Energy Conversion and Management 174 (2018) 626–638

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance and economic investigations of solar power tower plant integrated with direct contact membrane distillation system

Mujeeb Iqbal Soomro[a,b], Woo-Seung Kim[c,*]

[a] Department of Mechanical Design Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan, Gyeonggi-do 15588, Republic of Korea
[b] Department of Mechanical Engineering, Mehran University of Engineering & Technology, SZAB Campus, Khairpur Mir's 66020, Sindh, Pakistan
[c] Department of Mechanical Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan, Gyeonggi-do 15588, Republic of Korea

ARTICLE INFO

Keywords:
CSP plant
SAM Software
System integration
Desalination
MATLAB

ABSTRACT

Direct contact membrane distillation (DCMD) powered by solar energy is an attractive solution to mitigate freshwater supply problems. This paper presents an investigation on performance and cost of a 111 MWe solar power tower (SPT) plant integrated with DCMD system. The SPT plant comprised of an evaporative cooling with seawater as cooling agent in the condenser. Additionally, warm seawater leaving the condenser was introduced into DCMD system as feed water. For SPT plant, simulations revealed that an increment in incident solar power enhanced the electricity production and consequently the cooling water requirements. Annual gross electric output and cooling water requirements were estimated to be 493.8 GWh and 1,422,364 m^3, respectively. Whereas the energy cost was estimated to be 13.03 cents per kWh. Furthermore, a mathematical model was developed and solved for evaluating the DCMD system. The model was validated by means of the experimental data. In DCMD system, permeate flux and evaporation efficiency increased when feed water temperature was increased. However, specific thermal energy consumption decreased with an increase in feed water temperature. The average freshwater production by the proposed system was estimated up to 40,759 L/day with a cost of \$0.392/m^3.

1. Introduction

Freshwater and energy are essential for life on the globe and sustainability of the world. The demand of freshwater and energy has been considerably increased due to population growth, urbanization, and industrialization. To cope with the growing demand, researchers are focusing on integrated power and desalination plants (IPDP). Most of the research on IPDP is focused on fossil fuel fired power plants; however, few studies have considered renewable energy for it. Solar energy is a powerful resource among renewable energy sources since the earth annually receives 885 million TWh energy from the sun [1]. This enormous amount of energy is around 6200 times the commercial energy required for the entire world [1]. Energy production from solar energy can be achieved in two ways, which are concentrated solar power (CSP) and solar photovoltaic. The solar photovoltaic converts solar energy directly into electricity using photovoltaic cells, whereas CSP exploits solar energy to increase the temperature of a heat transfer fluid (HTF) for a power cycle.

CSP is a prominent technology for large-scale energy power generation due to its maturity and relatively low cost [2]. CSP is suitable for areas that have high solar radiation and clear sunny days. The CSP uses mirrors/reflectors to concentrate solar energy onto a specific area. A HTF is generally utilized to collect thermal energy from concentrated area and transfer it for further process. Presently, CSP technology is categorized into four main families that are characterized by the way sun rays are focused and received by the absorber: parabolic trough (PT), linear Fresnel reflects (LFR), solar power tower (SPT), and parabolic dish systems [2]. In CSP plants, a thermal energy storage (TES) system is customarily incorporated in order to ensure continuous energy production even after sunset. The commercialization of CSP has been significantly increased recently. For instance, renewable global status report (REN21) revealed that the worldwide CSP installed capacity increased to 4755 MW by the end of 2015 [3]. Spain, being the leader in CSP, have an installed capacity of 2300 MW followed by the United States which have an installed capacity of 1738 MW, as depicted in Fig. 1 [3]. General applications of CSP plants include heating fluid for a process, steam generation, and desalination [4]. However, the mutual production of electricity and freshwater is of particular interest in many regions of the world [5]. This mutual production (electricity and freshwater) concept using CSP and desalination (CSP + D) can

* Corresponding author.
E-mail addresses: mujeebiqbal@hanyang.ac.kr, mujeebsoomro@muetkhp.edu.pk (M.I. Soomro), wskim@hanyang.ac.kr (W.-S. Kim).

https://doi.org/10.1016/j.enconman.2018.08.056
Received 21 May 2018; Received in revised form 14 August 2018; Accepted 16 August 2018

Nomenclature

Acronyms

AC_{total}	total annual cost
AC_{fixed}	annual fixed cost
$AC_{O\&M}$	annual operation & maintenance cost
AC_{MT}	annual maintenance cost
AC_{MR}	annual membrane replacement cost
AC_{labor}	annual labor cost
AC_{BD}	annual brine disposal cost
$AC_{electricity}$	annual electric cost
CC	capital cost
CDM	clean development mechanism
CER	certified emissions reductions
CSP	concentrated solar power
CSP + D	concentrated solar power integrated desalination
DCMD	direct contact membrane distillation
DCC	direct capital cost
DNI	direct normal insolation
DGM	dusty-gas model
EE	evaporation efficiency
GHG	greenhouse gases
HTF	heat transfer fluid
ICC	indirect capital cost
IPDP	integrated power and desalination plants
KP	Kyoto protocol
kWh	kilo Watt hours
LCE	levelized cost of energy
LFR	linear Fresnel reflects
MED	multi-effect distillation
MD	membrane distillation
MSF	multi-stage flash
PT	parabolic trough
PTFE	polytetrafluoroethylene
RO	reverse osmosis
SAM	system advisor model
SPT	solar power tower
STEC	specific thermal energy consumption (kWh/m^3)
TES	thermal energy storage
TPC	temperature polarization coefficient
UAE	United Arab Emirates
WPC	water production cost ($/m^3)

Symbols

a	amortization factor
A_{DCMD}	area of membrane (m^2)
¢/kWh	cents per kilowatt-hour
C_o	project equity investment of CSP plant ($)
C_n	project annual cost of CSP plant ($)
C_p	specific heat (J/kg °C)
D	molecular diffusion coefficient (m^2/s)
D_m	membrane distillation coefficient (kg/m^2 Pa h)
D_h	hydraulic diameter (m)
d	mean diameter of membrane pores (m)
d_e	collision diameter of water vapor and air (m)
f	availability of the DCMD system (%)
h	heat transfer coefficient (W/m^2 °C)
h_m	convective heat transfer coefficient for membrane (W/m^2 °C)
h_f	convective heat transfer coefficient for feed side (W/m^2 °C)
h_p	convective heat transfer coefficient for permeate side (W/m^2 °C)
H_v	latent heat of vaporization of water (kJ/kg)
i	annual interest rate
J_m	permeate flux (kg/m^2 h)
K	thermal conductivity (W/m °C)
K_B	Boltzmann constant (1.3807 × 10^{-23} J/K)
K_n	Knudsen number
K_m	thermal conductivity of membrane (W/m °C)
L	channel length (m)
M	molecular weight (kg/mol)
N	analysis period of CSP plant
n	life time of the CSP plant
Nu	Nusselt number
Pr	Prandtl number
P_{avg}	average pressure inside the membrane pores (Pa)
P_{air}	entrapped air pressure (Pa)
${P_a}^v$	vapor pressure at feed side (Pa)
${P_b}^v$	vapor pressure at permeate side (Pa)
P^v	vapor pressure (Pa)
${P_s}^v$	vapor pressure at a given concentration (Pa)
Q_f	heat transfer from the feed side (W/m^2)
Q_v	evaporative heat transfer (W/m^2)
Q_c	conductive heat transfer for the membrane material (W/m^2)
Q_m	heat transfer through the membrane (W/m^2)
Q_n	electricity generated in N year
Q_p	heat transfer to permeate side (W/m^2)
Q_t	total heat transfer in the DCMD membrane module
Q_w	amount of water produced (m^3/day)
R	universal gas constant (8314 J/mol K)
Re	Reynolds number
r	radius of membrane pore (m)
T	absolute temperature inside the membrane pores (°C)
T_f	feed temperature (°C)
T_p	permeate temperature (°C)
T_{bf}	bulk feed side temperature (°C)
T_{bp}	bulk permeate side temperature (°C)
T_{mf}	membrane surface temperature for feed side (°C)
T_{mp}	membrane surface temperature for permeate side (°C)
U	overall heat transfer coefficient (W/m^2 °C)
x_s	weight fraction of salt in water

Greek symbols

λ	mean free path (m)
δm	membrane thickness (m)
ε	membrane porosity (%)
τ	membrane tortuosity
ρ	water density (kg/m^3)
ν	momentum diffusivity (m^2/s)
μ	dynamic viscosity (N s/m^2)
α	thermal diffusivity (m^2/s)

reduce energy consumption and cost compared to individual plants. CSP + D can be achieved either by utilizing electricity energy produced by the CSP plant and/or utilizing waste heat from the CSP plant to power a desalination unit. Generally, desalination is accomplished by two main methods, namely membrane-based desalination methods and thermal desalination methods. Thermal desalination methods involve a phase change process such as and multi-stage flash (MSF), and multi-effect distillation (MED). On the contrary, in membrane-based desalination method, a hydrophobic membrane only allows water vapors to pass it due to a pressure gradient across both sides of the membrane.