Experimental and theoretical study of a solar desalination system located in Cairo, Egypt

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Abstract

The experimental and theoretical study of a solar desalination system located in Cairo, Egypt, is presented in this research. A modification unit is provided to enhance the performance of the solar desalination. The modification unit includes a solar parabolic trough (solar energy concentrator) with focal pipe and simple heat exchanger (serpentine). Oil is selected as working fluid. Oil is flowing as cycle through the focal pipe and serpentine. Oil has high thermal properties. The modification unit is utilized during sun duration and night. The oil in the heat exchanger is heated during the sunlight by two purposes, direct solar radiation and solar energy concentrator (solar parabolic trough). The parabolic trough is tracking the sun using simple mechanism to collect the highest amount of solar radiation by optimum angle. The trough is covered with transparent plastic sheet to avoid the heat transfer by convection to the surrounding (i.e. the green house effect is utilized). Copper serpentine of the heat exchanger is painted by Black color and is installed in the bottom of the still basin. It is attached extremely with thermally insulated pipelines through the trough. The oil is forced flow using small pump which may be powered by PV system. The saline water is heated directly by solar radiation and also, by the oil in the heat exchanger as the oil cycle. The thermal analysis of the proposed solar desalination system is expressed using the energy balance equations for different components of the system. The performance curve of the pump and the characteristics of the motor are illustrated. The overall efficiency of the proposed system is computed. Two experiments are carried out at April and June 2005. Type-K thermocouples (±0.5°C), digital temperature devise and remote control unit are used for measuring the system temperature points. The forecast of the typical climatic conditions of the experimental Cairo site at the selected days are obtained from the “Egyptian Solar Radiation Atlas” of the Geophysical Institute. The comparison between the performance of the conventional and the modified solar desalination systems is presented. The economic study of the present system is determined. The results show that fresh water productivity is increased by an average of 18%, due to the modification.

Keywords: Forced flow; Natural flow; Oil heat exchange; Parabolic trough; Small pump; Solar desalination

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1. Introduction

The main problem facing humankind in arid and coastal areas is the shortage of fresh water, although saline or brackish water is available in these areas. Solar desalination systems are suitable and more economical in these areas. The intensity and availability of the solar energy in Egypt is among the highest in the world. Proving test for a solar-powered desalination system in Gaza-Palestine is presented by Abu-Jabal et al. [1]. Solar thermal desalination system with heat recovery is presented by Klemens et al. [2]. In their study, it was seen that 50.2 L are collected at the end of the day. This represents a rate of 25 L/m² for a value of 4.8 kWh/m²/d of solar radiation, according to a rate of 5.2 L/kWh m². Analysis of an innovative water desalination system using low-grade solar heat is investigated by Al-Kharabsheh et al. [3]. Their results showed that the output from its proposed system can reach 6.5 kg/m²d as compared to 3–4 kg/m²d from a conventional type solar still. Klemens et al. [4] presented a theoretical and experimental study of a modular solar desalination system with flat plate collector to enhance the performance of conventional solar still. Its desalination tower had six stages, each with three trays. The area of each stage was 1 m². Their results showed that the water production rate 1.49 L/kWh/m² of collector area as 2.67 times greater that the tank type distillers in the same day. Desalination of seawater studies is presented by Howa [5]. Theoretical and experimental studies of heat and mass transfer inside single sloped solar still is presented by Ghoraba [6]. In this work, solar energy is utilized, parabolic trough and pipelines are provided, oil is selected as working fluid in serpentine and pipeline to enhance the performance of the solar desalination systems. Experimental work and theoretical analysis are presented.

2. Experimental work

Two experimental set-up solar desalination systems are built: one is conventional and other with proposed modification under case study. Figs. 1–4 show the schematic diagrams and photography pictures of the experimental set-up of the present work. Two experiments are carried out under the case study of forced oil flow at April and June 2005. Type-K thermocouples (±0.5°C), digital temperature devise and remote control unit are used for measuring the system temperature points. The forecast of the typical climatic conditions of the experimental Cairo site at the selected days are obtained from the “Egyptian Solar Radiation Atlas” of Geophysical Institute (Figs. 5–8) [7]. In the following, the components of the present modified system are described and characterized.

2.1. Geometrical description of the solar parabolic trough and oil cycle

The parabolic trough is solar concentrator, reflector and collector. It is manufactured from stainless steel (304) sheet of 0.4 mm thickness and 80 cm long. Copper pipe with a diameter of 7/8" is fixed on the axis line with the focal of the parabola. Fig. 9 shows the profile of the present parabolic concentrator. Copper pipe with a diameter of 5/8" is thermally insulated with glass
wool that attached extremely with serpentine loop as simple heat exchanger. This heat exchanger is installed in the bottom of the stiller. Internal basin walls and serpentine pipe are painted with black color to absorb the highest amount of incident solar radiation during sunlight. Oil is selected as working fluid that flows through the loop under effect of forced flow using small pump.

2.2. Optical analysis of the present parabolic concentrator

The optical analysis of the present parabolic concentrator is presented. Optical and geometrical concentration ratios, \( CR_o \) and \( CR_g \) are calculated as the following, respectively [8] (Fig. 9).
Fig. 5. Solar intensity of Cairo site in April.

Fig. 6. Climatic conditions of Cairo site in April.

Fig. 7. Solar intensity of Cairo site in June.

Fig. 8. Climatic conditions of Cairo site in June.

\[ CR_o = \frac{1}{I_a} \int A_t \, dA_r \]  \hspace{1cm} (1)

\[ CR_s = \frac{A_t}{A_r} \]  \hspace{1cm} (2)

where \( I_a \) is average radiant flux, \( A_a \) and \( A_r \) are the collector aperture and receiver area in \( \text{m}^2 \), respectively, \( d \) is the aperture diameter of the trough and \( f \) is focal length in m. The equations of the parabola are given as:

\[ A_a = L \times d \]  \hspace{1cm} (3)

where \( L \) is the length of a parabolic cylinder.

\[ A_r = \frac{2}{3} d \times h \]  \hspace{1cm} (4)

where \( h \) is the height of parabola in terms of focal length and aperture diameter which it is the distance across the aperture of the parabola and the distance from the vertex to the aperture. It can be computed as:

\[ h = \frac{d^2}{16f} \]  \hspace{1cm} (5)

Assume that the origin is taken at the vertex \( V \) and the \( x \)-axis along the axis of the parabola. The parabola with its vertex at the origin and symmetrical about the \( x \)-axis in polar coordinates takes the following equation:
Fig. 9. Profile of the present parabolic concentrator.

\[ y^2 = 4fx \]  
(6)

where \( f \) is the focal length and it is the distance (VF) from the vertex to the focus.

\[ \frac{4f}{r} = \frac{\sin^2 \theta}{\cos \theta} \]  
(7)

where \( r \) is the distance from the origin and \( \theta \) is the angle from \( x \)-axis to \( r \).

The parabolic radius \( r_p \) (m) can be calculated from the following formula:

\[ r_p = \frac{2f}{1 + \cos \psi} \]  
(8)

where \( \psi = 2P \) is careful inspection of the geometry described in Fig. 9.

2.3. Oil specifications

Oil carries the maximum heat from the solar collector (trough) due to its thermal and physical properties. Table 1 gives the thermal and physical properties of the selected fluids.

\[
\begin{array}{cccc}
\text{Fluid} & \rho \text{ (kg/m}^3\text{)} & C_p \text{ (kJ/kg.k)} & \eta \text{ (N.s/m}^2\text{)} & K \text{ (kJ/m.s.k)} \\
\hline
\text{Oil} & 850 & 1.966 & 0.0686 & 0.00014 \\
\text{Water} & 1000 & 4.18 & — & 0.026 \\
\end{array}
\]

2.4. Motor characteristics

Motor current flow, \( I \) 10 Amp  
Motor voltage, \( V \) 38 Volts  
Output power, \( P \) 0.65 HP \( \approx 0.5 \) kW  
Armature resistance, \( R \) 0.1 \( \Omega \)  
Motor angular speed, \( \omega_m \) 100 rad/s = 958 rpm

2.5. Pump characteristics

Net head, \( H \) 2 m  
Maximum head, \( H_{\text{max}} \) 28 m  
Maximum suction, \( S_{\text{max}} \) 8 m  
Pump torque, \( \tau \) 2.4 N.m.  
Pump angular speed, \( \omega_p \) 120 rad/s = 1150 rpm  
Pump capacity, \( Q \) 0.38\( \times 10^{-2} \) m\(^3\)/s  
Speed ratio, \( r = \frac{\omega_p}{\omega_m} = 1.2 \)

The performance curve of the present pump is shown in Fig. 10.
3. Thermal analysis of the present solar desalination system

At any given time the still produces an amount of distillate water equal to \( W_p \) (L/m\(^2\)) per unit area of the glass cover. \( T_w, T_g \) and \( T_o \) (°C) are the average temperatures of basin water, the glass cover and ambient, respectively. The still receives solar radiation per unit area of \( I \) (W/m\(^2\)). The operation of solar desalination system is governed by the following heat balance equations.

### 3.1. Solar energy equations of glass cover (\( q_g \))

The thermal energy balance equations of the glass cover are given as:

\[
q_g = \alpha_g I - q_{Lg}, \text{ W/m}^2 \tag{9}
\]

where

\[
q_{Lg} = q_{cg} + q_{rg}, \text{ W/m}^2 \tag{10}
\]

\[
q_{cg} = h_{cg} (T_g - T_o), \text{ W/m}^2 \tag{11}
\]

\[
q_{rg} = \varepsilon_g \sigma [T_g^4 - (T_o - 11)^4], \text{ W/m}^2 \tag{12}
\]

where \( q_{Lg} \) is the sum heat losses from the glass to the surrounding, \( q_{cg} \) is the heat losses by convection, \( q_{rg} \) is the heat losses by radiation between glass cover and the surrounding. The rate of heat dissipation depends on the radiation to sky and on convection by air circulation. Radiation to sky depends on the effective sky temperature, which is generally taken as 11°C, less than the ambient temperature. \( \varepsilon_g \) is glass emissivity and \( \sigma \) is the Stefan Boltzman constant which equals 5.67×10\(^{-8}\) W/m\(^2\)K\(^4\). \( h_{cg} \) is the heat transfer coefficient from the glass cover to the surrounding and can be calculated as from Duffie and Backman [9]:

\[
h_{cg} = 5.7 + 3.8 \times w_s, \text{ W/m}^2\text{k} \tag{13}
\]

where \( w_s \) is the wind speed.

### 3.2. Solar energy absorbed by basin water (\( q_w \))

The thermal energy equations of basin water are expressed as from Rai [10]:

\[
q_w = (\tau \alpha)_w I - q_{Lw}, \text{ W/m}^2 \tag{14}
\]

where \( (\tau \alpha)_w \) is the thermal transmissivity-absorptivity of water, dimensionless and equals 0.816.

\[
q_w = q_{ew} + q_{rw} + q_{cw} + q_{oil} + q_{Lb}, \text{ W/m}^2 \tag{15}
\]

where \( q_{iw} \) is the input thermal energy to the basin water and can be obtained from the following equations:

1. \( q_{ew} \) is evaporated heat transfer rate at the saline water surface and is a function of the hourly distilled production of the fresh water (\( W_h \)) and is calculated from the following relationship:

\[
q_{ew} = \frac{L_w w}{610 \times 3600 \times \rho_w \times \rho_\eta} \times \rho_\eta, \text{ W/m}^2 \tag{16}
\]

where \( L_w \) is the latent heat of water evaporation at the cover temperature and equals 2.35×10\(^3\) kJ/kg.

The efficiency of the system is the ratio of the actual distilled water obtained per day to the energy input and can be computed as follows:

\[
\eta_d = \frac{W_d \times 10^{-6} \times \rho_w \times L_w}{3600 \times I}, \text{ W/m}^2 \tag{17}
\]

where \( W_d \) is the daily total distillate water and \( I \) is the total solar radiation, kJ/(m\(^2\) d).

2. \( q_{rw} \) is the heat transfer rate by radiation between the saline water and the inner glass cover surface and is given as:

\[
q_{rw} = \sigma F_{w-g} [\varepsilon_w T_w^4 - \varepsilon_g T_g^4], \text{ W/m}^2 \tag{18}
\]

where \( \varepsilon_w \) and \( \varepsilon_g \) are water and glass absorptivity, dimensionless, and equal 0.96 and 0.89, respec-
tively, and $F_{\text{rad}}$ is the radiation shape factor from saline water to the inner glass surface and equals here 0.9.

(3) $q_{cw}$ is the convective heat transfer rate between the saline water and the inner glass cover surface, and is calculated as:

$$q_{cw} = h_{cw} (T_w - T_g), \text{ W/m}^2$$

where $h_{cw}$ is the convective heat transfer coefficient and is calculated from the following equation:

$$h_{cw} = 8.84 \times 10^{-4} \times (T_w - T_g) \times \left(\frac{P_w - P_g}{2.65 \times (P_i - P_w)}\right)^{1/3}, \text{ W/m}^2 \cdot ^\circ \text{C}$$

where $P_w$, $P_g$ and $P_i$ are vapor pressure of water at temperature of water surface, vapor pressure of water at temperature of transparent glass cover and atmospheric pressure, (N/m$^2$), respectively.

(4) $q_{\text{oil}}$ is the rate of heat transfer from the oil to water which is energy absorbed by oil (in serpentine) and transferred to the basin water due to the heat exchange between them.

$$q_{\text{oil}} = \left[ \frac{\dot{m} \cdot C_p \cdot (T_{\text{in}} - T_{\text{out}})}{A} \right]_{\text{oil}} = UA(T_{\text{in}} - T_{\text{out}})_{\text{oil}}, \text{ W/m}^2$$

where $U$ is the overall heat transfer coefficient, W/m$^2$ °C.

From the performance curve of the pump (Fig. 10), \( \dot{m} = \rho_{\text{oil}} \cdot V \), it is mass flow rate of oil and \( w = \dot{V} / A \), where \( \dot{V} \) (m$^3$/s) is the volumetric flow rate of the pump. \( \dot{V} \) (for a head of 21 m) = 0.00174 m$^3$/s, \( A = 0.000126 \text{ m}^2 \) and \( \rho_{\text{oil}} = 852 \text{ kg/m}^3 \); then \( \dot{m} = 0.39 \text{ kg/s} \).

The outlet temperature of the oil is determined as follows, where $T_{\text{in}}$ is known.

$$T_{\text{out}} = T_{\text{in}} + \frac{q_{\text{oil}}}{\dot{m} \cdot C_p}, \text{ K}$$

The overall heat transfer coefficient of the heat exchanger, $U$, is to be determined, and the following assumptions are drawn:

1. Steady operating conditions exist.
2. The heat exchanger is installed in the bottom of the basin, which the heat transfer from the hot fluid (oil) is equal to the heat transfer to the cold fluid (water).
3. Changes in the kinetic and potential energies of fluid streams are negligible.
4. There is no fouling.
5. Fluid properties are constant.
6. The thermal resistance of the inner tube is negligible since the tube is thin-walled and highly conductive.

Then the overall heat transfer coefficient of the heat exchanger, $U$, can be calculated as:

$$U = \frac{q_{\text{oil}}}{A \Delta T_{\text{oil}}}, \text{ W/m}^2 \cdot \text{K}$$

(5) $q_{\text{lb}}$ is the heat losses from the basin base to the ground and can be calculated as:

$$q_{\text{lb}} = h_{\text{lb}} (T_w - T_0), \text{ W/m}^2$$

where $h_{\text{lb}}$ (W/m$^2$K) is the convective heat transfer coefficient of the basin base and it is function of thermal conductivity and the thickness of the insulation material which can be calculated as follows [10]:

$$h_{\text{lb}} = \frac{K_{\text{in}}}{X_{\text{in}}}, \text{ W/m}^2 \cdot \text{K}$$

where $K_{\text{in}}$ and $X_{\text{in}}$ are the thermal conductivity and thickness of the thermal insulation and equal 0.03 W/m$^2$°C and 0.05 m, respectively.

4. Economics study

For a desalination unit, the major items of annual cost are: capital cost of the components,
Table 2
Description and costs of the components of the present solar desalination systems, 2005

<table>
<thead>
<tr>
<th>Components</th>
<th>Specification</th>
<th>No. × cost (LE)</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanized steel sheet, m</td>
<td>(1×1) m, 08 mm thickness</td>
<td>2 × 50</td>
<td>100</td>
</tr>
<tr>
<td>Still supported (H-section), m</td>
<td>5 m, 2 mm thickness</td>
<td>5 × 20</td>
<td>100</td>
</tr>
<tr>
<td>Glass cover, sheet</td>
<td>1.02 × 1.02 4 mm</td>
<td>1 × 75</td>
<td>75</td>
</tr>
<tr>
<td>Parabolic trough (solar collector), sheet</td>
<td>Stainless steel 314, 04 mm</td>
<td>1 × 300</td>
<td>300</td>
</tr>
<tr>
<td>Silicon rubber</td>
<td>Clear</td>
<td>3 × 10</td>
<td>30</td>
</tr>
<tr>
<td>Plastic tank, m3</td>
<td>0.2</td>
<td>1 × 10</td>
<td>10</td>
</tr>
<tr>
<td>Parabolic trough iron stand (L-section), m</td>
<td>Steel skeleton with multi position sides (0° to 180°)</td>
<td>1 × 100</td>
<td>100</td>
</tr>
<tr>
<td>Valves</td>
<td>0.5 inch</td>
<td>3 × 10</td>
<td>30</td>
</tr>
<tr>
<td>Foam, 5 cm thickness, sheet</td>
<td>2 m²</td>
<td>2.2 × 15</td>
<td>33</td>
</tr>
<tr>
<td>Glass wool insulation, m</td>
<td>5 m</td>
<td>5 × 15</td>
<td>75</td>
</tr>
<tr>
<td>Trough copper pipe line, m</td>
<td>2 m, 7/8 inch hardened copper</td>
<td>2 × 27.5</td>
<td>55</td>
</tr>
<tr>
<td>Serpentine heat exchanger copper pipe</td>
<td>20 m, 5/8 inch</td>
<td>20 × 10</td>
<td>200</td>
</tr>
<tr>
<td>Oil + oil small pump</td>
<td>$Q_{max} =30$ L/min, $H_{max} = 28$ m, 0.5 HP</td>
<td>1 × 225</td>
<td>225</td>
</tr>
<tr>
<td>Added costs</td>
<td>Claim of this work</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Total costs of initial construction</td>
<td>Present system</td>
<td>1 × 1383</td>
<td>1383</td>
</tr>
</tbody>
</table>

The cost of the modified system for one year = 1383/10 = (LE) 138.3, and the daily cost = 138.3/366 = (LE) 0.378. The average cost of 1 L of distillate water from the modified system = 0.378/5.5 = (LE) 0.069. From the specific economics study, the modified system may be economical.

The cost of the conventional system for 10 years = (LE) 858, the cost for one year = (LE) 85.8, and the daily cost = (LE) 0.24. The average cost of 1 L of distillate water from the conventional system = (LE) 0.078. From the previous economic study, the modified system may be more economy with large scale.

5. Results and discussion

The temperature variation of the components, variation of fresh water productivity, accumulated fresh water per day and the performance for the conventional and the modified solar desalination systems under case study are presented and illustrated in Figs. 11–22. According to the hourly variation of the solar radiation, $I$, for the conventional and modified solar desalination systems at date days April 6/2005 and Jun 5/2005, the results have been illustrated. The variation of the ambient, $T_a$, and inner glass cover temperatures, $T_{gg}$, are varied and have peak values around the noon interval (11:30–3:30) (Figs. 11 and 16). The hourly variation of basin water temperatures, $T_w$, and ambient temperature, $T_a$, are plotted in Figs. 12 and 17. It is noticed, as time goes on, all temperatures increase and begin decrease after 4:00 PM with respect to the variation of the solar radiation, although the temperature values of the modified system are higher than the conventional one. Figs. 13 and 18 show the temperature variations of the oil cycle for the selected days. It is
Fig. 11. Variations of ambient temperature and inner glass temperature for standard and modified solar stills.

Fig. 12. Variations of ambient temperature and basin water for standard and modified solar stills.

Fig. 13. Temperature variations of oil cycle.
Fig. 14. Fresh water productivity for the conventional and modified solar stills.

Fig. 15. Accumulative fresh water productivity for the conventional and modified solar stills.

Fig. 16. Variations of ambient temperature and inner glass temperature for standard and modified solar stills.
Fig. 17. Variations of ambient temperature and basin water for standard and modified solar stills.

Fig. 18. Temperature variations of oil cycle.

Fig. 19. Fresh water productivity of conventional and modified solar stills.
Fig. 20. Accumulative fresh water productivity of conventional and modified solar stills.

Fig. 21. Efficiency comparison between the conventional and modified desalination systems.

Fig. 22. Efficiency comparison between the conventional and modified desalination systems.
noticed that the temperatures of the oil in the trough pipe, $T_{o, tr}$, inlet oil to the heat exchanger, $T_{o, in}$ and the oil in the heat exchanger, $T_{o, He}$ (installed in the bottom of the basin) have higher values than the temperature values of the outlet oil from the heat exchanger as the heat exchanging between the basin water and the oil in the heat exchanger.

The hourly fresh water productivity is shown in Figs. 14 and 19. It is clear that the highest water productivities are obtained from the modified system. Figs. 15 and 20 give the accumulative fresh water productivities. It is found that the highest quantities of fresh water are obtained from the modified system.

The performance of the present work is plotted in Figs. 21 and 22. It is clear that the modified system is an efficient one.

6. Conclusions

Based on the results, conclusions are drawn as follows:

- The modified system of solar desalination is an efficient one.
- The fresh water productivity is increased by an average percentage of 18%, according to the modification design.

References