- Read
- Summarize and write up
Using the attached format
at least 10 pages.
- Minimal Direct Copying

- **Introduction**
  - Background of the Problem
  - Statement of the Problem
  - Significance of the Study
  - Definition of Terms
- **Literature Review**
  - Previous Work
  - The Gap(s) Which Author(s) Try to Fill
- **Methodology**
  - Methodology (Analytical, Numerical, or Experimental)
  - Assumptions and Limitations
- **Research Findings**
  - Summary of Findings
  - Discussion
  - Conclusion
  - Suggestions for Future Research

International Journal of Low-Carbon Technologies Advance Access published September 27, 2013

Energy and exergy analysis of passive solar distillation systems

K.R. Ranjan[1,2*], S.C. Kaushik[1] and N.L. Panwar[1]

[1]*Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, 110016, India;* [2] *Faculty of Mechanical Engineering, Department of Training and Technical Education, New Delhi, India*

Abstract

In this communication, a comprehensive thermodynamic model for exergy analysis of a passive solar distillation system is presented. Temperatures of basin-liner, saline water body and inner and outer glass cover are estimated theoretically with the help of a computer program using a set of typical design and operating parameters. Energy and exergy analysis of a single-effect, single-slope horizontal passive solar still has been carried out under climatic conditions of India. It has been shown that the passive solar still can produce 4.17 l/m^2 of freshwater daily. Energy and exergy efficiency of the solar still are 30.42 and 4.93%, respectively. Causes, quantity and place of exergy destruction have also been explored for further research and improvement in the design and performance of solar stills. Exergy destruction or irreversibility in the process of each component, i.e. basin-liner, saline water body and glass cover, has been evaluated as 3353, 1633 and 362 W/m^2, respectively, corresponding to the total solar exergy input of 6958 W/m^2 on a typical day. Their corresponding exergy efficiencies are found to be 3.91, 17.67 and 42.36%. The global exergy efficiency of the solar still is also estimated as 23.14%, taking these exergy destructions into account. The basin-liner is identified as the component around which there is highest possibility of improvement.

Keywords: solar thermal; low-carbon technology; exergy destruction; energy and exergy efficiency; solar still; sustainable development

*Corresponding author: kumarranjan@rediffmail.com

Received 28 July 2013; revised 22 August 2013; accepted 28 August 2013

1 INTRODUCTION

There is acute shortage of fresh drinking water in remote and rural areas of many countries. At most of the places, enough saline water is available. But, it is not suitable for drinking and other domestic, agricultural and industrial applications. On the other hand, people are unable to use existing popular desalination devices to get fresh water because of limited or even no supply of grid-connected electricity. As most of the desalination technologies require electricity to run these devices, there is dire need to find some desalination systems operating with locally available renewable energy sources. Concern about harm to the environment, global warming and climate change owing to exploitation of fossil fuels has also made it necessary to find alternative ways even for urban areas. In the present circumstances, utilization of solar energy for desalination shall be the best solution for rural as well as urban areas [1].

The use of solar energy is a promising option for desalination of saline water. It is locally available in abundance at zero energy cost. Solar distillation systems for desalination of saline water are extensively discussed elsewhere in literature. It has been established as a low-carbon technology, which is technically feasible for freshwater production having large potential of saving high-grade energy. But the initial cost of device to intercept the low-density solar radiation and its conversion to low-grade solar thermal energy for use in distillation is high. And the energy efficiency of the solar distillation systems is in lower range. Therefore, it has become essential to design solar distillation systems of higher energy efficiency minimizing thermal losses and irreversibility in the components to make it technically as well as economically feasible. The unit cost of desalination of saline water is estimated to be US$ 0.034/l corresponding to 30.42% energy efficiency of a passive solar still. It decreases to US$ 0.024/l using modified model incorporating the factor of

International Journal of Low-Carbon Technologies 2013, 0, 1–11

doi:10.1093/ijlct/ctt069

equivalent cost of environmental degradation and high-grade energy savings for solar stills. Among other solar distillation systems, a single–effect, basin-type horizontal passive solar still is found to be comparatively cheaper [2]. It is also simple in design and easier to construct and operate with minimum requirement of repair and maintenance, anywhere, if adequate solar radiation is available. It comprises of three main components: metallic basin-liner, saline water body and glass cover as shown in Figure 1. It operates on the basic principle of evaporation and condensation similar to the phenomenon of natural raining but within a confined space. It relies on the distillation process to remove fresh water from saline or brackish water.

The evaluation of energy efficiency and distillate output of any solar stills is primarily done by energy analysis, which is based on the first law of thermodynamics. It considers only the quantitative aspect of the energy transfer. The quality of energy, i.e. availability of energy (potential for use) or exergy, defined by the second law of thermodynamics is usually ignored. The technique of exergy analysis is proved to be the most effective thermodynamic tool for achieving the goal of more efficient resource use, as it enables the locations, types and true magnitudes of waste and loss to be determined [3]. It has been successfully applied in the optimization of the entire system or specific variables in a single component of thermal systems, such as steam power plants, solar thermal power plants, steam or gas turbine, boiler, etc. [4, 5]. This knowledge can also be used to design a solar still, to reduce the sources of inefficiency and irreversibility in the existing processes and components of the solar still. It may prove to be very useful to achieve higher cost-effective efficiency and productivity.

A number of research works are available in literature on the optimization of design and operating parameters to maximize the energy efficiency and productivity of the passive solar stills based on energy analysis. The reported energy efficiency and distillate output per unit area of the solar still is found to be low in the range of 20–46% and with <6 l/m^2/day of fresh water production for most cases, even under optimized operating conditions [6–9]. A new approach to enhance the productivity of a solar still by introducing an additional basin in the double-slope solar still was attempted by Rajaseenivasan *et al.* [10]. Maximum productivity has been found to be 5.68 l/m^2/day for double-basin solar still. Cooper [11] has calculated and observed that the maximum theoretical and experimental efficiency of an ideal single-effect solar still can reach up to 60 and 50%, respectively. Therefore, despite of all efforts reported in references of the above-mentioned papers, there is much scope to improve the performance of the actual solar still to bring it at commercial stage. It may be possible by increasing distillate production utilizing maximum solar energy available without increasing the expensive solar energy collection area/device.

In view of authors of this paper, this task can be accomplished by the improvement in design of solar still based on exergy analysis in addition to conventional energy analysis. Some works on exergy analysis of other types of desalination systems are found in literature. But only a few literatures are available on exergy analysis of the passive solar stills. A general overview about exergy efficiency of collector and evaporator–condenser component of a solar still was given by Kwatra [12]. It has been illuminated here that a theoretical thermodynamic interpretation based on 'availability' helps to explain the individual contributions of the two energy conversion processes within the still to its overall efficiency. Garcia-Rodriguez and Gomez-Camacho [13] have performed the exergy analysis of a solar multi-effect distillation system. Energetic and exergetic analysis of a triple-effect distiller driven by solar energy has been carried out by Sow *et al.* [14]. The results of this paper show the exergetic efficiencies between 19–26% for a triple-effect system, 17–20% for a double effect system and <4% for a single-effect system. The exergy analysis of a passive solar still was presented by Torchia-Nunez *et al.* [15]. It is reported that for the same exergy input, a collector, brine and solar still have exergy efficiencies of 12.9, 6 and 5%, respectively. An energy, exergy and life cycle cost analysis of single- and double-slope solar stills has been carried out by Dwivedi and Tiwari [16]. It is observed that double-slope solar still gives higher distillate output in summer with low annual distillate, higher exergy efficiency, low cost of production and low energy payback time as compared with single-slope solar still. Tiwari *et al.* [17] have investigated the effect of the number of collectors and water depth on exergy and thermal efficiency of the active solar still. Kumar and Tiwari [18] have analyzed the energy and exergy efficiency of a shallow basin passive solar still. It is found that with decrease in absorptivity (0.9–0.6) with time, the energetic and exergetic efficiencies decrease by 21.8 and 36.7%, respectively. The effect of glass cover tilt is found to be insignificant, and the respective efficiencies decrease by 0.75 and 0.47% per degree increase in tilt. These efficiencies increase rapidly up to a wind velocity of 2 m/s. Kianifar *et al.* [19] have conducted an exergy analysis to show the effect of a

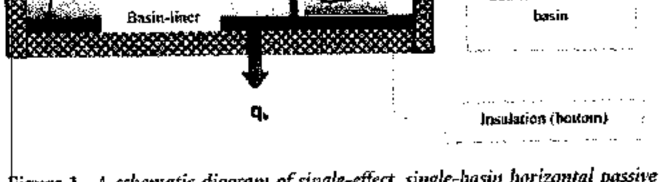


Figure 1. *A schematic diagram of single-effect, single-basin horizontal passive solar still showing the mechanism of major energy transfer.*

small fan on the exergy efficiency in a pyramid-shaped solar still. The effect of seasonal change on exergy efficiency has also been reported here. Theoretical overall instantaneous exergy efficiency of a passive solar still having 30° tilt angle of glass cover and water depth of 0.04 m on a typical day in June was evaluated by Kaushik *et al.* [20]. They have found it in the range of 0.06–5.9% for the variation in experimental results of overall instantaneous energy efficiency from 8 to 87.2%. The daily energy and exergy efficiency of the solar still is 20.7 and 1.31%, respectively. An optimum exergy efficiency of the ideal solar still is found to be 21.11% corresponding to 80% ultimate energy efficiency defined by Cooper [11] and at a typical operating condition. A feasible target of optimum exergy efficiency has been set under assumed ideal conditions to achieve in the future for the real working passive solar stills.

The methodology and results reported by the above-mentioned researchers are inspiring and motivated us to analyze a single-effect passive solar still energetically as well as exergetically with added dimensions and integrated approach. In the present work, a comprehensive thermodynamic model for exergy analysis is presented. Exergy balance equations of all three components of the passive solar still are given. Exergy efficiencies are estimated and compared with corresponding energy efficiencies. An attempt has also been made to explore the causes, sites and rate of exergy destruction in the components and processes leading to freshwater production by the passive solar stills.

2 SELECTION OF THE LOCATION AND THE PASSIVE SOLAR DISTILLATION SYSTEM FOR STUDY

Various improved designs of the passive solar distillation system are suggested and tested for increasing the efficiency and productivity by researchers. Special solar stills have also been designed for specific purpose like wars, expeditions, voyages, etc. [6]. This success has been achieved on the cost of increase in the unit cost of drinking water from these improved systems owing to higher initial capital cost and more operation and maintenance (O & M) cost involved. These systems comprise of the common components for performing different task of heat and mass transfer but differ in configuration and material of construction only.

Therefore, in the present analysis, a single-effect, basin-type horizontal passive solar still (Figure 1) is selected for investigations. This schematic diagram shows the major energy transfer mechanisms of the solar still producing potable water. Results of many theoretical and experimental studies on solar stills in IIT Delhi and other parts of India are available in literature. But no theoretical studies are reported for climatic conditions of Udaipur (Rajasthan). Rajasthan has a tropical desert climate varying from arid to sub-humid. There is acute shortage of drinking water. Hence, it is decided to select the location 'Udaipur' for present study so that experimental results may be compared in future for performance investigation of solar stills. The operating and climatic parameters of the selected passive solar distillation system are similar to passive solar stills shown in Figure 2. It is in actual operation at the Department of Renewable Energy Engineering, College of Technology and Engineering, MPUAT, Udaipur (Rajasthan), India. Typical set of operating and climatic parameters assumed on a typical day with reference to Udaipur (27° 42′ N, 75° 33′ E) and design parameters assumed for 'energy and exergy analysis' in this paper are presented in Tables 1 and 2. The findings of Cooper [11] about the percentage reflectance, absorptance and transmittance of the glass cover, water and basin-liner of a solar still is used in the present analysis.

The following assumptions have been considered for the energy and exergy analysis of the passive solar still:

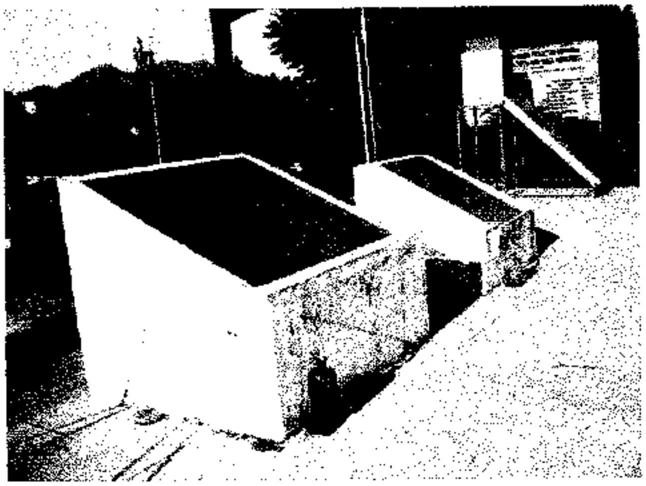


Figure 2. *A photograph of single–slope, basin-type passive solar stills (courtesy—MPUAT, Udaipur, India).*

Table 1. *Operating and climatic parameters of the passive solar still.*

Time	G_s (W/m^2)	Ambient temperature, t_a (°C)
07.00 a.m.	65	9.2
08.00 a.m.	330	12.8
09.00 a.m.	538	15.6
10.00 a.m.	735	18.3
11.00 a.m.	809	19.6
12.00 p.m.	861	22.3
01.00 p.m.	872	23.4
02.00 p.m.	884	28.4
03.00 p.m.	826	24.3
04.00 p.m.	745	24.2
05.00 p.m.	592	23.8
06.00 p.m.	189	22.4

Initial water temperature inside the passive solar still, $t_{w(i)} = 13.8$°C.
Initial inside glass cover temperature, $t_{gi(i)} = 11.2$°C.
Wind velocity = 0.0 m/s.

Table 2. *Design parameters of the passive solar still.*

Parameter	Value
Specific heat of saline water, C_w	4190 J/kg K
Latent heat of vaporization, h_{fg}	2260×10^3 J/kg
Thermal conductivity of water, K_w	0.590 W/m K
Depth of saline water in the basin, X_w	0.01 m
Emissivity of glass, ε_g	0.94
Time interval, Δt	3600 s
Area of basin-liner, A_b	1m × 1m
Thermal conductivity of glass cover, K_g	0.78 W/m K
Thermal conductivity of insulating material, K_i	0. 35 W/m K
Thickness of glass cover, X_g	0.003 m
Thickness of insulation, X_i	0.005 m
Effective absorptance of basin-liner [11], $\alpha_{eff,b}$	0.5814
Effective absorptance of glass cover [11], $\alpha_{eff,g}$	0.05
Effective absorptance of water [11], $\alpha_{eff,w}$	0.27
Glass cover tilt angle from horizontal, θ	30°
Stefan Boltzmann constant, σ	5.6697×10^{-8} W/m^2 K^4

(i) It is a single-slope solar still having 'θ' tilt angle of the glass cover with the horizontal.
(ii) It operates in quasi-steady state.
(iii) There is no temperature gradients across the basin-liner and saline water depth of solar still.
(iv) The basin of the solar still is kept horizontally on the ground, and it is vapor leak proof.
(v) The heat capacity of the basin-liner, glass cover and insulating materials is negligible.
(vi) The heat transfer coefficients are temperature dependent.
(vii) The inside and outside glass cover temperatures are different (i.e. $T_{gi} \neq T_{go}$).
(viii) The side heat loss from the solar still is negligible because of very small area of side wall of the still as compared with basin-liner area.
(ix) The solar still is a closed system and the level of saline water in the basin is maintained at a constant level.
(x) All properties of saline water are assumed to be similar to that of water for simplicity.
(xi) Attenuation of solar energy within the saline water is not considered.

3 THERMODYNAMIC MODELING FOR EXERGY ANALYSIS OF THE PASSIVE SOLAR DISTILLATION SYSTEMS

The energy and exergy analysis are complementary thermodynamic tools. Energy analysis alone is not sufficient to understand all the aspects of energy utilization in the processes or components of the system. Exergy analysis is a technique that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design, optimization and improvement of the energy systems. Sustainable quality assessment of energy for any thermodynamic system is possible by the method of exergy analysis. Furthermore, one of the main objectives of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. The concept of exergy destruction or rate of irreversibility is widely used for the exergy analysis of thermal systems such as boiler, turbine, thermal power plants, etc. [3, 21, 22]. But its application in the analysis of passive solar still is a few. The thermodynamic model for the exergy analysis of the passive solar distillation systems considered here is presented in this section. It is based on the methods suggested by Moran and Shapiro [3], Bejan [21], Petela [23] and as applied by Torchia-Nunez *et al.* [15]. The energy analysis of the passive solar still is carried out based on the concept put forwarded by Dunkle [24] and Cooper [11], including various improvements suggested by the researchers. It is summarized elsewhere in literature [6, 25, 26]. Energy balance equations are not reproduced here but used according to the assumptions made in the previous section for energy analysis of this study.

The exergy (work potential) of heat or exergy transfer accompanying heat, E_{X_q} (in W/m^2) connected to internal and external heat transfer of passive solar stills through conduction, convection or evaporation (i.e. excluding radiation) is expressed as follows [3, 27]:

$$E_{X_q} = q\left(1 - \frac{T_a}{T}\right) \qquad (1)$$

where q is the rate of heat transfer (W/m^2) through conduction, convection or evaporation process, T is the temperature of the system in Kelvin and T_a is the temperature of the dead state or reference temperature (K) of the environment, i.e. temperature of the atmosphere outside the solar still. $(1 - T_a/T)$ is a Carnot coefficient factor.

The exergy transfer associated with blackbody radiation $E_{X_{radiation}}$ [23] at surface temperature T, i.e. thermal radiation (q_r) from the component of the solar still, with reference to a reference temperature T_a, is expressed similar to the solar exergy described in the next section:

$$E_{X_{radiation}} = q_r\left[1 + \frac{1}{3}\left(\frac{T_a}{T}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T}\right)\right] \qquad (2)$$

Temperatures of the basin-liner (T_b), saline water (T_w) and glass cover inside (T_{gi}) and outside (T_{go}) are the unknown operating variables to be determined for the calculation of energy and exergy flow, energy and exergy losses, and exergy destructions. All other parameters like heat transfer coefficients, partial vapor pressures, etc., are dependent on temperatures. Analysis based on experimental studies use measured values of these operating temperatures and ambient temperature (T_a), including other design and climatic parameters. But theoretical analysis based on the laws of thermodynamics requires determination of the unknown variables by solving energy and exergy balance equations. These equations are programmed by the authors using computer for the estimation of unknown operating variables, comprehensive calculations and graphical presentation of the results. The input data used in the analysis are given in Tables 1 and 2.

3.1 Exergy balance equations

Exergy is consumed or destroyed (E_{X_d}) because of irreversibility E_{X_d} in the process or components. The exergy balance for any system or its components can be obtained by combining the conservation of law of energy and non-conservation of exergy [28] as:

$$\text{Exergy input} - \text{exergy output (useful and/or losses)} - \text{exergy accumulation} = \text{exergy consumption or destruction}$$

Exergy flow diagram of the passive solar still is shown in Figure 3. The exergy balance equations of the three main components of the solar still are given here, neglecting exergy accumulation in the components as the heat capacity of the basin-liner, glass cover and insulating materials is assumed to be negligible.

3.1.1 *Basin-liner*

Basin-liner of the passive solar still absorbs the fraction of solar exergy ($E_{X_{sun}}$) reaching on it. A part of this, i.e. useful exergy (E_{X_w}) is utilized to heat the saline water and a little is lost through insulation ($E_{X_{insul}}$) and remaining is destroyed ($E_{X_{d,b}}$).

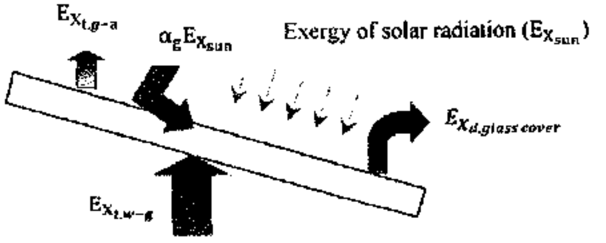
$$E_{X_{d,b}} = (\tau_g \tau_w \alpha_b) E_{X_{sun}} - (E_{X_w} + E_{X_{insul}}) \qquad (3)$$

where τ_g, τ_w and α_b are transmittance of the glass cover, transmittance of the saline water and absorptivity of the basin-liner, respectively.

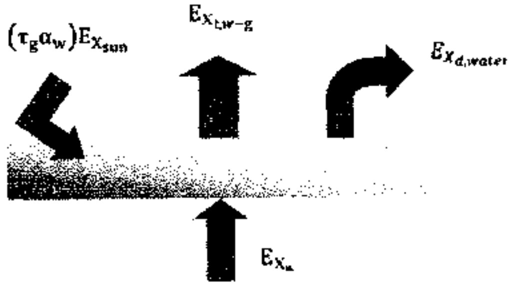
Here, the rate of incoming solar exergy, i.e. exergy of the solar radiation ($E_{X_{sun}}$), on the glass cover of passive solar still per unit area is calculated by multiplying the rate of incident solar radiation, G_s (in W/m^2) to the Petela expression (Ψ) [29, 30], i.e.

$$\psi = \left[1 + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_S}\right)\right] \qquad (4)$$

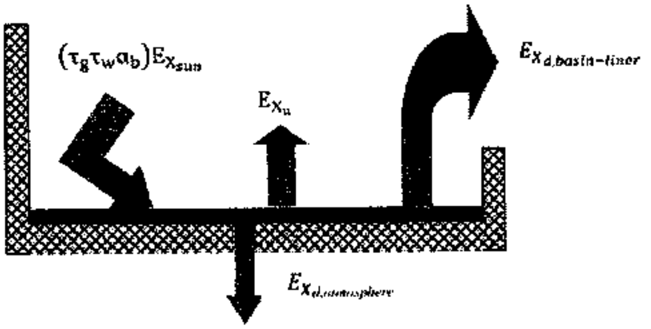
where T_a is the temperature of the dead state or reference temperature of the environment, i.e. temperature (K) of the atmosphere outside the solar still and T_S is the temperature of the sun (6000 K for the present analysis).



(i). Exergy balance on the glass cover



(ii). Exergy balance on the water body



(iii). Exergy balance on the basin-liner

Figure 3. *Schematic diagrams showing the exergy transfers in the components of a single–effect, basin-type horizontal passive solar still. (i) Exergy balance on the glass cover. (ii) Exergy balance on the water body. (iii) Exergy balance on the basin-liner.*

Exergy of the solar radiation on the solar still per unit area, $E_{X_{sun}}$ (in W/m^2), is given as:

$$E_{X_{sun}} = G_s\left[1 + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_S}\right)\right] \qquad (5)$$

3.1.2 *Saline water*

Input exergy to the mass of saline water in the basin is the sum of the fraction of incident solar exergy absorbed by water, i.e. $(\tau_g \alpha_w) E_{X_{sun}}$ and useful exergy from the basin-liner (E_{X_w}). A part of it is utilized as the exergy associated with the heat transfer between saline water surface and the glass cover inside the solar still ($E_{X_{t,w-g}}$) and remaining is destroyed ($E_{X_{d,w}}$).

$$Ex_{d,w} = (\tau_g \alpha_w) Ex_{sun} + Ex_w - Ex_{t,w-g} \tag{6}$$

where α_w is the absorptivity of saline water and $Ex_{t,w-g}$ is the exergy associated with the heat transfer through evaporation ($Ex_{e,w-g}$), radiation ($Ex_{r,w-g}$) and convection ($Ex_{c,w-g}$) between saline water surface and the glass cover inside the solar still and is calculated as follows:

$$Ex_{t,w-g} = Ex_{e,w-g} + Ex_{r,w-g} + Ex_{c,w-g} \tag{7}$$

3.1.3 *Glass cover*

$$Ex_{d,g} = \alpha_g Ex_{sun} + Ex_{t,w-g} - Ex_{t,g-a} \tag{8}$$

where α_g is the absorptivity of glass cover and $Ex_{t,g-a}$ is the exergy loss associated with heat losses from glass cover to the atmosphere owing to radiation ($Ex_{r,g-a}$) and convection ($Ex_{c,g-a}$) and is given as:

$$Ex_{t,g-a} = Ex_{r,g-a} + Ex_{c,g-a} \tag{9}$$

The thermal exergy associated with the heat transfers and that owing to blackbody radiation appeared in Equations (6) to (9) are calculated using Equations (1) and (2) as described in Appendix.

3.2 Expressions of productivity, energetic and exergetic efficiencies

The expression for the hourly distillate output (m_{wo}) from the passive solar still (kg/m^{2}h) is given as [26]:

$$m_{wo} = \frac{h_{c,w-g}(T_w - T_{gi})}{h_{fg}} \times 3600 \tag{10}$$

where $h_{c,w-g}$ is evaporative heat transfer coefficient between saline water and glass cover (W/m^2 K), and h_{fg} is the latent heat of vaporization of water (J/kg).

The theoretical overall instantaneous energy efficiency (η_e) of a passive solar still at any time is defined as the ratio of heat transfer rate in the still by evaporation-condensation ($q_{e,w-g}$) to the rate of incident solar radiation (G_s) on the glass cover of solar still, i.e.

$$\eta_e = \frac{q_{e,w-g}}{G_s} \tag{11}$$

The daily overall energy efficiency of a passive solar still may be calculated as follows:

$$\eta_{e,\text{daily}} = \frac{\text{Total energy available in distillation output of the passive solar still/m}^2\text{/day}}{\text{Total input of solar energy on the passive solar still/m}^2\text{/day}} \tag{12}$$

Hence,

$$\eta_{e,\text{daily}} = \frac{\sum m_{wo} \times h_{fg}}{\sum G_S \times 3600} \tag{13}$$

Global energy efficiency of the passive solar still may be defined and expressed as:

$$\eta_{e,\text{solar still}} = 1 - \left[\frac{(\text{energy lossess})}{G_S}\right] \tag{14}$$

The overall instantaneous exergy efficiency of the passive solar still is defined as the ratio of exergy output of solar still to the exergy of the incident solar radiation, i.e.

$$\eta_{ex} = \frac{\text{exergy output of the passive solar still}}{\text{exergy intput of the passive solar still}} \tag{15}$$

Exergy output of the passive solar still is the useful exergy associated with heat transfer through evaporation, i.e. $Ex_{e,g-a}$, which is responsible for the transportation of the water vapor from saline water surface to the glass cover and distillate is produced after condensation. Hence,

$$\eta_{ex} = \frac{Ex_{e,w-g}}{Ex_{sun}} = \frac{q_{e,w-g}\left(1 - \frac{T_a}{T_w}\right)}{Ex_{sun}} \tag{16}$$

Similarly, exergy efficiencies of different components are given as:

$$\eta_{ex,\text{basin-liner}} = \frac{Ex_w}{(\tau_g \tau_w \alpha_b) Ex_{sun}} \tag{17}$$

$$\eta_{ex,\text{saline water}} = \frac{Ex_{t,w-g}}{(\tau_g \alpha_w) Ex_{sun} + Ex_w} \tag{18}$$

The glass cover can be assumed to work as a heat engine performing useful work by helping in the condensation of distillate by rejecting heat to the atmosphere. Therefore, exergy efficiency of the glass cover can be expressed as the ratio of exergy in the distillate yield and the maximum possible work obtainable from the total heat gained by the glass cover [12]. Hence, the exergy efficiency of the glass cover may be given as:

$$\eta_{ex,\text{glass cover}} = \frac{m_{wo} h_{fg}\left(1 - \frac{T_a}{T_w}\right)}{\alpha_g Ex_{sun} + Ex_{t,w-g}} = \frac{Ex_{e,w-g}}{\alpha_g Ex_{sun} + Ex_{t,w-g}} \tag{19}$$

The global exergy efficiency of the passive solar still or exergy efficiency of the passive solar still may be evaluated by taking exergy destruction or irreversibility of the components of the solar stills into account. It is defined as:

$$\eta_{\text{ex, solar still}} = 1 - \left[\frac{(\text{exergy destruction or irreversibilities})}{E_{X_{\text{sun}}}}\right] \quad (20)$$

$$\eta_{\text{ex, solar still}} = 1 - \left[\frac{(E_{X_{\text{d,b}}} + E_{X_{\text{d,w}}} + E_{X_{\text{d,g}}})}{E_{X_{\text{sun}}}}\right] \quad (21)$$

Using Equations (3), (6) and (8), an expression for global exergy efficiency is derived in this paper and expressed in terms of exergy losses and effective absorptance of the components defined by Cooper [11], i.e.

$$\eta_{\text{ex. solar still}} = 1 - \left[\{\alpha_{\text{eff.b}} + \alpha_{\text{eff,w}} + \alpha_{\text{eff,g}}\} - \frac{(E_{X_{\text{insul.}}} + E_{X_{\text{r,g-a}}})}{E_{X_{\text{sun}}}}\right] \quad (22)$$

where $\alpha_{\text{eff.b}} = (\tau_g \tau_w \alpha_w)$, $\alpha_{\text{eff.w}} = (\tau_g \alpha_w)$ and $\alpha_{\text{eff.g}} = \alpha_g$.

4 NUMERICAL RESULTS AND DISCUSSION

Energy and exergy analysis of a passive solar still has been carried out in this research work to investigate the effect of changes in various performance parameters and to suggest improvement measures. A number of results have been obtained, but only some specific findings that are unique and not published elsewhere are presented and discussed here.

Numerical results obtained here by the energy analysis are in good agreement with the results published in literature [6–11] with respect to the effect of design and climatic parameters on productivity and energy efficiency of the passive solar stills. It has been observed that the most prominent parameter is solar radiation incident on the solar still. Productivity of a passive solar still increases with the increase in the amount of incident solar radiation. This increase in productivity is the result of consequent rise of temperature of saline water, which leads to efficient evaporation of water.

The effect of solar radiation on the hourly overall instantaneous energy and exergy efficiency is illustrated in Figure 4. It is observed that the exergy efficiency is very much lower than the energy efficiency. It is mainly due to less available energy or exergy associated with the evaporative heat corresponding to the lower system temperature, i.e. saline water temperature, which varies in the lower range of 15–95°C only. It can be explained by taking one extreme example when the water temperature has reached maximum, i.e. 94.35°C at ~2 p.m. The higher instantaneous energy efficiency is found as 49.29% owing to the higher quantity of evaporative thermal energy (436 W/m^2) as the output. But corresponding instantaneous exergy efficiency is found as 9.48%. This lower value is attributed to less available energy or low quality of evaporative thermal energy, i.e. exergy (78.2 W/m^2) associated with 436 W/m^2 of evaporative thermal energy in quantity with reference to the ambient temperature, 28.4°C. The erratic fluctuations in the graph of Figure 4 is attributed to deviation in the assumed steady state condition of the solar still owing to thermal inertia [31], rise in temperatures of water after 10 a.m. and consideration of hourly mean values. Similar trends are found even in the experimental results available in literatures [26, 32].

The goal of the exergy analysis is not only to calculate the exergy efficiency but to find the quantity and location where exergy destruction takes place so that measures for improvement can be suggested. In the present analysis, the rate of instantaneous exergy destruction has been evaluated for the components of passive solar stills and results are shown in Figure 5. It shows

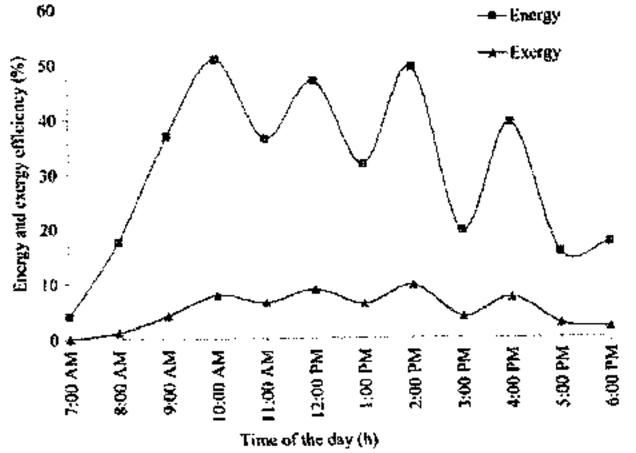


Figure 4. *Hourly variation in overall instantaneous energy and exergy efficiency of the passive solar still.*

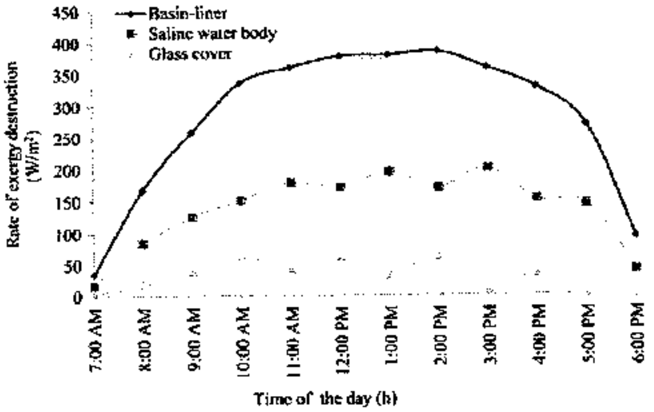


Figure 5. *Hourly variation in exergy destruction (irreversibilities) rate in the components of the passive solar still.*

that the maximum hourly rate of exergy destructions in basin-liner, water body and glass cover reach up to 386, 62.5 and 9.7 W/m^2, respectively. It has been found that the rate of exergy destruction in the components is very much dependent on the rate of incident solar radiation. But it is not so simple to predict in reality as it is dependent on many other parameters also as given in Equations (6) to (9). It is observed that the highest exergy is destructed in the basin-liner (3353 W/m^2/day) and lowest in the glass cover (362 W/m^2/day) corresponding to the total solar exergy input of 6958 W/m^2 on a typical day. The effect of exergy losses through insulation ($E_{X_{\mathrm{insul.}}} = 484$ W/m^2/day) has marginal impact, and it can be taken care of by reducing thermal energy losses using insulating material of lower thermal conductivity or other means. The major cause of exergy destruction in the basin-liner is due to lower rate of useful heat transfer (E_{X_u}) to water body as difference in the basin-liner temperature and water temperature ($T_b - T_w$) is observed to be <1°C during the operation periods. Increase in (T_b–T_w) increases the useful energy transfer to water ($E_{X_w}$of Equation A.1) significantly, as increment in h_w has slight impact (150% increment of h_w causes only 0.9% increase in E_{X_u}). Consequently, exergy destruction in the basin-liner reduces and both energy and exergy efficiency of the solar still increases. The method of increasing the (T_b–T_w) is a matter of further research and technological development.

It has been established that higher temperature difference between water and inner glass cover (T_w–T_{gi}) increases the rate of total exergy transfer from water to the glass cover ($E_{X_{t,w-g}}$) which may reduce the exergy destruction in water body. It increases the exergy efficiency and overall instantaneous exergy efficiency of the solar still. The glass cover has lowest rate of exergy destruction and highest exergy efficiency among the components of solar stills. Variations in hourly exergy efficiency of the components of the passive solar still are shown in Figure 6. The daily exergy efficiencies have been estimated for the basin-liner, saline water body and the glass cover as 3.91, 17.67 and 42.36%, respectively. Results shown in Figures 5 and 6 are completely in agreement thermodynamically that the higher exergy destruction leads to lower energy and exergy efficiencies of the passive solar stills. This observation may be very useful for the further improvement in the design of solar stills to increase the cost-effective efficiencies leading to higher productivity.

Through energy analysis, it is estimated that maximum global energy efficiency of the passive solar still lies in the range of 33.61–67.44% if the convective and radiative heat transfers from saline water to the glass cover are not accounted as losses. The global exergy efficiency of the passive solar still is calculated using Equation (21), and results are shown in Figure 7. The instantaneous global exergy efficiency gradually increases to a maximum, 26.7% corresponding to 826 W/m^2 incident solar radiations at 3 p.m. The daily average global exergy efficiency is estimated as 23.14%.

Both instantaneous global and daily average global exergy efficiency is higher than the overall instantaneous and daily average exergy efficiency. This is due to consideration of the inter-related effect of exergy destruction of each component, and finally it depends on the total exergy losses from the solar still on account of $E_{X_{\mathrm{insul.}}}$ and $E_{X_{t,g-a}}$as shown in the derived expression (22). The instantaneous global exergy efficiency accounts for internal as well as external exergy transfers of the passive solar still. Negative effect of exergy transfer during one process sometimes produces useful effect for the other process, if it is seen in totality. It can be explained by taking an example of exergy balance in the glass cover in Equation (8); it is evident that $E_{X_{d,g}}$ is dependent on $E_{X_{t,w-g}}$ and $E_{X_{t,g-a}}$in two different temperature zones of ($T_w - T_{gi}$) and ($T_{go} - T_a$). It is desirable to have higher value of $E_{X_{t,w-g}}$ for maximum output of distillate, which depends on $E_{X_{e,w-g}}$, a larger part of $E_{X_{t,w-g}}$leading to higher exergy destruction in the glass cover. At the same time, for maximum output of distillate, the rate of condensation should be faster. It is possible by increasing $E_{X_{t,g-a}}$, which leads to lower exergy destruction in the glass cover.

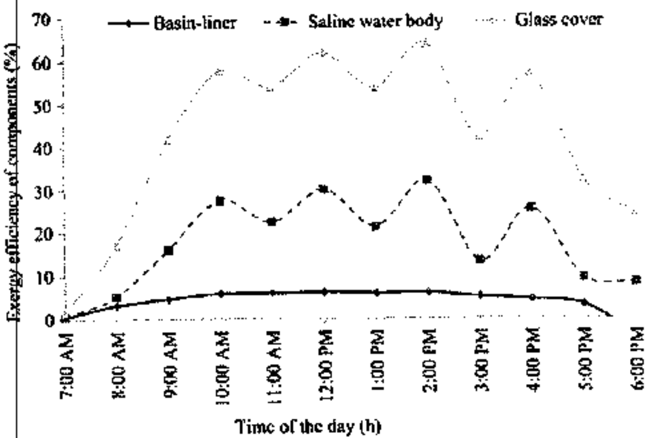


Figure 6. *Hourly variation in exergy efficiency of the components of the passive solar still.*

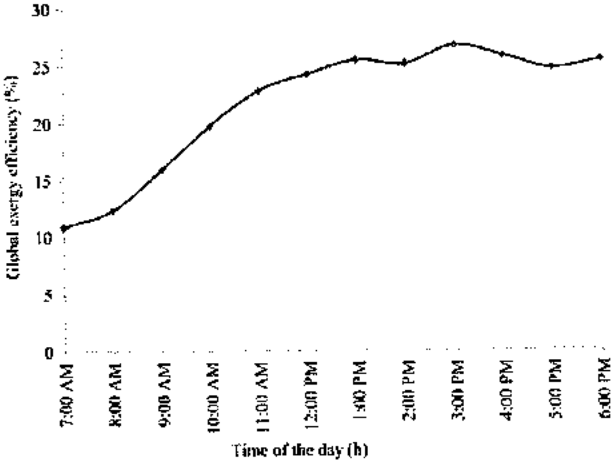


Figure 7. *Hourly variation in global exergy efficiency of the passive solar still.*

Similar case is for both basin-liner and water body also. But from Equation (16), it is evident that the instantaneous overall and daily average exergy efficiency of solar still is only due to useful evaporative heat transfer responsible for distillate production with respect to incoming solar exergy on the glass cover. $Ex_{e,w-g}$ is comparatively much lower than the input solar exergy. Therefore, there is a need to optimize all factors for maximization of overall exergy efficiency, utilizing solar exergy efficiently and economically in the case of solar distillation system, even though solar exergy is available at zero fuel cost. Raising the limit of energy and exergy efficiency by means of changing design parameters increases the capital cost significantly, i.e. not desirable. Hence, finding the methods of effective utilization of solar exergy is justified for higher cost-effective efficiencies.

In this analysis, effects of the operating, climatic and design parameters on the daily yield, as well as on the daily average overall energy and exergy efficiency of the passive solar still, are extensively examined. The daily yield as well as daily average overall energy and exergy efficiency decreases with increase in water depth in the range 10–40 mm. By regression analysis, it is found that there is nearly linear decrease in daily yield of ~17% with every 10-mm increase in water depth. Daily average overall energy and exergy efficiency decreases following second-order polynomial equation with increase in water depth. This is because of the higher heat storage capacity of water at the higher depth of saline water. At lower depth, the thermal inertia of the passive solar still remains low. Consequently, the required minimum temperature difference between saline water and the glass cover for condensation under side of the glass cover is reached readily. It produces more freshwater with higher energy and exergy efficiency.

It is observed that daily yield and energy efficiency increases and exergy efficiency decreases with increase in wind speed (V). The rate of increase and decrease is faster till 1 m/s of wind speed. After that these rates become slower and nearly constant up to V=4 m/s. The effect beyond 4 m/s is also examined, but there is not much contribution of it for the improvement of the performance technically as it is a climatic parameter beyond human control. It is also inferred that any mechanical effort to increase the wind velocity beyond 1 m/s over glass cover may not be technically as well as economically beneficial. The trend and reasons for variations in the yield and energy efficiency given by various researchers are confirmed in this analysis also. It is due to higher temperature difference in saline water–glass cover temperature arising out of higher convective heat loss from the glass cover to the atmosphere at higher wind speed. Here, it has been found that with increase in wind velocity, there is a decrease in the average temperature of both the saline water and glass cover individually, but $(T_w - T_{gi})$ increases. The decrease in average glass temperature is attributed to the increase in convective heat loss from the glass cover to the atmosphere at higher wind speed, but the decrease in the average saline water temperature is found to be due to increased overall heat loss coefficient (U_L).This fact is in good agreement with the results reported by Sharma and Mullick [33]. The reason of gradual decrease in exergy efficiency lies in this finding about the decrease in the water temperature with increase in wind speed, as the available energy in the evaporative heat transfer becomes lower with reference to the ambient temperature referring Equation A.3.

The effect of insulation thickness on efficiencies and daily distillate yield is also studied here. All three performance parameters of the passive solar still increase with the increase in the insulation thickness. 100% increase in insulation thickness of the passive solar still results in an increase in energy efficiency, exergy efficiency and daily yield by 5.33, 7.71 and 5.52%, respectively. Higher percentage of rise in exergy efficiency in comparison with the energy efficiency is due to a reduction in exergy destruction by 0.50 and 0.45% in the basin-liner and water body, respectively, and increment by 1.66% in the glass cover for 100% increase in the insulation thickness.

The effect of glass cover tilt on efficiencies and daily distillate has been found very significant. It is observed that better performance of the passive solar still is achieved at lower angle of inclination. Increase in inclination angle from 15° to 60° reduces the rate of heat loss from glass cover to the atmosphere and irreversibility of the glass cover by 26.8 and 9.4%, respectively, and increases the irreversibility of the basin-liner and water body by 4.47 and 21.15%, respectively, which causes overall lower performance at higher angles of inclination. At 15° inclination of the glass cover, energy efficiency, exergy efficiency and daily yield are 32.90%, 5.53% and 4.52 l/m^2/day, respectively. In this analysis, theoretically maximum performance is observed at 0°. But it should not be $<10°$ to avoid the drop back of the distillate after condensation [6]. These results are in good agreement with the views presented in literature given by Jabbar and Khalifa [34].

The above-mentioned findings have been found similar to the results presented by researchers mentioned in the reference. It validates the present thermodynamic model used here for the energy and exergy analysis of the passive solar distillation system. A little variation in results based on exergy analysis is due to different design and operating parameters of the passive solar still and modification in the model for exergy analysis as compared with the model suggested by Torchia-Nunez *et al.* [15]. In this article, unique observations and discussions are highlighted about the exergy destructions, energy and exergy efficiencies and measures to improve the performance of the passive solar still.

5 CONCLUSIONS AND RECOMMENDATIONS

A passive solar still is analyzed through the energy and exergy analysis methods of thermodynamics. Parametric study has been conducted to find out the effects of different parameters such as saline water depth, wind velocity, thickness of insulation and angle of inclination of the glass cover on the productivity, energy and exergy efficiency of the basin-type passive solar still. The causes, factors and exact locations responsible for lower energy and exergy efficiency and ultimately less productivity of the passive solar still are ascertained. Some concluding remarks from this study are as follows:

- (i) The exergy efficiency of the passive solar still is lower than the energy efficiency. It is mainly due to less available energy in the evaporative heat transfer as the system temperature in the form of saline water temperature varies in the lower range of 15–95°C only.
- (ii) The maximum instantaneous overall energy and exergy efficiency and hourly yield are 49.29%, 9.48% and 0.69 l/m^2, respectively.
- (iii) Daily average energy efficiency, exergy efficiency and productivity are found to be 30.42%, 4.93% and 4.17 l/day, respectively.
- (iv) Largest exergy destruction takes place in the basin-liner. The maximum rate of exergy destruction in the basin-liner, water body and glass cover has been estimated as 386, 62.5 and 9.7 W/m^2, and the consequent exergy efficiencies of 3.91, 17.67 and 42.36% have been found for the components of passive solar still, respectively. The global exergy efficiency is estimated as 23.14%.
- (v) There is nearly linear decrease in daily yield of ~17% with every 10 mm increase in water depth. Energy and exergy efficiency also decrease with an increase in water depth.
- (vi) It is observed that daily yield and energy efficiency increases and exergy efficiency decreases with an increase in wind speed. The rate of increase and decrease is faster till 1 m/s of wind velocity.
- (vii) 100% increase in insulation thickness of the passive solar still increases the energy efficiency, exergy efficiency and daily yield by merely 5.33, 7.71 and 5.52%, respectively.

There is a need for much stronger collective effort in R&D by engineers, researchers and academicians of the concerned areas to suggest the ways of reducing the exergy destruction to increase the exergy efficiency of the solar distillation systems. Widespread use of solar energy for desalination will contribute a lot to reduce the amount of greenhouse gas emissions to the environment causing global warming and climate change. Therefore, sincere steps are to be taken to bring solar distillation systems from laboratory or experimental stage to commercial stage with higher cost-effective efficiencies for sustainable development.

ACKNOWLEDGEMENT

Authors thank the Head of the Department of Renewable Energy Engineering, College of Technology and Engineering, MPUAT, Udaipur, Rajasthan (India), for giving an opportunity to observe the actual working of passive solar stills and providing required data for this theoretical analysis and comparison with the experimental results.

APPENDIX

The atmospheric temperature is considered as the reference temperature. The rate of thermal exergy transfer associated with the heat transfers and that owing to blackbody radiation are calculated using Equations (1) and (2). Expressions are given as follows:

$$E_{X_w} = h_w(T_b - T_w)\left(1 - \frac{T_a}{T_b}\right) \qquad (A.1)$$

where h_w is the convective heat transfer coefficient between basin-liner and saline water (W/m^2 K).

$$E_{X_{insul.}} = h_b(T_b - T_a)\left(1 - \frac{T_a}{T_b}\right) \qquad (A.2)$$

where h_b is the overall heat transfer coefficient between basin-liner and atmosphere (W/m^2 K).

$$E_{X_{e,w-g}} = h_{e,w-g}(T_w - T_{gi})\left(1 - \frac{T_a}{T_w}\right) \qquad (A.3)$$

where $h_{e,w-g}$ is the evaporative heat transfer coefficient between saline water and glass cover (W/m^2 K).

$$E_{X_{c,w-g}} = h_{c,w-g}(T_w - T_{gi})\left(1 - \frac{T_a}{T_w}\right) \qquad (A.4)$$

where $h_{c,w-g}$ is the convective heat transfer coefficient between saline water and glass cover (W/m^2 K).

$$E_{X_{r,w-g}} = h_{r,w-g}(T_w - T_{gi})\left[1 + \frac{1}{3}\left(\frac{T_a}{T_w}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_w}\right)\right] \qquad (A.5)$$

where $h_{r,w-g}$ is the radiative heat transfer coefficient between saline water and glass cover (W/m^2 K).

$$E_{X_{r,g-a}} = h_{r,g-a}(T_{go} - T_a)\left[1 + \frac{1}{3}\left(\frac{T_a}{T_{go}}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_{go}}\right)\right] \qquad (A.6)$$

where $h_{r,g-a}$ is the radiative heat transfer coefficient between glass cover and atmosphere (W/m^2 K).

$$E_{X_{c,g-a}} = h_{c,g-a}(T_{go} - T_a)\left(1 - \frac{T_a}{T_{go}}\right) \qquad (A.7)$$

where $h_{c,g-a}$ is the convective heat transfer coefficient between glass cover and atmosphere (W/m^2 K).

REFERENCES

[1] Ranjan KR, Kaushik SC. Energy, exergy and thermo-economic analysis of solar distillation systems: a review. *Renew Sustain Energy Rev* 2013;27:709–23.

[2] Ranjan KR, Kaushik SC. Economic feasibility evaluation of solar distillation systems based on the equivalent cost of environmental degradation and high-grade energy savings. *Int J Low-Carbon Technol* 2013; doi: 10.1093/ijlct/ctt048.

[3] Moran MJ, Shapiro HN. *Fundamentals of Engineering Thermodynamics. SI Version*, 6th edn, New Delhi: Wiley India (P) Ltd, 2010.

[4] Singh N, Kaushik SC, Mishra RD. Exergetic analysis of a solar thermal power system. *Renew Energy* 2000;19:135–43.

[5] Kaushik SC, Reddy VS, Tyagi SK. Energy and exergy analyses of thermal power plants: a review. *Renew Sustain Energy Rev* 2011;15:1857–72.

[6] Tiwari GN, Tiwari AK. *Solar Distillation Practice for Water Desalination Systems*. India: Anamaya Publishers, 2007.

[7] Samee MA, Mirza UK, Majeed T, *et al.* Design and performance of a simple single basin solar still. *Renew Sustain Energy Rev* 2007;11:543–9.

[8] Velmurugan V, Srithar K. Performance analysis of solar stills based on various factors affecting the productivity—a review. *Renew Sustain Energy Rev* 2011;15:1294–304.

[9] Kabeel AE, El-Agouz SA. Review of researches and developments on solar stills. *Desalination* 2011;276:1–12.

[10] Rajaseenivasan T, Elango T, Murugavel KK. Comparative study of double basin and single basin solar stills. *Desalination* 2013;309:27–31.

[11] Cooper PI. The maximum efficiency of single-effect solar stills. *Sol Energy* 1973;15:215–7.

[12] Kwatra HS. Performance of a solar still: predicted effect of enhanced evaporation area on yield and evaporation temperature. *Sol Energy* 1996;56:261–6.

[13] Garcia-Rodriguez L, Gomez-Camacho C. Exergy analysis of the SOL-14 plant. *Desalination* 2001;137:251–8.

[14] Sow O, Siroux M, Desmet B. Energetic and exergetic analysis of a triple effect distiller driven by solar energy. *Desalination* 2005;174:277–86.

[15] Torchia-Nunez JC, Porta-Gandara MA, Cervantes-de Gortari JG. Exergy analysis of a passive solar still. *Renew Energy* 2008;33:608–16.

[16] Dwivedi VK, Tiwari GN. Annual energy and exergy analysis of single and double slope passive solar stills. *Trends Appl Sci Res* 2008;3:225–41.

[17] Tiwari GN, Dimri V, Chel A. Parametric study of an active and passive solar distillation system: energy and exergy analysis. *Desalination* 2009;242:1–18.

[18] Kumar S, Tiwari GN. Analytical expression for instantaneous exergy efficiency of a shallow basin passive solar still. *Int J Therm Sci* 2011;50:2543–9.

[19] Kianifar A, Heris SZ, Mahian O. Exergy and economic analysis of a pyramid-shaped solar water purification system: active and passive cases. *Energy* 2012;38:31–6.

[20] Kaushik SC, Ranjan KR, Panwar NL. Optimum exergy efficiency of single-effect ideal passive solar stills. *Energy Effi* 2013;6:595–606.

[21] Bejan A. *Advanced Engineering Thermodynamics*. Hoboken, New Jersey: John Wiley and Sons, Inc., 2006.

[22] Kotas TJ. *The Exergy Method of Thermal Plant Analysis*. London: Butterworths, 1985.

[23] Petela R. *Engineering Thermodynamics of Thermal Radiation: for Solar Power Utilization*. New York: The McGraw -Hill Companies Inc, 2010.

[24] Dunkle RV. *Solar water distillation: the roof type still and a multiple effect diffusion still*. In: 1961;5:895–902.

[25] Duffie JA, Beckman WA. *Solar engineering of thermal processes*. John Wiley and Sons Inc., 2006.

[26] Sampathkumar K, Senthilkumar P. Utilization of solar water heater in a single basin solar still—an experimental study. *Desalination* 2012;297:8–19.

[27] Cerci Y. The minimum work requirement for distillation processes. *Exergy Int J* 2002;2:15–23.

[28] Dincer I, Rosen MA. *Exergy: Energy, Environment and Sustainable Development*. First edn, UK: Elsevier Ltd., 2007.

[29] Petela R. Exergy of heat radiation. *Trans ASME J Heat Trans* 1964;2:187–92.

[30] Petela R. Exergy analysis of the solar cylindrical-parabolic cooker. *Sol Energy* 2005;79:221–33.

[31] Porta MA, Chargoy N, Fernandez JL. Extreme operating conditions in shallow solar stills. *Sol Energy* 1997;61:279–86.

[32] Dev R, Tiwari GN. Characteristic equation of a passive solar still. *Desalination* 2009;245:246–65.

[33] Sharma VB, Mullick SC. Estimation of heat-transfer coefficients, the upward heat flow, and evaporation in solar still. *J Sol Energy Eng* 1991;113:36–41.

[34] Jabbar A, Khalifa N. On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes. *Energy Conver Manag* 2011;52:431–6.