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Performance evaluation of a brine-recirculation multistage flash desalination system coupled with nanofluid-based direct absorption solar collector

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ABSTRACT

A mathematical model for multistage flash (MSF) desalination system with brine recirculation (BR) configuration is developed in this study. The heat source for BR-MSF is chosen to be a nanofluid-based direct absorption solar collector (DASC) for which a numerical model is developed. Both these systems, BR-MSF and DASC are coupled via a counter-flow heat exchanger. The overall performance of the combined system is quantified in terms of gained output ratio (GOR). Moreover, the variation in GOR caused by various influencing parameters such as height (H) and length (L) of solar collector, nanoparticle volume fraction (f_v) and incident flux on the collector (q) is studied in detail. The effect of these parameters on the top brine temperature (T_o) is also discussed. The study shows that DASC can be used as a heat source for BR-MSF system and gives high GOR ranging between 11 and 14 depending on the various operating conditions. This system is also compared with a parabolic trough collector (PTC) based BR-MSF system and it is found that DASC-based BR-MSF system gives higher GOR under identical conditions (relatively 11% higher). The exergy analysis is also presented for this system which shows the irreversibilities associated with various physical processes and components of the overall system and in addition to that exergy efficiency is also calculated for the overall system.

1. Introduction

Over two-third of the earth's surface is covered with water, out of which about 97% is saline water present in seas and oceans. This saline water is not suitable for direct use such as drinking and other industrial and domestic applications. The remaining 3% is fresh water, however about 70% of this fresh water is frozen in ice caps and glaciers and is therefore inaccessible for human use. Nearly 29% of the fresh water is underground water and only about 0.25% of fresh water is contained in the lakes and rivers [1–3]. Due to very less amount of fresh water available on the earth and in view of factors such as increasing population, industrialization, urbanization and contamination of various available fresh water resources, water scarcity has become one of the most serious global challenges of the present time [4,5].

Presently, over one-third of the world's population is living in water stressed countries and this figure is expected to increase in the future [6,7]. Water reuse and desalination are the two possible methods to increase the water supply beyond what is available from the natural hydrological cycle. As mentioned earlier, sea water is present in huge amount on earth and desalination of seawater is a potential solution to meet the both current and future fresh water demands [4,8]. Desalination is the method of removing total dissolved salts (TDS) from seawater or brackish water having high salinity and thus making it potable with total dissolved salts within the permissible limit (500 ppm or less) [1]. Excessive amount of salts can cause severe health issues and is not suitable either for human consumption or various domestic and industrial uses [1]. There are various methods to desalinate the seawater which are broadly categorized as membrane-based processes and thermal energy-based (or phase change processes). Membrane based processes such as reverse osmosis (RO), and electro dialysis (ED) require electrical energy which in turn may be provided by conventional energy sources or renewable energy sources. The thermal-based processes are mainly the phase change processes

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Nomenclature

A	area [m^2]
C_p	specific heat [J/kg-K]
c_o	speed of light [m/s]
D	mean particle diameter of nanoparticles [nm]
$\dot{E}$	exergy flow rate associated with a fluid stream [kW]
ΔEX	rate of exergy loss [kW]
f_v	nanoparticle volume fraction (within the base fluid)
H	height of the solar collector [m]
h	specific enthalpy [kJ/kg]
h_{Planck}	Planck constant, $h = 6.6256 \times 10^{-34}$ J-s
h_{conv}	convection heat transfer coefficient [W/m^{2}K]
$h_{fg,\ avg}$	enthalpy of vaporization or condensation [J/kg]
h_{nf}	enthalpy of the nanofluid [J/kg]
I_λ	spectral intensity of radiation [W/m^2-str-μm]
j	number of heat rejection stages
K	radiative coefficients [m^{-1}]
k	thermal conductivity of nanofluid [W/mK]
k_B	Boltzmann constant, $k_B = 1.38 \times 10^{-23}$ J/K
L	length of the solar collector [m]
$\dot{M}$	mass flow rate of the seawater [kg/s]
m	normalized refractive index, $m = n + i\kappa$
$\dot{m}_{nf}$	mass flow rate of nanofluid [kg/s]
N	number of stages in the MSF system
n	index of refraction
Q_{conv}	heat loss through convection from the glass cover of the collector [J/s]
$Q_{transfer}$	heat transfer from nanofluid to recycled brine in the heat exchanger [J/s]
q_{ra}	radiative flux obtained from sun [W/m^2]
s	specific entropy [J/kgK]
T	temperature [K]
δt	temperature drop in the flashing stage due to losses [°C]
t_1	temperature of recycled brine at the exit of the heat recovery section [°C]
U	nanofluid velocity in the collector [m/s]
W	width of the solar collector [m]
X	salinity of the seawater [ppm]
x	direction in which the nanofluid flows
y	distance from the top surface of the solar collector [m]

Greek Symbols

α	size parameter
ε	effectiveness of the heat exchanger
η	efficiency
κ	index of absorption
λ	wavelength of incident radiation [μm]
ρ	density [kg/m^3]
τ	transmissivity of the glass cover
ϕ	solid angle [str]

Subscripts

II	second
a	absorption
abs	absorbed
amb	ambient
avg	average
b	brine
black	blackbody
c	condenser
cw	cooling seawater
conv	convection
d	distillate
e	extinction
f	feed sea water
HX	heat exchanger
i	stage number
in	inlet of the collector
nf	nanofluid
o	top brine
out	outlet of the collector
r	recycled brine
ra	radiative
st	per stage temperature drop
trans	transfer
v	saturated vapor

Abbreviations

BPE	boiling point elevation
BR	brine recirculation
CD	chemical disequilibrium
DASC	direct absorption solar collector
ED	electro dialysis
FDM	finite difference method
FPC	flat plate collector
GOR	gained output ratio
HDH	humidification dehumidification
MED	multi-effect distillation
MSF	multi-stage flash
MVC	mechanical vapor compression
NEA	non-equilibrium allowance
OT	once through
PTC	parabolic trough collector
RO	reverse osmosis
RTE	radiative transport equation
TBT	top brine temperature
TD	thermal disequilibrium
TDS	total dissolved salts
TVC	thermal vapor compression

such as multi-effect distillation (MED), multistage flash desalination (MSF), thermal vapor compression (TVC), mechanical vapor compression (MVC) and humidification and dehumidification (HDH). All these thermal-based processes require thermal energy or steam [9,10]. This thermal energy can either be supplied from power plants operating on fossil fuels, natural gas or may be supplied via renewable energy sources such as solar energy or geothermal energy [8,11]. Desalination using these processes requires significant amount of energy either in the form of electrical energy (for membrane based processes) or thermal energy (for phase change processes) to achieve the separation of salts from seawater [3]. This amount of energy is highly significant due to recurrent cost and only a very few water-scarce regions of the world can afford this huge cost. When this significant amount of energy is supplied using conventional energy sources, it can cause serious hazards to the environment by releasing CO_2 which may lead to climate change [1,12–14]. In order to save the environment and to make the desalination process affordable for every part of the world, desalination should be accomplished using renewable energy sources.