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Exergy analysis of double slope active solar still under forced circulation mode

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ABSTRACT

Potable water is a basic necessity for human being along with food and air. Direct uses of water from sources like rivers, lakes, sea, and underground water reservoirs are not always advisable because of the presence of higher amount of salt and contamination. Solar still is a simple device which can convert available waste or brackish water into potable water using solar energy. Clean water is evaporated from the brackish water and condensed on the glass cover, which is drained out for use. In this paper, thermal efficiency and exergy analysis are carried out for evaluating the thermal performance of double slope active solar still under forced circulation mode. The daily thermal efficiency of solar still varies from 13.55 to 31.07% and the exergy efficiency varies from 0.26 to 1.34%.

Keywords: Solar distillation; Exergy analysis; Thermal efficiency

1. Introduction

Human life on land is vitally dependent on renewable fresh water, a resource that comprises only a tiny fraction of the global water pool. In many regions of the world, the amount and quality of water available to meet human needs are limited. The gap between freshwater supply and demand will widen during the coming century as a result of climate change and increasing consumption of water. Growing demands of freshwater resources are creating an urgent need to develop self-sustained system to meet the demand. Distillation is a good method to obtain portable water. However, the conventional distillation processes such as multi-effect fresh evaporation, thin film distillation, reverse osmosis and electro dialysis are energy intensive techniques and are not feasible for large fresh water demands. Therefore, solar distillation seems to be a promising method and an alternative way for supplying small communities in remote areas and islands.

Solar stills of different designs have been investigated by many researchers. Relationship for convective and evaporative heat transfer coefficients for an air–water system in the roof type still has been developed in 1961 [1]. Tiwari and Yadav have shown that a single slope distiller gives better performance than a double slope solar still for cold climatic conditions, whereas a double slope distiller gives better performance than a single slope for summer climatic conditions [2]. Ahmad studied about single-effect solar stills with an internal condenser [3]. The performance testing and analysis of a double-glazed, air-blown

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solar still with thermal energy recycling are carried out in 1998 [4]. Dincer reported the linkage between energy and exergy, exergy and the environment, energy and sustainable development and energy policy making [5]. Exegetic analysis and performance evaluation of a wide range of renewable energy resources were reviewed by Hepbasli [6]. Koca et al. has done the energy and exergy analysis of latent heat storage system with phase change material for a solar collector [7]. Dwivedi and Tiwari has done the energy and exergy analysis for passive solar still [8]. Torchia et al. carried out an analysis of the exergy flows and its destruction in a solar still operating in steady and unsteady state [9]. Farahat et al. developed a procedure to design and optimization of flat plate solar collectors based on exergy analysis [10]. Eldalil presented a new concept of active vibratory solar still with an average daily efficiency of about 60% [11]. Kumar and Tiwari has developed an expression for instantaneous exergy efficiency of a passive solar still [12]. Dev and Tiwari developed the characteristic equation for double slope passive solar stills [13]. Saidur et al. carried out a comprehensive literature review on exergy analysis of various solar energy systems [14]. Ahsan et al. presented the design, fabrication, cost, water production analysis of the old and new tubular solar still. A relationship between the water production flux and the temperature difference inside the still is also demonstrated [15].

In the present work, a double slope active solar still has been fabricated and their thermal performance mainly thermal efficiency and exergy analysis has been carried out.

2. Solar distillation setup

The schematic diagram and photograph of double slope active solar still under study have been shown in Fig. 1a and 1b. Double slope active solar still of basin area 2.0 m × 1.0 m was fabricated using fiber reinforced plastic of low thermal conductivity integrated with flat plate collector and DC water pump as shown in Fig. 1. In this setup, interior surfaces of the basin are painted black with dye to increase its absorptivity to solar radiations. The top of the basin is covered with glass of thickness 0.004 m, inclined at 25° and oriented due East and West (E–W) direction, respectively, to receive the maximum possible solar radiation. A calibrated solarimeter of least count of 20 W/m^2 had been used to measure solar radiations.

The condensed water is collected in a galvanized iron channel fixed at the lower end side of both the glass covers. The distillate collected is continuously drained through flexible pipe and stored in a jar placed outside on both side. The collected distillate yield has been measured using graduated cylinder with least count of 1 mL.

A hole in the basin side wall allows inserting the wires of thermocouples to measure the different temperatures. Calibrated copper constantan thermocouples were used to measure the temperature of water, vapor and condensing cover with the help of digital temperature indicator having a least count of 0.1℃. Calibrated mercury thermometer of least count 1℃ has been used to record the ambient air temperature.

An inlet pipe is also fixed in the side wall of solar still to feed the brackish water in the basin. The whole unit is mounted on an angle iron stand. In this solar

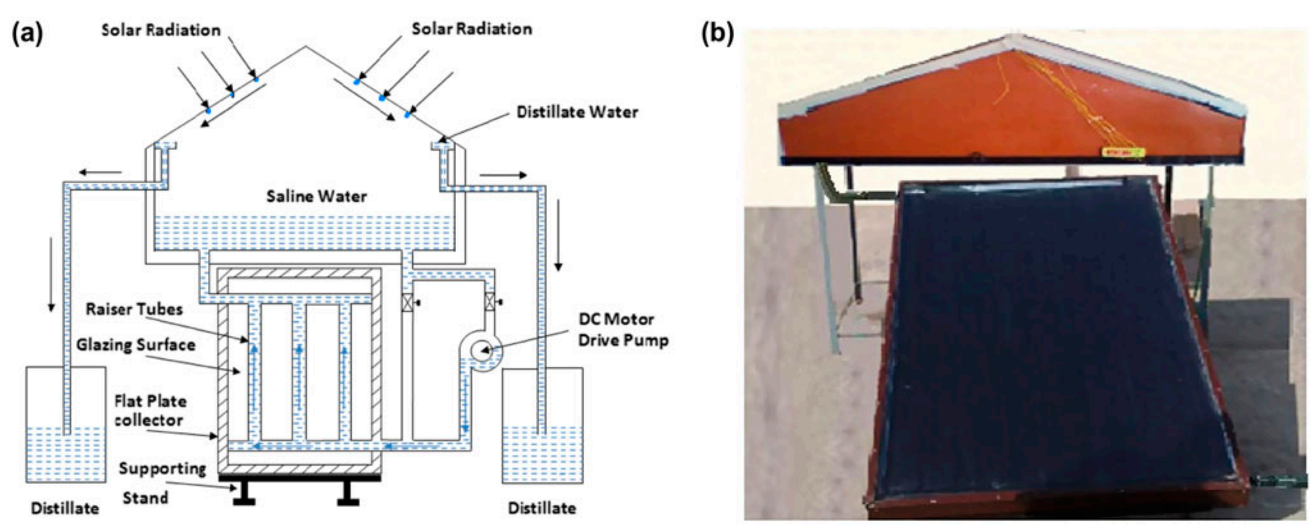

Fig. 1. (a) Cross-sectional view of a double slope active solar still and (b) double slope active solar still set up.

still, the water in the basin gets heated directly as well as indirectly through the flat plate collectors. Flat plate collectors is connected and integrated to the basin of solar still by using insulated pipes. The collector has an effective area of 2.0 m^2. The whole system is made vapor tight using silicone rubber sealant, as it remains elastic for long time.

The DC water pump of size 40 W is used to circulate the water in forced mode of operation. The pump is driven directly by the DC power. The pump operates only during sunshine hour, to avoid reverse heat flow from water during off sunshine hours.

3. Experimental observation

Experiments were conducted at the Galgotias College of Engineering and Technology Greater Noida, UP, India throughout a year starting from July 2011 to June 2012 and carried out from nine a.m. and lasted for 24 h. The solar radiation on solar still and collector plate, ambient air temperature, temperature of water, glass cover temperature, and distilled water output are measured at an interval of 1 h. Performance of double slope solar still are investigated at water depth of 0.03, 0.04, and 0.05 m.

The hourly experimental observation for a water depth of 0.03 m for a typical day of 6 June 2012 has been given in Table 1. The average experimental observation for different water depth and month and year has been given in Table 2. The average experimental data has been used to evaluate monthly and yearly output by multiplying it by number of clear days has been given in Table 3.

4. Mathematical modeling

4.1. Overall thermal efficiency of an active solar still

The daily yield can be obtained by adding hourly yield for a period of 24 h and can be obtained as

$$M_w = \left(\sum_{i=1}^{i=24} (m_{wE} + m_{wW}) \right) \quad (1)$$

Table 1
Measured parameters for 0.03 m water depth in a double slope active solar still of 25° inclination of condensing cover on a day of 6 June 2012

Time (h)	T_a (°C)	T_W (°C)	I_C (W/m^2)	Double slope (East side)			Double slope (Westside)		
				T_{ciE} (°C)	I_{tE} (W/m^2)	m_{wE} (kg)	T_{ciW} (°C)	I_{tW} (W/m^2)	m_{wW} (kg)
9AM	32	40.7	420	35.5	360	0.024	34.1	340	0.016
10AM	34	42.5	600	37.6	540	0.031	36.7	500	0.034
11AM	37	48.7	720	41.7	640	0.095	40.8	600	0.131
12Noon	38	53.4	720	45.9	660	0.176	43.4	620	0.213
1PM	39	58.7	680	51.7	700	0.295	54.3	720	0.434
2PM	40	66.4	660	55.9	680	0.44	58.7	700	0.403
3PM	41	71.3	500	57.9	540	0.426	61.4	640	0.422
4PM	40	68.4	280	54.8	300	0.392	58.7	440	0.338
5PM	39	63.7	100	52.7	120	0.337	56.5	180	0.292
6PM	38	56.8	0	47.6	0	0.271	50.6	0	0.242
7PM	37	52.3	0	44.7	0	0.174	47.8	0	0.148
8PM	36	50.2	0	42.9	0	0.11	44.9	0	0.102
9PM	34	48.9	0	41.4	0	0.094	43.5	0	0.086
10PM	32	46.7	0	40.2	0	0.062	41.8	0	0.056
11PM	32	42.7	0	38.8	0	0.044	39.9	0	0.034
12AM	31	37.3	0	36.6	0	0.037	37.3	0	0.031
1AM	31	35.2	0	34.5	0	0.029	34.4	0	0.026
2AM	30	34.3	0	33.9	0	0.023	33.6	0	0.021
3AM	29	33.4	0	33.2	0	0.019	31.6	0	0.018
4AM	29	33.7	0	32.8	0	0.017	31.4	0	0.015
5AM	29	32.6	0	32.4	0	0.017	30.9	0	0.014
6AM	29	32.1	0	31.8	0	0.014	31.4	0	0.011
7AM	29	33.4	120	31.6	80	0	31.4	80	0
8AM	30	35.4	240	33.8	180	0.013	32.8	140	0.011

Table 2
Average ambient temperature, water temperature, solar intensity and daily yield for double slope solar still under forced circulation mode for different water depth for each month during July 2011 to June 2012

Month and year	Water depth														
	0.03 m					0.04 m					0.05 m				
	T_a (°C)	I_C (W/m^2)	I_t (W/m^2)	T_w (°C)	M_w (kg/d)	T_a (°C)	I_C (W/m^2)	I_t (W/m^2)	T_w (°C)	M_w (kg/d)	T_a (°C)	I_C (W/m^2)	I_t (W/m^2)	T_w (°C)	M_w (kg/d)
July 2011	31	4,640	4,520	43.4	5.03	32	4,740	4,560	43.8	4.64	31	4,580	4,490	42.2	4.56
August 2011	30	4,380	4,170	40.6	4.82	29	4,220	4,070	38.4	4.51	31	4,460	4,480	40.1	4.37
September 2011	29	4,180	4,050	38.4	4.48	28	3,860	3,760	36.3	4.25	30	4,320	4,150	37.9	4.16
October 2011	28	3,740	3,660	36.6	4.11	28	3,660	3,420	35.4	3.61	29	3,860	4,020	36.1	3.56
November 2011	23	3,100	2,860	30.4	3.31	24	3,180	2,880	30.6	3.18	24	3,080	2,840	30.1	2.65
December 2011	18	2,760	2,440	24.8	2.65	19	2,860	2,470	24.6	2.57	17	2,720	2,690	22.2	2.16
January 2012	17	2,940	2,730	23.1	2.89	18	3,020	2,770	23.2	2.50	18	2,980	2,770	23.0	2.46
February 2012	20	3,780	3,640	28.7	3.62	21	3,920	3,770	28.6	3.88	21	3,840	3,760	28.2	3.55
March 2012	25	4,240	4,150	37.4	5.30	24	4,160	4,050	35.2	5.48	24	4,020	4,000	34.6	4.95
April 2012	30	4,820	4,560	45.3	6.58	29	4,580	4,380	42.8	5.66	30	4,740	4,540	43.2	5.51
May 2012	33	4,960	4,680	49.7	7.05	32	4,760	4,620	46.6	6.57	33	4,940	4,620	48.5	5.90
June 2012	34	5,040	4,880	46.6	6.24	33	4,900	4,740	44.3	5.67	32	4,740	4,540	42.0	5.74

Table 3
Summary of monthly and annual yield obtained by the double slope solar still under forced circulation mode for different water depth on the basis of clear days for each month during July 2011 to June 2012

Month	No. of clear days	Water depth		
		0.03 m	0.04 m	0.05 m
		M_W	M_W	M_W
	(D)	(kg)	(kg)	(kg)
July 2011	16	80.54	74.30	72.96
August 2011	13	62.70	58.67	56.78
September 2011	16	71.69	67.95	66.59
October 2011	24	98.76	86.69	85.54
November 2011	30	99.40	95.40	79.63
December 2011	21	55.67	53.98	45.41
January 2012	22	63.49	55.07	54.07
February 2012	24	86.92	93.23	85.19
March 2012	29	153.71	158.90	143.65
April 2012	29	190.81	164.08	159.80
May 2012	30	211.36	197.06	177.00
June 2012	26	162.21	147.36	149.14
	280	1,337.246	1,252.687	1,175.758

The values of M_w for different water depth, months and year for double slope active solar still are given in Table 2.

The daily thermal efficiency is defined as

$$\eta_{th} = \frac{M_w \times L}{(A_s \times \sum I_t \times 3,600) + (A_C x \sum I_C \times 3600)} \quad (2)$$

where L is given by this equation

$$L = 2.4935\times10^6 \times [1 - (9.4779\times10^{-4} T_w + 1.3132\times10^{-7}\times T_w^2 - 4.7974\times10^{-9}\times T_w^3]$$

The daily thermal efficiency of solar still is given in Table 4.

4.2. Exergy analysis of double slope active solar still

Energy conversion/utilization processes have been evaluated based on the first law of thermodynamics—energy analysis. In recent times, use of exergy analysis to gain better understanding of such processes has become popular. Exergy analysis is derived from the second law of thermodynamics and serves as a measure of the ability of energy to do

Table 4
Thermal efficiency of double slope active solar still

Month and year	Thermal efficiency (%) η_{th} water depth		
	0.03 m	0.04 m	0.05 m
July 2011	18.25	22.25	16.72
August 2011	18.79	24.37	16.28
September 2011	18.17	24.96	16.41
October 2011	18.59	23.03	15.13
November 2011	18.70	23.92	15.09
December 2011	17.24	22.29	13.55
January 2012	17.24	14.64	14.48
February 2012	16.44	22.84	15.74
March 2012	21.10	29.92	20.69
April 2012	23.25	28.19	19.73
May 2012	24.12	31.07	20.40
June 2012	20.82	26.16	20.56

work; it is equal to the maximum amount of work that can be extracted from a given quantity of energy.

The general exergy balance for solar still can be written, Hepbalsi [6], as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \quad (3)$$

Or,

$$\dot{E}x_{Sun} - (\dot{E}x_{evap} + \dot{E}x_{work}) = \dot{E}x_{dest} \quad (4)$$

where the exergy input to the solar still is radiation exergy and can be written, Petela [16] as:

$$\dot{E}x_{in} = \dot{E}x_{sun} = \left(A_s \times \sum I_t + A_C x \sum I_C\right) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s}\right)^4\right] \quad (5)$$

The exergy of work rate for solar still is given by

$$\dot{E}x_{work} = \dot{W} = 0 \quad (6)$$

The exergy output of a solar still can be obtained as follows:

$$\dot{E}x_{evap} = M_w L \times \left[1 - \left(\frac{T_a + 273}{T_W + 273}\right)\right] / 3,600 \quad (7)$$

The daily exergy output will be evaluated by Eq. (7) and the results are given in Table 5.

The monthly exergy input to solar still and exergy output of solar still can be obtained by multiplying Eqs. (5) and (7), respectively, by the number of clear days and results are given in Table 6.

The exergy efficiency of solar still is defined, Hepbalsi [6], as follows:

$$\eta_{EX} = \frac{\text{Exergy Output of solar still } (\dot{E}x_{evap})}{\text{Exergy Input to solar still } (\dot{E}x_{in})} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (8)$$

The daily exergy efficiency is also given in Table 5.

5. Results and discussion

- The experimental studies were conducted from July 2011 to June 2012. The average ambient temperatures ranged 17–34˚C during these experiments. The maximum average ambient temperature recorded was 34˚C in the month of June 2012, while the maximum average temperature of the brackish water in the solar still was 49.70˚C in the month of June 2012.
- The yield output is principal factor in solar still. Table 2 shows average ambient air temperature, water temperature, daily yield and solar intensity for water depth of 0.03, 0.04, 0.05 m for solar still in every months of a year. Fig. 2 shows that solar still gives higher yield 7.05 kg/d in the month of May 2012 at water depth of 0.03 m, while lower yield 2.16 kg/d in the month of December 2011 at water depth of 0.05 m.
- The daily thermal efficiency of solar still is calculated by Eq. (2) and shown in Table 4. From Table 4 and Fig. 3, it is found that it varies from 13.55 to 31.07%. The daily thermal efficiency is maximum in the month of May 2012 at water depth of 0.04 m, while minimum in the month of December 2011 at water depth of 0.05 m.
- Daily actual solar exergy is calculated with the help of Petela Eq. (7). Monthly and annual exergy output is calculated with number of clear days in each month of a year. Daily, monthly, and annual exergy output is summarized in Table 5 and Table 6. The daily exergy efficiency as calculated by Eq. (8) and it varies from 0.26 to 1.34% as shown in Fig. 4.

Table 5
Daily exergy analysis of solar still

Month and year	Water depth								
	0.03 m			0.04 m			0.05 m		
	E_{xin} (W)	E_{xevap} (W)	η_{EX} (%)	E_{xin} (W)	E_{xevap} (W)	η_{EX} (%)	E_{xin} (W)	E_{xevap} (W)	η_{EX} (%)
July 2011	1,7034.88	131.05	0.77	17,290.94	114.86	0.66	16,867.50	107.75	0.64
August 2011	15,904.40	108.58	0.68	15,424.59	90.94	0.59	16,625.74	84.60	0.51
September 2011	15,312.95	90.28	0.59	14,181.48	76.22	0.54	15,755.59	70.62	0.45
October 2011	13,772.05	76.43	0.55	13,176.5	58.02	0.44	14,661.73	54.77	0.37
November 2011	11,105.83	54.36	0.49	11,289.37	46.49	0.41	11,028.56	35.95	0.33
December 2011	9,701.65	40.94	0.42	9,941.731	32.72	0.33	10,095.94	25.83	0.26
January 2012	10,581.15	40.28	0.38	10,802.41	29.77	0.28	10,727.79	28.13	0.26
February 2012	13,836.66	70.37	0.51	14,336.6	65.96	0.46	14,168.81	57.20	0.40
March 2012	15,626.14	141.47	0.91	15,294.68	133.32	0.87	14,940.72	114.36	0.77
April 2012	17,448.34	209.69	1.20	16,671.21	164.33	0.99	17,262.32	152.83	0.89
May 2012	17,918.64	240.70	1.34	17,439.68	198.71	1.14	17,769.94	188.01	1.06
June 2012	18,434.52	163.12	0.88	17,918.64	133.95	0.75	17,253.76	121.12	0.70

Table 6
Monthly exergy analysis of solar still

Month and year	No. of clear days	Water depth					
		0.03 m		0.04 m		0.05 m	
	(D)	E_{xin} (W)	E_{xevap} (W)	E_{xin} (W)	E_{xevap} (W)	E_{xin} (W)	E_{xevap} (W)
July 2011	16	272,558	2,097	276,655	1,838	269,880	1,724
August 2011	13	206,757	1,412	200,520	1,182	216,135	1,100
September 2011	16	245,007	1,445	226,904	1,220	252,089	1,130
October 2011	24	330,529	1,834	316,236	1,392	351,882	1,314
November 2011	30	333,175	1,631	338,681	1,395	330,857	1,078
December 2011	21	203,735	860	208,776	687	212,015	542
January 2012	22	232,785	886	237,653	655	236,011	619
February 2012	24	332,080	1,689	344,078	1,583	340,051	1,373
March 2012	29	453,158	4,103	443,546	3,866	433,281	3,317
April 2012	29	506,002	6,081	483,465	4,766	500,607	4,432
May 2012	30	537,559	7,221	523,191	5,961	533,098	5,640
June 2012	26	479,297	4,241	465,885	3,483	448,598	3,149
Total	280	4,132,643	33,498.46	4,065,589	28,027.6	4,124,504	25,418.55

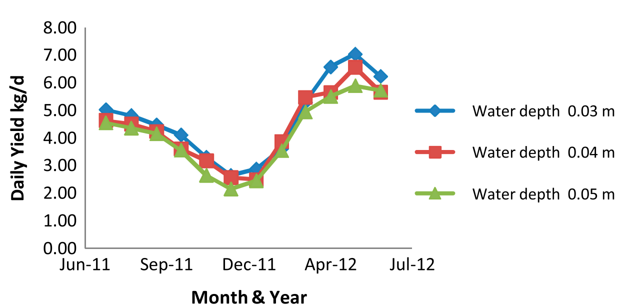

Fig. 2. Daily yield output.

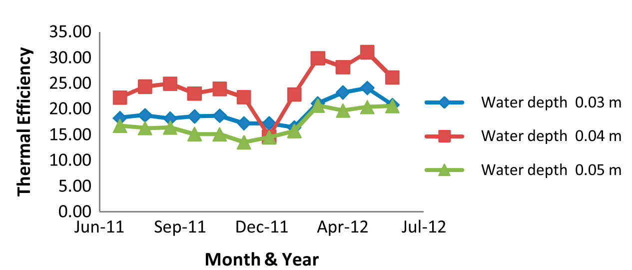

Fig. 3. Daily thermal efficiency.

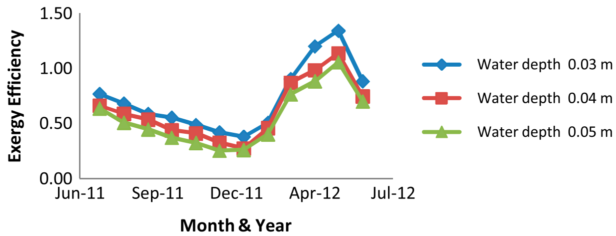

Fig. 4. Daily exergy efficiency.

6. Conclusions

Following conclusion can be made on the basis of present studies

- On the basis of experimental data, double slope solar still gives higher yield in the peak summer months and lower yield in winter months.
- The daily thermal efficiency of solar still is varies with change of water depth.
- Exergy performance of a solar still utilizing direct solar energy was presented. It was observed that the overall exergy efficiency was very low.

Symbols

A_s	—	basin area of solar still, m^2
A_C	—	collector plate area, m^2
C_w	—	specific heat of water in solar still, $J\,kg^{-1}\,{}^{o}C^{-1}$
$\dot{E}x_{in}$	—	exergy input of solar still, W
$\dot{E}x_{evap}$	—	exergy output of solar still, W
$\dot{E}x_{dest}$	—	exergy destructed in solar still water, W
$\dot{E}x_{sun}$	—	exergy input from the Sun on solar still, W
$\dot{E}x_{work}$	—	exergy of work rate for solar still, W
h_{ew}	—	evaporative heat transfer coefficient from water surface to glass, $Wm^{-2}\,{}^{o}C^{-1}$
I_t	—	incident Solar radiation on solar still, Wh/m^2
I_C	—	incident total radiation on collector plate, Wh/m^2
L	—	latent heat of vaporization, J/kg
M_w	—	daily distillate output, kg/d
D	—	no. of clear day in a month
$\dot{Q}_{ew}$	—	thermal energy in evaporation of water vapors, Wm^{-2}
T_a	—	ambient air temperature, ℃
T_{ci}	—	inner temperature of condensing cover, ℃
T_s	—	sun temperature, K
T_W	—	water temperature, ℃
η_{EX}	—	exergy efficiency
η_{th}	—	daily thermal efficiency

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