A naturally circulated humidifying/dehumidifying solar still with a built-in passive condenser

Hassan E.S. Fath, Samy Elsherbiny*, Ahmad Ghazy

Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt
Tel. +20 (10) 514-2218; Fax: +20 (3) 546-9378; email: h_elbanna_f@hotmail.com

Received 7 October 2003; accepted 9 December 2003

Abstract

A numerical study has been carried out to investigate the transient thermal performance of a naturally circulated humidifying/dehumidifying solar still. A comparison of forced circulation performance and the influence of different environmental, design, and operational parameters on the still productivity and efficiency were investigated. The naturally circulated still shows very similar results to that of forced circulation. This finding is of significant technical and economic importance. Different attempts have been considered to investigate the effect of partial storage of basin energy and partial recovery of condensation energy. The results show insignificant changes on still performance. An economic assessment of water production cost was also highlighted and showed that solar stills can challenge other technologies for special applications.

Keywords: Desalination; Solar still; Humidification; Dehumidification

1. Introduction

Fresh water is the essence of life and is the most important constituent of the environment. Water is a basic human requirement for domestic, industrial and agriculture purposes. Rapid international developments and population explosion all over the world have resulted in a large escalation of demand for fresh water. On the other hand, surface water (rivers and lakes) pollution caused by industrial, agricultural and domestic wastes limits the availability of fresh water in many regions. By the beginning of this century, fresh water shortages and quality became an international problem confronting humans and countries. The problem is more apparent in the Middle Eastern/North African (MENA) countries due to their limited natural resources.

According to the International Atomic Energy Agency (IAEA), an estimated 1.1 billion people have no access to safe drinking water, and more than 5 million die from water-borne diseases each year. Provisions are no better even for the future.
It is estimated that more than 2.7 billion people will face severe water shortages by the year 2025 if the world continues consuming water at the same rate per capita and real population growth fits the forecasted trend. The crisis is mainly due to the mismanagement of existing water resources, population growth, and continuous climatic changes. It is, therefore, necessary that a sincere effort be made to face the looming water crisis and conserve shrinking water supply amid the rising demand [1].

Seawater desalination has already confirmed its partial potential to resolve the fresh water problem in numerous countries. Although it seems more expensive in area of surface or ground water availability, it is not so in areas 300–500 km from surface fresh water availability or of deep ground fresh water. For municipalities with large water demands, conventional desalination technologies such as MSF, MED, RO and VC proved to be technically and economically suitable. Considering the fact that areas of very small communities exposed to the water scarcity are at the same time characterized by high levels of solar radiation, appropriate consideration needs to be given to the opportunity of using solar energy — no doubt a bit costly — but with optimal features for its coupling with desalination processes. This is true, especially in isolated and remote areas, having no access to an electrical grid or fuel supply and with very few technical capabilities.

Direct solar distillation, in many respects, might be an ideal solution to small communities in many MENA countries due to the following:

- Many of these countries enjoy an abundant solar intensity (annual daily average is between 200–300 W/m²) and annual sun hours (3000–5000 h/y); with an incident energy of about 5–6 kWh/d.
- The diurnal and seasonal fluctuation in solar distillation productivity is intrinsically linked to the fluctuating water demand.
- Direct solar stills involve simple technology that needs fewer design, manufacturing, operation and maintenance capabilities.
- Solar energy is available in almost every location and, in addition, is an environmentally friendly energy resource (with no CO₂ emission).

Many researchers have investigated and developed solar stills of different configurations in order to increase still efficiency and yield (see, e.g., Fath [2,3], Delyannis [4], Hamed et al. [5], Nafey et al. [6,7]). The efficiency of solar stills can be increased by increasing input energy. This could be partially achieved by (1) having the liquid surface oriented at an optimal inclination to receive maximum solar radiation and (2) placing the transparent glass cover of the still parallel to the water surface to minimize reflection losses. Several methods have been tried, including the inclined stepped still [8], tilted tray, and multiple ledge multi-wick [9].

Humidification/dehumidification techniques have also been introduced as an effective solar distillation system. Different systems have been proposed in the literature: (1) with/without air heating, (2) with/without water heating, (3) forced/natural air circulation (see, e.g., Dater [10], Fath and Ghazy [11], Nafey et al. [12,13], Younis et al. [14] and Muller-Holst et al. [15,16]).

There are two main drawbacks to most of these single-effect solar stills. The first is the loss of large amounts of condensation energy from the still. The combined evaporation, convection and radiation energy received by the condensation surface(s) represents about 40–50% of the energy lost to the atmosphere. One may consider the partial recovery of this heat for (1) feed preheating, as in Mink et al. [17,18] and Kunze [19], or (2) in an energy storage system for after sunset energy recovery. Note that a full recovery of condensation energy is impossible since the glass...
(as a condensing surface and the door of the inlet solar energy) cannot be covered during the day. An additional condenser might be used for additional heat and mass sink as presented by Fath et al. [20,21]. The capital and running cost of any energy recovery system, as well as the additional technical complexities, should be justified with additional yield production. The second drawback is the sinusoidal trend of the still’s temperature and water productivity. Water is not produced after sunset and during cloudy periods where the atmospheric temperature is minimum and heat sink is mostly available. High midday temperatures lead to greater energy losses and a need for more expensive absorbing materials. This drawback can, however, be overcome by increasing the thermal storage capability of the system in order to store part of the solar energy and reutilize it after sunset and during cloudy periods. The incorporation of such energy storage systems should be justified against a simple still with daily water production.

For both absorber and condensation energy storage and after sunset recovery, two thermal storage systems could be used — either a sensible or a latent heat system. The latent heat thermal energy storage system (LHTESS) has many advantages over sensible heat storage, including (1) larger energy storage capacity per unit volume, and (2) an almost constant temperature for energy charging and discharging (see Fath [22]). Paraffin wax and Glauber’s salt are typical phase change materials (PCM) generally used in solar energy storage systems. Table 1 shows the main properties of the energy storage materials: paraffin wax (to be used for basin energy storage) and Glauber’s salt (to be used for condensation energy storage and recovery).

Fath et al. [2] proposed a simple and efficient humidifying/dehumidifying distiller (HDD). The main drawback of this still is the forced circulation, which requires a fan. On the other hand, the authors indicated that, within the parametric values studied, a decreasing circulating air flow rate showed an insignificant effect on still productivity and efficiency. This result leads to the possible use of natural circulation to drive the air flow rate. Natural air circulation with a small still is more desirable since the absence of a circulating fan means a large reduction of both capital and operation costs in addition to the elimination of the technical complexities. How natural air circulation affects the total productivity and other performance parameters of the still (with and without energy storage and recovery) is the focus of the present study.

### 2. System description and analysis

#### 2.1. Description

Fig. 1a illustrates the proposed HDD configuration and its main components [2]. The still body is a thin rectangular box constructed of

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Sand (Sunoco – P116)</th>
<th>Paraffin wax</th>
<th>Glauber’s salt Na₂SO₄·10H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature, °C</td>
<td>60</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Latent heat of fusion, kJ/kg</td>
<td>190</td>
<td>251</td>
<td></td>
</tr>
<tr>
<td>Solid/liquid density, kg/m³</td>
<td>1500</td>
<td>930/830</td>
<td>1460/1330</td>
</tr>
<tr>
<td>Thermal conductivity, W/m.°C</td>
<td>0.29</td>
<td>0.21</td>
<td>2.25</td>
</tr>
<tr>
<td>Solid/liquid sp. heat, kJ/kg.°C</td>
<td>0.798</td>
<td>2.1</td>
<td>1.72/3.3</td>
</tr>
</tbody>
</table>
1.0 mm thick framed aluminum sheeting with a 3.0 mm (window-type) glass cover. A central stepped absorber sheet (connected to the two still side walls with two slots at the top and bottom side walls) divides the still into two chambers, upper (glass to absorber) chamber and lower
Table 2
Thermo-physical properties of the still’s main components [23]

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass cover</th>
<th>Basin/condenser</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Window glass</td>
<td>Aluminum Fiber glass</td>
<td>Fiber glass</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>2700</td>
<td>2707</td>
<td>24</td>
</tr>
<tr>
<td>Specific heat, kJ/kg. °C</td>
<td>0.754</td>
<td>0.896</td>
<td>0.7</td>
</tr>
<tr>
<td>Thermal conductivity, W/m.°C</td>
<td>0.78</td>
<td>204</td>
<td>0.038</td>
</tr>
<tr>
<td>Absorbitivity</td>
<td>0.1</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The dividing stepped sheeting carries a series of insulated and black coated basins which contain the saline water. The dehumidifying condenser is made of 1.0 mm aluminum sheeting. Air is circulated between the upper chamber (where it is heated and humidified) and the lower chamber (where it is cooled and dehumidified for water production). The still has a tilted configuration to enhance solar energy reception. Table 2 summarizes the main physical and thermal properties for the proposed still’s component materials.

2.2. Heat and mass balance

Fig. 1b illustrates the energy balance of one basin (element) of the proposed still. Incident solar energy (1) is partially reflected (2) and partially absorbed (3) by the glass cover. The main part is transmitted through the glass cover (4) to the saline water and absorber. Part of the transmitted energy is reflected back from the water surface (5), and the rest is absorbed by saline water (6) and the absorber surface (7). Part of the absorber energy is transferred to the seawater by convection, another part is conducted to the insulation (8), and the rest heats the absorber. Some of the insulation energy is transferred to the dehumidifier by convection (9) and to the condenser by radiation (10).

As soon as the water temperature exceeds the surrounding air temperature, saline water starts transferring heat and vapor to the circulating air in the humidifying channel. The generated vapor carries both convection (11) and evaporation (12) energies. Saline water surfaces also radiate some energy (13) to the glass cover. Part of the entrained water vapor in the circulating air is condensed on the glass and leaves its convective (14) and condensation energy (15), while the air carries the rest of the entrained vapor to the next element. As a limiting criterion, the circulating air humidity cannot exceed the saturation condition at its temperature. The heated glass cover loses its heat to the surroundings by convection (16) and to the atmosphere by radiation (17).

When the absorber contains PCM for partial energy storage, heat is conducted from the basin to the PCM for energy storage. Heat is first stored (charging process) as sensible heat till PCM reaches its melting temperature. Additional charging heat is then stored as latent heat, and the melted PCM thickness increases. After complete melting, any additional heat will be stored as liquid PCM sensible heat. When the absorber cools down (after sunset, say), the liquid PCM transfers heat to the absorber (discharging process) and its temperature decreases till it reaches the solidification temperature, after which any discharged heat will be extracted as latent heat till the PCM layer is fully solidified. More extracted heat will be sensible heat to cool the solid PCM. The charging–discharging processes for the stored energy in the condenser PCM are similar.

2.3. Governing equations

Based on the heat and mass balance discussed above, the governing equations for the still components can all be written in the form:
In this equation, the PCM (wax or Glaubert’s salt) and its container (absorber, condenser, and insulation) are combined as one equivalent body (for each element). Based on its temperature, the PCM and its container are combined as the container material equivalent mass ($M_{eq}$) of heat capacity equivalent to:

- the sensible heat for both the container and solid PCM (for $T<T_m$)
- the sensible heat of the container and the latent heat of fusion ($T=T_m+\delta$)
- the sensible heat for both the container and liquid PCM ($T>T_m$)

For example, the equivalent absorber/PCM (wax) heat capacity [Eq. (4)] is calculated as follows:

$$M_{eq} C_{ab} = \begin{cases} M_{ab} C_{ab} + M_{pcm} C_{pcm} & \text{for } T_{ab} < T_m \\ M_{ab} C_{ab} + M_{pcm} H_{l} & \text{for } T_{ab} = T_m + \delta \\ M_{ab} C_{ab} + M_{pcm} C_{l} & \text{for } T_{ab} > T_m \end{cases}$$

Similar equations are written for the condenser/PCM (Glaubert’s salt) and other combinations. Details of the above terms can be expressed as follows:

$$I = I_o \sin \left( \frac{\pi}{t/t_o} \right)$$

$$Q_{su-g} = \alpha_{g} I A_p$$

$$Q_{Rsw-g} = \sigma e_{sw} A_p \left( (T+273)^4 - (T+273)^4_{sw} \right)$$

$$Q_{Ca-g} = H_{Ca-g} (T_a - T_g) (A_p + A_{sid})$$

$$Q_{CDa-g} = H_{CD} (P_{a} - P_{g}) (A_p + A_{sid})$$

$$Q_{Rg-sk} = \sigma e_{g} (A_p + A_{sid}) \left[ (T+273)^4 - (T+273)^4_{sk} \right]$$

$$Q_{Cg-am} = H_{G} (A_p + A_{sid}) (T_g - T_{am})$$

$$Q_{Csw-a} = H_{Csw-a} A_p (T_{sw} - T_a)$$

$$Q_{Esw-a} = H_{E} A_p (P_{sw} - P_{a})$$
\[ Q_{s-ab} = \alpha_{ab} \tau_{sw} \tau_p A_p \]
\[ Q_{Cab-sw} = H_{Cab-sw} A_b (T_{ab} - T_{sw}) \]
\[ Q_{Kab} = (K_i / Th_i) A_p (T_{ab} - T_i) \]
\[ Q_{su-sw} = \alpha_{sw} \tau_{sw} A_p \]
\[ Q_{Ri-cu} = F_{gi} A_p [(T_i + 273)^4 - (T_{cu} + 273)^4] \]
\[ Q_{Ci-a} = H_{Ci-a} A_p (T_i - T_a) \]
\[ Q_{Ca-cu} = H_{Ca-cu} (A_p + A_{sid}) (T_a - T_{cu}) \]
\[ Q_{CDa-cu} = H_{CDa-cu} (P_a - P_{cu}) (A_p + A_{sid}) \]
\[ Q_{Ccu-am} = H_{Ccu-am} (A_p + A_{sid}) (T_{cu} - T_{am}) \]
\[ Q_{Rcu-erth} = F_{gcu} (A_p + A_{sid}) [(T_{cu} + 273)^4 - (T_{am} + 273)^4] \]
\[ M_{E/CD} = Q_{E/CD}/H_{fg(t)} \]
\[ T_{am} = T_{am-min} + T_{am-o} \sin(\pi t / t_{day}) \]
\[ T_{ab} = [(0.0552 (T_{am} + 273)1.5) - 273] \]
\[ H_{Chot-cold} = 0.884 [(T_{hot} - T_{cold}) + (P_{hot} - P_{cold})] \]
\[ H_{fg(t)} = [2503.3 - 2.398 (T(t))]*10^3 \]

### 2.3.1. Natural circulation air flow rate

The naturally developed air mass flow depends on the balance between both driving and resisting forces (pressures). The driving force depends on: (1) the difference of average air density in both humidification and dehumidification channels (which varies along with air temperature and humidity) and (2) the still’s height. The resisting force varies with circuit resistance and flow velocity. The air flow rate can then be calculated as follows:

\[ m_a = (\Delta P_D / \Delta P_R)^{0.5} \quad (5) \]

where (see Ghazy [24]):

\[ \Delta P_D = (p_{db} - p_h) g L \cos(\theta) \]
\[ \Delta P_R = \Delta P_{R1} + \Delta P_{R2} + \Delta P_{R3} \]
\[ \Delta P_{R1} = 0.018 L/2 D_h \rho_h A_a^2 \]
\[ \Delta P_{R2} = 0.018 L/2 D_h \rho_h A_a^2 \]
\[ \Delta P_{R3} = (0.3/2 A_a^2) (1/\rho_{db} + 1/\rho_h) \]
\[ D_{hyd} = 4 A_a / \text{perimeter} \]
\[ A_a = L (B - Th_i)/2 \]

\[ \text{Perimeter} = 2 [L + (B - Th_i)/2] \]

### 2.3.2. Productivity and efficiency

The still’s productivity and instantaneous and daily average efficiencies are calculated as follows:

\[ \text{Productivity} = M_{pw-g} + M_{pw-cu} = \Sigma M_{E}(t) \Delta t \quad (6) \]
\[ \eta_{inst} = (M_{pw-g} + M_{pw-cu}) H_{fg(t)} [(I A_p) / [M_{E}(t) H_{fg(t)}]] \]
\[ \eta_{av} = [M_{E}(t) H_{fg(t)}] \Delta t / [\Sigma I(t) \Delta t A_p] \quad (7) \]

A computer program was developed to solve simultaneously the above equations. The still’s component transient temperatures, heat transfer components, still productivity, instantaneous and daily average efficiencies are then calculated.
3. Results and discussion

Table 3 summarizes the environmental, design, and operational parameters and their studied values for the parametric study.

3.1. Circulating air flow rate

As indicated above, the circulating air flow rate depends on the balance between the driving and resisting forces (pressures). Both forces depend on air conditions along the chambers and channel configurations in the still. The prediction of circulating air flow rate requires an iterative approach for the solution of Eq. (5) simultaneously with Eqs. (1)–(4). Fig. 2 shows the changes in the air flow rate with time for the reference values. Air flow rate increases sharply in the first 3 h after sunrise, then remains almost uniform for the next 7 h (of about 0.0138 kg/s), then drops near sunset. Comparing with Fath et al. [2],

Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. value</th>
<th>Reference (base) value</th>
<th>Max. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar intensity at mid-day, ( I_0 ) (W/m²)</td>
<td>600</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>Min./max. ambient temperature, °C</td>
<td>10/20</td>
<td>20/30</td>
<td>30/40</td>
</tr>
<tr>
<td>Wind speed ( (V_w) ), m/s</td>
<td>0</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Design:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin absorbitivity ( (\alpha_{bs}) )</td>
<td>0.5</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Condenser absorbitivity ( (\alpha_{cs}) )</td>
<td>0.5</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Condenser/projected area ratio</td>
<td>1</td>
<td>1.5, 2.0</td>
<td></td>
</tr>
<tr>
<td>Evaporation/projected area ratio</td>
<td>1</td>
<td>1.5, 2.0</td>
<td></td>
</tr>
<tr>
<td>Basin (glass wool) insulation thickness, mm</td>
<td>10</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Operational:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin water mass ( (M_b) ), kg</td>
<td>12</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Initial water temperature, °C</td>
<td>20</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Still tilting angle (from horizontal)</td>
<td>10</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

Fig. 2. Naturally circulating air flow rate.
the results indicate that natural air circulation gives a very close value of air flow rate to that of the forced circulation most of the effective hours of the day. A forced air flow rate of 0.01 kg/s is almost the average value of the natural circulation rate.

3.2. Energy balance

Fig. 3 illustrates the still overall energy balance for the reference value at midday. The figure shows that for an incident solar intensity of 800 W, 80 W are absorbed on the glass cover, 72 W are reflected from the seawater basin, and
56.5 W are reflected from the absorber surface. The rest is mainly absorbed in the absorber (518.4 W) and the seawater (72 W). Very little of the absorbed energy in the seawater is radiated to the glass cover (16.3 W), and the large amount forms evaporation heat (525.2 W), in addition to convection heat of 33.5 W, transferred from the seawater to the circulating air in the humidifying channel. The circulating air carries the added energy to its large recirculating enthalpy of 3995.74 W (note here that the values of the enthalpy are not drawn to the same scale of the still energy components, but are just descriptive).

The air enthalpy (4181.26 W) is mainly recirculated to the dehumidifying channel where it is partially transferred to the condenser as convection (30.6 W) and condensation (309.95 W) heat. Condensation heat produces the condenser water (after dividing by the latent heat of condensation). The total heat transferred to the condenser is dumped into the environment by convection to the atmosphere (238.8 W) and radiation to the earth (109.5 W).

The recirculated air enthalpy to the humidifying channel (4181.26 W) is partially transferred to the glass cover by convection (18.64 W) and condensation (200.38 W) and the rest (3995.74 W) is recirculated to repeat the cycle. Condensation heat on glass produces the glass cover water production (after dividing by the latent heat of condensation). Heat transferred to and absorbed by the glass is dumped to the environment by convection to the atmosphere (289.8 W) and radiation to the sky (23.5 W). Note that at midday a very small amount of energy is stored in the glass cover (1.95 W), seawater (5.03 W), insulation material (0.21 W) and condenser (0.75 W).

Fig. 4 shows the still’s main overall performance parameters. The figure shows very close results between the present naturally circulated air and that of forced circulation [2]. With natural circulation, the still daily average efficiency ($\eta_{av}$) is about 56% and still productivity is 5.1 kg/d.m$^2$. In both cases, water production ends almost 1–2 h after sunset due to the limited system heat capacity. Water production at the glass cover is about 2.15 kg/d.m$^2$ (42 % of the total), while the condenser produces 2.95 kg/d.m$^2$ (58% of the total).

Fig. 5 shows that the still temperature profile follows the sinusoidal trend following the input solar intensity. Fig. 5 also shows the gradual changes in still components temperature along its length. As was expected, the absorber has the highest still temperature followed by (with a very small difference) the saline water, and then the flowing air (humid and dehumid), glass cover, and condenser, respectively. The saline water temperature in the basins reaches its maximum value of about 69°C at the highest (top) nodes, almost half an hour after midday. The difference in temperatures between the first and last nodes is in the range of 3–5°C. Humidified and dehumidified air temperature difference is in the range of 0.5–2.0°C.
3.3. Circulating air conditions

Similar to the forced case of Fath et al. [2], air condition lies always on the saturation line of the psychrometric chart (Fig. 6). During daylight hours, air is heated and humidified till midday and its temperature reaches about 57°C at the humidifier exit and 53°C at the dehumidifier exit. After midday, air starts to cool till sunset, and its temperature almost reaches ambient conditions.

3.4. Parametric study

The effect of environmental, design, and operation parameters (Table 3) on the still’s productivity was studied. Very similar results were obtained to that of forced circulation as shown. The results indicated that increasing the solar intensity, ambient temperature, basin absorbitivity, and initial saline water temperature increases the system productivity. On the other hand, increasing wind velocity, basin insulation thickness, evaporation and condensation surface areas, condenser emissivity, and saline water mass have little effect on the productivity.

The natural circulation operating parameter that influences the system circulating airflow rate is the still’s tilting angle. Fig. 7 shows that increasing the tilt angle of the still increases the airflow rate (higher driving force). However, within these values, the air flow rate does not influence the still’s yield. Increasing airflow rate has two effects: the first is to increase the capability of flowing air to entrain and carry more vapor; and the second is to reduce the heat
Fig. 7. Influence of the tilt angle on performance of the still.

content of the hot water (and therefore the evaporation rate). These two effects seem to balance out.

3.5. Energy storage and condensation energy recovery

Different cases have been considered to investigate the effect of both the partial basin energy storage and partial recovery of condensation energy at the condenser. These cases cover (1) only partial storage of basin energy for after sunset reuse, (2) only partial recovery of condensation energy at the condenser, and (3) a combination of partial basin energy storage and partial recovery of condensation energy.

3.5.1. Partial basin energy storage

Fig. 8 shows the case of only partial basin energy storage for overnight reuse. The first attempt assumes 2.0 cm of paraffin wax (melting temperature of 60°C) to be contained within the high temperature absorber. The figure shows a comparison of overall still performance with and without energy storage. With paraffin wax (solid lines), the component’s temperatures are flatter during both the wax melting/solidification period (hour 5 to hour 12), after which they gradually drop till hour 24. The absorber temperature is maintained almost constant at 60°C due to wax melting (energy charging period continues till almost midday) and solidification (energy discharges from midday to about sunset). By the sunset hour, the absorber/wax temperature starts to drop and heat is discharged from the absorber/wax as sensible heat. Similarly, the air and glass temperatures follow approximately the same trend. For the still without wax (dotted lines), these parameters follow the sinusoidal trend of the solar energy (i.e., no energy is available after sunset; Fig. 5). Fig. 8 also shows a small reduction in both the still’s daily average efficiency and yield. The productivity of the still is about 9.6 kg/d.2m² as compared to 10.2 kg/d.2m² without wax.

The second attempt assumes replacing the insulation material with the 2.0 cm paraffin wax so that the wax acts as both basin insulator and energy storage medium. The results show a similar trend as the case presented above with even more reduction in productivity and daily average efficiency. A reversed air circulation flow took place after hour 20, as explained in other cases below.

These two attempts clearly indicated that storing water produced during the day is more effective and economical than storing the energy for overnight reuse. Storing energy is technically more complicated by adding wax (or other PCM) within the still than storing water in the product tank.

3.5.2. Partial condensation energy recovery

Figs. 9 and 10 show the second case of only partial recovery of condensation energy (no basin
Fig. 8. Effect of partial storage of the basin energy on still performance.

energy storage); 2.0 cm of Glaubert’s salt (melting temperature of 30°C) was assumed to be contained within the low temperature condenser.

The figure shows a comparison of the still’s overall performance with and without Glaubert’s salt. With Glaubert’s salt (solid lines), there are
Fig. 9. Effect of partial recovery of condensation energy on still performance.

Fig. 10. Effect of partial recovery of condensation energy on still temperature and air flow rate.

Fig. 11. Air conditions with partial recovery of condensation energy.
no significant changes in the effective heat gained ($Q_{\text{eff}}$), average daily efficiency and total still productivity. The water productivity increased on the condenser at the expense of glass cover productivity. The circulating air flow rate shows a reversed circulation after sunset (Fig. 10). The reason is that the condenser temperature rises above the glass temperature, and consequently the air in the dehumidification channel becomes hotter (and lighter) than air in the humidification channel. This is more apparent in the temperature distribution where the dehumidified air temperature is lower than the humidified air till hour 12, after which the case is reversed. Fig. 10 also shows that the condenser temperature increases till hour 3 where its temperature reaches the melting temperature of the built-in Glaubert’s salt at 30°C. Condenser temperature is maintained constant till all the Glaubert’s salt is melted, at about hour 8, after which the condenser temperature increases. By about hour 10, the condenser temperature reaches its maximum and starts to drop again till the solidification temperature of 30°C, where it maintains constant (during solidification process) till hour 21 where it is fully solidified and the temperature drops again. It is clear that at about hour 11, the condenser temperature starts to be higher than the glass temperature, and so is the dehumidified air above the humidified air which causes air circulation to reverse. The reversed circulated air does not cause any significant vapor to condense on the glass cover since the air condition departs from the saturation conditions after hour 13, as shown in the psychrometric charts of Fig. 11.

### 3.5.3. Combined energy storage and recovery

Figs. 12–14 show the third case of combining the partial storage of basin energy for overnight

![Diagram](image-url)
Fig. 13. Effect of combined absorber energy storage and condensation energy recovery on still temperature and circulating air.

Fig. 14. Effect of combined absorber energy storage and condensation energy recovery on air conditions.

reuse and the partial recovery of condensation energy at the condenser. 2.0 cm of paraffin wax (melting temperature of 60°C) is assumed to be contained within the high temperature absorber.

In addition, another 2.0 cm of Glaubert’s salt (melting temperature of 30°C) is assumed to be contained within the low temperature condenser. Fig. 12 shows the overall performance of the still with and without these modifications. With these modifications (solid lines), the figure shows a small reduction in both still daily average efficiency and productivity. Similar to Fig. 9, the condenser water productivity increased at the expense of glass cover productivity. Fig. 13 shows the circulating air flow rate with reversed circulation after sunset between hours 13 to 21. However, there is a shift for the starting reversed air flow than that shown in Fig. 10 due to partial energy storage in the basin. For the same reason, and after hour 21, the humidifying channel starts to get hotter than the dehumidifying channel, which causes the air to recirculate in the normal direction again. The figure also shows that between hours 5 to 10 the temperature difference between the humidifying channel and the dehumidifying channel is constant (melting process of paraffin wax at 60°C and Glaubert’s salt at 30°C). This causes a constant air circulation flow rate during this period. The almost reversed constant flow rate is due to the same reason but in reverse. Fig. 14 shows that the air condition is maintained at saturation with water vapor up to hour 14, after which it is far from saturation conditions.

One last attempt to combine the partial recovery of condensation energy and reuse the energy for basin heating is shown in Fig. 15. In this case, 2.0 cm of Glaubert’s salt (melting temperature of 30°C) is assumed to be attached to the condenser as side by side strips for condensation energy storage. When the basin is cooled down and its temperature is reduced to 30°C, the 2.0 cm of Glaubert’s salt strips are moved from the condenser side and placed under the basins to
Fig. 15. Condensation energy recovery is placed under the basin.

heat it with the recovered stored energy. The figure shows a comparison of the overall still performance with and without this modification. With the modifications (solid lines), the figure shows a very small improvement in the still’s productivity. Also, the circulating air flow rate shows a reversed circulation after sunset and continues till hour 24. The air condition is maintained at saturation level till hour 12, after which it shifts away from saturation.

All of the above attempts for absorber energy storage and condensation energy recovery show an insignificant contribution in the still’s productivity. A simple still without these modifications is, therefore, more efficient both technically and economically.
3.6. Economical assessment

The water production unit cost is the sum of both initial and running costs contribution. The initial cost covers all expenses starting from the project’s conception until its commissioning. The running costs cover all the O&M expenses (staff salaries, energy and its conversion, chemicals, overheads, etc.) [25].

The proposed solar still configuration was manufactured for testing as shown in Fig. 16. It costs 500 Egyptian pounds (about US $75). The expected lifetime is 10 years and its yield is about 4 L/m².d. For a 1.0 m³/d unit (1000 L/d), 250 units are required; 10% of the stills are added to guarantee the continuous production of water in case of failure or malfunction of some stills. Table 4 summarizes the cost calculations for a 1.0 m³ water production unit through a farm of stills. The table shows that 1.0 m³ of water costs 45 EP ($9). The contribution of the capital cost represents more than 87% of the water production cost. Therefore, if the still cost is reduced from 500 EP to 100 EP, then 1.0 m³ will cost only 25 EP ($3.0). Still costs could be reduced through the selection of inexpensive materials and mass production.

In general, solar stills cannot challenge the lower cost of large units (MSF, RO, etc.) which produce water at a cost of less than US $1/m³. However, for special applications such as (1) very small communities demand, (2) unavailability of local or nearby drinking fresh water supply (remote areas), (3) unavailability of energy (fuel or electric grid) and (4) unavailability of technical capabilities within the community (for O&M of high-technology systems such as RO), the solar still seems to be the only technically and economically competing alternative.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal case</th>
<th>Cheaper -1-</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still area, m²</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Still productivity, L/m².d</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit no. of stills</td>
<td>275</td>
<td>275</td>
<td>Assumed 10% extra stills</td>
</tr>
<tr>
<td>Unit area, m²</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual production, m³</td>
<td>350</td>
<td>300*</td>
<td>*Assumed less efficient still</td>
</tr>
<tr>
<td>Still cost, EP</td>
<td>500</td>
<td>100*</td>
<td>*Inexpensive material and mass production</td>
</tr>
<tr>
<td>Unit cost, EP</td>
<td>137,500</td>
<td>27,500</td>
<td></td>
</tr>
<tr>
<td>Annual O&amp;M</td>
<td>2,000</td>
<td>2,000</td>
<td>One operator for 10 units; 500 EP/month + 800 EP spare parts</td>
</tr>
<tr>
<td>Capital installment, EP</td>
<td>13,750*</td>
<td>5,500**</td>
<td>*10 years, 0% interest</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>**5 years, 0% interest</td>
</tr>
<tr>
<td>Total annual cost, EP</td>
<td>15,750</td>
<td>7,500</td>
<td></td>
</tr>
<tr>
<td>Cost of 1.0 m³, EP</td>
<td>45 ($9)</td>
<td>25 ($5)</td>
<td></td>
</tr>
</tbody>
</table>
4. Conclusions

1. The thermal performance of a naturally circulated HDD solar still was investigated. The still has a simple design with a tilted configuration. The results show still productivity and efficiency of about 5.1 kg/m².d, similar to that of a forced circulation model [2]. In addition to its simplicity, natural circulation is more economical and technically less complex than a forced circulation still.

2. The influence of different environmental, design, and operational parameters shows that increasing solar intensity (high input energy) and ambient temperature (less energy loss) improves the still’s productivity. This is an advantage of solar desalination as water production increases under summer conditions, which are consistent with the water demand during this season.

3. Different attempts to partially store basin energy and/or recover condensation energy were also studied. These attempts cover (1) only partial storage of basin energy for overnight reuse, (2) only partial recovery of condensation energy at the condenser, and (3) a combination of energy storage and partial recovery. The results show an insignificant improvement in the still’s productivity. It is more economical, therefore, to store water rather than store energy.

4. An economical assessment of water production costs shows that 1.0 m³ of product water costs 45 EP ($9). However, if the still cost is reduced to 100 EP, then 1.0 m³ will cost only 25 EP ($5). In general, solar stills cannot challenge the lower cost of large units (MSF, RO, etc.). However, for special applications of (1) very small communities demands, (2) unavailability of fresh drinking water in remote areas, (3) unavailability of energy (fuel or electricity) and (4) unavailability of technical support within the communities, solar stills seem to be the only (technically and economically) competing alternative.
5. Symbols

\( A \) — Area, m\(^2\)

\( B \) — Still width, m

\( C \) — Specific heat, J/kg \( ^\circ \)C

\( Gr \) — Grashof number

\( h \) — Specific enthalpy, J/kg

\( H_{fg} \) — Latent heat of evaporation, J/kg

\( H \) — Film coefficient of heat transfer, W/m\(^2\)\( ^\circ \)C

\( I \) — Solar intensity, W/m\(^2\)

\( K \) — Thermal conductivity, W/m.\( ^\circ \)C

\( L \) — Characteristic length, m

\( M \) — Mass, kg

\( m \) — Mass rate, kg/s

\( P \) — Pressure, Pa

\( Pr \) — Prandtl number

\( Q \) — Heat transfer rate, W

\( t \) — Time, s

\( T \) — Temperature, \( ^\circ \)C

\( Th \) — Thickness, m

\( U \) — Overall coefficient of heat transfer, W/m\(^2\)\( ^\circ \)C

\( v \) — Velocity, m/s

\( V \) — Volume, m\(^3\)

\( w \) — Specific humidity, kg water/kg air

\( \alpha \) — Absorbtivity

\( \Delta \) — Difference

\( \varepsilon \) — Emissivity

\( \eta \) — Efficiency

\( \theta \) — Tilt angle

\( \rho_e \) — Density

\( \rho \) — Reflectivity

\( \sigma \) — Radiation constant

\( \Sigma \) — Summation

\( \tau \) — Transmissivity

\( \text{av} \) — Average

\( \text{ab} \) — Absorber

\( \text{b} \) — Basin

\( \text{C} \) — Convection

\( \text{CD} \) — Condensation

\( \text{co} \) — Condenser

\( \text{D} \) — Drive

\( \text{Dh} \) — Dehumidification

\( \text{E} \) — Evaporation

\( \text{erth} \) — Earth

\( g \) — Glass

\( \text{h} \) — Humidification

\( \text{hydr} \) — Hydraulic

\( \text{i} \) — Insulation

\( \text{in} \) — Input

\( \text{K} \) — Conduction

\( \text{out} \) — Output

\( \text{p} \) — Projected

\( \text{pw} \) — Product water

\( \text{R} \) — Radiation

\( \text{Re} \) — Resisting

\( \text{sid} \) — Side

\( \text{sk} \) — Sky

\( \text{su} \) — Sun

\( \text{sw} \) — Saline water

\( \text{w} \) — Wind

\( \text{l} \) — Inlet

\( \text{2} \) — Outlet

Greek

\( \alpha \) — Absorbtivity

\( \Delta \) — Difference

\( \varepsilon \) — Emissivity

\( \eta \) — Efficiency

\( \theta \) — Tilt angle

\( \rho_e \) — Density

\( \rho \) — Reflectivity

\( \sigma \) — Radiation constant

\( \Sigma \) — Summation

\( \tau \) — Transmissivity

Subscripts

\( a \) — Air

\( \text{am} \) — Ambient

References


