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Performance evaluation and economic analysis of solar desalination device made of building materials for hot arid climate of India

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ABSTRACT

Solar desalination devices made of cement concrete hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement have been designed, developed and constructed. These are basin type solar stills with absorber area 4.2 m^2 of each device and the bottom is painted with epoxy paint. The longer dimension of the device is in the east west direction so that it collects more solar radiation. One 3.5 mm thick clear window glass is provided over it having 20° tilt from the horizontal and two distillate channels are fixed for collection of distilled water. The performance evaluation of the devices made of cement concrete hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement during winter and summer month were carried out by measuring distilled water obtained per day. The average output of the device during summer month (May 2017) was 8065, 8117, 8230, 8340 and 8540 ml d^{-1} and in winter month (December 2017) was 7029, 7173, 7285, 7395 and 7595 ml d^{-1}. The unit made of vermiculite-cement gave the higher yield due to better insulation and reduced heat loss. The average efficiency was 24.61%, 28.21%, 28.55%, 29.54% and 30.25% respectively. The distillate output of solar desalination device is to be mixed with the available saline water in appropriate proportion to make it drinkable. In fact as much as 20 L/d of potable water (150 ppm TDS) can be made available in a day from raw water containing 300 ppm TDS by a solar desalination device. The economic evaluation of the vermiculite-cement type solar desalination device revealed that high value of IRR (151 per cent) and low value of payback period (0.65y) make the unit very cost efficient. The economic attributes of the system revealed its economic viability. Therefore this solar desalination device can be successfully used for desalination of saline water in rural arid areas for meeting requirement of potable water.

Keywords: Basin type solar desalination device; Building materials; Economic analysis

1. Introduction

Water is a basic necessity of man along with food and air; the importance of supplying hygienic potable/fresh water (less than 500 ppm of salt) can hardly be over stressed. The man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. However, use of water from such sources is not always possible or desirable on account of the presence of large amount of salts and harmful organisms. The impact of many diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. But there are still countries in the world today where large amounts of the population are lacking fresh drinking water [1]. As far as drinking water is concerned, it is scarcely available in western arid region of India and people depend on rain water collected from rooftop, which is too little to meet their drinking water demand. The impact of waterborne infectious diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. Generally in summer season, villagers travel many miles in search of fresh water. It is observed that at least one or two family members are always busy in bringing fresh water from distant sources. The worst conditions

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are generated if the resources of water are not available and villagers are forced to take highly saline underground water containing nitrate and fluorides or contaminated with pathogenic microbes [2]. Fortunately, India is blessed with abundant solar radiation. In arid part of Rajasthan, India solar irradiations are available in abundance and almost 300 clear sky days are observed. Amount of solar irradiation received in the region is about 7600–8000 M Jm^{-2} per annum, whereas in semi-arid region it is about 7200–7600 M Jm^{-2} per annum and in hilly areas it is about 6000 M Jm^{-2} per annum [3].

The conventional desalination technologies like multi stage flash, multiple effect, vapor compression, iron exchange, reverse osmosis, electro dialysis are expensive for the production of small amount of freshwater, also use of conventional energy sources has a negative impact on the environment. Solar distillation provides partial support to human needs for fresh water with free energy, simple technology and clean environment. Therefore, solar distillation seems to be a good substitute for conventional methods. The distillate output of solar still is to be mixed with the available saline water in appropriate proportion to make it drinkable. In fact as much as 20 L/d of potable water (150 ppm TDS) can be made available in a day from raw water containing 300 ppm TDS by installing a solar still of capacity 10 L/d. Solar distillation has been in practice for a long time. Solar distillation is carried out in solar still. Historical review of desalination of water was reported by Nebbia and Menozzi [4]. The basin-type solar still is in the most advanced stage of development. Several researchers have investigated the effect of climatic, operational and design parameters on the performance of such still [5]. Researchers have done different types of analysis on basin-type solar still [6–9]. Many experimental and theoretical studies were conducted by various researchers on single-basin solar still to increase the productivity [10]. Al-Hussaini and Smith [11] described the effect of applying vacuum inside the solar still and found that the water productivity increased by 100%.

Velmurugan et al. [12] studied the influence of black gravel on the productivity of the solar still coupled with a mini solar pond. Suleiman and Tarawneh [13] carried out the performance evaluation of a double-slope solar still by varying the water depth and observed that the productivity is strongly dependent on the climatic, design, and operational conditions. Sampathkumar et al. [14] found that the still performance can be increased by reducing the water depth and thereby increasing the evaporation rate. The temperature difference between water in the basin and condensing glass cover also has a direct effect in the performance of the still [14]. Velmurugan et al. [15] described that the black paint coated inside the bottom of the basin absorbs all the incident solar radiation and the temperature of the water increases and it has direct effect on the still productivity. Velmurugan et al. [15] experimented on fin-type passive solar still and found that the yield was increased by 52%. Murugavel et al. [16] found that the still productivity depends on parameters like solar radiation intensity, atmospheric temperature, basin water depth, glass cover material, thickness and its inclination, wind velocity, and the heat capacity of the still.

The objective of this work is to overcome the problem of corrosion of metallic still and improve the production of distilled water by designing a solar still made of different types of building/construction materials. The economic analyses of a vermiculite-cement based solar still have also been carried out in order to study the real-time possibilities for its use in desalination process. The productivity and, in turn, efficiency is further improved by means of painting black coating the bottom of the still basin.

2. Materials and methods

2.1. Experimental set -up and observations

Solar desalination devices made of cement-concrete, cement hollow block, vermiculite-cement, brick and stone masonry and plastered with cement have been designed, developed and constructed (Fig. 1). These are basin type solar stills and made of different types of building/construction materials. The condensing cover of 3.5 mm thickness is made of plane glass which has been placed over the basin of solar still. The inclination of condensing cover for solar still is 20° from the horizontal. The absorber area of each device is 4.2 m^2. The bottom surface of the still was painted with epoxy enamel black to have high absorptivity of solar radiation and resistance to salt and heat. The longer dimension of the device is in the east west direction so as to collect more solar radiation. The output from the solar desalination unit is collected into two distillate channels provided at lower side and is taken out through a pipe into a cylinder (Fig. 2).

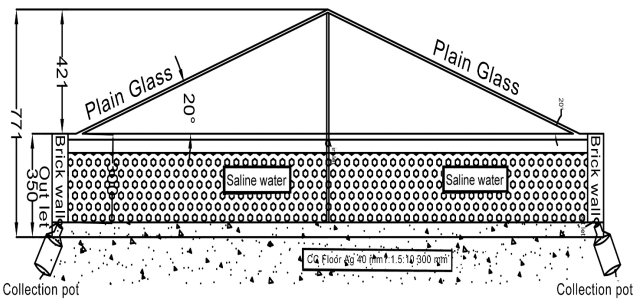

Fig. 1. Schematic diagram of basin type solar desalination device.

Fig. 2. Solar desalination devices made of vermiculite-cement plastered material.

2.2. Experimental arrangement and procedure

To predict the performance of solar still on-field experiments were conducted at the campus of Central Arid Zone Research Institute, Jodhpur, India, (26°18′N and 73°04′E) for carrying out the performance in winter and summer months during 2017 for five different types of desalination devices made of cement concrete hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement. Experiment for each solar still are started at 10:00 am and lasted for 24 h. In these experiments, the solar radiation intensity (I_b) on a horizontal surface was measured using a thermopile pyranometer. DTM-100 thermometer with point contact thermocouples (accuracy 0.1°C) was used to measure the inside water temperatures. Ambient air temperature was measured using a mercury thermometer (accuracy 0.1°C) placed in an ambient chamber and the distillate output are measured by a measuring cylinder having a least count of 10 ml. The performance evaluation of the devices made of hollow block, vermiculite-cement, cement-concrete, brick and stone masonry have been carried out by measuring distilled water obtained per day by a measuring jar. The distillation efficiency and system efficiency were computed by using the following formulae,

$$\eta_{distillation}(\%) = \frac{m_e \times \mathrm{L} \times 100}{I_{bav.} \times A_p \times \mathrm{hr} \times 3600} \quad (1)$$

$$\eta_{system}(\%) = \frac{\left[m_{water} \times C_{pw}\left(T_f - T_i\right) + m_e \times L\right] \times 100}{I_{bav.} \times A_P \times \mathrm{hr} \times 3600} \quad (2)$$

where A_p = aperature area (m^2); C_{pw} = specific heat (J/kg/°C); I_b = beam radiation (W/m^2); L = latent heat of distiller water (J/kg); m_e = mass of distill water obtained (lit.); m_{water} = Mass of water remaining in evaporative vessel (L); T_i = initial temperature of evaporative vessel (°C); T_i = final temperature of evaporative vessel (°C); $\eta_{distillation}$ = distillation efficiency (%); η_{system} = system efficiency (%).

3. Results and discussion

Table 1 shows the hourly experimental observations of average air temperature, water temperature and solar intensity for a typical day in the month of May and December 2017 for the period of 11 h in day times, i.e., 8:00 to 18:00 h in the cement concrete hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement-basin type solar still. The average maximum water temperature (brackish water) in the case of May and December month is 49.2°C and 45.1°C and the ambient temperature is 39.5°C and 31.5°C (Table 1). The average solar insolation varied in the range of 430 W/m^2 to 890 W/m^2 in the month of May and 250 W/m^2 to 670 W/m^2 in the month of December as shown in Table 1.

Fig. 3 and Fig. 4 show the instantaneous distillate yield of the cement concrete hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement-basin type solar still in the summer (May 2017) and winter (December 2017) month. The distillate yield was measured with a measuring jar at sixty minute intervals from 8.00 AM to 6.00 PM including day and night condensation. It was observed that inside temperature increased as the solar intensity increased and hence rate of heat utilization for heating the water was more at noon time and accordingly higher evaporation was observed after noon hours and then rate of condensation increased than noon time as solar intensity decreased. It was observed that maximum distillation rate obtained between 4 PM to 5 PM which was highest as 200 ml in all the basin type solar stills.

In the summer month of May 2017, the total cumulative amount of daily productivity obtained by the hollow blockwalled was 8065 ml d^{-1} including day and night condensation, while the productivity of the stone masonry type solar still was 8117 ml d^{-1}. With the different building material, productivity increased to 8230 ml d^{-1} in cement-concrete walled and 8340 ml d^{-1} in the case of still with brick and stone masonry walls. Finally, with walls with vermiculite-cement blocks, productivity increased to 8540 ml d^{-1} which was 475 ml d^{-1} more than the still with cement concrete hollow block, and provided the highest distillate output because of better insulation and reduced heat loss that

Table 1
Performance of basin type solar still in summer and winter

Time (h)	Insolation (W/m^2)		Inside water temperature (°C)		Ambient temperature (°C)	
	May	December	May	December	May	December
8:00	430	250	29.2	25.2	27.1	22.8
9:00	630	420	34.8	32.8	30.2	24.0
10:00	770	560	38.7	36.9	33.4	25.8
11:00	860	640	44.2	41.0	36.0	29.8
12:00	940	710	48.5	45.1	38.1	31.5
13:00	890	650	52.6	43.8	39.5	32.0
14:00	790	570	50.2	42.1	41.2	31.5
15:00	650	450	48.8	40.4	40.8	29.4
16:00	540	350	46.2	40.0	40.1	28.5
17:00	460	260	45.1	39.1	38.1	27.0
18:00	340	190	43.6	38.0	36.0	25.1

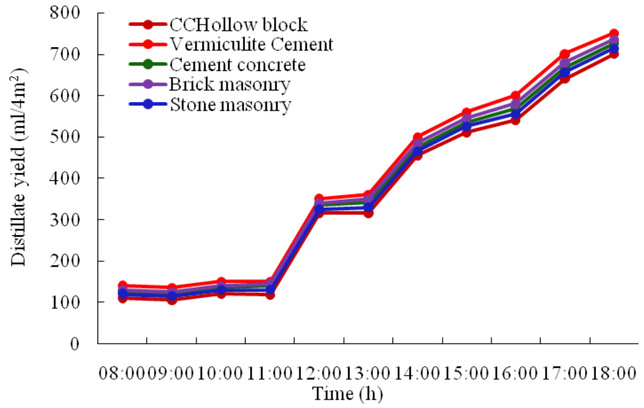

Fig. 3. Variation of distillate yield for different basin type of solar still during May 2017.

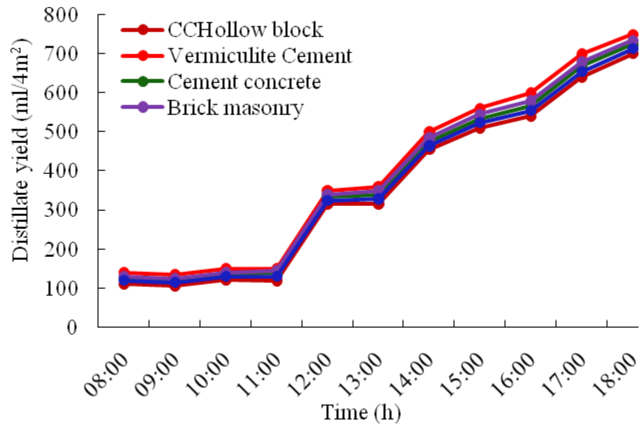

Fig. 4. Variation of distillate yield for different basin type of solar still during December 2017.

is why it gave better performance over other units. Variation of total distillate output/day with respect to different type of basin still is shown in Fig. 5. As expected, performance of the stills increases when the insulating material of the base changes from different building materials with salt encrustation.

In the winter month of Decemer 2017, the total cumulative amount of daily productivity obtained by the hollow blockwalled was 7029 ml d^{-1} including day and night condensation, while the productivity of the stone masonry type solar still was 7173 ml d^{-1}. With the different building material, productivity increased to 7285 ml d^{-1} in cement-concrete walled and 7395 ml d^{-1} in the case of still with brick and stone masonry walls. Finally, with walls with vermiculite-cement blocks, productivity increased to 7595 ml d^{-1} which was 566 ml d^{-1} more than the still with cement concrete hollow block, and provided the highest distillate output because of better insulation and reduced heat loss that is why it gave better performance over other units. Variation of total distillate output/day with respect to different types of basin still is shown in Fig. 5.

By using Eqns. (1) and (2), the performance evaluation of the devices made of hollow block, stone masonry, cement-concrete, brick masonary and vermiculite-cement basin type solar stills for which the distillate efficiencies

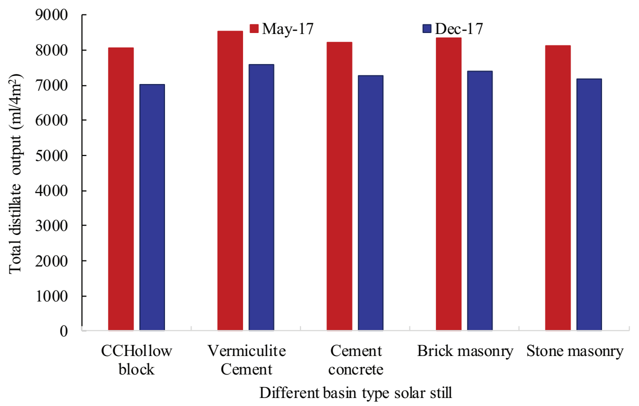

Fig. 5. Total distillate output including night for various basin type solar still.

were 24.61%, 28.21%, 28.55%, 29.54% and 30.25% and system efficiencies were found 28.3%, 32.7%, 32.8%, 33.6% and 34.5%, respectively. A comparison between conventional RO plant and desalination units made of building materials was also done using highly saline and the performance of such units was found to be better than that of conventional RO plant. Electrical conductivity (EC) of raw saline water having salt varying from 15.1 mm hos to 17.38 mm hos that was reduced to 1.84 mm hos to 4.82 mm hos in commercial RO plant while it varied from 0.14 mm hos to 0.64 mm hos in solar desalination devices respectively (Table 2).

4. Economic analysis of basin type solar desalination device

The economic analysis of the present brick masonry type solar desalination device was carried out by computing the life cycle cost (LCC) and life cycle benefit (LCB) of the device. In addition, five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and pay back period (PBP) were also determined for judging the economic viability of the technology.

4.1. Life cycle cost (LCC)

Life cycle cost (LCC) of the vermiculite-cement blocks type solar still is the sum of all the costs associated with a solar desalination energy system over its lifetime in terms of money value at the present instant of time and takes into account the time value of money [17]. The initial investment (P) in desalination unit is INR 9000. The annual cost of operation and maintenance (O&M) including labour are taken as INR 8000/y. The benefit was computed for desalination output at a rate of 7.5 L/d for 300 d a year priced at INR 10/L. The salvage value is taken as 10% of initial investment.

4.1.1. Determination of (LCC):

Economics of vermiculite-cement blocks type solar desalination unit was calculated through life cycle cost (LCC)

Table 2
Comparison of desalination unit with conventional RO

S. No.	Electrical concductivity (EC) of raw water (mm hos)	Electrical conductivity (EC) after desalination (mm hos)	
		Conventional RO	Desalination unit
1	15.09	1.84	0.14
2	17.11	3.85	0.44
3	17.38	4.82	0.64

analysis. Let P_i is initial investment (INR), P_w is operational and maintenance expenses including replacement costs for damaged components (INR), n is life of the desalination unit (Year), P_w (SV) is salvage value of the solar desalination unit at the end of the life (INR). The procedure of life cycle cost estimation as adopted by [18–22], the LCC is given as,

(i) LCC (Unit) = Initial cost of unit (P_i) + P_w (O & M Costs including labour) – P_w (SV) (3)

$$LCC = P_i + P_w \frac{X(1-X^n)}{1-X} - SV(1+i)^{-n}$$

$$LCC = 9000 + 8000 \frac{X(1-X^n)}{1-X} - 900(1+i)^{-n}$$

$$LCC = 9000 + 8000 \frac{X(1-X^{10})}{1-X} - 900(1+0.1)^{-10}$$

$$LCC = 9000 + 8000 \frac{0.945(1-0.945^{10})}{(1-0.945)} - 900(1.1)^{-10}$$

LCC = 68197.28

where $X = \frac{1+e}{1+i} = \frac{1+0.04}{1+0.1}$

where e = annual escalation in cost (in fraction); i = interest or discount rate (in fraction).

4.1.2. Life cycle benefits (LCB)

The values of R (annual benefit) is obtained by using the desalination output at a rate of 7.5 L/d for 300 d a year priced at INR 10/L. The ensuring annual benefit from basin type solar still was about INR 22500/-

The LCB can be given as,

$$LCB = R\frac{X(1-X^n)}{(1-X)} \quad (4)$$

LCB = 167468.30

where R = annual benefit (Rs.) and $X = \frac{1+e}{1+i}$

4.2. Economic attributes

i. BCR: The ratio of discounted benefits to the discounted values of all costs given as LCB/LCC
ii. NPW: It is the sum of all discounted net benefits throughout the project given as LCB-LCC
iii. The annuity (A) of the project indicates the average net annual returns given as, (Annuity) = $\frac{NPW}{\sum_{t=1\ to10}\left(\frac{1+e}{1+i}\right)^n}$
iv. PBP: It is the length of time from the beginning of the project before the net benefits return the cost of capital investments (value n for LCB – LCC = 0)
v. IRR: It is that rate of interest which makes life cycle benefits and life cycle cost equal (LCB – LCC = 0)

4.2.1. Determination of economic attributes

i. BCR: The ratio of discounted benefits to the discounted values of all costs can be expressed as:

Benefit cost ratio (BCR) =

$$\frac{\textit{Life cycle benefits of brick masonry type solar still}}{\textit{Life cycle cost of brick masonry type solar still}}$$

$$BCR = \frac{R\frac{X(1-X^n)}{(1-X)}}{P_i + P_w - P_w(SV)} = \frac{LCB}{LCC} = \frac{167468.30}{68197.28} = 2.46$$

ii. NPW = LCB – LCC = 99270.97
iii. The annuity (A) of the project indicates the average net annual returns. This term can be given as,

$$A\ (\text{Annuity}) = \frac{NPW}{\sum_{t=1\ to10}\left(\frac{1+e}{1+i}\right)^n} = 13371.62- \quad (5)$$

iv. Pay-back period can be determined as following: –LCC + LCB = 0

$$\text{Or } 9000 + 8000 \times \frac{0.945(1-0.945^{10})}{(1-0.945)} = 22500\ \frac{0.945(1-0.945^{10})}{(1-0.945)}$$

$$\text{Or } 9000 = 14500 \cdot \frac{0.945(1-0.945^{10})}{(1-0.945)}$$

$$\text{Or } (1-0.945^n) = \frac{9000\ (0.055)}{14500 \times 0.945}$$

$$\text{Or } 0.945^n = 1 - \frac{9000\ (0.055)}{14500 \times 0.945} = 0.964$$

Or $n \log 0.945 = \log 0.964$

$$n = \frac{\log(0.964)}{\log(0.945)}$$

n = 0.65 years

Or pay-back period (PBP) = 0.65 y

v. Internal rate of return (IRR):

The values of NPW at varying discount rates are given in Table 2. From Table 2 it may be inferred that at 10% interest rate the NPW is INR99270.97/- respectively. At 90% rate of

Table 3
Values of NPW for different rates of discount/interest (*i*)

Interest rate *i* (%)	10	90	200
NPW (Rs.)	99270.97	8466.12	–3968.69

Table. 4
Values of economic attributes

Sr. No.	Attributes economics	Values
1	BCR	2.46
2	NPW	99271
3	A	13371.62
4	IRR (per cent)	151
5	PBP (y)	0.65

interest the NPW is INR8466.12. However, the NPW is negative at 200% interest rate (i.e. NPW = INR –3968.69/-). The IRR can determined using data presented in Table 3 and the following relationship:

$$IRR = lower\ discount\ rate + \frac{Difference\ of\ discount\ rate\ x\ NPW\ at\ lower\ discount\ rate}{(NPW\ at\ lower\ discount\ rate - NPW\ at\ higher\ discount\ rate)}$$

$$\text{IRR} = 90 + \frac{90 \times 8466.12}{8466.12 + 3968.69} = 151.27\%$$

The internal rate of return (IRR) which comes to 151.27% in the present case, which is very high for a project to be economically viable.

The values of five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and pay back period (PBP) was presented in Table 4.

5. Conclusion

Solar desalination device is very much useful in rural arid areas which are deprived of potable water and only saline water is available. The device is very cost effective can provide 8–10 L of distilled water per day on clear sunny days. The solar still can be successfully used for desalination of saline water in rural areas for meeting requirement of potable water. The distillate output of solar still can be mixed with the available saline water in appropriate proportion to make it drinkable. In fact as much as 20 L/d of potable water (150 ppm TDS) can be made available in a day from raw water containing 300 ppm TDS by improved solar still. The use of solar desalination device would help in conservation of conventional fuels, such as firewood, cow dung cake and agricultural waste in rural areas of India. Conservation of firewood helps in preserving the ecosystems and cow dung cake could be used as fertiliser, which could help increase the agricultural production. Moreover, the use of this device would result in the reduction of the release of CO_2 to the environment. The solar desalination unit will overcome the problem of corrosion associated with metallic solar still. In addition, there is a wide scale adoption of distilled water in dispensaries, laboratories, batteries etc.

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