Modelling and Simulation of Domestic Solar Water Desalination System, Az Zawiya-Libya as a case study

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نمذجة ومحاكاة لوحدة تحلية مياه منزلية تعمل بالطاقة الشمسية، مدينة الزاوية كحالة للدراسة

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الملخص

يُنظر إلى الماء النظيف والنقي الصالح للشرب على أنه ضرورة حيوية لحياة الإنسان. معظم الموارد المائية في العديد من البلدان مالحة أو قد تحتوي على بكتيريا ضارة تحول دون استخدامها بشكل مباشر من المصادر المائية. تعدّ ليبيا واحدةً من الدول التي تعاني من إجهادٍ مائي مرتفع، وتتأثر التنمية المستدامة في البلاد بنقص موارد المياه المتجددة وكذلك الإفراط في استغلال المياه الجوفية لتلبية الطلب المتزايد على المياه. وتشمل التحديات الأخرى تسرب مياه البحر وتدهور جودة المياه. هناك العديد من الطرق لإنتاج الماء المقطر او الصالحة للشرب بواسطة المعدات الصناعية بناءً على العديد من التقنيات، غير انه لتحقيق مبدأ الاستدامة ، يمكن استخدام الطاقة الشمسية لإنتاج مياه صالحة للشرب دون ان يصاحب ذلك أي آثار سلبية على البيئية. التحلية الشمسية تعتمد على ظاهرة طبيعية يطلق عليها دورة التبخر والتكثف المسببة لتكون الامطار. تهدف هذه الدراسة إلى تصميم وحدة تحلية منزلية تعمل بالطاقة الشمسية لتحقق اعلى انتاجية. النموذج الرياضي تم تطويره بناءاً على موازنات الطاقة لأجزاء وحدة التحلية. تقدم الدراسة وصف للسلوك الحراري وصولا الى حساب الإنتاجية المتوقعة من الماء المقطر. من أجل تعزيز الإنتاجية ، تم اقتراح سخان شمسي يعمل كنظام للتسخين المسبق لمياه التغذية، تم استخدام جميع بيانات المناخية ومعدلات الاشعاع الشمسي لمدينة الزاوية في الحسابات. خلصت الدراسة على انه بالامكان الحصول على متوسط سنوي (كجم\متر^2\يوم) اكثر من متوسط الاستهلاك اليومي من مياه الشرب للشخص الواحد.

Abstract

The clean and pure water is seen as a vital necessity for human life. The most water resources in many countries are salty or may contain harmful bacteria. The freshwater resources are limited and access to it is difficult in many regions. There are several methods of producing required distilled water. To provide sustainability, the solar energy can be used to produce distilled water, without any environmental impacts. This technique based on natural phenomenon; Humidification Dhimmification Humidification. This study aims to estimate daily productivity of distilled water per unit solar collector area ($L/m^2/day$). The passive solar desalination technique is based on natural phenomenon; humidification-dehumidification (HDH) desalination cycle. The system was modelled using the energy balance of different parts of the system. The study presents the thermal behavior of the system to arrive the productivity. In order to enhance the productivity, a solar heater was proposed as preheating system. As a case study, all meteorological data of Az-Zawiya-Libya were taken in the calculations. The study concluded that, Domestic Solar Desalination System can produce an annual-average yield ($L/m^2/day$) more than the daily water consumption per capita (L/day).

Keywords: *solar desalination system, sustainability, water still, solar energy,*

Nomenclature

English Letters

A	Area (m^2)
C_p	Specific heat (J/kg/K)
hc	Convection heat transfer coefficient ($W/(m^2K)$)
hr	Radiation heat transfer coefficient ($W/(m^2K)$)
hev	Evaporation heat transfer coefficient ($W/(m^2K)$)
hfg	Latent heat of evaporation of water in (J/kg)
I	Solar radiation (W/m^2)
k	Thermal conductivity (W/(m K))
L	Spacing (m)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Heat transfer rate (W)

Subscripts

a	Ambient air
av	Average
b	Basin liner
ev	Evaporation
fg	Water vapor
g	Glass cover
w	Water
i	Insulator

Greek symbols

β	Coefficient of volumetric expansion
α	Absorptivity, Solar altitude angle, thermal

R	Reflectance
t	Time (second)
T	Temperature (K, °C)
V	Velocity (m/s)
g	Gravitational acceleration (9.81 m/s^2)

	diffusivity (m^2/s)
δ	Thickness (m)
ε	Emissivity
η	Efficiency
μ	Absolute viscosity (kg/(m s))
ν	kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Stefan-Boltzmann constant
τ	Transmittance
φ	Latitude angle

1. Introduction

The clean and pure water is seen as a vital necessity for human life. The most water resources in many countries are salty or may contain harmful bacteria. The freshwater resources are limited and the groundwater is very poorly managed and inefficiencies used specially in agriculture, where irrigation consumes a huge amount of extracted water. The top 20 water-scarce countries are in Middle East and North Africa (MENA) [1]. Libya is the 20th country among the countries most affected by water shortage [2]. To meet growing water demand, Libya currently has about twenty-one operating seawater desalination plants along a coastal, with a total capacity of 525.680 m^3/day [3]. Unfortunately, these plants are not sustainable and it is fossil fueled, which has a negative impact on the environment including rising in water temperature, dissipating aquatic organisms and their natural habitats, decreasing the dissolved oxygen concentration, turbidity, and salinity as the consequences of the brine discharge Therefore, an acceptable desalination plant should respect the environmental regulations [4]. Generally, the water supplied by the Water National Network required purification or filtration before used for drinking. Among many water purification techniques, the solar desalination method is the best way to provide the sustainability, the Domestic Solar Water Desalination System (DSWDS) is a passive technique based on natural phenomenon named Humidification-Dehumidification principle (HD) used to produce distilled water without any energy intensive and consumable filters and membranes. Unfortunately, the solar desalination method produces small amounts of water may not sufficient to sustain the population. The DSWDS is a solar collector with a transparent cover, water layer and basin liner. The basin liner is an asphalt layer or sheet metal colored by the black for high absorbance of radiation. Copper, aluminum and steel are most commonly metals used for their high thermal conductivity [5]. Typical configuration; Single-basin single-slope solar still has been widely used for its simplest structure and ease of operation. But in the literature, many efforts were conducted to increase productivity by some ideas such a double slope solar still, multi-stage or multi-effect solar still, inverted trickle solar still, stepped solar still, weir type solar still, hemi-spherical solar still, spherical solar still, v-type solar still, pyramid solar still (triangular and square), cylindrical solar still, tubular solar still, conical solar still, etc. and by integrated systems with solar still such solar still integrated with solar collectors, integrated with hybrid PV/T system, integrated with heat exchanger, integrated with solar pond, etc. [6]. In order to select optimum configuration parameters of DSWDS according to the literature, Mink et al. [7] observed that, the productivity of 3-mm-thick glass cover was 16.5% more than 6-mm-thick glass cover. For the slop angle, the glass cover can be fixed with annual optimum inclined angle. Akash et al. [8] performed experiments by tilting the glass cover, they observed that tilting angle same as latitude was more efficient in comparison with other inclinations. Another important parameter is the water depth, Arjunan et al. [9] carried out the experimental study for different parameters, they reported that the maximum productivity of the still was attained at the water depth of 20 mm, and the thickness of basin liner is 5mm. For high flexibility to conduct the parametric studies, where the experimental research needs longer duration with high investment cost, the numerous theoretical models were developed by various investigators, namely Dunkle, Adhikari, Kumar and Tiwari, etc. The aim of this study is to develop a flexible simulation tool to assess the productivity of the solar desalination system. The simulation tool written via MATLAB software and based on basic concepts and thermal energy balance equations of system components, as well as well-known correlations, then solve them simultaneously. All meteorological data of Az Zawiya city has been taken in calculations.

2. Mathematical Modeling on Solar Desalination System

In order to predict the productivity of DSWDS, the thermal energy equations are modeled based on the heat and mass transfer operation. The productivity or yield of

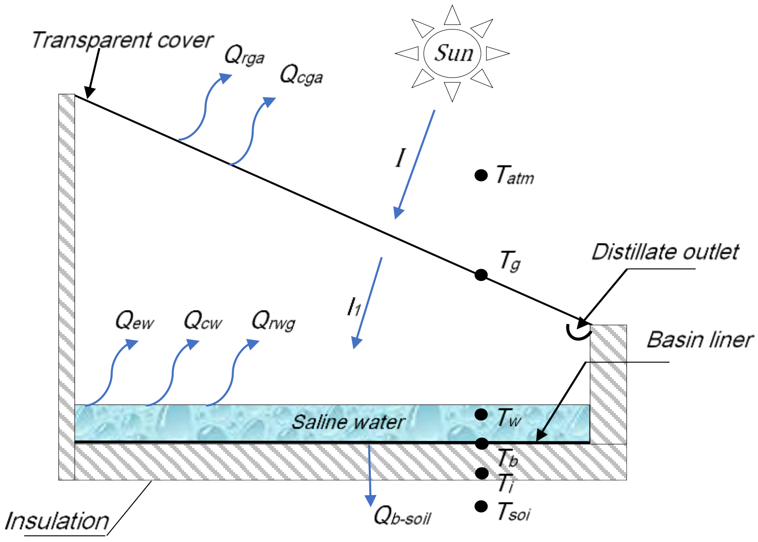

Figure (1) Thermal distribution of Solar desalination system

a solar still is generally characterized by the quantity of water evaporated by unit area of the basin per day. In this section, the development of the theoretical model was detailed. The energy balance equations for all elements of the simple still, such as glass cover, basin liner، water in the basin. Figure (1) shows the thermal distribution of all components involved in the operation of DSWDS.

The following few assumptions were accounted in the modelling [44]:

- The system under quasi-steady-state condition, i.e., there are no thermal energy storage in the system; that means the heat capacity of all components are negligible.
- water depth is constant.
- Water vapor condensing at the glass cover.
- The system is completely sealed.
- The amount of water evaporated equal to the amount of distilled water.
- The temperature gradient across the thickness of glass cover and water depth is negligible.
- The ground to be at a temperature equal to ambient.

2.1. Energy Balance

Based on the first law of thermodynamics, the conservation of energy principle may be expressed in the rate form [10], as:

$$\begin{pmatrix} Rte\ of\ energy \\ transfer\ to\ the \\ system \end{pmatrix} - \begin{pmatrix} Rte\ of\ energy \\ leave\ the \\ system \end{pmatrix} = \begin{pmatrix} Rate\ of\ change\ the \\ total\ energy\ of \\ system \end{pmatrix} \quad (1)$$

Apply equation (1) to each component.
The thermal behavior of the desalination system can be represented by the thermal network model as shown in figure (2).

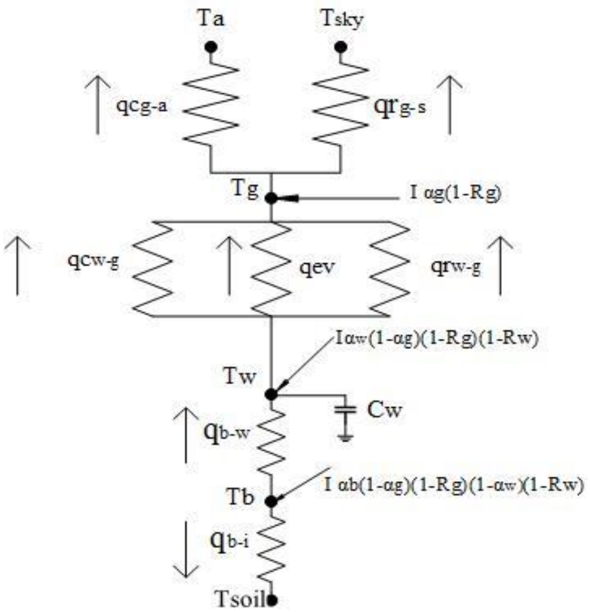

Figure (2) thermal network of present model

2.1.1 Energy balance of the glass cover

According to assumptions, there are no energy storage in glass cover, then the energy equation become:

$$\left(Q_{c_{w-g}} + Q_{ev} + Q_{r_{w-g}} + I\, A_g \alpha_g (1 - R_g)\right) - \left(Q_{c_{g-a}} + Q_{r_{g-sky}}\right) = 0$$

$$\left(h_{c_{w-g}} + h_{ev} + h_{r_{w-g}}\right) A_w (T_w - T_g) + I\, A_g \alpha_g (1 - R_g) - h_{c_{g-a}} A_g (T_g - T_a) - h_{r_{g-sky}} A_g (T_g - T_{sky}) = 0$$

$$h_{t_{w-g}} = h_{c_{w-g}} + h_{ev} + h_{r_{w-g}}$$

$$T_g = \frac{h_{t_{w-g}} A_w T_w + h_{c_{g-a}} A_g T_a + h_{r_{g-sky}} A_g T_{sky} + I\, A_g\, \alpha_g (1 - R_g)}{h_{t_{w-g}} A_w + h_{c_{g-a}} A_g + h_{r_{g-sky}} A_g} \quad (2)$$

2.1.2 Energy Balance of the water layer

The energy balance equation for the water mass present in the still basin is written as follows:

$$\left(Q_b + I\, A_w \alpha_w (1 - \alpha_g)(1 - R_g)\right) - \left(Q_{c_{w-g}} + Q_{ev} + Q_{r_{w-g}}\right) = m_w\, C_{p_w} \frac{dT_w}{dt}$$

$$\left(h_{c_{b-w}} A_b (T_b - T_w) + I\, A_w \alpha_w (1 - \alpha_g)(1 - R_g)\right) - h_{t_{w-g}} A_w (T_w - T_g) = m_w\, C_{p_w} \frac{dT_w}{dt}$$

$$m_w = \rho_w A_w \delta_w$$

$$A_w = A_b$$

$$h_{c_{b-w}} (T_b - T_w) + I\, \alpha_w (1 - \alpha_g)(1 - R_g) - h_{t_{w-g}} (T_w - T_g) = \frac{dT_w}{dt}$$

$$\frac{dT_w}{dt}+\frac{\left(h_{c_{b-w}}+h_{t_{w-g}}\right)}{\rho_w\delta_w\,C_{p_w}}T_w=\frac{1}{\rho_w\delta_w\,C_{p_w}}\left[h_{c_{b-w}}T_b+h_{t_{w-g}}T_g++I\,\alpha_w(1-\alpha_g)(1-R_g)\right]$$

Using an Integrating Factor Method, the solution becomes:

$$T_w{}^t=\frac{f(t)}{a(t)}\left(1-e^{-a(t)\,t}\right)+T_w{}^i\,e^{-a(t)\,t} \qquad (3)$$

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$$f(t)=\frac{1}{\rho_w\delta_w\,C_{p_w}}\left[h_{c_{b-w}}T_b+h_{t_{w-g}}T_g++I\,\alpha_w(1-\alpha_g)(1-R_g)\right]$$

$$a(t)=\frac{\left(h_{c_{b-w}}+h_{t_{w-g}}\right)}{\rho_w\delta_w\,C_{p_w}}$$

2.1.3 Energy Balance of the basin linear

The basin liner is the asphalt layer or thin material, painted by the black color and glued on to the basin area to improve the productivity of the system. The energy balance of the basin linear can be written as:

$$I\,A_b\alpha_b(1-\alpha_g)(1-R_g)(1-\alpha_w)(1-R_w)-(Q_{b-w}+Q_{b-soil})=0$$

$$I\,A_b\alpha_b(1-\alpha_g)(1-R_g)(1-\alpha_w)(1-R_w)-h_{c_{b-w}}A_b(T_b-T_w)-\frac{k_i}{\delta_i}A_b(T_b-T_{soil})=0$$

$$T_b=\frac{h_{c_{b-w}}T_w+(k_i/\delta_i)T_{soil}+\ I\,\alpha_b(1-\alpha_g)(1-R_g)(1-\alpha_w)(1-R_w)}{h_{c_{b-w}}+k_i/\delta_i} \qquad (4)$$

The simulation tool developed in this study based on solving equations; (2), (3) and (4), simultaneously for each time interval. Heat transfer coefficients, solar model and thermo-physical properties are three subroutines that introduced to performs a specific task.

2.2. Calculate the distilled water

For the desalination purpose, the quantity of distilled water calculated from evaporation rate of energy Q_{ev} as:

$$Q_{ev}\ =h_{ev}\,A_w(T_w-T_g)$$

Then the hourly mass of distilled water calculated from following expression;

$$\dot{m}_w=\frac{Q_{ev}}{h_{fg}}\,x\,3600\quad\left[\frac{kg}{hr}\right] \qquad (5)$$

2.3. Heat transfer coefficients subroutine

2.3.1 Convection heat transfer coefficient between glass cover to surrounding

The convective heat transfer coefficient for air flowing over the outside surface of the cover depends primarily on the wind velocity. McAdams [11], reported the correlation for the convection coefficient of the wind effect as:

$$h_{c_{g-a}}=5.7+3.8\,V_w \qquad (6)$$

2.3.2 Radiation heat transfer coefficient between glass cover to sky

The radiative heat transfer coefficient between the cover and atmosphere (sky) given as:

$$h_{r_{g-sky}} = \frac{\sigma\varepsilon_c\left(T_g^2 + T_{sky}^2\right)\left(T_g + T_{sky}\right)\left(T_g - T_{sky}\right)}{\left(T_g - T_a\right)} \tag{7}$$

Where

The sky temperature calculated by simple empirical relation in term of ambient temperature [12]:

$$T_{sky} = 0\ 0552 * T_a^{1.5}$$

Where T_a and T_{sky} are expressed in degree Kelvin.

2.3.3 Convection heat transfer coefficient between water to glass cover

The convective heat transfer coefficient within the enclosed space is expressed in terms of water temperature and air temperature at glass cover by the following expression [13]:

$$h_{c_{w-g}} = 0.884 * \left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)T_w}{268{,}900 - P_w}\right]^{\frac{1}{3}} \tag{8}$$

Where

$$P_w = exp\left[25.317 - \left(\frac{5144}{T_w}\right)\right]$$

$$P_g = exp\left[25.317 - \left(\frac{5144}{T_g}\right)\right]$$

2.3.4 Radiation heat transfer coefficient between water to glass cover

The radiation heat transfer coefficient between water and glass cover surface can be attain by the well-known expression:

$$h_{r_{w-g}} = \sigma\varepsilon_{eff}\left(T_b^2 + T_g^2\right)\left(T_b + T_g\right) \tag{9}$$

Where

$$\varepsilon_{eff} = \left(1/\varepsilon_b + 1/\varepsilon_g - 1\right)^{-1}$$

2.3.5 Evaporation heat transfer coefficient between water to glass cover

Evaporation process is a main task of thermal process in the desalination system to produce water vapor. This process occurs when the vapor pressure becomes lesser than the diffusion pressure of water at a given temperature [13], the evaporative heat transfer coefficient expressed as:

$$h_{ev} = 16.273 * 10^{-3} * h_{c_{w-g}} * \frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)} \tag{10}$$

Or in terms of latent heat of evaporation of water h_{fg}

$$h_{ev} = 9.15 * 10^{-7} * h_{c_{w-g}} \frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)} h_{fg} \tag{11}$$

2.3.6 Convection heat transfer coefficient between basin linear to water

Convection heat coefficient between basin linear (absorber) and water, correlations suggested by McAdams [14]:

$$h_{c_{b-w}} = N_u \frac{k}{L} \tag{12}$$

In general, the Nusselt number N_u of the fluid at upper surface of hot plate correlated as

$$N_u = 0.54\, {R_a}^{1/4} \quad \text{for} \quad 10^4 \geq R_a \geq 10^7$$

$$N_u = 0.15\, {R_a}^{1/3} \quad \text{for} \quad 10^7 \geq R_a \geq 10^{11}$$

$$R_a = \frac{g\,\beta\,\Delta T\,L^3}{v\,\alpha} = \frac{\rho^2\,c_p g\,\beta\,\Delta T\,L^3}{\mu\,k}$$

$$\alpha = \frac{k}{\rho\,c_p}\ ,\beta = \left(\frac{T_b + T_w}{2}\right)^{-1}\ ,T(K)\ ,v = \frac{\mu}{\rho}$$

2.4. Thermo-physical properties subroutine

The high-order equations in this section derived from regression analysis of tables in ref. [14].

2.4.1. Thermo-physical properties of air between basin water and glass cover, T_{ev} (°C)

$$T_{ev} = \frac{T_w - T_g}{2} - 273.15$$

$$h_{fg}=3044205.5\text{-}1679.1109T_{ev}\text{-}1.1425{T_{ev}}^2$$

$$K_{fg} = 0.0244 + 0.7673 * 1e - 4 * T_{ev}$$

$$\rho_{fg} = \frac{353.44}{T_{ev} + 273.15}$$

$$cp_{fg} = 999.2 + 0.1343 * T_{ev} + 0.01 * 1e - 4 * {T_{ev}}^2 - 6.758 * 1e - 8 * {T_{ev}}^3$$

2.4.2. Thermo-physical properties of water T(°C)

$$\mu=6.026 * 1e\text{-}13 * T^8\text{-}2.962 * 1e\text{-}10 * T^7\text{+}6.345 * 1e\text{-}8 * T^6 - 7.873 * 1e - 6 * T^5 + 0.0006401 * T^4 - 0.03719 * T^3 + 1.676 * T^2 - 62.21 * T + 1792$$

$$\rho= 2.45 * 1e\text{-}14 * T^8\text{-}9.995 * 1e\text{-}12 * T^7\text{+}1.655 * 1e\text{-}9 * T^6\text{-}1.41 * 1e\text{-}7 * T^5\text{+}6.318 * 1e\text{-}6 * T^4\text{-}0.0001079 * T^3\text{-}0.006092 * T^2\text{+}0.05004 * T\text{+}999.8$$

$$c_p=3.932 * 1e\text{-}10 * T^6\text{-}1.526 * 1e\text{-}7 * T^5\text{+}2.479 * 1e\text{-}05 * T^4\text{-}0.002167 * T^3\text{+}0.1156 * T^2\text{-}3.401 * T^6\text{+}4220$$

$$k=7.949 * 1e\text{-}16 * T^6\text{-}1.403 * 1e\text{-}13 * T^5\text{-}4.28 * 1e\text{-}10 * T^4\text{+}1.272 * 1e\text{-}07 * T^3 - 2.114 * 1e - 05 * T^2 + 0.002491 * T + 0.5557$$

$$\alpha=4.819 * 1e\text{-}11 * T^4\text{+}9.426 * 1e\text{-}9 * T^3\text{-}4.338e\text{-}6 * T^2\text{+}0.0006523 * T\text{+}0.1319$$

2.5. Solar model subroutine

This subroutine includes the calculations of solar radiation and solar position by means solar angles which important for estimate reflected and transmitted fractions of solar radiation

2.5.1.Solar radiation

Neglecting the reflection component, the hourly global solar radiation intensity on a horizontal surface, I_h in clear sky model is given by Meinel and Mainel [15]:

$$I_h = I_a\, 0.7^{m^{0,678}}$$

where, I_a is the extraterrestrial irradiance on a horizontal surface:

$$I_a = G_{SC}\left[1 + 0.033\, cos\, \frac{2\,\pi\, n}{365}\right] sin\, \alpha$$

Where G_{SC} the solar constant = 1.367 kJ/m^{2}s, and m is air mass ratio calculated for clear sky:

$$m = [1229 + (614\, sin\, \alpha)^2]^{0.5} - 614\, sin\, \alpha$$

For the horizontal surface i.e.; slop angle equal zero (*β=0)*

$$sin\, \alpha = cos\, \delta\, cos\, \phi\;\; cos\, \omega + sin\, \delta\, sin\, \phi$$

$$\delta = 23.45\, sin\left(360\, \frac{284 + n}{365}\right)$$

where, n is the number of days of the year starting from January 1. The hour angle (ω) is an angular measure of time and is equivalent to 15 per hour with morning (+) and afternoon (-). It is measured from noon-based local solar time (ST):

$$\omega = 15(12\; - \; \mathrm{ST})$$

$$ST = LT + \frac{ET}{60} + \frac{4}{60}(L_S - L_L)$$

$$ET = 9.87\, sin\, 2B\; - 7.53\, cos\, B\; - \; 1.5\, cos\, B$$

$$B = \frac{360\, (n - 81)}{365}$$

Incidence angle (θ) for the horizontal surface (*β=0)* expressed as:

$$\cos\theta = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega$$

For minimizing the incident angle θ, which means reduce reflectance fraction of solar radiation and increase productivity. In northern hemisphere, for maximum annual energy availability, the glass cover directed to the south with declination angle equal to the latitude angle [11].

2.5.2. Optical properties of system components

2.5.2.1. Reflectance of glass cover (R_g)

For smooth surfaces Fresnel has derived expressions for the reflection of unpolarized radiation on passing through transparent medium [11].

$$\theta_2 = sin^{-1}\left(\frac{sin\ \theta_1}{1.526}\right)$$

$$r_\perp = \frac{sin^2(\theta_2 - \theta_1)}{sin^2(\theta_2 + \theta_1)}$$

$$r_\parallel = \frac{tan^2(\theta_2 - \theta_1)}{tan^2(\theta_2 + \theta_1)}$$

$$R_g = \frac{1}{2}[r_\perp + r_\parallel]$$

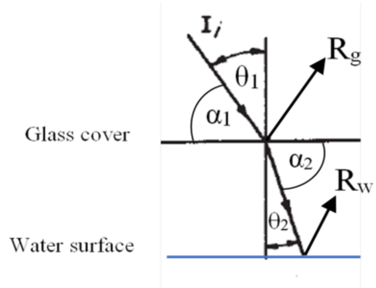

Figure (3) incidence, reflection and refraction angles of solar radiation

2.5.2.2. Transmittance of glass cover (τ_g)

The transmittance of a single cover approximately expressed in the form:

$$\tau_g \cong \tau_r\,\tau_a$$

where

$$\tau_r = \frac{1}{2}\left(\frac{1 - r_\parallel}{1 + r_\parallel} + \frac{1 - r_\perp}{1 + r_\perp}\right)$$

where the subscript (r) is a reminder that only reflection losses have been considered.

$$\tau_a = \exp\left(-\frac{K\,L}{\cos\theta_2}\right)$$

The subscript (a) is a reminder that only absorption losses have been considered, and K is the proportionality constant, which is assumed to be a constant in the solar spectrum. the value of K varies from approximately 4 m^{-1} for "water white glass" (which appears white when viewed on the edge) to approximately 32 m^{-1} for high iron oxide content (greenish cast of edge) glass [11].

2.5.2.3. Absorptance of glass cover (α_g)

The absorptance of a solar collector cover can be approximated as:

$$\alpha_g \cong 1\text{-}\tau_a$$

2.5.2.4. Reflectance of water (R_w)

Anderson [16], in the Lake Hefner study, reported that, the reflectance of solar energy from plain water surface can be approximated in terms of refraction of solar altitude angle α_2 as:

$$R_w = 1.18\,{\alpha_2}^{-0.77}$$

2.5.2.5. Absorptance of saline water (α_w)

The absorptance of saline water was assumed to be constant in the reasonable range [9]:

$$\alpha_w = 0.05$$

2.6. Case study

The Monthly-Average of Hourly Data of Az Zawiya -Libya, includes ambient air temperature, solar radiation, wind speed and sea water temperature were used in the calculation. Noteworthy, the hourly data tabulated in table 1 to table 4 seeming noticeably less than the higher levels recorded because it is an average data.

Table 1 ambient temperature of Az Zawiya (^oC) [17].

Month / Hour	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7:00:00	10	10	13	16	19	25	25	26	25	21	15	13
8:00:00	10	10	12	16	20	26	26	26	24	21	15	13
9:00:00	12	11	13	17	21	27	27	27	26	21	15	13
10:00:00	12	11	13	19	22	28	28	28	26	22	16	13
11:00:00	13	13	16	21	25	31	31	31	29	25	19	16
12:00:00	13	13	17	22	26	32	32	31	29	25	19	16
13:00:00	15	16	19	25	27	35	34	34	31	27	22	19
14:00:00	15	16	19	25	27	35	34	34	31	27	22	19
15:00:00	15	16	19	26	27	35	33	34	31	27	22	19
16:00:00	15	16	19	26	27	34	33	33	31	27	22	19
17:00:00	15	16	19	25	26	34	33	33	30	27	22	19
18:00:00	15	16	19	24	26	33	32	32	30	26	21	18
19:00:00	15	16	18	23	25	32	31	31	29	26	20	18
20:00:00	14	14	15	21	23	29	29	29	27	24	18	16

Table 2 solar radiation of Az Zawiya (W/m^2) [18].

Month / Hour	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7:00:00	0	0	0	0	25	38	24	5	0	0	0	0
8:00:00	0	0	20	93	165	170	158	120	70	27	0	0
9:00:00	40	63	160	280	348	333	347	310	245	165	5	27
10:00:00	175	215	337	486	500	495	548	505	438	310	93	98
11:00:00	325	380	508	652	667	690	717	685	610	469	259	162
12:00:00	470	485	613	765	826	810	865	815	740	587	399	212
13:00:00	560	575	670	840	905	895	947	900	824	627	508	245
14:00:00	575	587	677	865	893	895	955	920	805	568	568	239
15:00:00	540	575	657	800	820	835	900	875	725	525	559	201
16:00:00	437	455	548	696	722	730	800	745	612	450	495	150
17:00:00	287	340	415	540	560	590	630	580	455	310	356	88
18:00:00	125	185	247	345	388	444	445	387	269	135	215	25
19:00:00	7	40	85	160	200	260	255	205	90	15	70	0
20:00:00	0	0	0	20	45	94	80	39	4	0	0	0

Table 3 average Monthly wind speed of Az Zawiya (m/s). [19]

Month	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed	6.4	5.4	4.5	5.1	5.5	4.9	4.9	4.8	4.6	4.4	4.9	5.5

Table 4 monthly average sea water temperature (^oC). [20]

Month	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed	16.2	15.2	15.6	16.9	19.2	22.2	25.4	26.9	26.2	23.6	20.1	17

In the end of this section, the flowchart diagram for the present simulation model used to calculate the distilled water is shown in Figure (4).

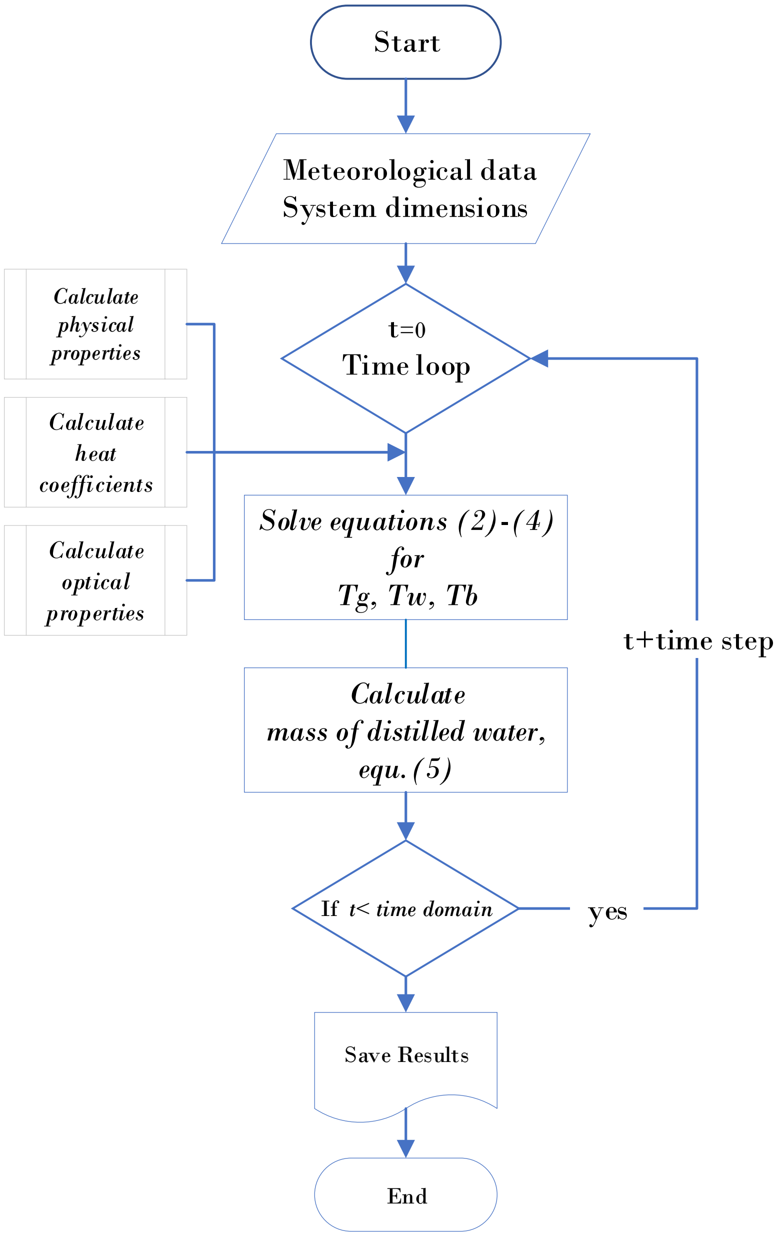

Figure (4) flowchart diagram for the present simulation model

3. Results and discussion

The main goal of this study is to calculate the hourly yield of the domestic solar desalination unit under conditions of Az Zawiya- Libya. Solar radiation, ambient air temperature, infeed water temperature, and wind speed are operating parameters effects on the productivity. Figure (5), shows the hourly variations of water yield a year. The results show that, the solar radiation is a major parameter effect on the productivity as well as the temperatures difference between water and glass cover. The figure shows, in the early morning when the solar radiation very low, naturally the water is cooler than glass cover and ambient air; this came from the fact that, the specific heat of the water is more than glass cover and ambient temperature, therefore, there are no evaporative process and no distillated water yield. also, in the evening the same behavior will occur because in the present model, the system hasn't thermal storage layer and almost all solar radiation absorbed by the water. in addition, the black basin liner is a thin layer used to collect the solar energy and transferred it to basin water. The highest yield (1.41 kg/m^2/hr.) was achieved in the July midday when the solar radiation in the maximum level,

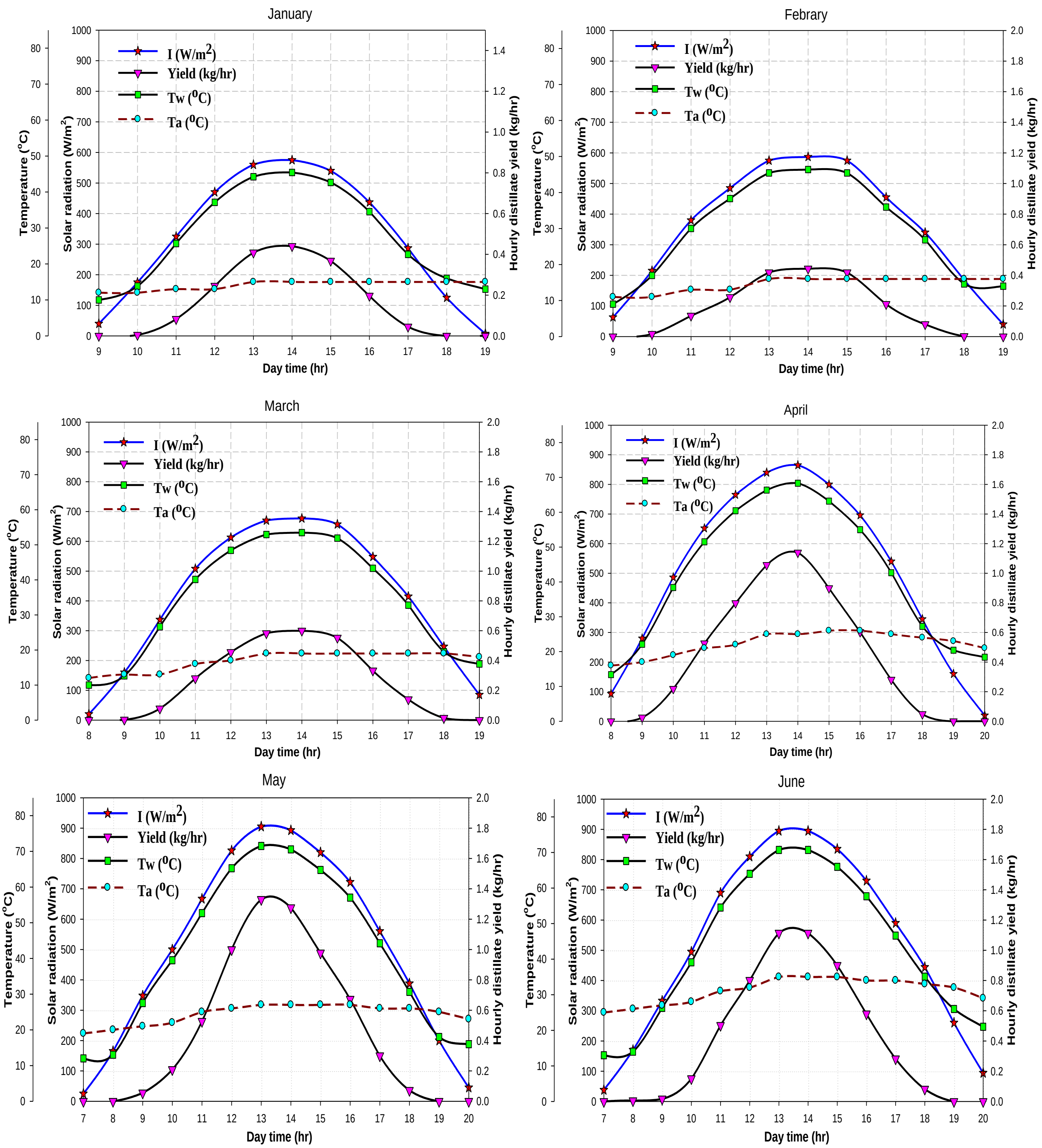

Figure (5) monthly-average hourly yield alongside with variation of major operating conditions, continued

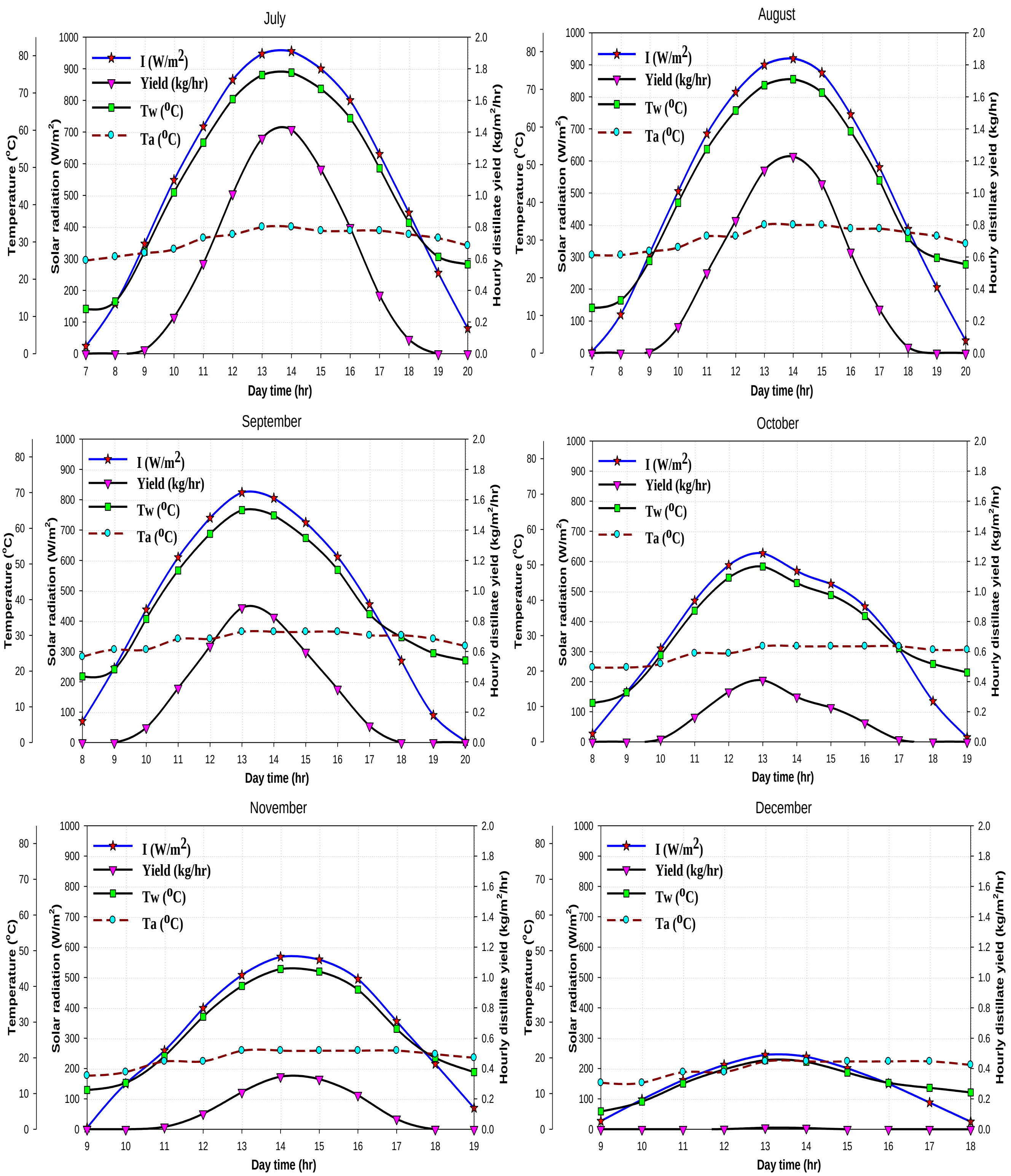

Figure (5) monthly-average hourly yield alongside with variation of major operating conditions

Figure 6 present the average monthly yield in (kg/m^2/day). The highest yield was achieved in the July and it is 7 kg/m^2/day, while in December almost on yield outcome from the system. The annual average yield is 3.7 kg/m^2/day. These levels of daily yield are a good agreement with literature. Some disparity is observed with the normal range of passive solar still which around 3 L/day (≈3kg/day) [21], the reason may be due the model not accounted the losses from side walls and the losses of latent heat for condensation. According to World Health Organization (WHO) guideline values, the daily per capita consumption of drinking-water is approximately 2 litres for adults [22], then, figure (6) conclude that, the DSWDS under Az Zawiya condition can produce an annual-average daily yield about 3.7 litre per m^2 per day, about 45.9 % more than the daily water consumption per capita.

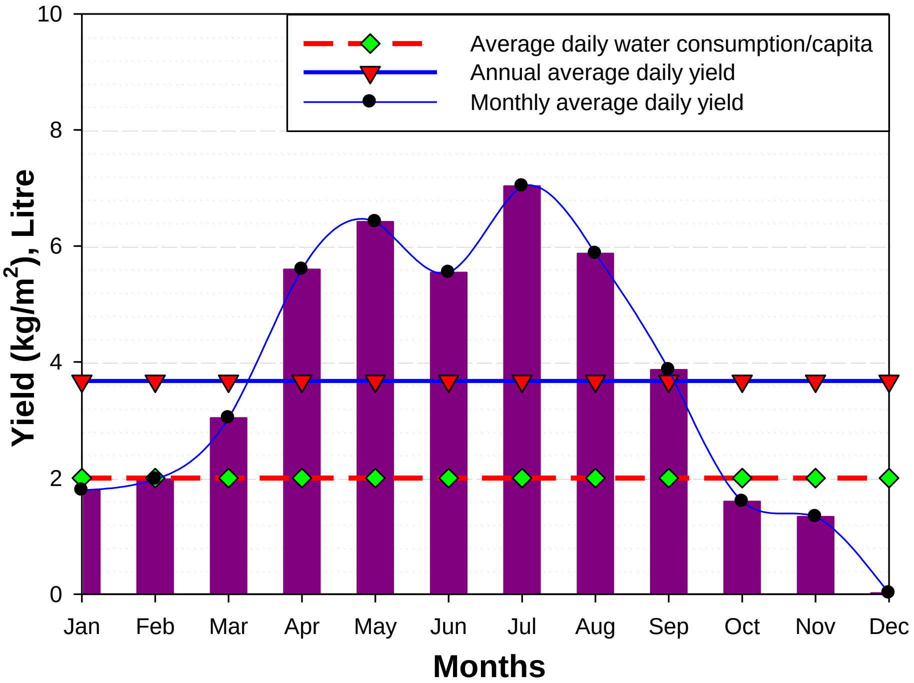

Figure (6) average daily yield vs. average daily consumption

in order to increase productivity, the effect of preheating the infeed water was considered, the Solar Water Heater SWH may use for this issue. Figure (7) present the amount of enhancement daily yield when increase the basin water temperature.

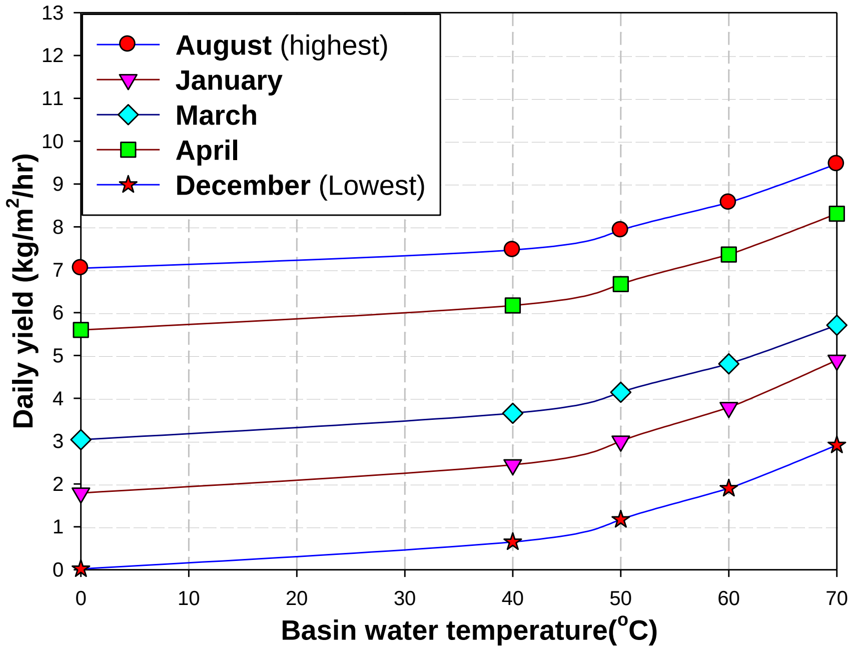

Figure (7) effect of increase basin water temperature on daily yield

It should be noted, the results presented in figure (7) was obtained when just established the basin water temperature, but the interactive between DSWD system and SWH system has large variables and should be carried out by special study.

4. Conclusion and recommendations

This study presents the productivity of Domestic Solar Water Desalination System under meteorological conditions of Az Zawiya-Libya. The results show that the main factors effects on productivity are the solar radiation and temperature difference between basin water and ambient air. The design parameters such water layer, glass cover and insulator thicknesses are selected as an optimum value according to literature. This study presents the thermal behavior of the system to arrive the productivity. The hourly average yield for all months was calculated, and the maximum distilled water yield of 7 kg/m^2/day was achieved in July. The study shows the DSWDS can produce an annual-average daily yield about 3.7 litre per m^2 per day, about 45.9 % more than the daily water consumption per capita. In order to increase productivity, the solar water heater was proposed as preheat system to increase the infeed water temperature. This paper recommended to continue develop present model to minimize the assumptions; carried-out the thermal energy storage, also improve configuration such a double slope, multi-effect, etc.

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