We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Factors Affecting the Yield of Solar Distillation Systems and Measures to Improve Productivities

Bao The Nguyen

Additional information is available at the end of the chapter

Abstract

This chapter presents a numerical model to estimate the performance of solar basin-type distillation systems, both for conventional passive solar stills and active (forced circulation) stills with enhanced heat recovery. It also analyzes the factors affecting the distillate outputs of the still, including environmental factors (external factors or natural), elements of the design and operation (subjective factors). The subjective elements as well as the measures taken to optimize these factors are thoroughly analyzed. With these measures, the distillate yields of solar stills are increased from 30 to 68% compared with traditional distillation systems. This has scientific significance and practicality enabling the application of this technology to solar water distillation using a source of clean and renewable energy. It provides a viable way to alleviating the problem of the availability of clean water, especially in those areas and communities in countries where water resources are increasingly polluted and salty.

Keywords: solar basin-type still, passive solar still, active solar still

1. Introduction

The demand for clean water for domestic use has increased rapidly, especially in certain water-scarce areas located in rural, remote and border areas, islands, arid areas or places with polluted and saline water sources. Therefore, the development and the production of devices to distil water from alkaline, brackish or saline water sources and thus supply fresh water to people in affected areas are a critical issue for many countries whether clean water shortages are periodic or permanent.

There are many research and review papers that focus on solar stills and the factors that affect the output of solar distillation. Manchanda and Kumar [1] comprehensively reviewed and analyzed the designs and performance parameters of passive solar stills, while Sampathkumar et al. [2] reviewed in detail different types of active distillation systems. Velmurugan and Srithar [3] appraised certain modifications to solar still systems and their resulting respective performance enhancement. Focusing on the single-basin passive solar still, Murugavel et al. [4] evaluated the progress in improving the effectiveness of this type of still. Similarly, Kabeel and El-Agouz [5] examined single-type passive solar stills, with emphasis on performance enhancing modifications. Badran [6] studied another aspect experimentally—the performance of a single-slope solar still using different operational parameters. Other researches by Kaushal and Varun [7] evaluated the effect of different designs and methods on solar still output. Muftah et al. [8] comprehensively reviewed the performance of existing active and passive basin-type solar stills and investigated the effects of climatic, operational and design parameters on the output of these stills. Recently, Sharshir et al. [9] reviewed in details factors affecting solar still productivity and improvement techniques, while Kabeel et al. [10] introduced, explained and discussed the effectiveness of different solar stills into which different condenser arrangements were integrated.

All the above-mentioned papers, although comprehensive and thorough, have the same drawbacks that all previous researches and papers reviewed had, namely, they were from countries with different climatic conditions and different levels of technology and manufacturing expertise. This would lead to inconsistencies and differences in improvements to the named stills' output and performance as compared to those outputs and performances claimed or reported. Furthermore, there has been very little information relating to factors affecting forced circulation solar stills with enhanced water recovery.

Therefore this chapter will present the results of the numerical and experimental research carried out in one location so that there is consistency in the factors affecting solar stills' production as well as the gains of the stills' outputs due to the measures taken to optimize these factors. In addition, there will be a focus on the factors affecting the performance of forced circulation solar stills with enhanced water recovery improvement techniques.

2. The numerical modeling of a conventional basin-type solar still

Dunkle [11] was the first to investigate the heat and mass transfer relationships in a solar still under steady-state conditions. Based on the widely used relations from Dunkle, this study has analyzed the transient performance of the solar still in which all coefficients and still parameters are calculated using equations within the model. The weather data used for simulation will be either from actual measured data or data generated from the computer program developed by Nguyen [12].

The heat and mass transfer processes in the still are shown in **Figure 1**. The following assumptions are made in order to develop the equations for the energy balances in the still:
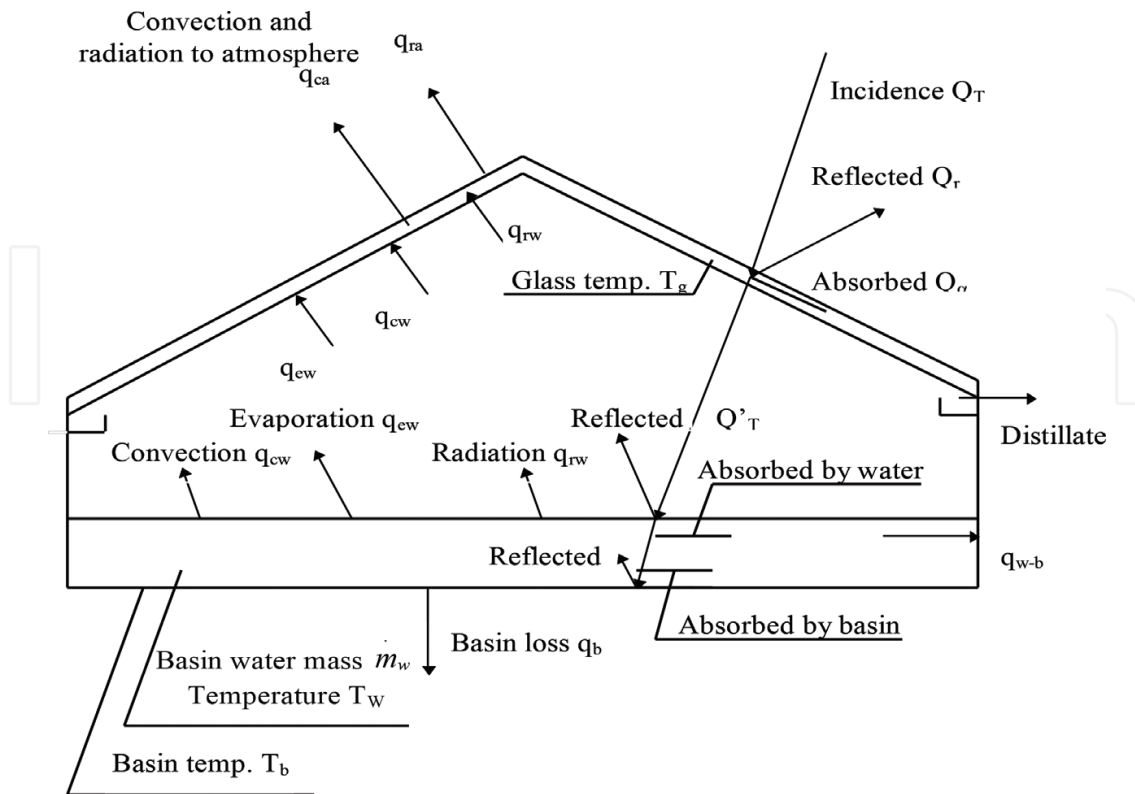
Figure 1. The heat and mass transfer processes in a conventional solar still.

1. The amount of water lost through evaporation is small compared to the amount of saline water in the basin.

2. The heat required to heat the water from the ambient (before adding to the basin) temperature to the temperature of water in the basin is negligible as compared to that required to evaporate the same quantity of water that means $C_{pw}(T_w - T_a) << h_w$.

3. There is no vapor leakage in the still, assuming a well-designed still.

4. The areas of the cover, the water surface and the basin are considered to be equal.

5. The temperature gradients along the cover thickness and the water depth are absent.

Based on these assumptions and from **Figure 1**, the energy balances for the glass, for the basin water, and for the basin are:

$$q_{cw} + q_{ew} + q_{rw} + \alpha_g Q_T = (q_{ra} + q_{ca}) + M_g \frac{dT_g}{dt}. \tag{1a}$$

$$\alpha_w Q_T' = q_{cw} + q_{ew} + q_{rw} + q_{w-b} + M_w \frac{dT_w}{dt}. \tag{2a}$$

$$\alpha_b Q_T'' + q_{w-b} = q_b + M_b \frac{dT_b}{dt}. \tag{3a}$$

where

- q_{cw} is the convective heat transfer rate between the basin water and the cover (in W/m^2) and can be calculated by using Dunkle's equation:

$$q_{cw} = 0.884 \left[(T_w - T_g) + \frac{\left(p_w - p_g\right)(T_w + 273.15)}{(268.9 \times 10^3 - p_w)} \right]^{1/3} (T_w - T_g). \tag{4}$$

with p_w and p_g being the partial pressure of water vapor at the temperatures of the basin water and the cover, respectively (in Pa).

- q_{ew} is the evaporative heat transfer rate between the basin water and the cover (in W/m^2):

$$q_{ew} = 16.276 \times 10^{-3} q_{cw} \frac{\left(p_w - p_g\right)}{(T_w - T_g)}. \tag{5}$$

- q_{rw} is the radiative heat transfer rate between the basin water and the cover (in W/m^2), expressed as:

$$q_{rw} = \varepsilon_w \sigma \left[(T_w + 273.15)^4 - (T_g + 273.15)^4 \right]. \tag{6}$$

with ε_w being the emissivity of water surface and σ the Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2.K^4.

- q_{ca} is the convective heat transfer rate between the cover and the ambient surroundings (in W/m^2), computed from [13]

$$q_{ca} = (5.7w + 3.8)(T_g - T_a). \tag{7}$$

where w is the wind speed (m/s) and T_a is the ambient temperature (°C).

- q_{ra} is the radiative heat transfer rate between the cover and the ambient surroundings (in W/m^2):

$$q_{ra} = \varepsilon_g \sigma \left[(T_g + 273.15)^4 - (T_a + 261.15)^4 \right]. \tag{8}$$

where ε_g is the emissivity of the cover

- q_{w-b} is the heat transfer rate between the water and the basin (in W/m^2):

$$q_{w-b} = h_{w-b}(T_w - T_b). \tag{9}$$

where h_{w-b} is the heat transfer coefficient between the water and the basin absorbing surface (in W/m^2.°C).

- q_b is the heat transfer rate between the basin and the ambient surroundings (in W/m²):

$$q_b = h_b(T_b - T_a). \tag{10a}$$

where h_b is the heat transfer coefficient between the basin and the ambient surroundings (in W/m².°C):

$$\frac{1}{h_b} = \frac{\delta_{insul}}{k_{insul}} + \frac{1}{h_i}. \tag{10b}$$

- δ_{insul} (m) and k_{insul} (W/m.°C) are the thickness and thermal conductivity of the basin insulation, respectively.

- h_i is the combined convective and radiative heat transfer coefficient between the insulation and ambient and can be computed by the derivation of Eqs. (6) and (7).

- Q_T is the total solar radiation incidence on the cover, in W/m².

- Q_T' is the total solar radiation incidence on the water surface, after transmittance through the cover, in W/m².

- Q_T'' is the total solar radiation incidence on the basin, after transmittance through the basin water, in W/m².

- α_g, α_w and α_b are the absorptance of the cover, of the water and of the basin for solar radiation, respectively.

- M_g, M_w and M_b are the heat capacities per unit area of the cover, of the water and of the basin for solar radiation, in J/m².°C.

- T_g, T_w and T_b are, respectively, the transient temperatures of the cover, of the water and of the basin for solar radiation, in °C.

Equations (1a), (2a) and (3a) can be rewritten as:

$$M_g \frac{dT_g}{dt} = \alpha_g Q_T + q_{cw} + q_{ew} + q_{rw} - (q_{ra} + q_{ca}). \tag{1b}$$

$$M_w \frac{dT_w}{dt} = \alpha_w Q_T' - (q_{cw} + q_{ew} + q_{rw} + q_{w-b}). \tag{2b}$$

$$M_b \frac{dT_b}{dt} = \alpha_b Q_T'' + q_{w-b} - q_b. \tag{3b}$$

It is convenient to present all solar components Q_T, Q_T' and Q_T'' in the above equations by the common total solar incidence of the sloped cover, Q_T, which is readily calculated [3]. If τ_g, τ_w and τ_b are defined as the fractions of solar insolation incident absorbed by the cover, basin water and basin liner, respectively, Eqs. (1b), (2b) and (3b) may be written as:

$$M_g \frac{dT_g}{dt} = \tau_b Q_T + q_{cw} + q_{ew} + q_{rw} \text{-} (q_{ra} + q_{ca}). \tag{1c}$$

$$M_w \frac{dT_w}{dt} = \tau_w Q_T - (q_{cw} + q_{ew} + q_{rw} + q_{w-b}). \tag{2c}$$

$$M_b \frac{dT_b}{dt} = \tau_b Q_T + q_{w-b} - q_b. \tag{3c}$$

3. The numerical modelling of a basin-type forced circulation solar still with enhanced water recovery

In this study, the heat and mass transfer relationships in the forced circulation solar still with enhanced water recovery will be developed. Then, this numerical modeling will be validated by comparing its results with those from the experimental model.

The forced circulation solar still has been chosen in this study for several reasons. Compared with other types of solar powered distillation systems such as the solar multistage flash distillation, solar vapor compression, solar powered reverse osmosis, solar powered electrodialysis and solar membrane distillation systems, solar stills represent simple, yet mature technology.

The low efficiencies of a conventional solar still may be overcome by changing the principle of operation as follows:

- Using air as an intermediate medium and substituting forced convection for natural convection to increase the heat coefficients in the still, resulting in increased evaporation of water

- Replacing saturated air in the standard still by "drier" air to increase the potential for mass transfer in the still, leading to higher outputs

- Circulating the air-vapor mixture from the standard still to external water-cooled condensers to gain efficiency from a lower condensing temperature. The cooler the cooling water available, the more effective this condensing process will be

- Recovering some of the heat extracted in the condensing process and using it to preheat the air-vapor mixture entering the still

- Substituting the condensing area of the flat sheet covers in the standard still by the external condenser with much larger heat exchange areas to increase condensation efficiencies

3.1. The development of the heat and mass transfer relationships in a forced circulation solar still

Figure 2 shows a schematic diagram of the forced circulation solar still with enhanced water recovery. The air flow having a temperature of T_{fin} and moisture content w_{in} enters the still and is heated up. It absorbs the vapor from the basin water and exits the still at a temperature of
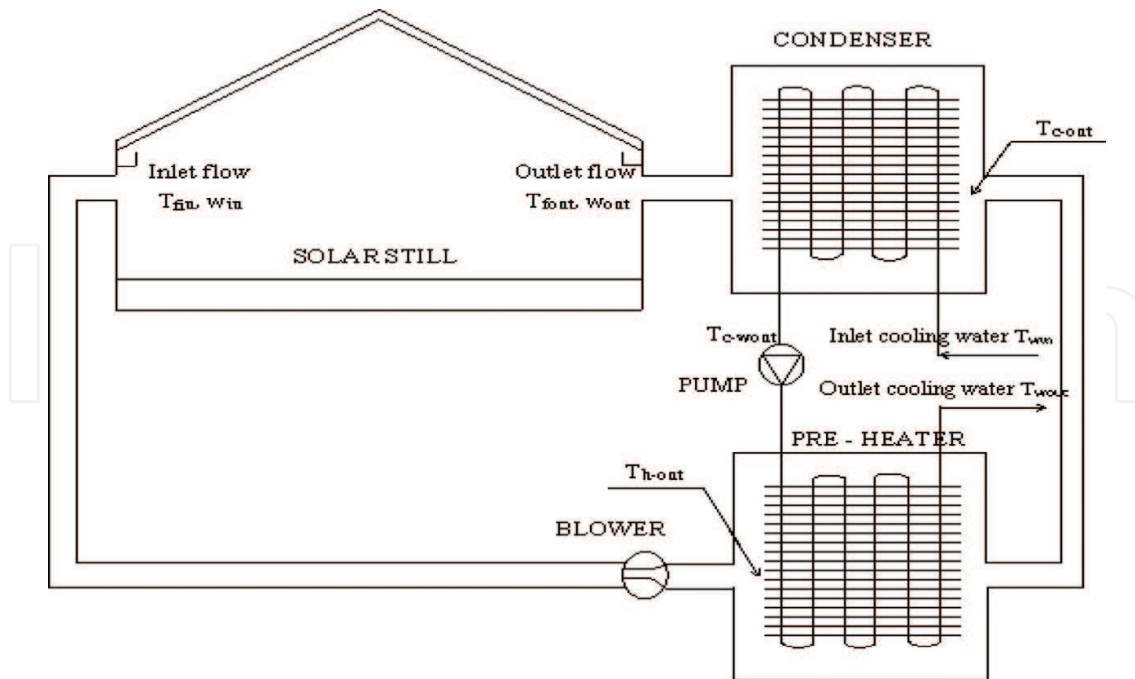
Figure 2. Schematic diagram of a forced circulation solar still with enhanced water recovery.

T_{fout} and moisture content w_{out}. This air flow goes through the dehumidifying coil, which acts a condenser. The hot air-vapor mixture from the still is passed over the coil and attached fins, while the cooling water runs inside the coil.

The hot air-vapor mixture losses heat to the cooling water and subsequently cools down. When the temperature of the mixture falls below its dew point temperature, the condensation process starts. The air exits the condenser at a temperature of T_{c-out} and a moisture content of w_{c-out}. Some of the heat extracted from the air flow will be recovered in the preheater, since the air flow goes through it before going back to the still.

The heat and mass transfer relationships in this still can be seen from **Figure 3**. From this figure, the energy and mass balances for the glass, for the flow in the still, for the basin water and for the basin are

$$q_{cfg} + q_{rw} + \alpha_g Q_T = (q_{ra} + q_{ca}) + M_g \frac{dT_g}{dt} \tag{11}$$

$$q_{ew} + q_{cwf} = q_{cfg} + m_f(h_{out} - h_{in}) + M_f \frac{dT_f}{dt} \tag{12}$$

$$m_{ew} = \frac{q_{ew}}{h_{fg}} = m_f(w_{out} - w_{in}) + m_{ew-g} \tag{13}$$

$$\alpha_w Q'_T = q_{cwf} + q_{ew} + q_{rw} + q_{w-b} + M_w \frac{dT_w}{dt} \tag{14}$$

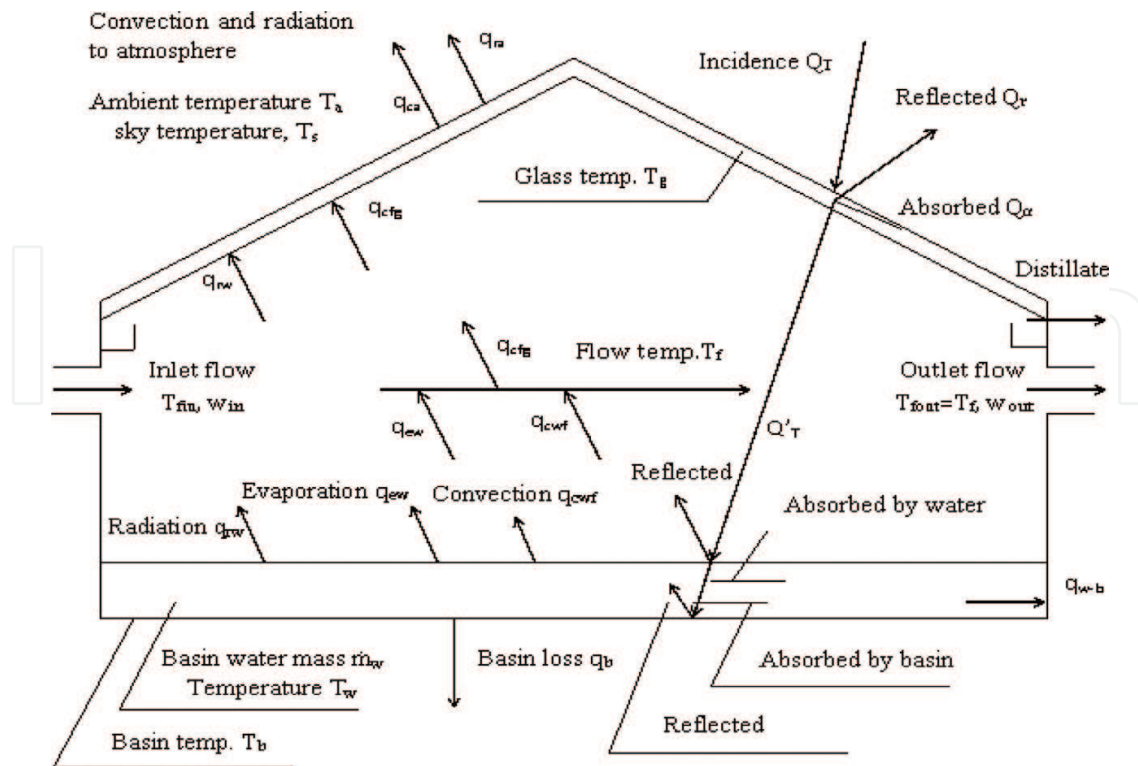$$\alpha_b Q''_T + q_{w-b} = q_b + M_b \frac{dT_b}{dt} \tag{15}$$

Figure 3. The heat and mass transfer process in a forced circulation solar still.

q_{cwf} is the convective heat transfer rate between the basin water and the flow (in W/m²). In principle, the blower used to transport the air should have the lowest possible energy consumption. The heat transfer process in the still may be natural convection or combined natural and forced convection. In this model, the heat coefficient in the still is calculated by using the forced and natural convection relations separately, and the larger one is chosen. The Grashof and the Reynolds number are first calculated [13]:

$$Gr = \frac{g' \Delta T L^3}{v^2} \tag{16}$$

$$Re = \frac{V D_h}{v} \tag{17}$$

where:

L = average spacing between the water surface and the cover, in m.

g = gravitational constant, 9.81 m/s².

β′ = volumetric coefficient of expansion, in K⁻¹; for air ′ = 1/T.

ΔT = temperature difference between the water and the cover, in K.

v = kinematic viscosity, in m/s².

V = air flow velocity, in m/s.

D_h = the hydraulic diameter of the still, defined as $D_h = \frac{4^* (flow\ area)}{wetted\ perimeter}$.

Then, if the natural convection dominates, the convective heat transfer rate between the basin water and the flow can be derived from

$$Nu = \frac{h_{cwf} L}{k} = 0.075\,(Gr.Pr)^{1/3} \qquad (18)$$

where Pr = · is the Prandtl number,

to achieve a similar equation to Dunkle's expression [2] with T_g replaced by T_f:

$$qcwf = 0.884 \left[(T_w - T_f) + \frac{(T_w - T_f)(T_w + 273.15)}{(268 \times 10^3 - p_w)} \right]^{1/3} (Tw\text{-}Tf) \qquad (19)$$

where p_w and p_f are partial pressures (in Pa) of water vapor at the temperatures of the basin water and the flow, respectively.

If the forced convection dominates, the relation between Nu and Re is given by [4]

$$Nu = \frac{h_{cwf} D_h}{k} = 0.664 \times Re^{1/2} \times Pr^{1/3} \qquad (20a)$$

Considering T_w = 50°C and T_f = 40°C and introducing the corresponding air properties into (20a), the convective heat transfer rate between the basin water and the flow can be computed by

$$q_{cwf} = 3.908 \left(\frac{V}{D_h} \right)^{1/2} (T_W - T_f) \qquad (20b)$$

q_{ew} is the evaporative heat transfer and the radiative heat transfer rates (in W/m^2) between the basin water and the air flow and can be approximated by (5) with T_g and p_g replaced by T_f and p_r.

q_{rw} is the radiative heat transfer rates (in W/m^2) between the basin water and the cover and can be calculated by (6).

q_{cfg} is the convective heat transfer rate (W/m^2) between the flow and the cover given by

$$q_{cfg} = 2.785 \left(\frac{V^{0.8}}{L_s^{0.2}} \right) (T_f - T_g) \qquad (21)$$

where V is the air flow velocity (m/sec) and L_s is the still length (m).

q_{ca} and q_{ra} are the convective and radiative heat transfer rates (in W/m^2) between the cover and the ambient surroundings, computed from by using Eqs. (7) and (8), respectively.

q_{w-b} and q_b are the heat transfer rates (in W/m^2) between the water and the basin and between the basin and the ambient surroundings and can be calculated from Eqs. (9) and (10), respectively.

Q_T is the total horizontal solar radiation incident on the still, in W/m^2.

Q'_T is the total solar radiation incident on the water surface, after transmittance through the cover, in W/m^2.

Q''_T is the total solar radiation incident on the basin, after transmittance through the basin water, in W/m^2.

m_f is the mass rate of the air flow, in kg/s.

m_{ew} is the mass rate pf the evaporation from the basin water to the air flow, in kg/s.

$_g$, $_w$ and $_b$ are the solar absorptance values of the cover, of the water and of the basin, respectively.

M_g, M_w, M_f and M_b are the heat capacities of the unit area of the cover, of the water, of the air in the still and of the basin, in J/m^2 °C.

T_g, T_w, T_f and T_b are, respectively, the temperatures of the cover, water, air in the still and the basin, in °C.

H_{fg} is the latent heat of vaporization of water at the temperature T_f, in J/kg.

w_{in} and w_{out} are the moisture contents of the air-vapor mixture at the inlet and outlet of the still, in kg/kg.

h_{in} and h_{out} are the enthalpies of the still inlet and outlet air, in J/kg. Assuming that the air in the still is reasonably well mixed, the enthalpy of the still outlet h_{out} can be calculated as a function of the temperature T_f as follows:

$$hout = (Tf + wout \times (2501 + 1.805Tf)) \times 103 \quad (J/kg) \tag{22}$$

The amount of the distillate water collected inside the still will depend on the temperatures of the air and the cover. Water will condense on the cover surface only when the dew point temperature of the air flow, T_{fd}, is higher than the cover temperature, T_g. In this case, the amount of the distillate water collected from the cover, m_{ew-g} (in kg/s.m^2), can be calculated from

$$\dot{m}_{ew-g} = \frac{q_{con-g}}{h_{fg}} \quad (kg/s.m^2) \tag{23}$$

h_{fg} is the latent heat of vaporization of water at the temperature, T_f, in J/kg.

$q_{con-g} = h_{con-g}(T_f{-}T_g)$ is the condensate heat transfer rate between the flow and the cover (in W/m^2). Using the Nusselt number in condensing:

$$Nu = \frac{h_{con-g}L_c}{k} = 0.943 \left(\frac{g^2 \sin h_{fg} L_c^3}{\mu \, k \, \Delta T} \right)^{1/4} \tag{24}$$

where:

L_c = the length of the cover, in m; $L_c = L_s$

k = thermal conductivity, in W/m K

g = gravitational constant, 9.81 m/s²

β = the slope of the cover, in degree

ρ = the air density, in kg/m³

ΔT = the difference between the dew point temperature of the flow and the cover temperature, in °K

μ = absolute viscosity, in Pa.s

Using the properties of the air at T_f = 40°C, one can achieve

$$q_{con-g} = 70.93 \left(\frac{\sin\beta}{\Delta TL_c} \right)^{0.25} \tag{25}$$

Therefore, using the five equations from Eqs. (11) and (12), the five unknown parameters, T_g, T_w, T_f, w_{out} and T_b, can be solved.

3.2. The performance of the condenser and preheater

The theory of the performance of dehumidifying and of heating coils has been developed and is presented in [14, 15]. However, an explicit procedure for calculating the performance of dehumidifying coils was not available in these references. Therefore, the modeling of the performance of the condenser and the preheater in this simulation program was derived from the handbook and the standard. The calculation procedures for the psychrometric properties of humid air were given in [14]. A detailed description of the procedures for modeling the performance of the preheater and dehumidifying coils in solar still is described in [15].

The procedure for modeling the performance of the preheating coil involves (i) calculating the overall coefficient of heat transfer for the coil, (ii) calculating the effectiveness of the coil and then (iii) computing the temperatures of the air and cooling water leaving the coil.

The procedure for modeling the performance of the dehumidifying coil involves using an iterative process to find a consistent set of temperature and humidity values, subject to the constraints imposed by the performance characteristics of the dehumidifying coil.

4. Analysis of factors affecting the production of solar stills

The important factors affecting the output of a solar still can be summarized in **Figure 4**.

4.1. Effects of weather conditions

4.1.1. Impact of solar radiation

Solar radiation is the main and the most important factor to yield distilled water. The greater the radiation received, the greater the volume of distilled water produced and vice versa. However, the greater the radiation, the greater the heat loss of the still. Therefore, the insulation of the still needs to be carefully considered.

4.1.2. Effect of wind speed

Wind speed values were varied from 0 to 6 m/s when inputted into SOLSTILL [12]. Hourly solar radiation data and ambient temperature data are included in the software.

The results showed that as the wind speed increased from 0 to 3 m/s, the higher wind speeds gave greater water output. This can be explained by noting that high wind speeds will cool the glass cover faster, leading to an increased temperature difference between the water and the
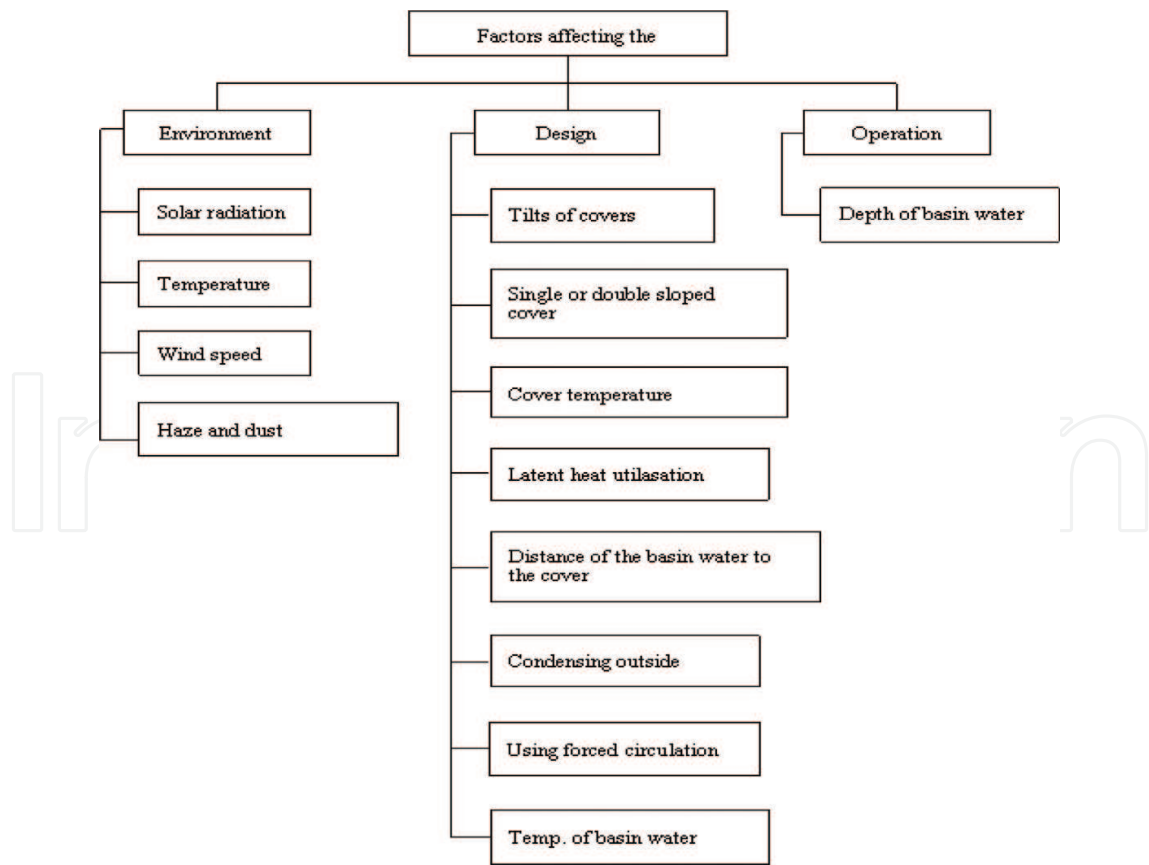

Figure 4. Factors affecting the outputs of solar distillation systems.

cover layer. However, when the wind speed increased from 3 to 6 m/s, the distilled water output increased only 1.6%. As noted above, the wind speed is too high and leads to heat loss, so that the gain in water output is almost negligible. This result is consistent with Cooper's survey [16]. In his research, as Cooper increased wind speeds from 0 to 2.15 m/s, the output of the still rose by 11.5%; when wind speed was increased from 2.15 to 8.81 m/s, the output of distilled water increased by only 1.5%.

4.1.3. Effect of ambient temperature

The influence of ambient temperature on (i) insulated distillation devices and (ii) uninsulated distilling equipment was studied, and the results are shown in **Figure 5**. In case (i), the decrease in ambient temperature leads to a higher distilled water output, while in the case of (ii), the opposite is observed. This can be explained as follows: for the distillation equipment with good insulation, lower temperature will help cool the glass cover faster, thereby increasing the temperature difference between the water layer and cover sheet. However, when the distillation equipment is not insulated, low ambient temperature increases heat loss of the device, leading to a reduction in water temperature in the equipment. Low-temperature still cools the glass cover, but the results in **Figure 5** show that the impact of increased heat loss is more important than the impact of lower glass temperature.

The change of ±5°C in well-insulated distillation systems will make the average distilled water output change ±4.5%. This result is consistent with the results of the Khalifa and Hamood [17]. Their research has shown that when the ambient temperature rose from 26.7 to 37.8°C, the outputs may rise 11% and when temperatures are reduced from 26.7 to 15.6°C, the outputs fall 14%.

The change of ±5°C ambient temperature for insulated distillation devices make the distilled water output ±2.5% change, as a result of SOLSTILL [12].
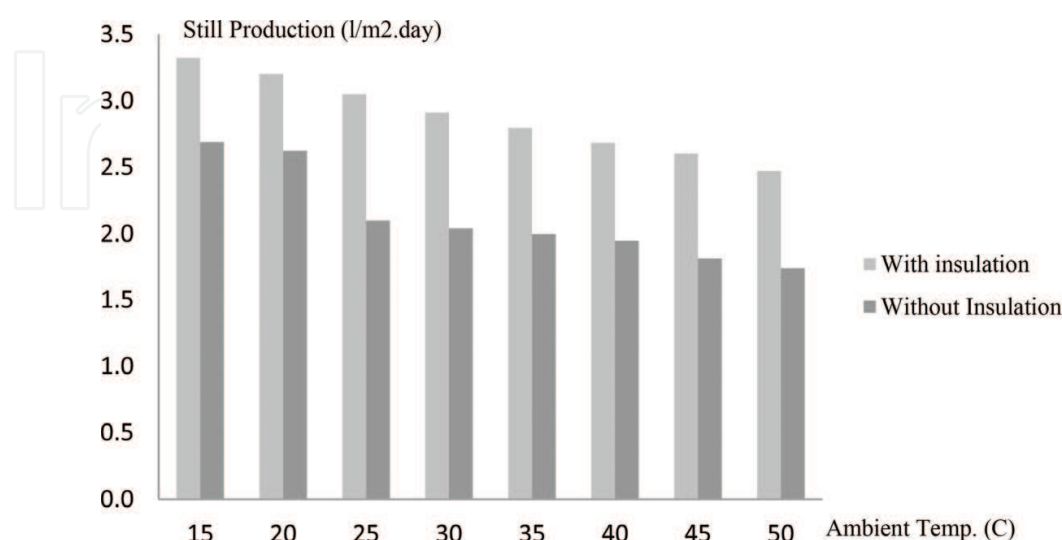

Figure 5. Effect of temperature on the output of solar stills [12].

4.1.4. Effect of the haze and dust

Solar stills, being placed outdoors to receive direct solar radiation, cannot avoid dust on the surface of coated glass. This reduces the coefficient of radiation incidents, thus reducing the efficiency of the distillation equipment. Additionally, if dust enters the inside surface of the glass, it can affect the condensation flow down to the collecting gutters with the distilled water dripping halfway down the glass. So, it is necessary to regularly check and clean the inside and outside of the cover to achieve the highest efficiency.

The simulation results of SOLSTILL show very clearly the dependence of distilled water output to the intensity of solar radiation that the distillation equipment receives [12].

4.2. Effects of cover properties

4.2.1. Effect of glass cover's tilt

Distilled water output depends very much on the elements of the cover's angle and tilt direction. To ensure the distilled water will not drip while halfway down to the collecting gutters, the tilt of the covers must be more than 15°. On the other hand, it is necessary to reduce the average distance between the water surface and the tilted covers; the tilt of the covers must be not more than 20° [17]. The SOLSTILL program also produces similar results, with the still output dropping rapidly when the cover slope angles are greater than 30° [12].

4.2.2. The effects of single-sloped and two-sloped (roof type) covers

SOLSTILL can also be used to simulate the distillation equipment using one cover (single sloped) and two covers (double sloped, also known as roof type); the tilt is 15° in both cases. This assumes that the coverings the two types of devices have are the same and their axes lie along the east-west direction. The yields of the two distillation devices are shown in **Figure 6**.

The results show that the distillation device with double-sloped cover works better in late spring and summer while the distilling equipment with single-sloped cover works better in
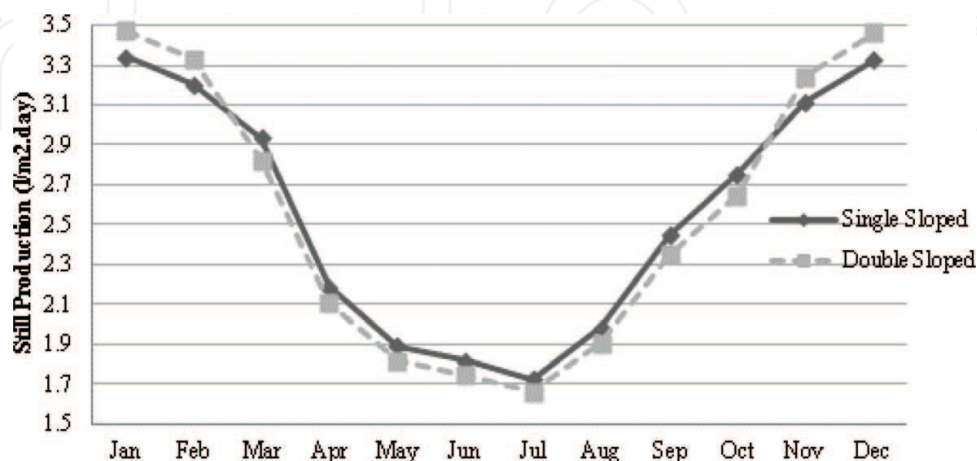

Figure 6. The output of distilled water per month single roof and roof-type double.

other seasons. This can be explained by the fact that in the late spring and summer, sunrise and sunset are to the south of the east-west axis. Therefore the kind of roof-type cover will benefit from having the second roof (that means a south heading) in the early morning and late afternoon. At other times of the year, the still with single-sloped cover will get all the available solar radiation and over a year; this still performs a little better. This is consistent with the experimental results of Garg and Mann [18].

Therefore, theoretically, one sloped cover should give a little more output than those having two slopes. In practice, however, the use of single slope introduces additional difficulties during system construction, requiring additional materials, and has more problems in terms of structural stability in high winds than the roof-type still. This may be the reason why the roof-type stills are still more favored.

4.2.3. Effect of the temperatures of the covers

Cooper, Khalifa and Hamood, Garg and Mann [16–18] showed that the glass covers can absorb approximately 4.75% of solar radiation energy, leading to an increase of the cover's temperature. On the other hand, the condensation of water below the glass surface creates a condensation water film, leading to a partially opaque glass surface and an increase in the glass' temperature. As a result, the temperature difference between the surface of the water and condensation glass cover will be reduced. Therefore, seeking to reduce the surface temperature of the glass is important in order to improve the water productivity (output) of the device [17].

To reduce the temperature of the glass cover, one can speed up the wind outside as mentioned in Section 4.1.2. However the wind is also a natural factor, and it is difficult to control this. So Husham [19] proposed a different approach—use a water cooling membrane on a piece of glass using tap sprays on the glass surface every 30 s with the time interval for the spray test of 10 and 20 min, respectively. Results of regular sprinkling helped increase productivity to 31.8 and 15.7%, respectively.

In the next section, the measures taken to reduce the temperature of covers and results achieved by this will be presented.

4.2.4. Utilizing the latent heat of evaporation

To take advantage of the latent heat of water vapor in the condensation, numerous studies have used distillation device models with two flat tanks (double basin) and three flat tanks (triple basin) [20]. This is a useful way to increase production of distilled water. However this device is complicated and costly. In Section 5 of this chapter, the results of experiments to take advantage of the latent heat of evaporation will also be shown.

4.2.5. Effect of the distance between the water level and covered glass

The distance between the water surface coverings can affect the effectiveness of the solar distillation systems. As discussed in Section 4.2.1, if the distance between the water surface and coverings is small, the convective resistance of wet air flow inside the device is smaller, so that efficiency will be improved. But this gap is influenced by the inclination of coated glass. If

the tilt of the cover is increased, then the average distance between the water surface and coverings is widened, so the output of the still will decrease. In the latter part of this paper, the measures on a stepped solar still to achieve the smallest distance between the water level and the glass in order to achieve highest distilled water output will be presented.

4.3. Effects of water properties

4.3.1. The effect of water temperature in the still

The water temperatures in the equipment greatly affect the output of distilled water. As mentioned in Section 4.2.3, water on the cover as a thin film cools down the glass before running into the still. By using the latent heat of steam in the steam condensation under the glass covers, water can be heated and fed into the device. This approach can be applied to both passive and active solar stills.

In Section 5 of this chapter, the use of glass vacuum tubes to heat up the water in the basin of the still will be presented.

4.3.2. The effects of water depth in the still

The depth of water in the device greatly affects the yield of distilled water. Due to thermal inertia, the deep water layers will make the absorption process of solar energy take longer, thus slowing the increase of water temperature and affecting the amount of distilled water. The experimental results of a single-basin solar still coupled with evacuated glass tubes [21] show that a test with a 1 cm depth of water in the basin produces 5.265 l/m^2, which is 13.4% higher than a test using a 2 cm depth of water which produces only 4.555 l/m^2, as shown in **Figure 7**. This agrees with the theoretical and experimental results in other researches [17, 22, 23].
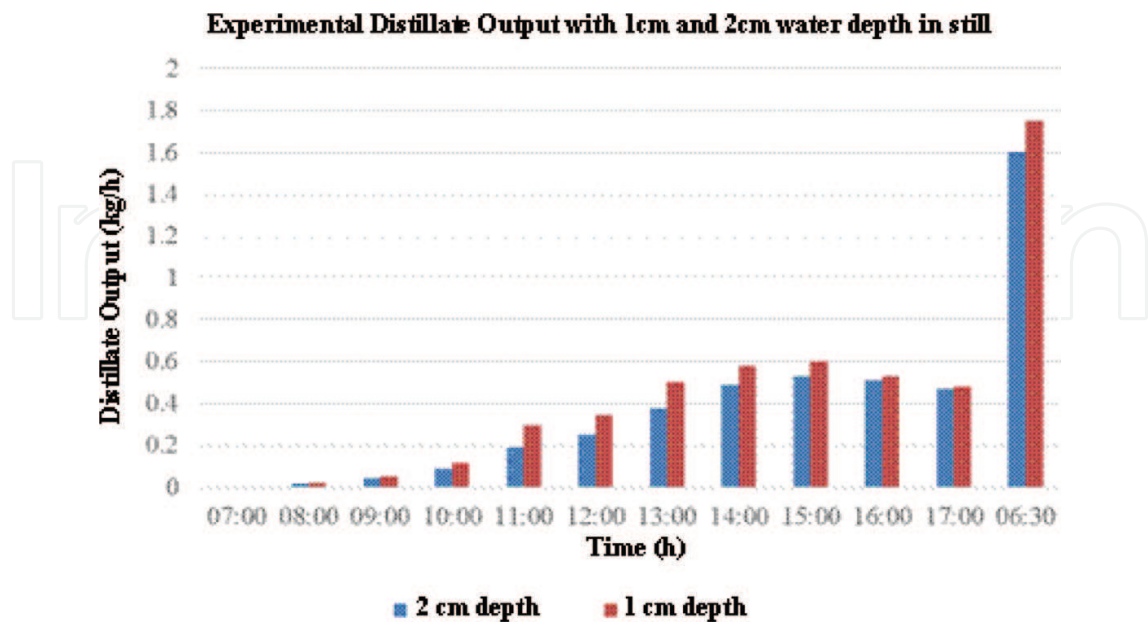

Figure 7. Experimental distillate output with 1 and 2 cm water depth in the single-basin solar still coupled with evacuated glass tubes [21].

4.4. Effects of other factors

4.4.1. Using the external condensing device

In traditional solar basin distillation systems, the glass covers are used to condense distilled water. This method enables the device to have a simple structure, but it also has two disadvantages:

- Latent heat of vaporization released during condensation makes the temperature of the coated glass increase, resulting in increasing water vapor pressure near the coverings. This reduces the pressure difference between the water evaporative layer and the condensation surface.

- The condensation of distilled water under the glass surface creates a film or droplet layer, reducing the ability of solar radiation penetrating the glass cover and reaching the bottom of the absorbing surface.

The use of an external condenser and a recovery heat exchanger to take advantage of moist air stream with high temperature and humidity returned to the distillation system was also proposed and tested [12]. The results showed that the use of an external condenser could increase output by 25% (average daily output of 3.87 l/m^2 compared to 3.10 l/m^2) and the use of a recovery heat exchanger to circulate the moist air can increase by nearly 54% the output of distilled water (average daily output of 4.76 l/m^2 compared to 3.10 l/m^2).

In Section 5 of this chapter, the results of theoretical and empirical research on the use of an external condenser for a solar passive (or natural convective) still will be presented.

4.4.2. The effect of the generation of forced convection inside the still

The process of heat and mass transfer inside a conventional solar still is a natural convective process. The low efficiencies of a conventional solar still may be overcome by changing the operation principles as follows:

- Using air as an intermediate medium and substituting forced convection for natural convection to increase the heat coefficients in the still, resulting in increased evaporation of water

- Replacing saturated air in the standard still by "drier" air to increase the potential for mass transfer in the still, leading to higher outputs

- Circulating the air-vapor mixture from the standard still to external water-cooled condensers to gain efficiency from a lower condensing temperature. The cooler the cooling water available, the more effective this condensing process will be

- Recovering some of the heat extracted in the condensing process and using it to preheat the air-vapor mixture entering the still

- Substituting the condensing area of the flat sheet covers in the standard still by the external condenser with much larger heat exchange areas to increase condensation efficiencies

In Section 5 of the chapter, this issue will be presented in greater detail.

5. Measures to improve the productivity of solar stills

As analyzed above, the elements of the environment are the objective factors and cannot change. In this section we focus on the main measures taken in the design of the still.

5.1. Reducing the cover's temperature

In the experiments on a stepped solar still [22], a cooling water flow is sprayed with 5 l/min for 30 s on the cover with the time between two injections being 10 and 20 min. The schematic diagram of the experimental stepped solar still is shown in **Figure 8**. Experimental results show that, for a day with average solar radiation of 600 W/m^2, the distilled water obtained is 4.45 and 4.35 l/m^2 corresponding to a period of 10 and 20 min between two injections, compared with 4.08 l/m^2 in the case with no cooling water spray to the coverings, which rises to 9 and 6.6%, respectively, as can be seen in **Figure 9**.

Similarly, in the active (forced circulated) solar still [12], the forced convection also helps to cool the covering surface, increasing the production of distilled water. When the speed of air flow in the distillation system reached 0.005 m/s, the output of distilled water was 3.53 compared to 3.05 l/m^2 in the case of traditional devices, with an increase of 15.7%. This result is consistent with results of Husham [19], as stated in Section 4.2.3.

5.2. Taking advantage of the latent heat of evaporation

In this study, a double-basin solar still (DBSS) combined with evacuated glass tubes has been fabricated and tested to compare it with a single-basin solar still (SBSS) with evacuated glass tubes. **Figures 10** and **11**, respectively, show the schematic diagrams of these two types of stills. Experimental results are shown in **Figure 12**. The outputs of distilled water of the two types
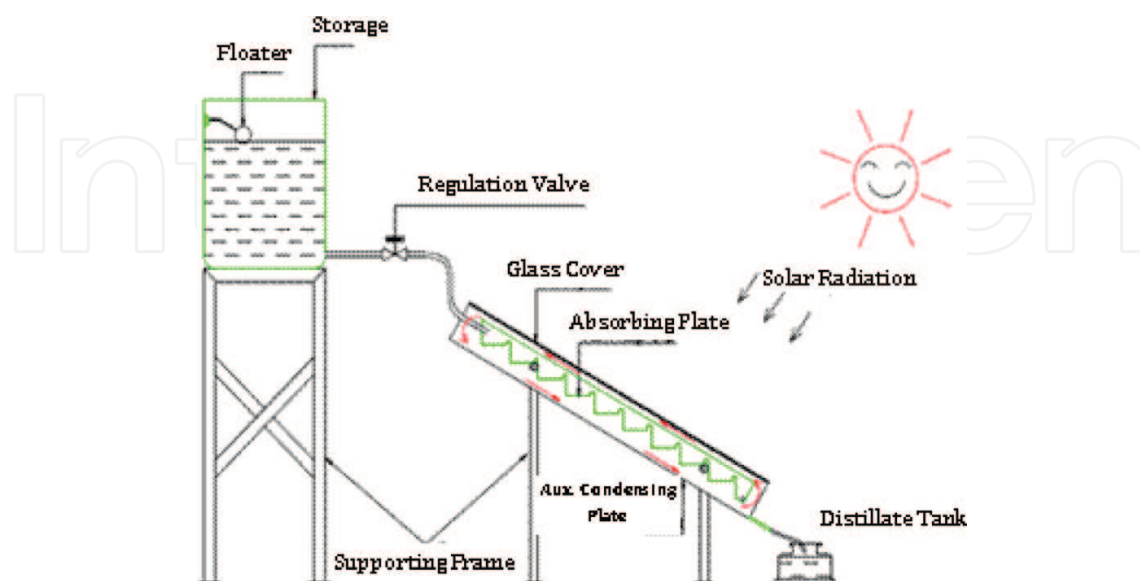

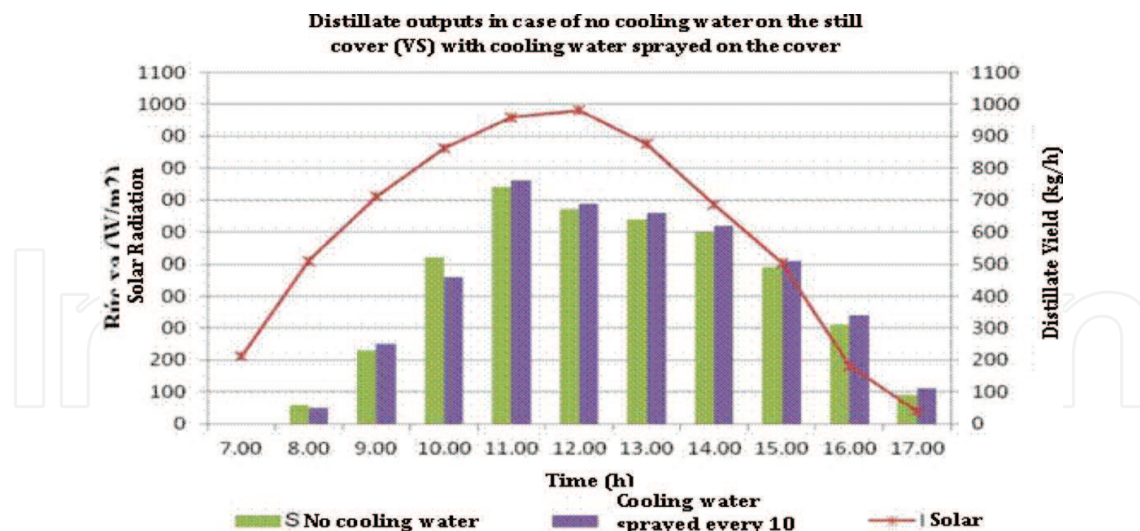**Figure 8.** The schematic diagram of the experimented stepped solar still [19].

Figure 9. Distillate outputs in the case of no cooling water on the still cover (VS) with cooling water sprayed on the cover.
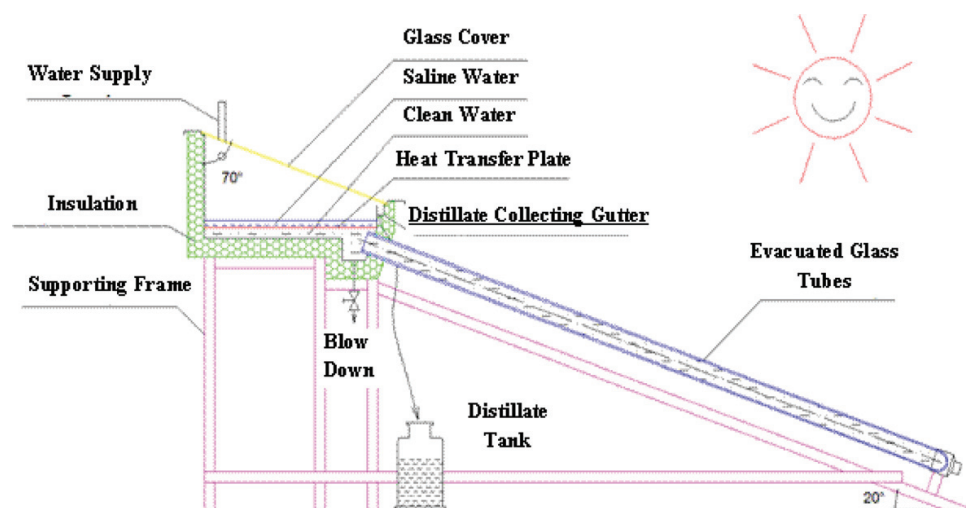

Figure 10. Single-basin solar still coupled with evacuated glass tubes.

are 6.49 and 4.99 l/m², respectively, on a day with 529 W/m² of radiation. Thus by utilizing the latent heat of evaporation, the yield of the solar double basin still was increased by 30%.

In a study on improvement of the Carocell solar distillation equipment [23], a heat exchanger with a coil size of 760 × 220 × 13 (mm) and a total length of pipe Φ8 of 6.5 m was fabricated and mounted just below the distillation equipment to utilize the heat of evaporation. On a good sunny day (700 W/m²), the amount of water collected using this heat exchanger was 6.8 compared to 5 l/m² in the case of the original Carocell still where an increase of 36% can be seen in **Figure 13**.

In the solar active still [12], taking advantage of latent heat of steam is achieved by circulating air flow through the recovery heat exchanger back to the distillation system. When the speed
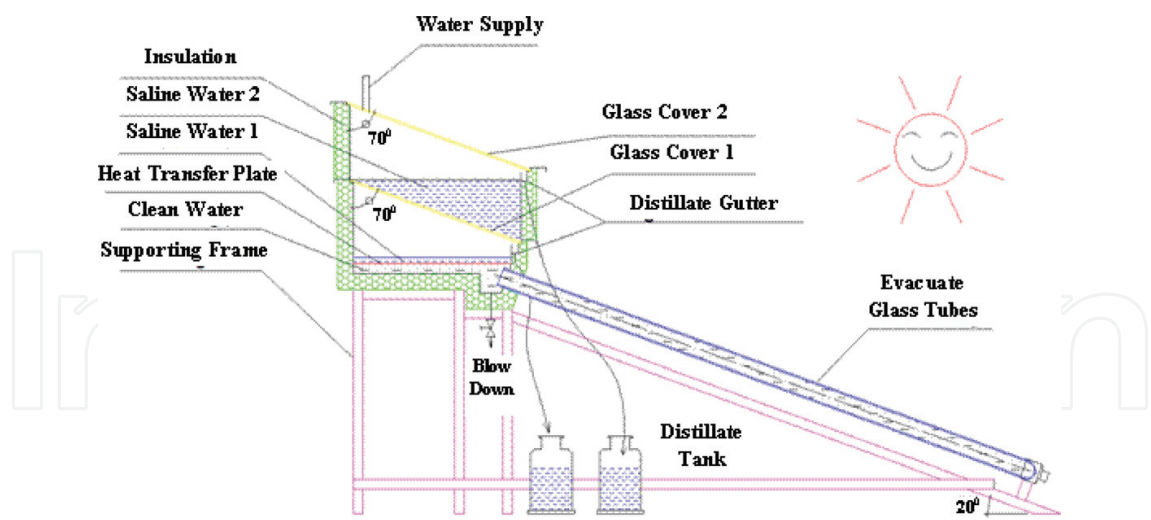
Figure 11. Double-basin solar still coupled with evacuated glass tubes.
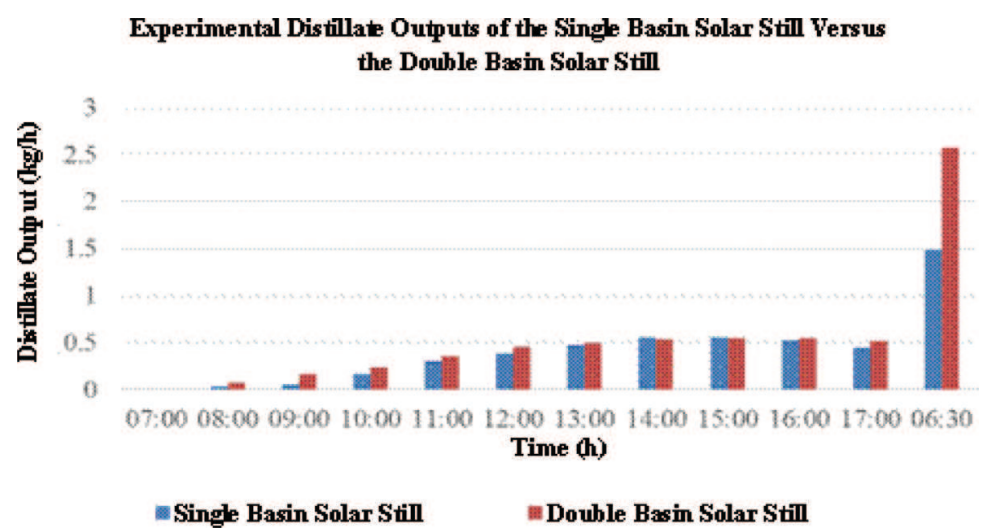

Figure 12. Experimental distillate outputs of the single-basin solar still versus the double-basin solar still.

of air flow in the distillation equipment reached 0.005 m/s, the output of distilled water obtained was 5.94 compared to 3.53 l/m^2 in the case of no circulation, which rose to 68%.

5.3. Reducing the gap between the glass cover and the water level

In order to reduce the gap between the glass and the water level in the still, a stepped solar distillation equipment was designed, fabricated and tested, as shown in **Figure 8** [22]. Some advantages of this device:

•   Over a full year, the total energy radiation projected onto the tilted surface was larger than the horizontal surface.
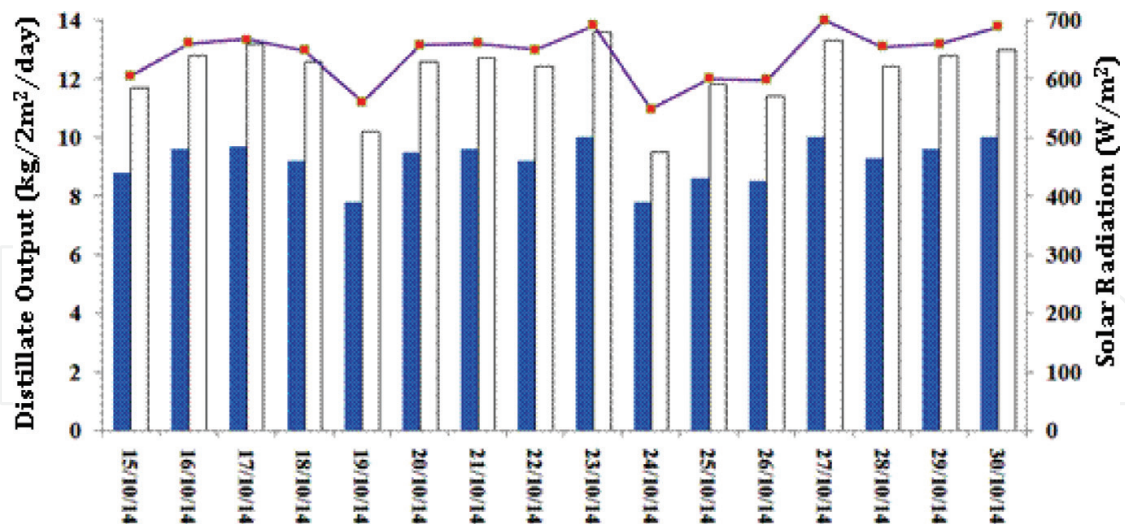
Figure 13. Distillate outputs of 2 m² Carocell solar still, with versus without a heat exchanger.

- The stepped still maintains the distance between the water and the cover at only 1 cm, reducing natural convective obstacles.

- Creating good conditions for condensation to flow into the gutters as well as reducing thermal condensation resistance of the water condensing on coverings.

The experimental results for distilled water output reached 4.9 l/m² with average radiation 635 W/m² compared to 3.05 l/m² in the case of traditional equipment, which rose about 60%, as shown in **Figure 14**.
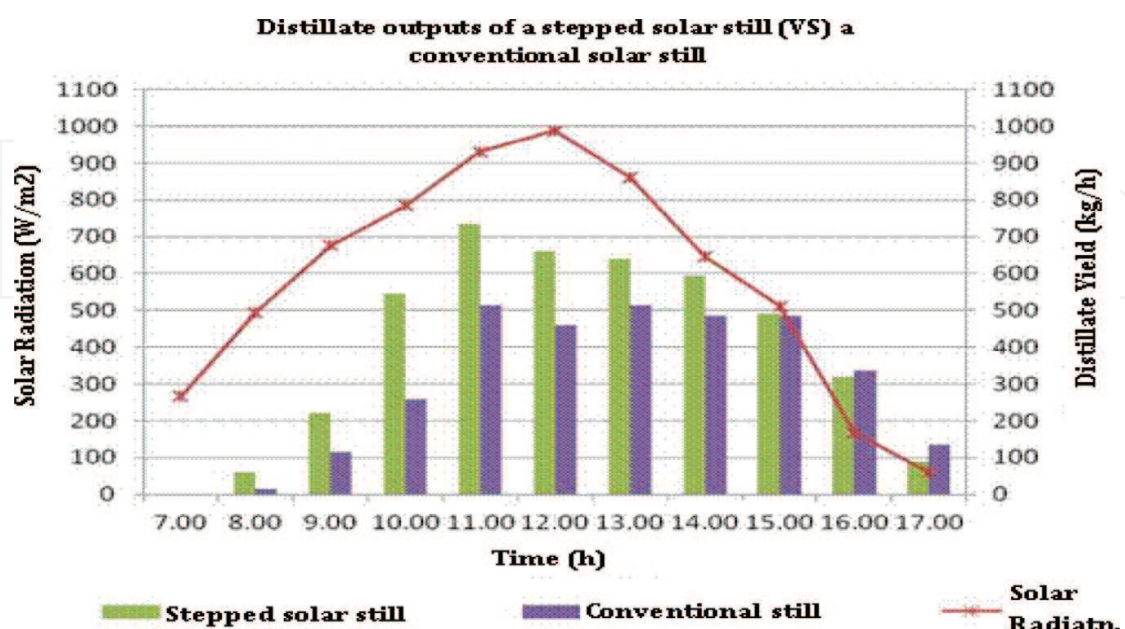

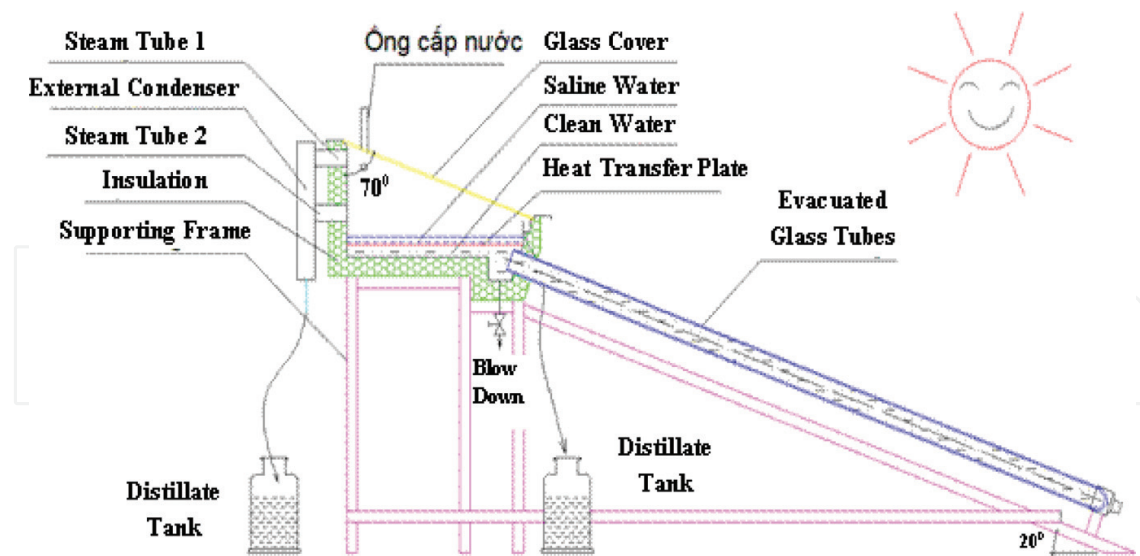**Figure 14.** Distillate outputs of a stepped solar still versus a conventional solar still.

Figure 15. Single-basin solar still coupled with evacuated glass tubes and external condenser.

5.4. Separating the processes of evaporation and condensation in the device

Section 4.4.1 presented the use of an external condenser and a heat recovery to take advantage of moist air stream at high temperature and humidity returning to the still (forced convection).

For a traditional (natural convective) still, the research group manufactured and tested a still with additional external condenser [21]. The schematic diagram of the experiment is shown in **Figure 15**, and the experimental results of the solar still with external condenser in comparison with the still without the external condenser are shown in **Figure 16**. The use of the external
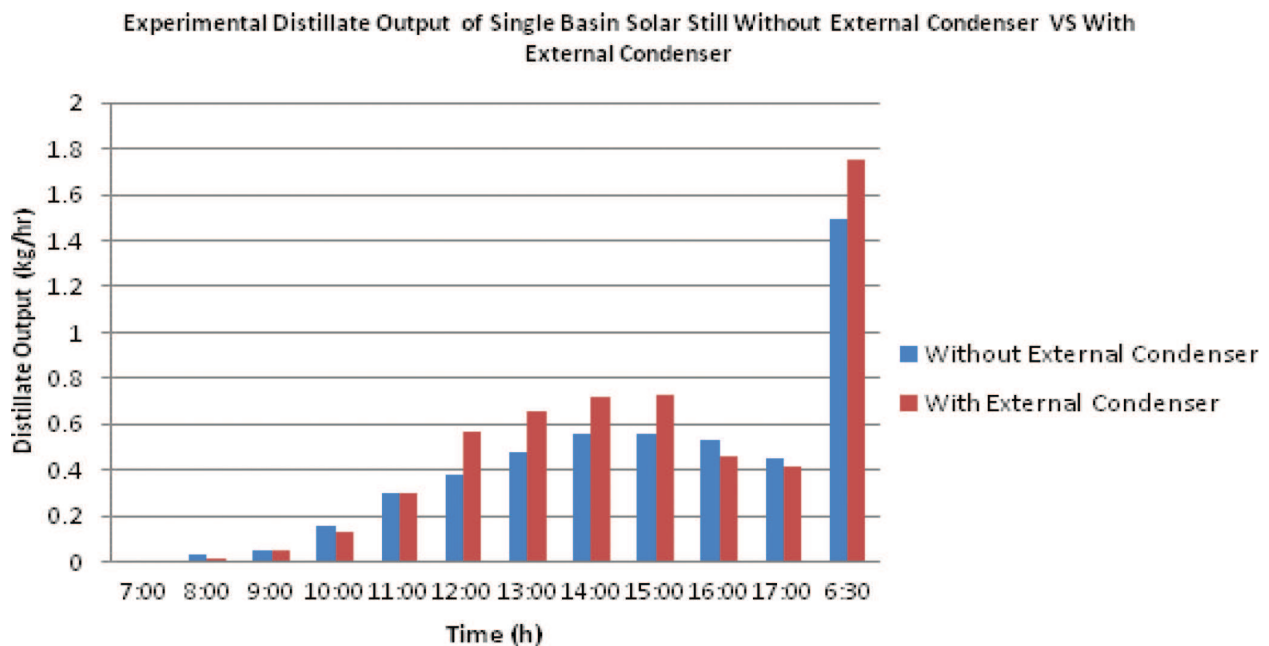

Figure 16. Experimental distillate output of single-basin solar still without external condenser versus with external condenser.

condenser resulted in the distilled water output reaching 6 l/day, almost 15% higher than the output of a still without external condenser, which achieved 5.23 l/day on a day with an average radiation intensity of 517.54 W/m^2.

5.5. Creating forced convection in the device

Theoretical and empirical research was conducted to assess the impact of forced convection on the solar distillation equipment [12]. The schematic diagram of the experiment is shown in **Figure 2**. A conventional solar still with a collecting area of 2,67m^2 (2,44 m × 1095 m), with an inside fan to change the speed of air flow, was made to measure parameters and process experimental data. Results for a typical day is shown in **Figure 17** where the water output increased 30–100% compared to a conventional solar still.

The simulation results of SOLSTILL for the production of distilled water for a whole year and the device performance in three cases—(i) forced convection with external condenser and no moist air circulated back to the still, (ii) forced convection with external condenser and moist air circulated back to the still, and (iii) traditional distillation equipment (natural convection)—show that the outputs and still efficiencies in the three cases are, respectively, 3.87, 4.76 and 3.10 l/m^2 and 42.9, 53.9 and 34.1% [12].

5.6. Increasing the working temperature of water in the still

To increase the working temperature of the water in the equipment in order to increase the production of distilled water, the research group used vacuum tubes to heat the water in the basin [21]. Experimental results corresponding to the day with solar radiation of 514 W/m^2 for
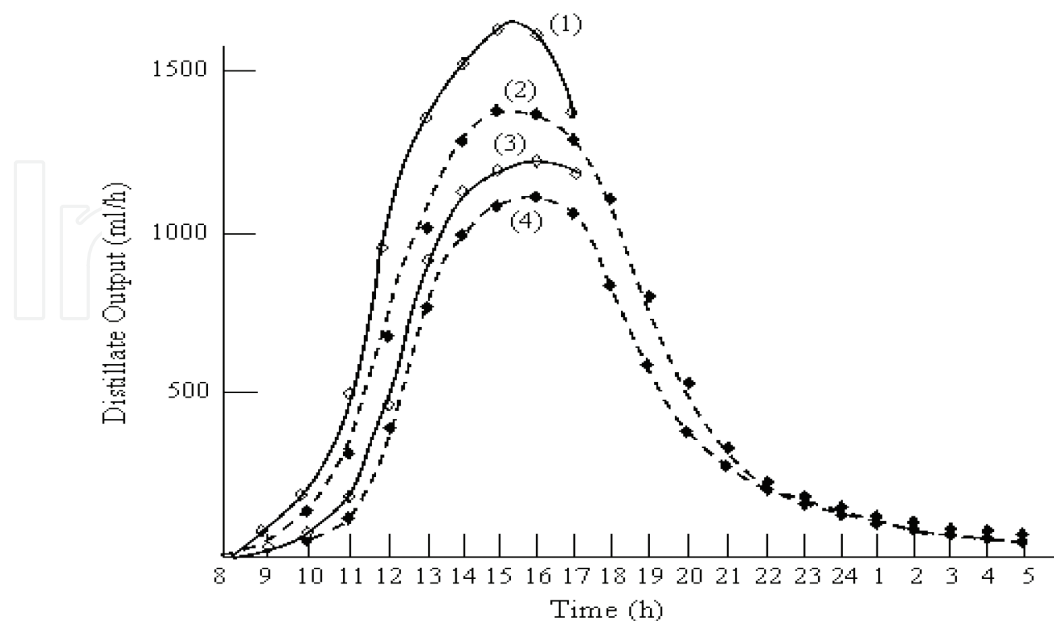

Figure 17. The effect of forced convection in the device to produce distilled water. (1) Data empirical forced convection. (2) The data forced convection theory. (3) Data empirical natural convection. (4) Data natural convection theory.

the production and performance of the device were, respectively, 5.86 l/m^2 and 50.3%, compared with production of 3.10 l/m^2 and efficiency of 34.1% of a conventional solar still.

6. Conclusion

This chapter presented a numerical model to estimate the performance of solar basin-type distillation systems, both for conventional passive solar stills and active (forced circulation) stills with enhanced heat recovery. It also analyzed the factors affecting the distillate outputs of the still, including environmental factors (external factors or natural) and elements of the design and operation (subjective factors). The subjective elements as well as the measures taken to optimize these factors were thoroughly analyzed. With these measures, the distillate yield of solar stills was increased from 30 to 68% compared with traditional distillation systems. This has scientific significance and practicality enabling the application of this technology to solar water distillation using a source of clean and renewable energy. It provides a viable way to alleviating the problem of the availability of clean water, especially in those areas and communities in countries where water resources are increasingly polluted and salty.

Author details

Bao The Nguyen[1,2]*

*Address all correspondence to: drthebao@gmail.com

1 Institute of Sustainable Energy Development (ISED), Ho Chi Minh City, Vietnam

2 University of Technology, Vietnam National University - Ho Chi Minh City, Vietnam

References

[1] Manchanda H, Kumar M. A comprehensive decade review and analysis on designs and performance parameters of passive solar still. Renewables: Wind, Water and Solar, Springer Open Journal. 2015;**2**:1-24

[2] Sampathkumar K, Arjunan TV, Pitchandi P, Senthilkumar P. Active solar distillation—A detailed review. Renewable and Sustainable Energy Reviews. 2010;**14**:1503-1526

[3] Velmurugan V, Srithar K. Performance analysis of solar stills based on various factors affecting the productivity—A review. Renewable and Sustainable Energy Reviews. 2011; **15**:1294-1304

[4] Murugavel KK, Chockalingam KKSK, Srithar K. Progress in improving the effectiveness of the single basin passive solar still. Desalination. 2008;**220**:677-686

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

[6] Badran OO. Experimental study of the enhancement parameters on a single slope solar still productivity. Desalination. 2007;**209**:136-143

[7] Kaushal A, Varun. Solar stills: A review. Renewable and Sustainable Energy Reviews. 2010;**14**:446-453

[8] Muftah AF, Alghoul MA, Fudhodi A, Abdul-Majeed MM, Sopian K. Factors affecting basin type solar still productivity: A detailed review. Renewable and Sustainable Energy Reviews. 2014;**32**:430-447

[9] Sharshir SW, Yang N, Peng G, Kabeel AE. Factors affecting solar stills productivity and improving techniques: A detailed review. Applied Thermal Engineering. 2016. 10.1016/j.applthermaleng.2015.11.041

[10] Kabeel AA, Omara ZM, Essa FA, Abdullah AS. Solar still with condenser—A detailed review. Renewable and Sustainable Energy Reviews. 2016;**59**:839-857

[11] Dunkle RV. Solar water distillation: The roof type still and a multiple effect diffusion still. In: International Developments in Heat Transfer, American Society of Mechanical Engineers, Proceedings of International Heat Transfer; 1961. pp. 895-902

[12] Nguyen BT. SOLSTILL—A simulation program for solar distillation systems. In: Proceedings of EUROSUN; Freiburg; 2004. pp. 96-105

[13] Duffie JA, Beckman WA. Solar Engineering of Thermal Processes. 4th ed. New York: John Wiley and Sons Inc.; 2013

[14] ASHRAE Systems and Equipment Handbook. New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2012

[15] AHRI. Forced-Circulation Air-Cooling and Heating Coils. Standard 410. Arlington, Australia: Air-Conditioning, Heating and Refrigeration Institute; 2014

[16] Cooper PL. Digital simulation of transient processes solar still. Solar Energy. 1969;**12**:333-346

[17] Khalifa AJN, Hamood AM. Effect of insulation thickness on the productivity of basin type solar stills: An experimental verification under local climate. Energy Conversion and Management. 2009;**34**:2457-2461

[18] Garg HP, Mann HS. Effect of climatic, operational and design parameters on the year round performance of single sloped and double sloped solar still under Indian arid zone conditions. Solar Energy. 1976;**18**:159-163

[19] Husham MA. Seasonal performance evaluation of external passive solar stills connected to condensers. Journal of Advanced Science and Engineering Research. 2012;**2**:1-11

[20] Tiwari GN, Singh SK, Bhatnagar VP. Analytical thermal modelling of multi-basin solar still. Energy Conversion and Management. 1993;**34**:1261-1266

[21] Hoang VV, Nguyen TB. Numerical modelling of a single basin solar still coupled with evacuated glass tubes, Vietnam. Journal of Mechanical Engineering. 2015;**6**:123-129. (in Vietnamese)

[22] Le XP, Hoang VV, Nguyen TB. Numerical modelling of a stepped solar still with a condensing auxiliary, Vietnam. Journal of Mechanical Engineering. 2016;**1 & 2**:298-214. (in Vietnamese)

[23] Tran XA, Hoang VV, Nguyen TB. Experimental study of heat exchanger to utilize the latent heat of evaporation in order to enhance performance of Carocell solar still. Thermal Energy Review Journal. 2015;**5**:45-67