledge gap. In this paper, a second law analysis is to be carried out to identify the key sources of irreversibility within the spray-assisted low-temperature desalination system. A thermodynamic model accounting for the effects of the design and the operating parameters will be developed. Applying the model, the entropy generation rates of each component will be calculated and their relative importance will be discussed to pinpoint the system's limiting components. In addition, the rates of entropy generation