Exergy Analysis of Active and Passive Solar Still

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Abstract Over the last few decades, the worldwide demand for freshwater is expanding quickly as the supply of freshwater is limited. Solar still (SS) is a profitable sun oriented device that is utilized for changing over the brackish and saline water into clean water. A number of experiments have been performed on SS to evaluate its execution under various climatic and operational conditions. Besides experiments, theoretical investigations have also been helpful in assessing the importance of SS. In this chapter, distinctive methodologies which have been utilized for exergy investigation of solar stills are discussed in detail.

Keywords Desalination · Principle of solar still · Classification of solar still · Exergy analysis

Nomenclature

A_s	Area of the basin of the still (m^2)
C_w	Solar still water-specific heat (J kg^{-1} $°C^{-1}$)
Ex_{input} , Ex_{sun}	Available energy input in the still (W/m^2)
Ex_{output}, Ex_{evap}	Availability output in the still (W/m^2)
$Ex_{d,b}$	Availability loss in the from basin (W/m^2)

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Ex_w	Availability used for water heating (W/m^2)
Ex_{ins}	Loss of availability due to insulation (W/m^2)
$Ex_{c,w-g}$	Availability due to water and the cover of glass in convection (W/m^2)
$Ex_{e,w-g}$	Availability due to water and the cover of glass in evaporation (W/m^2)
$Ex_{r,w-g}$	Availability due to water and the cover of glass in radiation (W/m^2)
$Ex_{r,g-a}$	Availability due to cover of glass and atmosphere in radiation (W/m^2)
$Ex_{c,g-a}$	Availability due to cover of glass and atmosphere in convection (W/m^2)
$\dot{E}x_{in}$	Input of available energy in solar still (W)
$\dot{E}x_{evap}$	Output of available energy in solar still (W)
$\dot{E}x_{dest}$	Loss of availability in solar still water (W)
$\dot{E}x_{sun}$	Available energy input from the sun to the still (W)
$\dot{E}x_{work}$	Availability of the rate of the work for a still (W)
h_{ew}	Heat transfer coefficient (evaporative) for interface between the surfaces of the glass and water ($W\ m^{-2}\ °C^{-1}$)
$I(t)$	Total radiation ($W\ m^{-2}$)
$\dot{Q}_{ew}$	Thermal energy in evaporation of water vapors ($W\ m^{-2}$)
$q_{c,w-g}$	Heat transfer (convective) from water surface to glass cover (W/m^2)
$q_{r,w-g}$	Heat transfer (radiative) from surface of water to cover of glass (W/m^2)
$q_{e,w-g}$	Heat transfer (Evaporative) from water surface to cover of glass (W/m^2)
$q_{c,b-w}$	Heat transfer (convective) from basin to surface of water (W/m^2)
q_b	Heat transfer (convective) from basin liner (W/m^2)
$q_{c,w-g}$	Heat transfer (convective) from surface of water to cover of glass (W/m^2)
T_a	Ambient air temperature (°C)
T_{ci}	Temperature of the inner cover of the condensing material (°C)
T_S	Temperature from the sun (K)
T_w	Temperature of water (°C)
α	Absorptivity
g	Cover of glass
η	Efficiency
τ	Transmissivity
w	Mass of water
t	Total
b	Basin liner

1 Introduction

Saline/salty water can be cleaned utilizing sun powered energy. The utilization of sun powered energy to create consumable water is a main factor in removing water contamination while majority of other water decontamination methods utilize conventional energy, for example, coal, oil, gas, and so forth.

A solar still is a device utilized for sunlight based cleaning in which freshwater is obtained from saline water. It is a kind of man made structure of certain materials, such as fiber reinforced plastic (FRP), cement, steel with protection. A glass sheet is used to cover the still from where the sun-oriented radiation enters the water surface. A little reflection and maximum transmission occurs at the cover of the glass and at the surface of water. A noteworthy amount of radiation is consumed by the liner of the basin. The exchange of heat is via convection to the saline water. Exchange from the water to the cover of the glass happens by three modes: evaporation, convection, and radiation. Vapor goes out of the majority of ingredients and microorganisms via heat dissemination to the liner of the basin. The vapor then rises and condenses in the inner cover which is at a temperature less than water. Vapor condensation occurs at the inner condensing cover, and this condensate trickles down toward the trough due to sloped glass cover [18]. Scientists have attempted to enhance the output of SS by proposing its different outlines, materials, and working criteria for various climate situations.

Tiwari and Tiwari have proposed that the SS for a single slope yields may fluctuate from 0.5 to 1.2 kg/m^2/day during winter time and 1.0–2.5 kg/m^2/day during summer time for Delhi (India) climatic conditions [29]. Tiwari and Tiwari estimated the effectiveness of the SS of single slope as 25.8, 19.7, 22.8% at glass cover slants 15°, 30°, and 45° separately for the mid-year climatic state of Delhi, India [30]. Malik et al. have demonstrated that the general effectiveness of a normal SS is accomplished with minimum amount of mass of water in the basin [18].

There are large varieties of stills which are used to obtain freshwater from saline water. Based on converting solar energy, generally solar stills are of 3 types—active, passive, and hybrid. Based on the shape, SS is differentiated as single slope and double slope. The various designs of SS are classified in Fig. 1.

The performance of SS can be increased by increasing saline water temperature using different techniques such as flat plate collector, external reflector [28], and solar pond [12]. The productivity of solar still can be increased by 16% by using inclined external reflector [27]. According to Deniz, various parameters influencing the productivity of solar still are as follows: inclination angle of condensing cover, cooling of condensing cover, gap distance between condensing cover and water surface, etc. [4].

The term exergy is used first time in 1956 by the Rant [22]. The exergy is the combination of two Greek words ex (external) and ergos (work). Available energy of a system is the maximum useful amount of work in the process when system comes in equilibrium with surroundings [26]. The nature of energy is understood by exergy examination in light of the thermodynamics second law and includes the

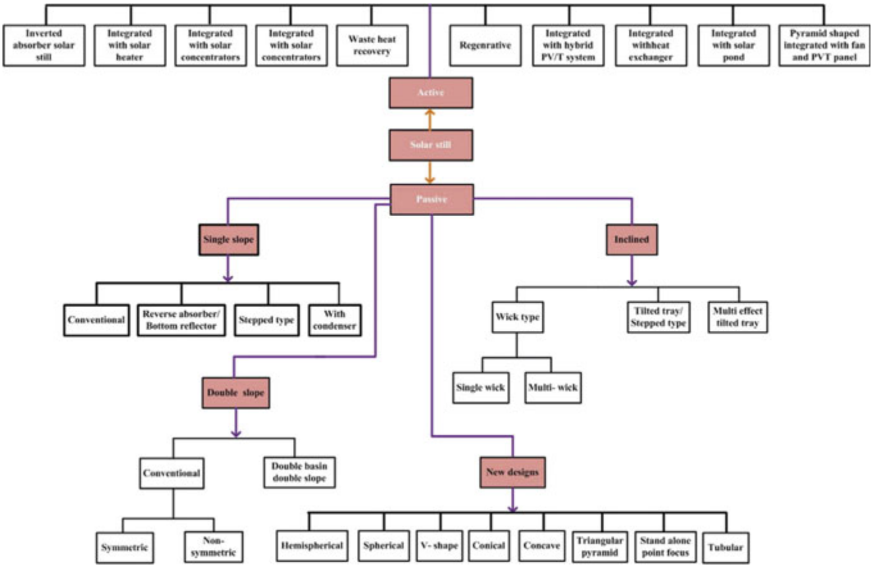

Fig. 1 Various design of active and passive solar still [32]

irreversibility. The exergy investigation gives an exact measurement of how the SS is a perfect desalination device [20]. Researchers have examined SS in view of exergy investigation [1, 3, 16, 20, 21, 24, 25, 33].

Dwivedi and Tiwari have calculated the energy payback time along with the exergy assessment for solar still [7]. Torchia et al. completed an investigation of the available energy in a SS of passive type [33]. Farahat et al. investigated exergy of flat plate solar collector [10]. Eldalil displayed another idea of solar still with a normal day by day efficiency of around 60% [9]. Kumar and Tiwari calculated available energy efficiency of a SS [16]. Dev et al. compared the energy and available energy analysis of SS for a passive slope type [5]. Saidur et al. audited an exergy investigation of different solar stills [23]. Ahsan et al. compared analysis of designing, fabricating, cost, and production of water between old and improved SS of tubular nature. A relation between the production of water and difference in temperature inside the still is too discussed [2].

Vaithilingam and Esakkimuthu studied distinctive depths of water from 1 to 2.5 cm. The impacts of depths of water on efficiencies of energy and available energy and available energy decimation of different segments of the solar still were considered. The greatest efficiencies of energy and available energy of 30.97 and 3.48% were acquired at depth of 1 cm of water. The day by day efficiencies of energy and available energy diminished from 30.9 to 19.21% and 3.48 to 1.81%, separately, when the depths of water increased from 1 to 2.5 cm [34].

Nematollahi et al. developed a model of SS by using solar collector and humidification tower. They concluded that by decreasing the length of humidification tower and inlet air temperature, the overall efficiency of available energy increases [19]. Kwatra did analysis of available energy for describing the thermal behavior of various SS [17]. Nunez et al. analyzed theoretical available energy of steady state and transient SS. The exergy examinations reveal that a better performance of the thermoactive is reached when differences in temperature are less after achieving higher temperatures [33].

2 Exergy Analysis of Solar Still

2.1 Passive Solar Still

A number of literatures with exergy investigation of different desalination systems are found. Various exergy investigations of the solar still have been accounted for in the writing. Ranjan et al. did examination of energy and available energy for a single slope solar still. It was seen that the efficiency of energy is in particular increments than the effectiveness of available energy. The momentary rate of available energy was assessed for the parts of detached solar still. It demonstrates that greatest rate on hourly basis of available energy decimations in cover of glass, body of water, liner of the basin reach up to 9.7, 62.5, and 386 W/m^2, separately. It has been discovered that available energy decimation value in the still segments is particularly reliant on the amount of sun oriented radiation with time [21].

Shanmugan et al. [25] considered, tentatively, the execution of SS and assessed the momentary available energy and energy productivity of it. The momentary productivity of the energy changes during the amid winter from 12.00 to 60.00% and amid summer from 32.00 to 57.00%. The momentary available energy productivity varies amid winter from 6.00 to 19.00% and amid summer from 7.00 to 18.00%.

Aghaei Zoori et al. [1] displayed hypothetically and tentatively investigation of the efficiencies in energy and available energy of SS. It was observed that the efficiency of the available energy and energy of the solar still incremented from 3.14 to 10.5% and 44.1 to 83.3%, respectively, when the bay salt water stream rate diminishes from 0.2% to 0.065 kg/min.

Kumar and Tiwari [16] thought about the exergy productivity of a slope of single type SS which is passive in nature and an active one where the SS was combined with a photovoltaic unit. They explained that the available energy effectiveness of the still of active type was about 5 times high than that of the passive one.

Kianifar et al. [14] investigated an active and a passive pyramid-molded still using 2 units to reveal both of available energy and monetary examination. In the detached SS water depths of 4 cm, the everyday efficiency of available energy observed to be 2.43% during winter and 3.06% during summer. For the mid-year, when the depth of water diminishes from 4 to 8 cm, the day by day efficiency of available energy diminished from 3.06 to 2.81%.

Hypothetical exergy effectiveness of a SS of passive type having 30° turned edge of cover of glass and water depths of 0.04 m on a usual day in the month of June was assessed by Kaushik et al. [13]. The day by day efficiency of energy and available energy of the solar still was found to be 20.7 and 1.31%, individually.

2.2 Active Solar Still

Various exergy investigations of the SS have been accounted for in the writing. Dwivedi and Tiwari [8] displayed warm investigation for a double slope active SS. The timely or hour basis efficiency of the available energy of a still of active type have been assessed for 30 mm salt water depths. It was seen that double slope active still gives 51% better efficiency in comparison with the still of passive type. The available energy effectiveness of a single slope SS is less than the available energy effectiveness of a dual slope active SS.

Tiwari et al. experimented active and latent SS on taking the time in an hourly basis efficiency [31]. The impact of the depth of water and the quantity of collectors on energy and available energy efficiency of the active SS is acquired. The outcomes demonstrated that as the depth of water and quantity of collectors reduce the energy productivity increments and the energy effectiveness undergoes huge changes in contrast to the adjustment in the available energy effectiveness.

Sethi and Dwivedi investigated double slope active still. It was observed that month to month and yearly, exergy yield increases with number of sunny mornings in every period of a year and it shifts from 0.26 to 1.34% [24].

Kumar et al. coordinated an emptied collector of tubular nature with a single slope solar still and worked in constrained condition [15]. The energy along with exergy efficiencies has been assessed. Results of exergy analysis for solar stills are shown in Table 1.

3 Exergy Balance Equations

The exergy for any solar still or its segments can be found by using the relation as given by Dincer and Rosen [6] as:

$$\text{Exergy input} - \text{exergy output}\left(\text{useful}\frac{\text{and}}{\text{or}}\text{losses}\right) - \text{exergy accumulation} = \text{exergy consumption or destruction} \quad (1)$$

Table 1 Results of exergy examination for solar stills

S. No.	Type of solar still	Authors	Remarks/findings	References
1	Passive solar still	Ranjan et al.	– The greatest exergy and energy efficiency of the still are 4.93 and 30.42% individually – The most extreme rate of availability hour wise obliterations in glass cover, water body and basin liner reach up to 9.7, 62.5	[21]
		Torchia-Núñez et al.	– The greatest exergy productivity of brackish water, authority, and SS are 6, 12.9 and 5%	[33]
		Kianifar et al.	– The most extreme day by day efficiency of availability for a still of passive nature at 4 cm water depths, is 2.43% during the winter months, and 3.06% during the summer months	[14]
		Shanmugan et al.	– The momentary exergy productivity changes amid winter in a range in between 6.00 and 19.00% and amid summer in between a range from 7.00 to 18.00%	[25]

(continued)

Table 1 (continued)

S. No.	Type of solar still	Authors	Remarks/findings	References
		Aghaei Zoori et al.	– The effectiveness of availability and energy for the solar still increments in between the range 3.14–0.5% and 44.1–83.3%, individually, at the point when the delta saline solution stream rate diminishes from 0.2 to 0.065 kg/min	[1]
		Kumar and Tiwari	– The efficiencies of availability and energy were diminished by 36.7 and 21.8%, individually, when the plate basin absorptivity reduced from 0.90 to 0.60 – They reasoned that the effectiveness of availability of the active solar still was about 5 times more than its passive one	[16]
2	Active solar still	Sethi and Dwivedi	– The day by day exergy yield fluctuates from 0.26 to 1.34% – The day by day thermal efficiency fluctuates from 13.55 to 31.07%.	[24]
		Tiwari et al.	– The greatest exergy efficiency of the still for various saline solution depths 5, 10, and 15 cm are 1.71, 1.13, and 0.81%, individually	[31]

(continued)

Table 1 (continued)

S. No.	Type of solar still	Authors	Remarks/findings	References
		Dwivedi and Tiwari	– It was seen the active still with the double slope sort during similar modes gives 51% more efficiency in contrast with the still of double slope detached sort	[8]
		Vaithilingam and Esakkimuthu	– The most extreme efficiencies due to availability and energy are of 3.48 and 30.97% and were acquired at 1 cm depth of water	[34]
		Kumar et al.	They coordinated a solar still of single slope and a collector of tubular type in constrained mode. The efficiencies due to availability and energy have been assessed	[15]

3.1 Basin Liner

The liner of the basin of detached solar still assimilates the portion of sun oriented available energy Ex_{sun} coming to it. A piece of this, i.e., helpful available energy Ex_w is used for heating up the saline water, and there is a very less loss in protection Ex_{ins} and the rest is demolished $Ex_{d,b}$.

$$Ex_{d,b} = \left(\tau_g \tau_w \alpha_b\right) Ex_{sun} - (Ex_w + Ex_{ins}) \quad (2)$$

whereτ_g, τ_w and α_b are the transmission capabilities of the cover of the glass, water, and the absorptivity of the liner basin liner, respectively.

3.2 Saline Water

Available energy of the mass of the saline water in the basin is the total of the division of sunlight based on available energy consumed by water, i.e., $\left(t_g\, \alpha_w\right) Ex_{sun}$

and available energy from the liner of the basin (Ex_w). Some portion is used as the available energy related to the exchange of heat among the surface of the saline water and cover of the glass in the still ($Ex_{t,w-g}$) and the rest is devastated $(Ex_{d,w})$.

$$Ex_{d,w} = (t_g \alpha_w) Ex_{sun} + Ex_w - Ex_{t,w-g} \tag{3}$$

where the saline water absorptivity is given by α_w and $(Ex_{t,w-g})$ is the available energy for the transfer of heat through evaporation $(Ex_{e,w-g})$, radiation $(Ex_{r,w-g})$, and convection ($Ex_{c,w-g}$) among the surface of the saline water and cover of the glass inside the still and is found out as given below:

$$Ex_{t,w-g} = Ex_{e,w-g} + Ex_{r,w-g} + Ex_{c,w-g} \tag{4}$$

3.3 Cover of Glass

$$Ex_{d,g} = \alpha_g Ex_{sun} + Ex_{t,w-g} - Ex_{t,g-a} \tag{5}$$

where the absorptivity of the cover of the glass is given by α_g and $Ex_{t,g-a}$ is loss of available energy due to loss of heat in between the cover of glass and the atmosphere due to radiation $Ex_{r,g-a}$ and $Ex_{c,g-a}$ convection and is given as:

$$Ex_{t,g-a} = Ex_{r,g-a} + Ex_{c,g-a} \tag{6}$$

4 Efficiency of Availability of a Still

The general exergy balance for solar still can be written, Hepbalsi [11], as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{7}$$

or,

$$\sum \dot{E}x_{sun} - \left(\sum \dot{E}x_{evap} + \sum \dot{E}x_{work}\right) = \sum \dot{E}x_{dest} \tag{8}$$

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

$$\dot{E}x_{in} = \dot{E}x_{sun} = A_s \times I(t) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s}\right)^4\right] \tag{9}$$

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

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{evap}} = \frac{\sum\left(1 - \frac{T_a + 273}{T_w + 273}\right) \times \dot{Q}_{ew}}{3600} \tag{10}$$

where,

$$\dot{Q}_{ew} = A_s h_{ew}(T_w - T_{ci}) \tag{11}$$

The availability of energy monthly is obtained by product of Eq. 10 and no of clear days.

The rate of availability work performed on the solar still is given by:

$$\dot{Q}_{ew} = A_s h_{ew}(T_w - T_{ci}) \tag{12}$$

The availability destroyed for the still water is given by:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest}} = M_w C_w (T_w - T_a)\left(1 - \frac{T_a + 273}{T_w + 273}\right) \tag{13}$$

The efficiency of availability of still is defined, Hepbalsi [11], and is given below:

$$\eta_{EX} = \frac{\text{Exergy output of solar still } \left(\dot{\mathrm{E}}\mathrm{x}_{\mathrm{evap}}\right)}{\text{Exergy input to solar still } \left(\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}}\right)} = 1 - \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{evap}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}}} \tag{14}$$

The availability output of a solar still can be calculated from the equation below:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{evap}} = A_s h_{ew} (T_w - T_{ci}) \times \left(1 - \frac{T_a + 273}{T_w + 273}\right) \tag{15}$$

The daily output of available energy will be sum of hourly exergy evaluated by Eq. 15.

5 Conclusion

The efficiency of energy and exergy are different and are basically climate dependent, i.e., if both the analysis of exergy and energy are considered, the former has an advantage as it gives actual insights in the working of the material in terms of the distillation process. Hence, analyzing the exergy of the solar still will give the value of the quality of energy of the solar still. That means how much the amount of useful energy being utilized from the energy of the sun. The lesser temperature difference between the basin liner and the water, more energy flow from the basin liner to the water. With the increase in the difference of the temperature the flow of exergy increases which further decreases the unavailability or unavailable energy. The more is the temperature difference between the surface of the water and the inner material, the more will the exergy due to evaporation and hence decreases the loss of available energy from the left-out water. The difference in the temperature of the glazing surface and the outer material is very high hence results in less loss of energy in the system. During the change in the form of energy from solar to heat, the efficiency of exergy is low in comparison to instatntaneous efficiency. The amount of loss of exergy from the liner of the basin to that of the left-out water and the surface of the glazing is maximum. Hence the analysis of exergy for a solar still together with all the parts is an effective way to design a technically and economically viable solar still.

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