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Energy-environment-economic investigations on evacuated active multiple stage series flow solar distillation unit for potable water production

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ABSTRACT

Multi stage solar distillation units are well known for their higher distillate productivity and are capable of fulfilling the potable water requirements of families in remote, rural, and coastal regions. In this article, active multiple stage series flow solar distillation unit has been proposed for desalting saline water and its performance, environmental benefits and economic feasibility were assessed by carrying out 3E (Energy-Environment-Economic) analyses using the developed mathematical model. Better performance was observed for the distillation unit with five distillation stages, two solar collectors connected in parallel configuration and saline water mass flow rate of 135.0 kg/d and 75.0 kg/d, during summer and winter seasons. Low-pressure operation in combination with evaporative cooling of condenser of last stage has enhanced the annual average daily distillate productivity from 12.60 kg/d to 48.80 kg/d. Distillate production was found to drop from 48.80 kg/d to 38.90 kg/d with the increase in salt concentration of saline water from 0 wt% to 10 wt%. Energy payback time of the unit desalting saline water with 5 wt% salt concentration was within 1.0 yr and the unit can mitigate nearly 221.80 tons of CO_2 emission, 1594.73 kg of SO_2 emission and 651.37 kg of NO emission from Indian coal based power plants during its 20 yrs lifespan under 250 clear day operation. Increased salt concentration in saline water reduces the emission mitigation potential and increases the energy payback time of the proposed distillation unit. Distillate production cost was increased by 16.0% for every 5 wt% increase in salt concentration. Amount invested in the unit can be regained with in 3.56 yr irrespective of interest rate for distilled water selling price of 0.06 USD/L (Rs. 3.91/L).

1. Introduction

Water is a valuable natural resource, which is necessary for existence of life on globe. Water demand is always on the higher side due to continuous industrial expansion and increasing trend of population growth. Due to limited availability and improper distribution of accessible fresh water reserves, global water stress is increasing day by day. In order to meet the potable water requirements, distillation of saline water has been considered as an effective option due to huge availability of saline water in oceans [1]. Conventional distillation technologies widely adopted are multi-effect distillation, multi-stage flash, mechanical vapor compression, and thermo vapor compression whose distillate is of very high quality and is suitable for drinking and industrial applications [2]. Higher energy requirement of these conventional distillation technologies makes it difficult for fossil fuel deficient developing and underdeveloped nations to implement these technologies to overcome their water scarcity problem [3]. Renewable energy is an effective candidate to fulfill the energy demand of these distillation technologies with minimal impact on environment by reducing green house gas emissions [4]. Solar thermal energy is a better option among renewable energies for water distillation as most of the water deficient countries have high solar energy potential and hence it can be effectively utilized for water distillation and detoxification [5]. At this moment, solar energy based distillation units is costly however in future continuous research and development in solar thermal technologies can bring down its distillate production cost [6]. However, for remote, arid and rural regions solar energy based distillation units are highly economical compared to the cost associated with water supply by large pipelines for long distances [7].

1.1. Solar stills: Distillate production enhancement

Conventional basin type solar stills produce 2.0–3.0 kg/m^2 d of high quality distillate. Many attempts have been made throughout the globe to enhance the distillate productivity of these distillation units, as they are more beneficial to environment in terms of CO_2 emission mitigation

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Nomenclature

A_c	aperture area of each solar collector (m^2)
A_e	area of evaporating surface (m^2)
A_l	area of lateral surface of each stage (m^2)
A_t	area of tilted metallic partition tray (m^2)
A_w	area of water surface of bottom basin (m^2)
Br_t	breadth of the metallic partition tray (m)
CC	capital cost of solar distillation unit (USD)
C_w	specific heat capacity of saline water (J/kg K)
C_{pb}	specific heat capacity of reject water (J/kg K)
C_{st}	specific heat capacity of tilted metallic partition tray (J/kg K)
$C_{pav(N-1)}$	specific heat capacity of humid air (J/kg K)
CPL	distillate production cost per litre (USD/L)
DPD	distillate produced per USD invested (L/USD)
E_{in}	embodied energy (kWh)
$EPBT$	energy payback time (Yr)
F'	collector efficiency factor
$F_{(1-2)}$	shape factor between 1st and 2nd stage
$F_{((N-1)-(N))}$	shape factor between (N − 1)th and Nth stage
$Gr'_{(1)}$	modified Grashof number of 1st stage
h	hour angle (degree)
h_{fg}	latent heat of evaporation (J/kg)
I_b	beam component of solar radiation (W/m^2)
I_d	diffuse component of solar radiation (W/m^2)
I_t	global solar radiation incident over solar collector (W/m^2)
IR	interest rate (%)
K_d	thermal conductivity of insulation (W/m K)
$K_{av(1)}$	thermal conductivity of humid air in 1st stage (W/m K)
L	latitude (°)
L_b	length of bottom basin (m)
$Le_{(N-1)}$	Lewis number of humid air in (N − 1)th stage
L_k	thickness of insulation (m)
LH	latent heat (kJ/kg)
LT	life time of the distillation unit (Yr)
$\dot{m}_{b(2)}$	mass flow rate of reject water leaving 2nd stage (kg/s)
$\dot{m}_{b(3)}$	mass flow rate of reject water leaving 3rd stage (kg/s)
$\dot{m}_c$	mass flow rate of fluid circulated through solar collector (kg/s)
$\dot{m}_{d(1)}$	distillate production rate of 1st stage (kg/s)
$\dot{m}_{d(N-1)}$	distillate production rate of (N − 1)th stage (kg/s)
$\dot{m}_f$	mass flow rate of feed water (kg/s)
M_{st}	mass of tilted metallic partition tray (kg)
M_w	mass of water in lower basin (kg)
M_v	molecular weight of water vapor (kg/kmol)
M_Y	annual distillate production (kg)
N_c	number of solar collectors connected in series or parallel
n_p	finance payback time (Yr)
OEF	overall efficiency factor
P_a	partial pressure corresponding to ambient temperature (Pa)
$P_{AM(N-1)}$	arithmetic mean pressure difference of (N − 1)th stage (Pa)
P_{cst}	partial pressure corresponding to condenser temperature of last stage (Pa)
P_o	operating pressure (bar)
$Pr_{(1)}$	Prandtl number of humid air in 1st stgae
$Pr_{(N)}$	Prandtl number of humid air in Nth stgae
PR	performance ratio
P_t	total pressure (Pa)
$P_{T_{st(N-1)}}$	partial vapor pressure corresponding to (N − 1)th stage temperature (Pa)
$P_{T_{st(N)}}$	partial vapor pressure corresponding to (N)th stage temperature (Pa)
$Q_{c(1-2)}$	convective heat transport between 1st and 2nd stage (W)
$Q_{c((cst)-(a))}$	convective heat transport between condenser of last stage and ambient (W)
$Q_{e(1-2)}$	evaporative heat transport between 1st and 2nd stage (W)
$Q_{e((cst)-(a))}$	evaporative heat transport between condenser of last stage and ambient (W)
$Q_{lb(1-a)}$	conductive heat loss from bottom of 1st stage to ambient through insulation (W)
$Q_{ls(1-a)}$	conductive heat loss from side walls of 1st stage to ambient through insulation (W)
$Q_{ls(2-a)}$	conductive heat loss from side walls of 2nd stage to ambient through insulation (W)
$Q_{r(1-2)}$	radiative heat transport between 1st and 2nd stage (W)
$Q_{r((cst)-(a))}$	radiative heat transport between condenser of last stage and ambient (W)
Q_{us}	useful heat energy supplied by solar collectors (W)
R	universal gas constant (J/kmol K)
$Ra'_{(N-1)}$	modified Rayleigh number of (N − 1)th stage
Sa	salt concentration (wt%)
S_p	selling price of treated water (USD/L)
TAC	total annualized cost (USD)
T_a	ambient temperature (°C)
T_{av}	average temperature between the stages (°C)
T_{ci}	inlet fluid temperature of solar flat plate collector (°C)
T_{co}	outlet fluid temperature of solar flat plate collector (°C)
T_{cst}	temperature of condenser of last stage (°C)
$T_{st(1)}$	temperature of 1st stage (°C)
$T_{st(2)}$	temperature of 2nd stage (°C)
$T_{st(N-1)}$	temperature of (N − 1)th stage (°C)
$T_{st(N)}$	temperature of Nth stage (°C)
U_l	overall heat loss coefficient of solar collector (W/m^2 K)
V	wind velocity (m/s)
$W_{(1)}$	average gap between evaporating and condensing surface of 1st stage (m)
α_p	absorptivity of absorber plate of solar collector
β	tilt angle of solar collector (°)
γ	tilt angle of metallic partition tray (°)
$\rho_{av(N-1)}$	density of humid air in (N − 1)th stage (kg/m^3)
ρ_g	ground reflectance
ε_p	emissivity of metallic partition tray
ε_w	emissivity of water
δ	declination (°)
σ	Stefan-Boltzmann constant ($W/m^2 K^4$)
τ_g	transmissivity of glass cover of solar collector
θ_i	incident angle of solar radiation (°)
φ	relative humidity (%)
Δt	time step (s)

[2,8]. Solar distillation units of capacity less than 0.2 m^3/d are highly economical when compared to other conventional fossil fuel powered distillation units [9,10]. Enhancement of distillate productivity of solar distillation units can be achieved by (a) increasing evaporator temperature (b) reducing condenser temperature and (c) reuse of latent heat of condensation [11].

1.2. Increasing evaporator temperature

Evaporator temperature of passive solar distillation units has been enhanced by (a) increasing solar radiation absorptivity; (b) concentrating solar radiation over the evaporator surface; (c) increasing evaporating surface area; (d) increasing thermal conductivity of evaporating fluid and (e) incorporation of heat storage materials. Solar