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Annual Energy and Exergy Analysis of Single and Double Slope Passive Solar Stills

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Abstract: In this study, the life cycle cost analysis of single and double slope passive solar still for composite climate of New Delhi has been carried out. The analysis is based on annual performance of energy and exergy of both solar stills. It has been observed that water produced by proposed double slope solar still is cheaper (Rs. 0.28 L^{-1}) than proposed single slope solar still (Rs. 0.33 L^{-1}; Rs. stands for Rupees, an Indian currency). The Energy Pay Back Time (EPBT) for proposed single and double slope solar stills are 1.64 and 1.60 years, respectively.

Key words: Solar distillation, purification of brackish water, heat, mass transfer

INTRODUCTION

The potable water is one of the basic needs for survival of human being. Due to fast increase in population in the world in general and India in particular, the potable water consumption has been increased tremendously. On the other hand available water in rivers, lakes and underground water has been polluted due to industrialization for up gradation of living standards for human being. Hence there is a need to develop self-sustained system to purify available brackish water into potable water for keeping healthy human being.

In order to meet the requirement of fresh water rigorous research have been carried out by various scientists on design, fabrication and development of solar stills for purification of brackish water. A Swedish engineer, Rudolph (1972) was the first who designed conventional solar still for supplying fresh water to a nitrate mining community in Chile, which was quite popular and was in operation for more than 40 years. Cooper (1969) discussed about the absorption of solar energy radiations in solar stills. Ahmad (1988) studied about single effect solar still with an internal condenser. Malik *et al.* (1982) reviewed the work on passive solar distillation system till 1982. Tiwari (2002) reviewed the work done on active and passive solar stills until 1992. Tanaka *et al.* (2000) developed a highly productive basin type-multiple effect coupled solar still. Tanaka *et al.* (2005) conducted indoor experiments for the vertical multiple effect diffusion- type solar still that consists of a number of vertical partitions in contact with saline-soaked wicks with narrow air gaps between partitions coupled with a heat pipe solar collector. Kurdish *et al.* (1998) have conducted performance testing and analysis of a double-glazed, air-blown solar still with thermal energy recycling. Faith (1996) and Delyannis (2003) have reviewed various designs of solar stills and studied the suitability of solar stills for providing potable water. Chaibi (2002) validated a simulation model for water desalination in a green house roof through laboratory experiments. Aybar (2006) developed mathematical model for an inclined solar water distillation system. Tripathi and Tiwari (2005) studied the effect of water depths

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on internal heat and mass transfer for active solar distillation system in winter climatic condition whereas Tiwari and Tiwari (2007a) studied the effect of water depths on heat and mass transfer in a passive solar still in summer climatic condition. Dayem (2006) demonstrated experimentally and numerically the performance of a simple solar distillation unit that is based on the multiple condensation-evaporation cycle. Tanaka and Nakatane (2006) carried out theoretical analysis of a basin type solar still with internal and external reflectors. Recently Tiwari and Tiwari (2007b) have reviewed the work carried out by various scientists till 2006. Dincer (2002) reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development and energy policy making and exergy in detail. Hepbasli (2006) reviewed exergetic analysis and performance evaluation of a wide range of renewable energy resources, which includes solar thermal systems like solar collector, photovoltaic, hybrid (PV/T) solar collector, wind energy, geothermal energy, biomass and other renewable energy systems. Koca *et al*. (2007) has done the energy and exergy analysis of latent heat storage system with phase change material for a solar collector and they found that the average net energy and exergy efficiencies are 45 and 2.2%, respectively.

Mukherjee and Tiwari (1986) have done the economic analysis and cost analysis of three types of solar stills, viz. a single-slope Fiber-Reinforced Plastic (FRP) still, a double-slope FRP still and a double-slope concrete still and found that the cost of distilled water produced from conventional stills is minimum. Life cycle cost analysis of solar stills have been carried out by different researchers but none of them have carried out life cycle cost analysis of passive solar stills on the basis of annual energy and exergy analysis. In this paper an attempt has been made to analyses life cycle cost analysis and Energy Pay Back Time (EPBT) on the basis of annual energy and exergy performance of single and double slope passive solar stills.

EXPERIMENTAL SET-UP AND OBSERVATIONS

Cross sectional view of a schematic diagram of a single and a double slope passive solar still is shown in Fig. 1a and b whereas Fig. 2a and b is the photograph of the single and double slope passive solar still which is designed and fabricated for the experiment. The body of solar still is made up of a very low thermal conductivity material known as Glass Reinforced Plastic (GRP) of thickness 5 mm. The condensing cover of 4 mm thickness is made up of plane glass has been placed on the basin of solar still. The inclination of condensing cover for both single and double slope solar still is 15°. Rubber gaskets are used to make the solar still airtight. The bottom surface of the still was painted black to have high absorptivity of solar radiation. Solar stills are mounted on iron stand as shown in the photograph (Fig. 2a, b). The single slope solar still was kept facing due south and double slope solar still was placed in east-west direction to receive the maximum possible solar radiation. The output from the solar still is collected into a channel provided at lower side and is taken out through a pipe into a cylinder. The basin area for single and double slope solar still is 1 and 2 m^2, respectively and maximum water depth in case of single and double solar still can be 19 and 22 cm, respectively. It has been found that lower water depth of 1 cm gives highest annual yield thus the size of solar still to reduce the initial investment can be kept 5 cm (lower height) and 32 cm (higher side) for both single and double slope solar still (Table 1).

To predict the performance of single and double slope solar still experiments are conducted in the campus of Indian Institute of Technology, New Delhi in winter as well as summer months starting from October 2005 to September 2006 for three different water depths namely 0.01, 0.02 and 0.03 m. Experiments for each water depth are started at 7 am in the morning and lasted for 24 h. Following parameters are measured at an interval of 1 h.

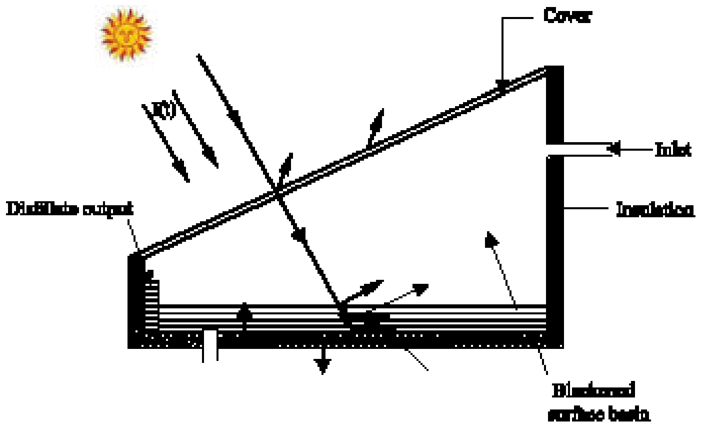

Fig. 1a: Cross sectional view of a single slope passive solar still

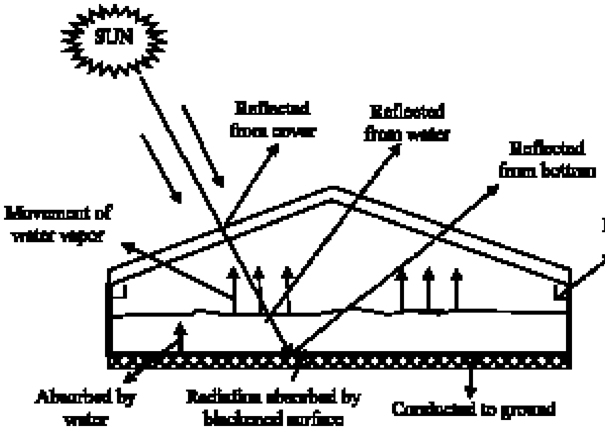

Fig. 1b: Cross sectional view of a double slope passive solar still

- Water temperature
- Vapor temperature
- Inner glass temperature
- Outer glass temperature
- Ambient air temperature
- Solar intensity on glass surface
- Distillate output

Copper-constantan thermocouples are used with the help of digital temperature indicator having a least count of 0.1°C to record the water, vapor and condensing cover temperatures. The ambient air temperature is recorded with the help of a calibrated mercury thermometer having a least count of 1°C and the distillate output are measured by a measuring cylinder having a least count of 10 mL. The solar intensity was measured with the help of a calibrated solarimeter, having least count of 2 mW cm^{-2}.

The hourly experimental observation for a typical day (11.10.2005) of the year has been given in Table 2a. The average experimental observation for different depth and month of the year has been given in Table 2b. The average experimental data has been used to evaluate monthly output by multiplying it by number of clear days and the results has been given in Table 3a.

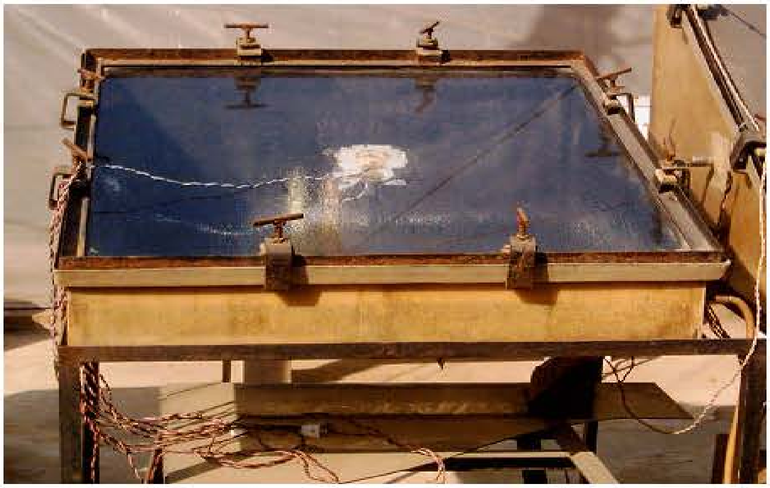

Fig. 2a: Photograph of single slope solar still

Fig. 2b: Photograph of double slope solar still

Table 1: Dimensions of the experimental and proposed solar still

Experimental solar still			Proposed solar still		
Dimension	Single slope	Double slope	Dimension	Single slope	Double slope
Length (L) (m)	1.00	2.00	Length (L) (m)	1.00	2.00
Breadth (B) (m)	1.00	1.00	Breadth (B) (m)	1.00	1.00
Lower height (H_1) (m)	0.19	0.22	Lower height (H_1) (m)	0.05	0.05
Higher height (H_2) (m)	0.47	0.48	Higher height (H_2) (m)	0.32	0.32

On the basis of predicted monthly performance of single and double slope solar still, the following studies will be carried out.

- Annual comparison between the performance of single and double slope solar still in terms of L m^{-2}.
- Life cycle cost analysis on basis of predicted annual yield of both solar still.
- Exergy analysis of both solar still on the basis of annual yield.

Table 2a: Various measured temperature and yield for single and double slope solar still for a typical day 11, October 2005 for 0.01 m water depth

Single slope							Double slope (East side)					Double slope (Westside)		
Time (h)	T_a. (°C)	T_{ci} (°C)	T_v (°C)	T_w (°C)	I (t) (W m^{-2})	Mw (kg)	T_{ci} (°C)	T_v (°C)	T_w (°C)	I (t) (W m^{-2})	Mw (kg)	T_{ci} (°C)	I (t) (W m^{-2})	m_w (kg)
7	18.0	19.9	18.8	19.8	0	0.000	19.0	22.2	20.1	0	0.000	17.3	0	0.000
8	19.0	20.3	24.0	21.4	180	0.008	17.0	24.0	21.2	160	0.010	19.4	50	0.011
9	20.5	21.6	36.8	25.2	370	0.015	20.1	25.0	22.5	320	0.011	25.2	150	0.012
10	24.0	24.7	48.8	37.5	460	0.056	22.4	27.7	29.4	460	0.007	26.4	350	0.014
11	27.0	30.5	56.2	48.7	520	0.120	29.2	33.0	37.0	510	0.070	35.3	500	0.036
12	28.5	36.8	52.2	52.0	650	0.240	30.4	37.5	43.5	440	0.160	36.6	560	0.085
13	31.0	39.5	54.8	53.5	670	0.265	32.2	38.8	48.6	420	0.220	40.0	600	0.145
14	30.0	37.0	64.2	61.0	670	0.240	39.8	49.9	58.5	300	0.200	42.7	580	0.220
15	28.5	34.6	63.3	58.2	330	0.200	43.3	47.7	60.0	140	0.185	43.2	440	0.200
16	27.5	36.6	52.5	49.5	150	0.140	37.6	42.0	47.3	50	0.136	37.5	250	0.185
17	25.0	29.9	38.0	38.3	0	0.100	29.7	36.4	38.7	0	0.100	33.7	0	0.116
18	23.0	28.6	30.7	31.9	0	0.055	27.4	31.9	34.3	0	0.085	30.9	0	0.098
19	23.0	23.4	23.2	24.3	0	0.035	21.4	22.5	26.2	0	0.057	25.0	0	0.066
20	18.5	21.1	20.1	21.4	0	0.025	19.4	20.4	23.0	0	0.040	21.4	0	0.045
21	18.0	19.8	18.2	20.1	0	0.020	19.1	19.0	20.9	0	0.035	18.1	0	0.030
22	17.5	18.1	17.3	19.8	0	0.018	17.6	18.5	19.8	0	0.030	17.4	0	0.024
23	17.0	16.5	16.2	18.9	0	0.016	16.5	17.4	18.5	0	0.028	15.8	0	0.020
24	16.0	16.3	15.3	66.0	0	0.008	15.6	16.6	17.6	0	0.022	14.8	0	0.018
1	15.0	15.6	14.5	16.6	0	0.009	14.9	15.8	16.5	0	0.018	13.8	0	0.016
2	15.0	14.0	13.7	16.4	0	0.008	14.3	15.2	15.8	0	0.012	12.9	0	0.011
3	14.5	13.6	13.2	15.4	0	0.007	13.7	14.7	15.1	0	0.011	12.3	0	0.010
4	14.0	13.0	12.7	15.1	0	0.007	13.1	14.1	14.5	0	0.011	11.7	0	0.011
5	14.0	12.6	12.3	14.2	0	0.008	12.6	13.7	14.0	0	0.010	11.2	0	0.010
6	14.0	12.1	11.8	12.5	0	0.007	12.2	13.3	13.6	0	0.009	10.6	0	0.009
7	13.5	13.2	11.7	13.4	0	0.007	11.6	13.0	13.3	0	0.008	10.4	0	0.008
Avg	20.5			30.8					27.6					

Table 2b: Average ambient air temperature, solar intensity, water temperature and daily yield for single and double slope solar still for different water depth in various months of a year

			Single slope			Double slope		
Months	Water depth (m)	T_a (°C)	I (t) (W m^{-2})	T_w (°C)	M_w (kg)	I (t) (W m^{-2})	T_w (°C)	M_w (kg)
October	0.01	20.5	4000	30.8	1.629	3140.00	27.6	1.44
	0.02	20.0	3370	29.2	1.419	2665.00	27.3	1.28
	0.03	21.1	3800	30.1	1.413	2955.00	28.0	1.22
November	0.01	18.7	3450	27.2	1.466	2530.00	24.2	1.15
	0.02	18.2	3760	25.8	1.403	2790.00	24.3	1.14
	0.03	16.1	3930	21.5	1.385	2785.00	21.5	1.08
December	0.01	10.3	3400	15.4	1.127	2240.00	16.4	0.88
	0.02	10.7	3480	16.1	1.089	2460.00	16.1	0.88
	0.03	11.6	1680	15.7	0.842	1240.00	14.2	0.65
January	0.01	10.6	2800	13.0	1.151	1960.00	15.4	0.94
	0.02	12.2	2560	17.8	1.073	1870.00	16.6	0.83
	0.03	16.8	3560	23.4	1.153	2490.00	22.2	1.05
February	0.01	20.5	4000	28.9	1.631	3140.00	27.6	1.34
	0.02	15.9	3240	23.6	1.490	2390.00	22.0	1.27
	0.03	16.8	3560	23.4	1.374	2490.00	22.2	1.24
March	0.01	22.3	4670	33.4	2.130	4040.00	33.0	2.06
	0.02	24.6	4740	39.4	2.077	4020.00	35.6	2.01
	0.03	25.1	4360	36.6	1.955	3700.00	38.0	1.83
April	0.01	27.5	4980	38.2	2.260	4590.00	39.0	2.27
	0.02	28.4	5200	39.2	2.218	4730.00	40.5	2.23
	0.03	32.1	4060	38.6	1.955	3775.00	44.0	2.02
May	0.01	31.8	5270	36.4	2.105	4475.00	35.6	2.20
	0.02	32.3	4640	43.8	2.080	4650.00	44.1	2.09
	0.03	32.1	4380	40.2	1.701	4190.00	42.9	1.64

Table 2b: Continued

			Single slope			Double slope		
Months	Water depth (m)	T_a (°C)	I (t) (W m^{-2})	T_w (°C)	M_w (kg)	I (t) (W m^{-2})	T_w (°C)	M_w (kg)
June	0.01	31.7	4780	44.0	2.198	5360.00	44.8	2.20
	0.02	32.3	4540	43.0	1.876	4730.00	44.4	1.89
	0.03	32.8	4620	40.0	1.821	4605.00	43.0	1.86
July	0.01	27.6	5210	36.8	1.894	4665.00	36.3	1.90
	0.02	28.2	5500	38.8	1.863	4420.00	36.8	1.90
	0.03	27.7	5300	38.7	1.734	4615.00	36.5	1.65
August	0.01	36.9	5210	35.9	1.884	4485.00	35.1	1.74
	0.02	26.7	5400	37.6	1.922	4390.00	35.4	1.59
	0.03	25.6	5320	37.1	1.757	5080.00	35.1	1.57
September	0.01	25.7	3830	35.9	1.793	4255.00	33.9	1.59
	0.02	25.4	5130	36.3	1.866	4275.00	34.1	1.50
	0.03	24.4	5230	36.0	1.659	4330.00	34.0	1.48

MATHEMATICAL MODELING

Overall Instantaneous Thermal Efficiency of a Passive Solar Still

The overall instantaneous thermal efficiency of a passive solar still is given below:

$$\eta_{en} = \frac{\dot{m}_{ew}\times L}{\left(I(t)\times A_S\times 3600\right)} \tag{1a}$$

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

$$M_{ew} = \sum_{i=1}^{i=24} \dot{m}_{ewi} \tag{1b}$$

The values of M_{ew} for different depth and months for single and double slope solar still are given in Table 2b.

The daily thermal efficiency is defined as:

$$\eta = \frac{M_w \times L}{\left(A_s \times \sum I(t)\times 3600\right)} \tag{1c}$$

The daily thermal efficiency of single and double slope solar still is given in Table 5.

Exergy Efficiency of Solar Still

The general exergy balance for solar still can be written, Hepbalsi (2006), as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{2}$$

Or,

$$\dot{E}x_{Sun} - \left(\dot{E}x_{evap} + \dot{E}x_{work}\right) = \dot{E}x_{dest} \tag{3}$$

Where, the exergy input to the solar still is radiation exergy and can be written as:

$$\dot{E}x_{in} = \dot{E}x_{sun} = A_s \times I(t) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s}\right)^4\right] \tag{4}$$

Where, A_s is area of solar still and I (t) is solar radiation on inclined glass surface of solar still and T_s is the Sun temperature in Kelvin.

$$\dot{E}x_{evap} = \frac{\sum\left(1 - \frac{T_a + 273}{T_w + 273}\right) \times \dot{Q}_{ew}}{3600} \tag{5}$$

Where:

$$\dot{Q}_{ew} = A_s\ h_{ew}\left(T_w - T_{ci}\right) \tag{6}$$

The monthly exergy can be obtained by multiplying Eq. 5 by the number of clear days in Table 3a and results are given in Table 3b

The exergy of work rate for solar still is given by

$$\dot{E}x_{work} = \dot{W} = 0 \tag{7}$$

The exergy destructed in solar still water is given by

$$\dot{E}x_{dest} = M_w C_w \left(T_w - T_a\right)\left(1 - \frac{T_a + 273}{T_w + 273}\right) \tag{8}$$

Table 3a: Details of monthly and annual yield obtained from single and double Slope solar still with different water depths

		Monthly yield for different water depths = daily yield×number of clear days					
		Single slope solar still (m)			Double slope solar still (m)		
	No. of	0.01	0.02	0.03	0.01	0.02	0.03
Months	clear days	(kg m^{-2})			(kg m^{-2})		
Oct-05	24	39.10	34.06	33.91	34.50	30.72	29.28
Nov-05	30	43.98	42.09	41.58	34.43	34.20	32.43
Dec-05	22	24.79	23.96	18.52	19.46	19.36	14.30
Jan-06	22	25.32	23.61	25.37	20.57	18.26	23.19
Feb-06	24	39.14	35.76	32.95	32.05	30.48	29.76
Mar-06	28	59.64	58.16	54.74	57.68	56.28	51.16
Apr-06	29	65.54	64.32	56.70	65.93	64.70	58.55
May-06	30	63.15	62.40	51.03	66.08	62.73	49.20
Jun-06	26	57.15	48.78	47.35	57.29	49.09	48.31
Jul-06	16	30.30	29.81	27.74	30.45	30.35	26.46
Aug-06	12	22.61	23.06	21.08	20.88	19.02	18.78
Sep-06	16	28.69	29.86	26.54	25.37	23.97	23.71
Total	279	499.41	475.85	437.52	464.68	439.16	405.13

Table 3b: Details of monthly and annual exergy output obtained from single and double slope solar still with different water depths

		Monthly exergy output for different water depths = daily exergy output×No. of clear days					
		Single slope solar still (m)			Double slope solar still (m)		
	No. of	0.01	0.02	0.03	0.01	0.02	0.03
Months	clear days	(W m^{-2})			(W m^{-2})		
Oct-05	24	836.9	649.5	630.7	513.0	467.9	416.6
Nov-05	30	781.8	672.1	478.3	396.4	437.9	371.3
Dec-05	22	273.7	280.9	166.7	259.2	227.3	81.0
Jan-06	22	130.6	282.9	356.7	215.8	175.0	265.0
Feb-06	24	682.9	582.8	463.7	475.3	392.0	340.4
Mar-06	28	1356.4	1728.5	1277.5	1263.9	1256.2	1334.4
Apr-06	29	1413.4	1401.9	740.0	1519.2	1573.0	1375.4
May-06	30	589.4	1420.9	826.9	510.8	1470.3	1054.3
Jun-06	26	1390.0	1034.9	690.3	1484.8	1173.2	982.7
Jul-06	16	560.7	639.1	619.0	535.2	531.4	471.9
Aug-06	12	414.4	508.1	491.3	348.5	337.2	364.0
Sep-06	16	595.3	659.4	628.8	424.5	426.8	468.2
Total	279	9025.4	9861.0	7369.9	7946.5	8468.2	7525.2

Where, M_W and C_W are mass and specific heat of solar still water, respectively.
The exergy efficiency of solar still is defined, Hepbalsi (2006), as follows:

$$\eta_{EX} = \frac{\text{Exergy output of solar still } (\dot{E}x_{evap})}{\text{Exergy input to solar still } (\dot{E}x_{in})} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \qquad (9)$$

The daily exergy efficiency is also given in Table 4b.
The exergy output of a solar still can be obtained as follows:

$$\dot{E}x_{evap} = A_s h_{ew}(T_w - T_{ci}) \times \left[1 - \left(\frac{T_a + 273}{T_w + 273}\right)\right] \qquad (10)$$

The daily exergy output will be sum of hourly exergy evaluated by Eq. 10 and the results are given in Table 4b

Life Cycle Cost Analysis

For a given initial investment, the uniform end of year annual cost of the passive solar distillation system can be written as follows (Tiwari, 2002)

$$UA_{net} = P_S.\ F_{CR,\,i,\,n'} + P_s.\ F_{CR,\,i,\,n'}\ M_S - S_S F_{SR,\,i,\,n'} \qquad (11)$$

Where, $F_{CR,\ i,n'}$ and $F_{SR,i,n'}$: represent the capital recovery factor and sinking fund factor, respectively and can be calculated by using the following formula:

$$F_{CR,\,i,\,n'} = \frac{i(1+i)^{n'}}{(1+i)^{n'} - 1} \qquad (12)$$

Table 4a: Monthly exergy of single and double slope solar still

Months	Water depth (m)	No. of clear days N	Single slope solar still Ex_{inM} W	Single slope solar still Ex_{evap} W	Double slope solar still Ex_{in} W	Double slope solar still Ex_{evap} W
October	0.01	24.00	92431.3	836.9	72558.5	513.0
	0.02	24.00	77881.9	649.5	61589.1	467.9
	0.03	24.00	87796.3	630.7	68273.2	416.3
November	0.01	30.00	99694.6	781.8	73109.4	396.4
	0.02	30.00	108665.6	672.1	80632.2	437.9
	0.03	30.00	113635.3	478.3	80527.8	371.3
December	0.01	22.00	72194.0	273.7	47563.1	259.2
	0.02	22.00	73885.3	280.9	52229.3	227.3
	0.03	22.00	35661.2	166.7	26321.3	81.0
January	0.01	22.00	59449.4	130.6	41614.6	215.8
	0.02	22.00	54333.1	282.9	39688.6	175.0
	0.03	22.00	75474.5	356.7	52789.7	265.0
February	0.01	24.00	92430.8	682.9	72558.2	475.3
	0.02	24.00	74950.8	582.8	55287.8	392.0
	0.03	24.00	82335.8	463.7	57588.8	340.4
March	0.01	28.00	125844.6	1356.4	108867.7	1263.9
	0.02	28.00	127661.1	1728.5	108269.5	1256.2
	0.03	28.00	117412.7	1277.5	99639.2	1334.4
April	0.01	29.00	138819.2	1413.4	127947.8	1519.2
	0.02	29.00	144920.7	1401.9	131822.1	1573.0
	0.03	29.00	113049.9	740.2	105114.2	1375.4
May	0.01	30.00	151813.1	589.4	128911.5	510.8
	0.02	30.00	133649.4	1420.9	133937.4	1470.3
	0.03	30.00	126165.2	826.5	120692.3	1054.3
June	0.01	26.00	119341.4	1390.0	133822.1	1484.8
	0.02	26.00	113332.1	1034.9	118075.0	1173.2
	0.03	26.00	115317.0	690.3	114942.6	982.7
July	0.01	16.00	80124.5	560.7	71743.0	535.2
	0.02	16.00	84573.6	639.1	67966.4	531.4
	0.03	16.00	81508.3	619.0	70973.7	471.9
August	0.01	12.00	60104.3	414.4	51740.4	348.5
	0.02	12.00	62298.7	508.1	50646.5	337.2
	0.03	12.00	61392.0	491.3	58622.4	364.0
September	0.01	16.00	58929.0	595.3	65468.1	424.5
	0.02	16.00	78936.7	659.4	65780.6	426.8
	0.03	16.00	80494.9	628.8	66643.0	468.2

Table 4b: Daily exergy analysis of single and double slope solar still

Months	Water depth (m)	Single Slope E_{xin} W	Single Slope E_{xevap} W	Single Slope η_{EX} %	Double slope E_{xin} W	Double slope E_{xevap} W	Double slope η_{EX} %
October	0.01	3851.3	34.9	0.91	3023.3	21.4	0.71
	0.02	3245.1	27.1	0.83	2566.2	19.5	0.76
	0.03	3658.2	26.3	0.72	2844.7	17.3	0.61
November	0.01	3323.2	26.1	0.78	2437.0	13.2	0.54
	0.02	3622.2	22.4	0.62	2687.7	14.6	0.54
	0.03	3787.8	15.9	0.42	2684.3	12.4	0.46
December	0.01	3281.5	12.4	0.38	2162.0	11.8	0.54
	0.02	3358.4	12.8	0.38	2374.1	10.3	0.44
	0.03	1621.0	7.6	0.47	1196.4	3.7	0.31
January	0.01	2702.2	5.9	0.22	1891.6	9.8	0.52
	0.02	2469.7	12.9	0.52	1804.0	8.0	0.44
	0.03	3430.7	16.2	0.47	2399.5	12.0	0.50
February	0.01	3851.3	28.5	0.74	3023.3	19.8	0.66
	0.02	3123.0	24.3	0.78	2303.7	16.3	0.71
	0.03	3430.7	19.3	0.56	2399.5	14.2	0.59

Table 4b: Daily exergy analysis of single and double slope solar still

		Single Slope			Double slope		
Months	Water depth (m)	E_{xin} W	E_{xevap} W	η_{EX} %	E_{xin} W	E_{xevap} W	η_{EX} %
March	0.01	4494.5	48.4	1.08	3888.1	45.1	1.16
	0.02	4559.3	61.7	1.35	3866.8	44.9	1.16
	0.03	4193.3	45.6	1.09	3558.5	47.7	1.34
April	0.01	4786.9	48.7	1.02	4412.0	52.4	1.19
	0.02	4997.3	48.3	0.97	4545.6	54.2	1.19
	0.03	3898.3	25.5	0.65	3624.6	47.4	1.31
May	0.01	5060.4	19.6	0.00	4297.1	17.0	0.40
	0.02	4455.0	47.4	0.01	4464.6	49.0	1.10
	0.03	4205.5	27.5	0.01	4023.1	35.1	0.87
June	0.01	4590.1	53.5	0.01	5147.0	57.1	1.11
	0.02	4358.9	39.8	0.01	4541.3	45.1	0.99
	0.03	4435.3	26.5	0.01	4420.9	37.8	0.85
July	0.01	5007.8	35.0	0.01	4483.9	33.4	0.75
	0.02	5285.8	39.9	0.01	4247.9	33.2	0.78
	0.03	5094.3	38.7	0.01	4435.9	29.5	0.66
August	0.01	4996.8	-3.8	0.00	4301.4	-6.4	-0.15
	0.02	5191.6	42.3	0.01	4220.5	28.1	0.67
	0.03	5116.0	40.9	0.01	4885.2	30.3	0.62
September	0.01	3683.1	37.2	0.01	4091.8	26.5	0.65
	0.02	4933.5	41.2	0.01	4111.3	26.7	0.65
	0.03	5030.9	39.3	0.01	4165.2	29.3	0.70

And

$$F_{SR,i,n'} = \frac{i}{(1+i)^{n'}-1} \tag{13}$$

The cost of distilled water per liter based on thermal energy can be calculated by dividing the annual cost of the system by annual yield of solar still. So,

$$CPL_{en} = \frac{UA_{net}}{M_{yen}} \tag{14}$$

Similarly, the cost of distilled water based on exergy can be calculated as follow.

$$CPL_{ex} = \frac{UA_{net}}{M_{yex}} \tag{15}$$

Where, M_{yen} and M_{yex} is the annual yield of solar still based on thermal energy and exergy, respectively.

Life cycle cost analysis has been using Eq. 14 and 15 with the help of Table 3 and 6.

Capital cost, salvage value and maintenance cost of single and double slope solar still are given in the Table 6. These values are useful in determining cost of water as given in Table 7a and 7b on the basis of energy and exergy analysis.

Energy Pay Back Time (EPBT)

Energy Pay Back Time (EPBT) of solar still can be evaluated by using the following formula

$$EPBT = \frac{\text{Embodied energy}}{\text{Annual yield}} \tag{16}$$

Table 5: Thermal efficiency of single and double slope solar still

Months	Water depth (m)	Single slope (η_{th})	Double slope (η_{th})
October	0.01	27.38	31.33
	0.02	28.35	32.72
	0.03	25.02	28.10
November	0.01	28.67	31.49
	0.02	25.21	28.10
	0.03	23.91	27.09
December	0.01	22.62	28.65
	0.02	21.34	24.82
	0.03	34.19	36.41
January	0.01	28.12	33.67
	0.02	28.54	31.17
	0.03	21.93	29.50
Feburary	0.01	27.46	29.08
	0.02	31.13	36.80
	0.03	26.13	34.76
March	0.01	30.58	34.27
	0.02	29.21	33.45
	0.03	29.97	32.98
April	0.01	30.29	32.84
	0.02	28.44	30.73
	0.03	32.12	35.71
May	0.01	26.70	33.85
	0.02	29.75	29.89
	0.03	25.74	27.55
June	0.01	30.51	26.52
	0.02	27.45	26.50
	0.03	26.26	26.80
July	0.01	24.30	25.40
	0.02	22.59	25.50
	0.03	21.82	24.17
August	0.01	24.19	26.39
	0.02	23.77	24.56
	0.03	22.06	20.58
September	0.01	31.31	25.40
	0.02	24.32	23.85
	0.03	21.22	23.14

Table 6: Capital cost (P_s), Salvage value (S_s) and maintenance cost (M_s) of Experimental and proposed single and double slope solar still

	Experimental solar still		Proposed solar still	
Components	Single slope (Rs.)	Double slope (Rs.)	Single slope (Rs.)	Double slope (Rs.)
GRP body	5846.4	9676.8	2187.36	3573.36
Glass cover	220.0	440.0	220.00	440.00
Iron Stand	450.0	900.0	450.00	900.00
Paint	50.0	100.0	50.00	100.00
Putty	30.0	60.0	30.00	60.00
Gasket	130.0	260.0	130.00	260.00
Glass cutting	50.0	100.0	50.00	100.00
Measuring Cylinder	25.0	50.0	25.00	50.00
(a) Capital cost (P_s)	6801.4	11586.8	3142.36	5483.36
(b) Salvage value of iron stand for single slope				
After 30 years (Rs.)		After 40 years	After 50 years	
at the rate of Rs. 15 per kg		at the rate of Rs. 20 kg^{-1}	at the rate of Rs. 30 kg^{-1}	
300		375.0	450.0	
(c) Salvage value of iron stand for double slope				
After 30 years (Rs.)		After 40 years	After 50 years	
at the rate of Rs. 15 per kg		at the rate of Rs. 20 kg^{-1}	at the rate of Rs. 30 kg^{-1}	
600		750.0	900.0	
(d) Maintenance cost (Ms) (It may varies between 8 to 12% of annual capital cost)				

Table 7a: Cost of water from experimental and proposed single and double slope solar still on the basis of energy analysis

(a) Cost per liter from experimental single slope solar still for 0.01 m water depth

P_s	M_s	S_s	i	n'	M_Y	$F_{CR,i,n'}$	$F_{SR,i,n'}$	UA_{net}	CPL_{en}
6801.4	0.08	300	0.04	30	500	0.0578	0.0178	419.44	0.84
6801.4	0.08	375	0.04	40	500	0.0505	0.0105	367.17	0.73
6801.4	0.08	450	0.04	50	500	0.0466	0.0066	338.99	0.68
6801.4	0.08	300	0.08	30	500	0.0888	0.0088	649.83	1.30
6801.4	0.08	375	0.08	40	500	0.0839	0.0039	614.55	1.23
6801.4	0.08	450	0.08	50	500	0.0817	0.0017	599.66	1.20
6801.4	0.08	300	0.12	30	500	0.1241	0.0041	910.66	1.82
6801.4	0.08	375	0.12	40	500	0.1213	0.0013	890.55	1.78
6801.4	0.08	450	0.12	50	500	0.1204	0.0004	884.33	1.77
(b) Cost per liter from experimental double slope solar still for 0.01 m water depth									
5793.4	0.08	600	0.04	30	465	0.0578	0.0178	351.14	0.76
5793.4	0.08	750	0.04	40	465	0.0505	0.0105	308.23	0.66
5793.4	0.08	900	0.04	50	465	0.0466	0.0066	285.36	0.61
5793.4	0.08	600	0.08	30	465	0.0888	0.0088	550.49	1.18
5793.4	0.08	750	0.08	40	465	0.0839	0.0039	521.81	1.12
5793.4	0.08	900	0.08	50	465	0.0817	0.0017	509.89	1.10
5793.4	0.08	600	0.12	30	465	0.1241	0.0041	774.26	1.67
5793.4	0.08	750	0.12	40	465	0.1213	0.0013	758.00	1.63
5793.4	0.08	900	0.12	50	465	0.1204	0.0004	753.06	1.62
(c) Cost per liter of proposed single slope solar still for 0.01 m water depth when produced on mass basis									
3142	0.08	600	0.04	30	465	0.0578	0.0178	185.54	0.40
3142	0.08	750	0.04	40	465	0.0505	0.0105	163.55	0.35
3142	0.08	900	0.04	50	465	0.0466	0.0066	152.07	0.33
3142	0.08	600	0.08	30	465	0.0888	0.0088	296.13	0.64
3142	0.08	750	0.08	40	465	0.0839	0.0039	281.67	0.61
3142	0.08	900	0.08	50	465	0.0817	0.0017	275.81	0.59
3142	0.08	600	0.12	30	465	0.1241	0.0041	418.78	0.90
3142	0.08	750	0.12	40	465	0.1213	0.0013	410.65	0.88
3142	0.08	900	0.12	50	465	0.1204	0.0004	408.24	0.88
(d) Cost per liter of proposed double slope solar still for 0.01 m water depth when produced on mass basis									
2741.6	0.08	600	0.04	30	465	0.0578	0.0178	160.53	0.35
2741.6	0.08	750	0.04	40	465	0.0505	0.0105	141.70	0.30
2741.6	0.08	900	0.04	50	465	0.0466	0.0066	131.94	0.28
2741.6	0.08	600	0.08	30	465	0.0888	0.0088	257.72	0.55
2741.6	0.08	750	0.08	40	465	0.0839	0.0039	245.41	0.53
2741.6	0.08	900	0.08	50	465	0.0817	0.0017	240.47	0.52
2741.6	0.08	600	0.12	30	465	0.1241	0.0041	365.09	0.79
2741.6	0.08	750	0.12	40	465	0.1213	0.0013	358.19	0.77
2741.6	0.08	900	0.12	50	465	0.1204	0.0004	356.17	0.77

Table 7b: Cost per liter from experimental and proposed single and double slope solar still on the basis of exergy analysis

(a) Cost per liter from single slope solar still for 0.01 cm water depth made for experiment

P_s	M_s	S_s	i	n'	M_{yex}	$F_{CR,i,n'}$	$F_{SR,i,n'}$	UA_{net}	CPL_{ex}
6801.4	0.08	300	0.04	30	14.4	0.0578	0.0178	419.44	29.13
6801.4	0.08	375	0.04	40	14.4	0.0505	0.0105	367.17	25.50
6801.4	0.08	450	0.04	50	14.4	0.0466	0.0066	338.99	23.54
6801.4	0.08	300	0.08	30	14.4	0.0888	0.0088	649.83	45.13
6801.4	0.08	375	0.08	40	14.4	0.0839	0.0039	614.55	42.68
6801.4	0.08	450	0.08	50	14.4	0.0817	0.0017	599.66	41.64
6801.4	0.08	300	0.12	30	14.4	0.1241	0.0041	910.66	63.24
6801.4	0.08	375	0.12	40	14.4	0.1213	0.0013	890.55	61.84
6801.4	0.08	450	0.12	50	14.4	0.1204	0.0004	884.33	61.41
(b) Cost per liter from double slope solar still for 0.01 cm water depth made for experiment									
5793.4	0.08	600	0.04	30	12.65	0.0578	0.0178	351.14	27.76
5793.4	0.08	750	0.04	40	12.65	0.0505	0.0105	308.23	24.37
5793.4	0.08	900	0.04	50	12.65	0.0466	0.0066	285.36	22.56
5793.4	0.08	600	0.08	30	12.65	0.0888	0.0088	550.49	43.52
5793.4	0.08	750	0.08	40	12.65	0.0839	0.0039	521.81	41.25
5793.4	0.08	900	0.08	50	12.65	0.0817	0.0017	509.89	40.31
5793.4	0.08	600	0.12	30	12.65	0.1241	0.0041	774.26	61.21
5793.4	0.08	750	0.12	40	12.65	0.1213	0.0013	758.00	59.92
5793.4	0.08	900	0.12	50	12.65	0.1204	0.0004	753.06	59.53

Table 7b: Continued

P_s	M_s	S_s	i	n'	M_{yex}	$F_{CR,i,n'}$	$F_{SR,i,n'}$	UA_{net}	CPL_{ex}
(c) Cost per liter of proposed single slope solar still for 0.01 cm water depth when produced on mass basis									
3142	0.08	600	0.04	30	14.4	0.0578	0.0178	185.54	12.88
3142	0.08	750	0.04	40	14.4	0.0505	0.0105	163.55	11.36
3142	0.08	900	0.04	50	14.4	0.0466	0.0066	152.07	10.56
3142	0.08	600	0.08	30	14.4	0.0888	0.0088	296.13	20.56
3142	0.08	750	0.08	40	14.4	0.0839	0.0039	281.67	19.56
3142	0.08	900	0.08	50	14.4	0.0817	0.0017	275.81	19.15
3142	0.08	600	0.12	30	14.4	0.1241	0.0041	418.78	29.08
3142	0.08	750	0.12	40	14.4	0.1213	0.0013	410.65	28.52
3142	0.08	900	0.12	50	14.4	0.1204	0.0004	408.24	28.35
(d) Cost per liter of proposed double slope solar still for 0.01 cm water depth when produced on mass basis									
2741.6	0.08	600	0.04	30	12.65	0.0578	0.0178	160.53	12.69
2741.6	0.08	750	0.04	40	12.65	0.0505	0.0105	141.70	11.20
2741.6	0.08	900	0.04	50	12.65	0.0466	0.0066	131.94	10.43
2741.6	0.08	600	0.08	30	12.65	0.0888	0.0088	257.72	20.37
2741.6	0.08	750	0.08	40	12.65	0.0839	0.0039	245.41	19.40
2741.6	0.08	900	0.08	50	12.65	0.0817	0.0017	240.47	19.01
2741.6	0.08	600	0.12	30	12.65	0.1241	0.0041	365.09	28.86
2741.6	0.08	750	0.12	40	12.65	0.1213	0.0013	358.19	28.32
2741.6	0.08	900	0.12	50	12.65	0.1204	0.0004	356.17	28.16

Table 8a: Energy analysis of single and double slope solar stills made for experimental setup

	Single slope solar still		
Name of component	Mass of component (kg)	Energy density (kWh kg^{-1})	Embodied energy (kWh)
GRP body	14.62	25.64	374.86
GI angle iron	15.00	13.88	208.20
Glass cover	9.68	8.72	84.41

Total embodied energy = 667.47 kWh

Annual yield m^{-2} of basin area = 465.0 kg

Annual energy available from solar still = 350.00 kWh

Energy pay back time (EPBT) = 1.91 years

	Double slope solar still		
Name of component	Mass of component (kg)	Energy density (kWh kg^{-1})	Embodied energy (kWh)
GRP body	24.19	25.64	620.23
GI angle iron	30.00	13.88	416.40
Glass cover	19.36	8.72	168.82

Total embodied energy = 602.73 kWh

Annual yield m^{-2} of basin area = 465.00 kg

Annual energy available from solar still = 325.50 kWh

Energy pay back time (EPBT) = 1.85 years

Table 8b: Energy analysis of proposed single and double slope Solar stills

	Single slope solar still		
Name of component	Mass of component (kg)	Energy density (kWh kg^{-1})	Embodied energy (kWh)
GRP body	10.93	25.64	280.25
GI angle iron	15.00	13.88	208.20
Glass cover	9.68	8.72	84.41

Total embodied energy m^{-2} of basin area = 572.85 kWh

Annual yield m^{-2} of basin area = 499.41 kg

Annual energy available from solar still = 350.00 kWh

Energy pay back time (EPBT) = 1.64 Years

	Double slope solar still		
Name of component	Mass of component (kg)	Energy density (kWh kg^{-1})	Embodied energy (kWh)
GRP body	17.86	25.64	457.93
GI angle iron	30.00	13.88	416.40
Glass cover	19.36	8.72	168.82

Total embodied energy m^{-2} of basin area = 521.57 kWh

Annual yield m^{-2} of basin area = 465.00 kg

Annual energy available from solar still = 325.50 kWh

Energy pay back time (EPBT) = 1.60 years

The annual yield for single and double slope solar still is given in Table 3a. The embodied energy of single and double slope solar still has been evaluated by multiplying mass of each component with their energy density as shown in Table 8a. Table 8b gives embodied energy of the proposed design as given in Table 1b.

RESULTS AND DISCUSSION

Table 2a shows the hourly experimental observations for a typical day in the month of October for 0.01 m water depth in the basin for single and double slope solar still. The maximum water temperature in case of single and double slope solar still solar still is 61 and 60°C, respectively.The average daily yield for single and double slope solar still is 1.629 and 1.44 kg m^2 of basin area, respectively. Table 2b shows average ambient air temperature, water temperature, daily yield and solar intensity for water depth of 0.01, 0.02 and 0.03 m for single and double slope solar still in every months of a year. On the basis of experimental data one can say that double slope solar still gives higher yield in summer months mainly in the months of April to July while single slope solar still gives higher yield in winter months. From Table 3a it is clear that annual yield of single slope solar still is higher as compared to annual yield of double slope solar still for each water depth and it decreases with increase in water depth. But the cost of water per liter as calculated by Eq. 14 and 15 is lower for double slope solar still as compared to single slope solar still as shown in Table 7a and b. The cost of water from the double slope solar still is lower because of the low capital cost of double slope solar still for unit area of basin surface as given in Table 6. Daily, monthly and annual exergy output is calculated with the help of Eq. 4 and number of clear days in each month of a year for water depth of 0.01, 0.02 and 0.03 m and is given in Table 3b. Annual exergy output of single slope solar still is higher for 0.01 and 0.02 m water depth as compared to the double slope solar still. The dimensions of experimental and proposed solar stills are given in the Table 1 whereas various costs such as capital cost (P_s), salvage value (S_s) and maintenance cost (M_s) of experimental and proposed solar still are given in the Table 6. The capital cost of proposed single and double slope solar still is lower (Table 6) as compared with experimental set-up because of smaller dimensions of proposed solar still as given in Table 1. In the economic analysis salvage value of only iron stand has been considered and the rate of iron scrap after 30, 40 and 50 years (expected life of solar still and iron stand) are taken as Rs. 15, Rs. 20 and Rs. 30 kg^{-1}, respectively. Maintenance cost of solar still varies from 8 to 12% of annual capital cost whereas the interest rate on capital investment varies from 4 to 12%, which depends on the bank rate. A subsidized interest of 4% is generally offered by government sectors while 12% is the normal rate of interest of a private sector bank. In this economic analysis life of solar still body made of GRP materials has been taken 30, 40 and 50 years. Table 7a shows the cost of water for single and double slope experimental and proposed solar still for different variable parameters such as interest rate, life of solar still, salvage value and fixed maintenance cost In this analysis the interest rate on capital cost is taken as 4, 8 and 12% whereas life of solar still is taken 30, 40 and 50 years. The maintenance cost is kept fixed at 8% of annual capital cost. The cost per liter of experimental and proposed single slope solar still is minimum for 0.01 m water depth (Rs. 0.68 and Rs. 0.33 L^{-1}) whereas the cost per liter from double slope experimental and proposed solar stills are (Rs. 0.61 and Rs. 0.28 L^{-1}) when the life of solar still is taken 50 years, rate of interest on capital cost 4% and maintenance cost 8% of annual capital cost. The cost of water on the basis of exergy has been given in Table 7b. The cost of water per liter on the basis of exergy for proposed single and double slope solar still is Rs. 10.56 and Rs. 10.46, respectively, which is very high as compared with the cost of water on the basis of energy analysis.

On the basis of the experimental data as given in the Table 2b daily exergy analysis of single and double solar stills are carried out and results are given in the Table 4b. The daily exergy efficiency as calculated by Eq. 9 of single slope solar still are found in the range of 0.22 to 1.35% while in the case of double slope solar still it varies from 0.31 to 1.34%. The monthly exergy analysis of single and double slope solar stills for different water depth is given in Table 4a. Eq. 1c calculates the daily thermal efficiency of single and double slope solar and it varies from 21.22 to 34.2% for single slope and 23.14 to 36.4% for double slope passive solar stills.

Energy Pay Back Time (EPBT) for experimental and proposed units in case of single and double slope solar still has been evaluated with the help of Eq. 16 and is given in Table 8a and b. Energy Pay Back Time (EPBT) for experimental single and double slope solar stills is 1.91 years and 1.85 years, respectively while EPBT for proposed solar still is 1.64 years for single slope and 1.60 years for double slope solar stills, respectively. Similar studies can also be carried out for active solar still and other design of passive solar stills.

CONCLUSIONS

Following conclusion can be made on the basis of present studies

- On the basis of experimental data one can say that double slope solar still gives higher yield in the peak summer months while single slope solar still gives higher yield in winter months but overall annual yield of single slope solar still is higher as compared to annual yield of double slope solar still.
- The daily thermal and exergy efficiency of double slope solar still is higher as compared with single slope solar still.
- Double slope solar still (Rs. 0.28 L^{-1}) is more economical than single slope solar still (Rs. 0.33 L^{-1}).
- Energy pay back time (EPBT) for proposed double slope solar still (1.6 years) is lower than proposed single slope solar still.

SYMBOLS

A_s : Basin area of solar still (m^2).
C_w : Specific heat of water in solar still (J kg^{-1} $°C^{-1}$).
CPL_{en} : Cost of distilled water per liter based on thermal energy.
CPL_{ex} : Cost of distilled water per liter based on exergy.
$\dot{E}x_{in}$: 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).
$F_{CR,i,n'}$: Capital recovery factor.
$F_{SR,i,n'}$: Sinking fund factor.
h_{ew} : Evaporative heat transfer coefficient from water surface to glass (Wm^{-2} $°C^{-1}$).
i : Rate of interest, fraction (%).
$I(t)_{Incident}$: total radiation (W m^{-2})
L : Latent heat of vaporization (J kg^{-1})

M_s : Annual maintenance cost of solar still as a fraction of annual cost of still (Rs. m^{-2}).
M_{yen} : Annual yield based on thermal energy.
M_{yex} : Annual yield based on exergy.
$\dot{m}_{ew}$: Hourly distillate output (kg).
M_{ew} : Daily distillate output (kg).
M_w : Mass of solar still water (kg).
n' : Expected life of solar still (year).
N : No. of clear day in a month.
$\dot{Q}_{ew}$: Thermal energy in evaporation of water vapors (Wm^{-2}).
P_s : Capital cost of solar still (Rs m^{-2} of basin area).
S_s : Salvage value of solar still as a fraction of capital cost P_s (Rs m^{-2}).
T_a : Ambient air temperature (°C).
T_{ci} : Inner temperature of condensing cover (°C).
T_S : Sun temperature (K).
T_v : Vapor temperature (°C).
T_w : Water temperature (°C).
UA_{net} : The uniform end of year annual cost.
η_{ex} : Exergy efficiency.
η_{en} : Instantaneous thermal efficiency.
η_{th} : Daily thermal efficiency.

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