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Techno-economic analysis of mini solar distillation plants integrated with reservoir of garden fountain for hot and dry climate of Jodhpur (India)

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ABSTRACT

Paper presents economic analysis of two small solar distillation plants coupled to fountain reservoir designed to meet drinking water requirement of 300 l/day for hot and dry climate of Jodhpur (India). Performance of proposed plants (1) FRP single slope solar still and (2) FRP multiple wick solar still is compared with conventional single slope solar still plant. To enhance product output of plants, it is proposed to utilize cooled water stored in reservoir to cool glass cover of solar stills. The result shows that still area (distillation area) required for proposed plants is 37.8% to 39.5% less in comparison to conventional single slope solar still plant (without flow). Cost of distilled water produced is Rs 0.40/l (US $0.0061/l) and Rs 0.41/l (US $0.0063/l) for proposed plant-1(FRP single slope solar still) and proposed plant-2 (FRP single slope multiple wick solar still) respectively, which is about 29.2% to 32.5% less than the conventional single slope solar distillation plant. To replenish loss of water due to evaporation over glass cover, average additional make-up water required in fountain reservoir is 738 l/day. The proposed plant is particularly suitable at a place were plenty of brackish (impure) water is available, may be near to river, lake, canal or pond. (1US$ = Rs65/-).

1. Introduction

Solar distillation is an easy, small scale and cost effective technique for providing safe water at homes or in small communities. Conventional solar distillation plants utilize a number of solar stills connected together in series and parallel as desired. However, low distillate output from a solar still is a major hurdle which limits the use of solar distillation technique for large scale production particularly due to large solar collection area requirement and high capital cost. For large scale production, commercially available distillation techniques, such as multistage flash desalination (MSF), vapor compression (VC) or reverse osmosis (RO), membrane distillation (MD) and electrodialasis are utilized. However, since conventional solar distillation plants are characterized by free energy and insignificant operating cost, the technology is suitable for small scale production, especially in remote and arid areas. Intensive research work has been carried out in past to increase the production output of solar still in order to increase production output of conventional solar distillation plants.

As more temperature difference between water in the basin and glass cover enhances the distillate output. There are many active and passive methods utilized to increase the temperature difference between basin water and glass cover. Frick and Sommerfield (1973) introduced a single wick solar still with a negligible thermal capacity, which increases the temperature of water and thus enhances the rate of evaporation. Sodha et al. (1981), proposed a new design of wick still, in which blackened wet jute cloths with their upper edges dipped in saline water. They reported an overall thermal efficiency of 34%. Tiwari et al. (1984) introduced a modified design with double condensing multiple wick solar still. To reduce the temperature of the glass cover flow of water over the glass cover is one of the known methods studied by various researchers [Tiwari et al. (1984, 1985), Lawrence et al. (1990), Bassam AK and Abu-hijleh (1996, 1997) and Badran (2009)]. Somwanshi and Tiwari (2014) proposed to flow cooled water at wet bulb temperature, from the tank of a desert cooler to flow over the glass cover of single slope solar still (or stills). They reported an annual increase in yield in between 56.5% to 41.3% for different climatic zones in India. They suggested that water from a cooler can be utilized for cooling the cover of more than one solar still depending on the size of air cooler which limits the usefulness of the concept.

Economic analysis is essential to determine the cost of product water, economic analysis of solar distillation system has been made earlier by various researchers. Mukherjee and Tiwari (1986) have carried out the economic analysis of three different types of the solar stills viz. Single slope, fiber-reinforced plastic (FRP) still, a double slope FRP

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Nomenclature

TAC	total annual cost (Rs)
FAC	first annual cost (Rs)
AMC	annual maintenance cost (Rs)
CRF	capital recovery factor
SFF	sinking fund factor
CC	construction cost or fixed cost (Rs)
S	Salvage or scrap value (Rs)
A_b	area of basin liner of solar still (m^2)
A_g	area of glass cover of solar still (m^2)
b	breadth of glass cover of solar still (m)
h	height of lower vertical side of solar still (m)
C_w	specific heat of water (J/kg°C)
d	depth of water in the basin (m)
d_t	diameter of pipe (m)
h_{1g}	sum of radiative and convective heat transfer coefficient between glass cover and ambient ($W/m^2\,°C$)
h_1	sum of radiative, convective and evaporative heat transfer coefficient between water in basin and glass cover ($W/m^2\,°C$)
h_2	Sum of radiative and convective heat transfer coefficient between film and air ($W/m^2\,°C$)
h_2'	convective heat transfer coefficient between glass cover and water film ($W/m^2\,°C$)
h_3	heat transfer coefficient between basin liner and water ($W/m^2\,°C$)
h_4	convective heat transfer coefficient between base and ambient ($W/m^2\,°C$)
h_b	overall bottom heat loss coefficient from basin liner to ambient through bottom insulation ($W/m^2\,°C$)
h_{cg}	convective heat transfer coefficient between glass cover and ambient ($W/m^2\,°C$)
h_{cw}	convective heat transfer coefficient between water in the basin and glass cover ($W/m^2\,°C$)
h_{cfa}	convective heat transfer coefficient between water film and air ($W/m^2\,°C$)
h_{rfa}	radiative heat transfer coefficient between water film and air ($W/m^2\,°C$)
h_{rw}	radiative heat transfer coefficient between water in the basin and glass cover ($W/m^2\,°C$)
h_{ew}	evaporative heat transfer coefficient between water in the basin and glass cover ($W/m^2\,°C$)
h_{rg}	radiative heat transfer coefficient between glass cover and ambient ($W/m^2\,°C$)
h_f	frictional head (m)
h_s	static head (m)
K_i	thermal conductivity of basin material (W/mk)
l	length of glass cover of solar still (m)
l_w	depth of water film (m)
L	latent heat of vaporization (J/kg)
L_t	length of pipe (m)
L_i	thickness of basin liner (m)
$\dot{m}_f$	mass flow rate of water film (kg/s)
M_w	mass of water in the basin (kg)
$\dot{m}_e$	hourly yield through solar still (kg/hm^2)
M_d	daily yield through solar still (kg/m^2)
M_m	monthly yield through solar still (kg/m^2)
M_a	annual yield through solar still (kg/m^2)
n	number of days in month
P_f	saturated vapor pressure at film temperature (N/m^2)
P_w	saturated vapor pressure at water temperature (N/m^2).
P_a	saturated vapor pressure at air temperature (N/m^2)
$\dot{q}_{ef}$	rate of evaporative heat transfer from film to air per unit area (W/m^2)
R	reflection coefficient
S	solar insolation on horizontal surface (W/m^2).
T_f	temperature of water film (°C)
T_a	ambient temperature (°C)
T_g	temperature of glass cover (°C)
T_b	temperature of basin liner (°C)
T_e	exit temperature of water from fountain reservoir
T_{fi}	inlet temperature of water film at $x = 0$ (°C)
T_{fl}	exit temperature of water film at $x = l$ (°C)
T_{wb}	wet bulb temperature of ambient air (°C)
$\overline{T}_f$	average film temperature (°C)
T_{w0}	initial temperature of water in basin at $t = 0$ ($°C$).
$\overline{T}_w$	average basin water temperature (°C)
T_{g0}	initial temperature of glass cover at $t = 0$ (°C)
$\overline{T}_g$	average glass cover temperature (°C)
	velocity of air (m/s)
v_p	velocity of water flowing inside pipe (m/s)
Q	volumetric flow rate (m^3/s)
P_p	pumping power (kW)
ΔP	pressure drop (N/m^2)
E	electric energy required (kWh)
f	friction factor

Greek letters

ε_w	emmisivity of water
ε_g	emmisivity of glass
ε_{eff}	effective emmisivity
σ	Stefans-Boltzman's constant ($W/m^2\,K^4$)
ρ	density of water (kg/m^3)
μ	refractive indices
α_w	absorption coefficient of water
α_g	absorption coefficient of glass
α_b	absorption coefficient of basin liner
α_{mb}	absorption coefficient of basin for multiple wick solar still
τ_1, τ_1'	fraction of solar energy absorbed by glass cover with and without film
τ_2, τ_2'	Fraction of solar energy absorbed by water in basin with and without film
τ_3, τ_3'	fraction of solar energy absorbed by basin liner with and without film
τ_4	fraction of solar energy absorbed by basin for multiple wick solar still with film
γ	relative humidity of ambient air
η_a	annual efficiency of solar still
η_f	efficiency of fountain reservoir

solar still and a double slope concrete solar still for Indian climatic conditions. They have evaluated the minimum cost of distilled water produced from conventional solar stills. Delyannis and Delyannis (1985) have carried over techno economic analysis of a small size of solar distillation plant of capacity 1 m^3/d, and estimated the cost of distilled water to be US \$12/m^3. Tleimat and Howe (1996) have reported that the solar distillation plants of capacity less than 200 L/day are more economical than the other type of plants. Madani and Zaki (1995) studied the effect of carbon powder and basin insulation on yield of solar still experimentally. They conducted economic analysis of the proposed design of plant of 50 m^3/d and estimated the cost to be US \$2.4/m^3. Singh and Tiwari (2011) presented annualized life cycle costing method for the economic evaluation of various designs of solar stills. They observed that the cost of distilled water per m^2 is most economical for the multi-wick double effect distillation unit due to low water depth in the basin and re-utilization of latent heat of

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