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Energy and exergy analysis of flat plate solar collector-assisted active solar distillation system

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ABSTRACT

Due to the fast increase in the world population, the need for the energy and water increases rapidly. Various studies have been made to meet this extra energy and water demand. Most of these studies have focused on solar energy and solar driven desalination systems. Solar water desalination is a well-known and proven technique which has been used for a long time at remote areas and places suffering from shortage of potable quality water. In this study, a flat plate solar collector-assisted water distillation system was designed and tested under actual conditions and its energy and exergy efficiencies were analyzed, which is the main contribution of this study to the literature related to solar desalination systems. The system works under closed cycle in order to prevent efficiency losses caused by internal fouling in both solar collector and distillation unit. The maximum daily energy efficiency of the system was obtained as 48.1% and the maximum exergy efficiency was found as 2.76% for optimum flow rate values.

Keywords: Solar energy; Active distillation System; Efficiency

1. Introduction

Energy and freshwater are among the most vital requirements for life on earth. A tiny fraction of global water resource (~1%) is available to be used by human beings, animals and plants [1].

Fresh water is a major health issue and strategic concern for most of the world today [2] due to several reasons such as; increasing population and industrialization, mostly in developing countries [3]. On the other hand, the lack of potable water poses a big problem in arid to semiarid regions of the world where freshwater is becoming very scarce and expensive. In those cases, fresh water has to be fed through a costly water distribution network or transported to distant places which significantly increase the costs.

In case of a shortage of fresh water, desalination (the process of separating salt from saline water) is a way to produce usable and drinkable fresh water from any source of saline water [4]. Especially the fossil fuels have a relatively high cost and environmental impacts (significant amount of pollution, greenhouse gas, and global warming) which inevitably leads to seeking for alternative methods. Using renewable energy sources is a good way to cope with energy shortage and environmental problems. Renewable energy sources can easily be replaced by fossil fuels in the near future, especially in stationary plants. Depleting reserves of fossil fuels and environmental problems make it necessary to use the reserves more carefully. The global capacity of desalination plants, including renewable desalination, is expected to grow at an annual rate of more than 9% between 2010 and 2016 [5].

The main issue for the renewable energy-driven desalination process is to find a low cost, environmentally friendly, readily available energy to drive the process. Solar energy is one of the best sources of this type and it is abundant throughout the year, especially in solar belt region where most of the water scarcity is suffered by about five billion people. Several methods using solar energy can be used easily to produce potable water from salt water to save people and agriculture from water scarcity. Main requirement of solar desalination process is thermal energy, and it can be provided through thermal and PV applications. This energy can be integrated with various types of structure and capacity distillation systems to produce fresh water. Fig. 1 shows a full classification and integrated big picture view of desalination processes and the place of solar energy among the other methods.

There are mainly two groups of solar-driven desalination systems as direct and indirect systems. Direct systems are low cost and suitable for small applications, and there are two types of direct desalination technique as humidification–dehumidification method and solar stills.

Basically, solar stills are classified as active or passive solar stills according to their operation modes and modifications. Active solar stills typically use a secondary external heat source such as; collector/concentrator panel, solar pond, hybrid PV/T systems, waste thermal energy from any chemical/industrial plant, etc. However, the efficiency losses because of the fouling and the problem of energy input continuity are disadvantages of the active systems caused by external heat sources. If there is no supplementary external heat source, the system is called a passive solar still [8]. Especially, active and passive solar stills are generally used in arid and semiarid regions with small population or in regions distant from the useful fresh water sources.

Taghvaei et al. experimentally investigated the performance variation of active solar stills depending on simultaneous effects of collector area and brine depth. According to their experimental results; (i) the amount of water production and efficiency of active solar stills, having different sized solar collecting areas, decrease by the brine depth, (ii) larger solar collecting area

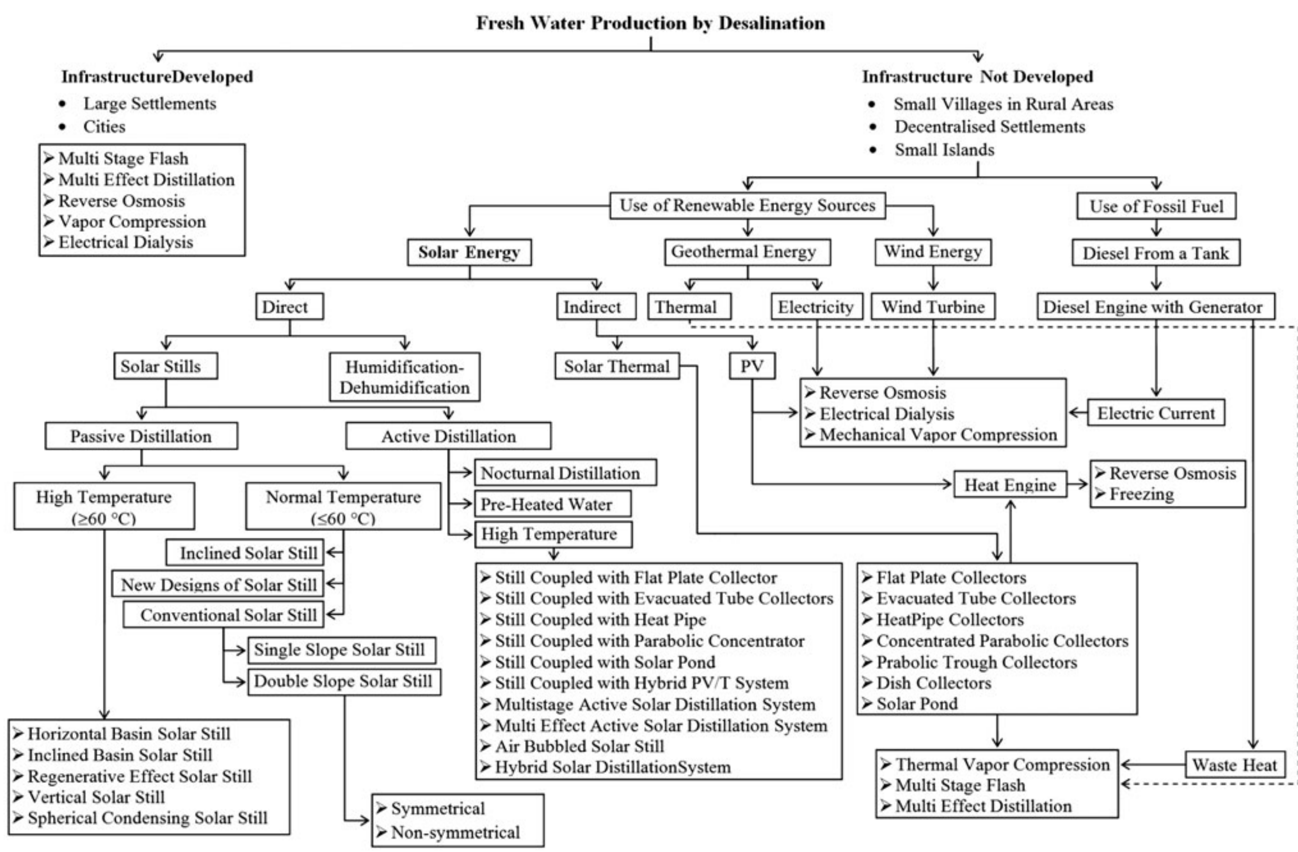

Fig. 1. Desalination techniques used for fresh water production [3,6,7].

increases the productivity and decreases the efficiency of active solar stills having different brine depth, (iii) as the solar collecting area becomes larger, brine depth becomes less effective on the productivity of active solar stills [9]. Kiatsiriroat et al. studied the performance of a multiple effect vertical solar still with a flat plate solar collector [10]. Zaki et al. performed experiments on a concentrator-supported solar still to calculate its performance and reported an increased output with externally fed thermal energy [11]. Abad et al. tested a pulsating heat pipe attached to solar still. The pulsating heat pipe proved to have some advantages such as short response time, flexibility, high thermal conductivity, etc. The experimental results have indicated an output increase in distillate by about 40% when pulsating heat pipe was used [12]. Deniz made a water distillation system with vacuum tube solar collector and tested at actual climatic conditions in Turkey. He developed a mathematical model in order to predict thermal performance of the solar still equipped with vacuum tube solar collector and then compared the predicted results with experimental results which showed a good agreement [13]. Panchal and Shah investigated the optimum water depth for a vacuum tube collector assisted double basin solar still and water cost per kg in Mehsana, Gujarat [14]. Liu et al. investigated the parameters affecting the thermal performance and economy of evacuated solar collector-assisted desalination system and found that increasing the number of effects and heating steam temperature of the first effect reduce the cost of fresh water [15]. Badran et al. investigated solar still assisted with flat plate collector (FPC) using tap water and saline water and found that using tap water increased distilled fresh water by about 4.5 times compared to using salt water [16]. Dwivedi and Tiwari compared double slope active solar still with double slope passive solar still under naturel circulation and observed 51% more fresh water production with active solar still. They also calculated that double slope active solar still has lower thermal efficiency but higher exergy efficiency than double slope passive solar still [17]. Yadav found that forced circulation used in a FPC assisted solar still gives 5–10% higher yield compared to the still with thermosyphon mode operation and there is no significant need for choosing forced circulation over thermosyphon mode in FPC-assisted solar still [18]. Tiris et al. tested a basin type solar still integrated with two flat plate solar collectors and found that integration of collector to solar still increases the yield about 100%. They found the maximum yield as 2.575 l/m^2 d for simple basin and 5.18 l/m^2 d for basin type with FPCs [19].

In this study, experimental and theoretical investigations have been performed on a flat plate solar collector-assisted distillation system under actual conditions. The experimental system has been designed to work as closed cycle in order to avoid efficiency losses caused by internal fouling in both solar collector and distillation unit. The study including the design of the system together with its energy and exergy analyses is a significant contribution to the related literature on this type of solar distillation systems. The experiments have been conducted for eight days during the months June and July in which the weather conditions were similar. The theoretical amount of distilled water and system's energy and exergy efficiencies has been calculated using the data obtained from the experiments.

2. Experimental setup and theoretical analysis of the system

2.1. Experimental setup

Fig. 2 shows the schematic diagram of the natural circulation FPC-assisted solar still used in the experiments. As shown in Fig. 2, FPCs can be used in active solar distillation systems with high efficiency and improve the amount of distillation. However, the collector should be used in closed cycle to avoid precipitation of salt and other contaminants in the tubes and deteriorate the performance of the collector. A heat exchanger should be used (Fig. 2) to transfer the heat to the basin water of the still in order to avoid this performance loss. The operation of these devices in thermosyphon mode is also more advantageous than the forced circulation mode in terms of simplicity, reliability and cost-effectiveness.

Absorber plate surface is heated by the solar energy. Water evaporates to become vapor and when it comes to the colder glass cover, condensation occurs to produce condensate which then fills into a condensate collecting channel and routed to the cavity sidewall to exit the collector. Fresh water accumulates in a storage tank and is measured here. The inclination of the system is 41° South, which is the latitude of Karabuk city-center.

Collectors were connected to the distiller directly providing a natural circulation to heat the water in the distiller. The height of the water in the distiller was 5 cm for all experiments. At the same time, the absorber surface color of the still was chosen as black in order to increase absorptivity. The water distilled in the distiller was collected by the distillate channels in the distiller and collected in the distilled water tank.

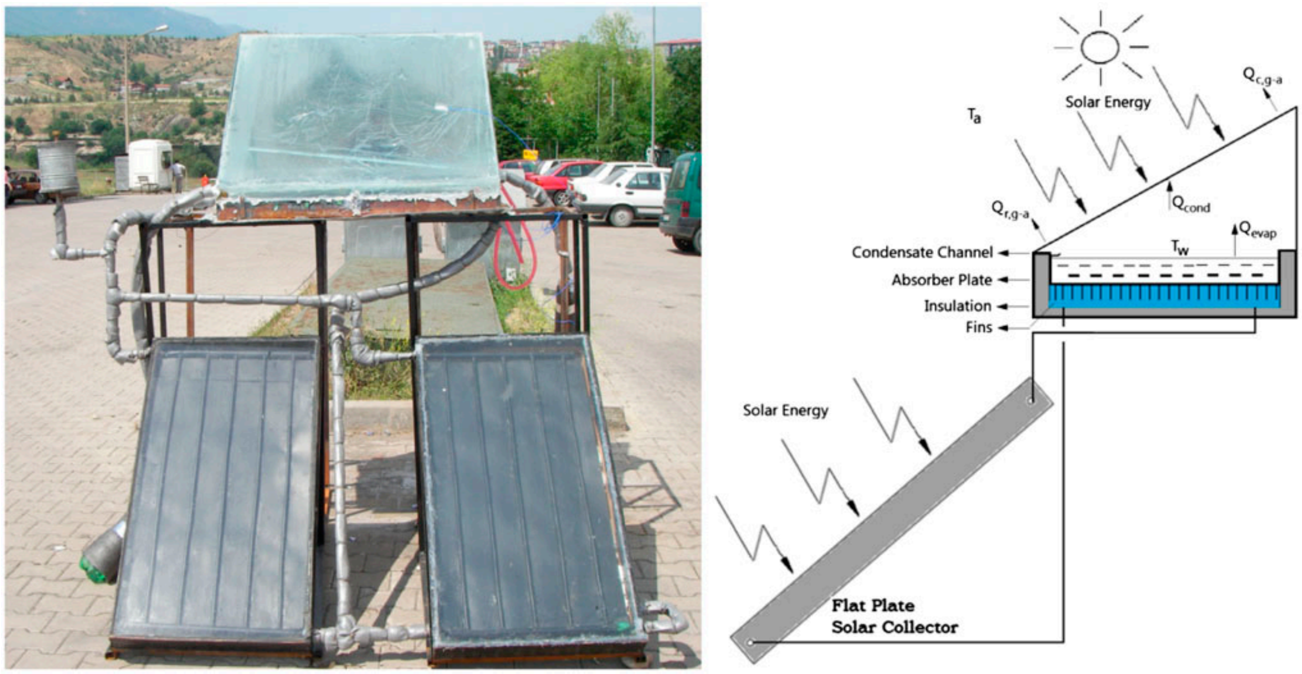

Fig. 2. Basin still coupled with a FPC in the natural circulation and closed cycle mode with its schematic diagram.

The test water (1,006 kg/m^3 of density) was taken from the Black Sea. The device is thoroughly insulated against heat loss by using 5 cm thickness polyurethane and XPS. Table 1 gives the design parameters of the solar still and the collector.

The experiments were done in Karabuk city in June 2013 (4 d) and July 2013 (4 d) in eight days from 09:00 to 18:00 on a flat plate solar collector assisted distillation system. Water temperature, ambient temperature, glass cover temperature, and vapor temperature along with the solar radiation were measured from different points of the system. The fresh water was accumulated in small tanks and distilled water mass per hour were measured.

Temperatures were measured by calibrated Cr-Al thermocouples which were connected to a data converter (Advantech Adam 4019+), with ±0.1% accuracy. The solar radiation intensity falling onto the system surface was measured by a Solar-130 type pyranometer with digital readout, which has an accuracy of ±1.5%, and the pH was measured using a TES 1380 model pH meter with ±0.01 pH accuracy.

Table 1
Design Parameters for single slope active solar still

Parameter	Value
A_c	1 m^2
A_{ss}	0.95 m^2
T_s	6,000 K
F_R	0.8
$(\alpha\tau)_c$	0.8
U_{LC}	6 W/m^2°C
Glass thickness (mm)	6
Slope of the system	41°

2.2. Theoretical analysis of solar still

Fig. 2 gives the illustration of the flat plate solar collector assisted distillation system. T_a, T_g, and T_w in the figure represents; ambient temperature, glass temperature and water temperature, respectively. h_{wg}, h_{ga}, and h_{wb} are the heat transfer coefficients for; water surface-glass, glass-environment, and water-basin liner, respectively [21]. h_{ew} is the coefficient of heat loss by evaporation from water surface, P_g is the glass saturated partial pressure, and P_w is the water saturated partial pressure [20,21]:

$$h_{ew} = 4.0\,\frac{p_w - p_g}{T_w - T_g} \tag{1}$$

$$P_g = e^{\left(25.317 - \frac{5144}{T_g}\right)} \tag{2a}$$

$$P_w = e^{\left(25.317 - \frac{5144}{T_w}\right)} \tag{2b}$$

Evaporative heat transfer correlation is given as follow:

$$Q_{ew} = h_{ew}(T_w - T_g) \tag{3}$$

hourly output of still is [20,22]:

$$\dot{m}_{ew} = \frac{h_{ew}\left(T_w - T_g\right)}{L} \times 3600 \tag{4}$$

The solar still overall thermal efficiency is considered to be the ratio of evaporative heat transfer to the solar irradiance on the absorber plate which can be formulated as following equation [20,22]:

$$\eta(\%) = \frac{Q_{ew}}{I_{eff} \cdot A} \tag{5}$$

2.3. Exergy analysis of solar still

Exergy analysis can be performed using the first and second thermodynamic laws and it can be defined as the maximum amount of work that a defined system can produce or a mass or energy flow as it comes to equilibrium with a reference environment [23]. The energy and exergy efficiencies of a system have different behaviors depending on climate and operating conditions. Basically, compared to energy analysis, exergy analysis gives us a better insight into how a physical process works. An increase in irreversibility increases entropy while decreasing the exergy of the system. Therefore, it is necessary to determine and reduce irreversibility for all parts of the apparatus [23].

Exergy balance equation of a control volume can be written in general form as follows [24]:

$$\sum \dot{E}\chi_{in} - \sum \dot{E}\chi_{out} = \sum \dot{E}\chi_{dest} \tag{6}$$

Exergy efficiency of solar stills is defined as the desired product exergy divided by the input exergy [25]:

$$\eta_{EX} = \frac{\dot{E}\chi_{product}}{\dot{E}\chi_{in}} = 1 - \frac{\dot{E}\chi_{dest}}{\dot{E}\chi_{in}} \tag{7}$$

For a defined solar still, exergy of the product or desired output (yield) which was produced by the condensation of vapor can be written as [26]:

$$\dot{E}\chi_{product} = \dot{m}_{ew} \times E\chi_{ew} \tag{8}$$

$$E\chi_{ew} = \left[L \times \left(1 - \frac{T_a + 273}{T_w + 273}\right)\right] \tag{9}$$

where $E\chi_{ew}$ is the exergy of latent heat of vaporization (J kg^{-1}) and $\dot{m}_{ew}$ is the hourly yield/output of solar still (kg h^{-1}). Exergy output of a solar still is a function of evaporation of the salt water and its condensation on the glass cover. In real system, some of the condensed water falls back to the basin from the glass cover where the vapor condenses. Therefore, actual experimental results of exergy would be less than the theoretically predicted exergy output. Hourly exergy output of a solar still can be written as [25]:

$$\dot{E}\chi_{product} = \frac{\dot{m}_{ew}}{\left(3600\,\text{s}\,\text{h}^{-1}\right)} \times \left[L \times \left(1 - \frac{T_a + 273}{T_w + 273}\right)\right] \tag{10}$$

where m_{ew} is hourly yield of solar still (kg/h), L is the latent heat of vaporization (J/kg), T_a is the ambient temperature (°C), and T_w is the water temperature (°C).

The solar still product is generated by means of: seawater, solar energy received on the surface of the solar still and the FPC and consumption of power for pumping. The solar still product can be expressed as:

$$\dot{E}\chi_{in} = \dot{m}_{sw}E\chi_{sw} + \dot{E}\chi_{sun}\,(\text{SS}) + \dot{E}\chi_{sun}\,(\text{FPC}) + \dot{E}\chi_{pump} \tag{11}$$

The exergy loses are through the heat loss to the outside and the brine discharge from the solar still. Using Eq. (11), the exergy efficiency is obtained from the following Eq. (12) as [26]:

$$\eta_{EX} = \frac{\dot{m}_{ew}E\chi_{ew}}{\dot{m}_{sw}E\chi_{sw} + \dot{E}\chi_{sun}\,(\text{SS}) + \dot{E}\chi_{sun}\,(\text{FPC}) + \dot{E}\chi_{pump}} \tag{12}$$

Assuming that the salt water is at thermodynamic dead state ($\dot{m}_{sw}E\chi_{sw} = 0$) (equilibrium of chemical composition, temperature, and pressure) and flate plate collector hasn't got any power consumption, like a circulation pump ($\dot{E}\chi_{pump} = 0$) exergy efficiency becomes [27]:

$$\eta_{EX} = \frac{\dot{m}_{ew}E\chi_{ew}}{\dot{E}\chi_{sun}\,(\text{SS}) + \dot{E}\chi_{sun}\,(\text{FPC})} \tag{13}$$

Exergy input of the passive solar still is only solar radiation exergy and can be evaluated using Petela [28] as:

$$\begin{aligned}\dot{E}\chi_{\text{in}} &= \dot{E}\chi_{\text{sun}}\,(\text{SS}) \\ &= A_{\text{s}} \times I(t)_{\text{s}} \\ &\quad \times \left[1 - \frac{4}{3} \times \left(\frac{T_{\text{a}} + 273}{T_{\text{s}} + 273}\right) + \frac{1}{3} \times \left(\frac{T_{\text{a}} + 273}{T_{\text{s}} + 273}\right)^4\right]\end{aligned} \tag{14}$$

where A_s is the basin area of the solar still (m^2), $I(t)_s$ is the solar radiation on the tilted glass surface of solar still (W/m^2), T_S is the temperature of sun, 6,000 K, and $\dot{E}\chi_{sun}$ (SS) is the exergy input to solar still through radiation.

The exergy input for the active solar still is the sum of radiation exergy on the solar still, the FPC and exergy of the pump. The radiation exergy input from the sun to the solar still and the FPC is combined to define exergy input to the active solar still as follows:

$$\dot{E}\chi_{\text{in}} = \dot{E}\chi_{\text{sun}}\,(\text{SS}) + \dot{E}\chi_{\text{sun}}\,(\text{FPC}) \tag{15}$$

Following equation can be used to calculate exergy input ($\dot{E}\chi_{sun}$(FPC)) from the sun to FPC:

$$\dot{E}\chi_{\text{sun}}\,(\text{FPC}) = \dot{Q}_{\text{u}}\left(1 - \frac{T_{\text{a}} + 273}{T_{\text{w,o}} + 273}\right) \tag{16}$$

Exergy input can be calculated below equation for solar distillation system:

$$\begin{aligned}\dot{E}\chi_{\text{in}} &= A_{\text{s}} \times I(t)_{\text{s}} \\ &\quad \times \left[1 - \frac{4}{3} \times \left(\frac{T_{\text{a}} + 273}{T_{\text{s}} + 273}\right) + \frac{1}{3} \times \left(\frac{T_{\text{a}} + 273}{T_{\text{s}} + 273}\right)^4\right] \\ &\quad + \dot{Q}_{\text{u}}\left(1 - \frac{T_{\text{a}} + 273}{T_{\text{w,o}} + 273}\right)\end{aligned} \tag{17}$$

where

$$\dot{Q}_{\text{u}} = A_{\text{c}}\,F_{\text{R}}\left[(\alpha\tau)_{\text{c}}\,I_{\text{c}} - U_{\text{LC}}\left(T_{\text{w,o}} - T_{\text{a}}\right)\right] \tag{18}$$

3. Results and discussion

Solar energy is a promising source of renewable energy that can be used for desalination process at virtually any place and scale. The main goal of a solar driven distillation system is to increase the distillate production. There are many parameters affecting the amount of distillate produced by the solar still such as; temperature of the feed water, insolation, air temperature, wind speed, humidity, sky conditions, salinity of water, thermal, and physical properties of the material used in its fabrication, orientation of the still, cover angle, gap between the cover, and water surface, insulation of the basin, vapor leakage, absorption-transmittance properties of the still, water depth in the basin.

Tests in this study were conducted for 10 h. Fig. 3 shows the hourly temperatures of the basin water, glass cover, absorber, and the ambient temperature. The incident solar radiation were measured on 23th of June and presented in Fig. 3 which clearly shows that the temperatures of the system vary depending on the solar radiation intensity. The maximum temperature and the maximum radiation incident were recorded at 15:30 and 13:30, respectively. Both temperature and radiation incident values decrease after this time.

The design parameters and climatic parameters were used to calculate the theoretical productivity of the still and the productivity and efficiency change by the time are plotted in Figs. 4 and 5, respectively. The hourly output from the still is a function of the temperature difference between water and the cavity, which is one of the most important parameters in condensation of water. The maximum hourly output of the still was obtained between 14:00 and 16:00 when the water temperature was at maximum.

Fig. 4 shows the comparison of the actual fresh water production of experimental setup and the results obtained from the theoretical calculation. Fig. 4 shows a good match between the theoretical and experimental results of hourly distiller output. The maximum amount of distilled water was produced while the water temperature was maximum during the operation of the system.

Fig. 5 shows the hourly variation of efficiency for the experiment conducted on 10th of July. The minimum efficiency value of the system was 1.8% at 09:00 o'clock and the maximum efficiency was 48% at 18:00. pH value of the distillate was measured as 6.2. System continues distillation after the sunset using the energy stored in the system during daytime. System has yielded about 350–500 ml distilled water after the sunset.

The exergy of solar irradiation is relatively high. However, it is not the same for the exergy efficiency of a solar collector. Daily exergy output and exergy efficiency values are listed in Table 2. The daily exergy efficiency is calculated by Eq. (7) and it varies from 0.0057 to 2.7658% as shown in Table 2.

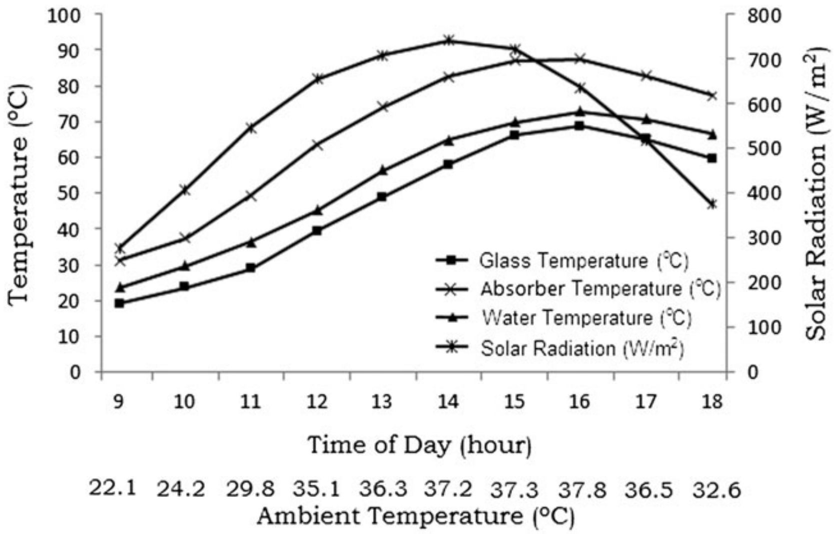

Fig. 3. Hourly variations of temperatures and solar radiation for solar collector-assisted solar still.

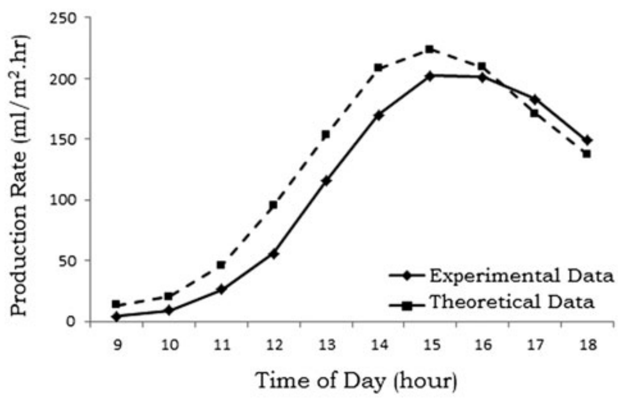

Fig. 4. Comparison between theoretical and experimental productivity.

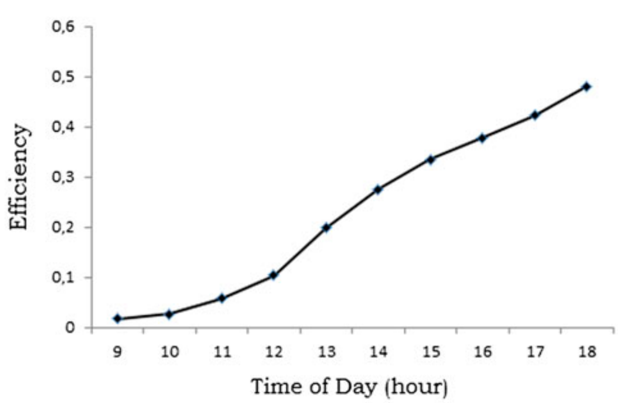

Fig. 5. Variation of the efficiency by the time.

Table 2
Daily exergy input, output, and efficiency of the solar still

Time of day (h)	$\dot{E}\chi_{\text{in}}$ (W)	$\dot{E}\chi_{\text{product}}$ (W)	η_{EX} (%)
09:00	263.2655	0.0149	0.0057
10:00	388.9128	0.1132	0.0291
11:00	525.4949	0.3745	0.0712
12:00	634.5822	1.1788	0.1857
13:00	689.6385	5.1147	0.7416
14:00	723.7161	9.0648	1.2525
15:00	702.9642	12.4860	1.7762
16:00	615.1651	13.2027	2.1462
17:00	496.6433	11.7998	2.3759
18:00	354.3860	9.8016	2.7658

Figs. 3 and 4 clearly show that the increase in the water temperature improves still efficiency. Higher water temperature increases the evaporation rate and improves the evaporation exergy and still efficiency. However, some other parameters such as glass surface temperature and ambient temperature also affect the system exergy and efficiency.

4. Conclusion

Thermodynamic analyses of the solar distillation system are presented above and here are some conclusions that can be made from the results of this study:

(1) Exergy efficiency of the single slope active solar still driven by direct solar energy was found to be very low.

(2) Increasing irradiation intensity improves the energy and exergy efficiencies while the increasing ambient temperature decreases the efficiency.
(3) While the amount of solar energy falling onto the system decreases near the sunset time, distillation process continues using the energy stored before. For this reason, the maximum daily energy and exergy efficiencies are observed during this time.
(4) Glass cover of the solar still was cooled down under control to determine the effect of wind speed variations.
(5) Regardless of the solar distillation system design, distillate output is a function of temperature difference between the evaporation and condensing covers. Greater temperature difference gives more distillate output.
(6) Insolation time, ambient temperature, wind speed, atmospheric humidity, and sky conditions are some of the major parameters affecting the fresh water yield of a solar still.
(7) It can also be concluded from this study that the convective and evaporative heat transfer coefficients are among the main design parameters of solar distillation system, and the temperature difference between the evaporating and condensing surfaces is also important for optimizing the operating temperature range.
(8) Wind speed changes the exergy efficiency. Since the ambient temperature and wind speed change, achieving the optimum exergy efficiency requires taking the mean value of these parameters into account during the solar still design.
(9) About 60% of world's population is expected to have water shortages in the near future and R&D activities on solar distillation systems should be supported and promoted.

Nomenclature

A_c	—	area of collector (m^2)
$\dot{E}\chi_{dest}$	—	exergy destroyed
$\dot{E}\chi_{evap}$	—	exergy output of solar still
$\dot{E}\chi_{ew}$	—	exergy of latent heat of vaporization (J/kg)
$\dot{E}\chi_{in}$	—	exergy input of solar still
F_R	—	heat removal factor
h_{ew}	—	heat loss coefficient by evaporation from water surface (W/m^2 K)
I_{eff}	—	effective solar radiation intensity (W/m^2)
I_c	—	solar intensity over the inclined surface of the collector (W/m^2)
L	—	latent heat of vaporization (J/kg)
$\dot{m}_{ew}$	—	hourly output of still (kg/m^2h)
$\dot{m}_{ew}$	—	hourly yield/output of solar still (kg h^{-1})
N	—	number of collectors
P_g	—	glass-saturated partial pressure (N/m^2)
P_w	—	water-saturated partial pressure (N/m^2)
Q_{ew}	—	evaporative heat transfer (W)
$\dot{Q}_u$	—	useful thermal energy gain from the collector (W/m^2)
T_a	—	ambient air temperature (K)
T_g	—	still glass cover temperature (K)
T_s	—	temperature of sun (6000 K)
T_w	—	still water temperature (K)
$T_{w,o}$	—	water temperature, fed from the collector to the solar still at the time of drawn
U_{LC}	—	overall heat transfer coefficient for the collector (W/m^2°C)
$\alpha\tau$	—	effective absorptance–transmittance product

Subscripts

C	—	collector
FPC	—	flat plate collector
SS	—	solar still

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