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Simulation of a solar still to investigate water depth and glass angle

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ABSTRACT

This paper presents a parametric study of a single-slope solar still (conventional solar still). In the parametric study, the effects of water depth in the basin and glass cover inclination angle on the productivity of the system are investigated. By proposing the best water depth and inclination angle, the accumulative productivity of the system is evaluated under the climatic condition of N. Cyprus on a typical day (21st March). The total productivity of the system was 5.3 kg/m^2.d while the error of the program was 3.37% comparing to experimental results.

Keywords: Solar desalination; Single-slope solar still; Conventional solar still; Simple solar still

1. Introduction

Many countries around the world suffer from lack of water. Population growth, human industrial and agricultural activities, climate changes due to global warming can be mentioned as important reasons of water scarcity. Desalination, purifying brackish water, seems to be the only solution for those countries which are in lack of potable water, especially those located in arid and semi-arid areas like Mediterranean basin and Middle East countries. Among renewable energy sources having zero emission and zero fuel cost solar energy is one of the best sources that can be used for desalination. Solar desalination seems to be the best method to produce potable water, specifically for places which not only lack of water but also electric grid connection. The basic principles of solar water distillation are simple, as distillation represents the purifying process of water in nature.

One of the most suitable solar desalination units is a single-slope solar still (conventional solar still), because of its low initial and maintenance cost, simple construction and operation, high fresh water productivity. Some experimental studies have been carried out to investigate the productivity of the still. Nijmeh et al. [1] have done an experiment on a single slope solar still in Al-Balqa Applied University in Amman, Jordan. The productivity of the still was checked with a basin covered with asphalt in order to increase the absorptivity of solar radiation. The reported productivity for the simple solar still was 2.95 kg/m^2.d, while the productivity for the system covered with asphalt was 4.120 kg/m^2.d. Aboul-Enein et al. [2] have investigated the productivity of the single basin solar still with deep basin experimentally and theoretically in Tanta University. The daily productivity of the system was 2.045 kg/m^2.d. Also, it was found that the daylight productivity decreases with an increase of water depth.

An experimental and theoretical study of a single-basin solar still was performed by Nijmeh et. al. [3] in Hashemite University, Zarqa, Jordan. The aim of this study was to check the effect of adding different materials to the water on the productivity of the system. The materials used to enhance the absorptivity of the water and finally the productivity, were dissolved salts, dye and charcoal 50%. The salts were potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$). The system containing just water produced 4.5 kg/m^2.d

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while the system containing potassium permanganate, potassium dichromate, violet dye and charcoal (50%) produced 5.75, 5.50, 5.50 and 5.50 kg/m^2.d respectively. Al-Hayek and Badran [4] have done an experiment on an asymmetric green house type still and a symmetrical one and compared the obtained results at Al-Balqa Applied University, Amman, Jordan. The asymmetrical one used the benefit of having mirrors on its inside wall. The productivity rates for symmetrical and asymmetrical green house type stills were found 3.97 and 5.12 kg/m^2.d respectively. Also an experimental and theoretical study has been carried out by Badran and Abu-Khader [5] in Al-Balqa Applied University, Jordan. It was found from the experimental results that the cumulative productivity was 3.56 kg/m^2.d. The experimental and theoretical results were in good agreement.

Two important factors having great effects on the productivity of the solar still are water depth in the basin and the inclination angle of the glass cover. The aim of this study is to thoroughly explain the thermal processes occurring in the system, to investigate the effects of water depth and the inclination angle of the glass cover on the productivity of the system and evaluate the total productivity of the system under the climatic condition of N. Cyprus on a typical day (21st March).

2. System description

The main components of the system are absorber plate painted black to increase the solar radiation absorptivity, glass cover, insulation and vessels to collect fresh water. The system width, length and height are 1 m, 1 m and 0.8 m respectively while the inclination angle of the glass cover is 35°. The absorber plate (1-mm thick) is made of galvanized steel and is painted black to form a black matte surface (absorptivity of 0.96 and emissivity of 0.08) [6]. Glass wool of 5 cm thickness with thermal conductivity of 0.032 W/m.K is used to reduce heat losses from the basin. Certain specifications needed for the glass cover in the still are: (a) minimum amount of absorbed heat, (b) minimum amount of reflection for solar radiation energy, (c) maximum transmittance for solar radiation energy and (d) high thermal resistance for heat loss from the basin to the ambient air.

The sun energy heats water to the point of evaporation. Although, evaporation happens at any temperature but as the water is heated, the rate of evaporation increases. When water vapor in the basin reaches the inclined glass cover, condensing starts on it since the glass cover has lower temperature than the dew point temperature of the air–vapor mixture in the cavity. Distilled water flows down toward the vessels due to the inclination of the glass cover to be taken out. This process removes impurities such as salts and heavy metals, and microbiological organisms. The end result is fresh edible water like rain water.

3. Mathematical modeling

Theoretical modeling of different solar desalination systems is an effective tool for predicting their productivities. Time dependent energy and mass balance equations are used for modeling and the equations are solved using 4th-order Runge–Kutta method in FORTRAN. The following assumptions are made to simplify the analysis, a) there is no vapor leakage in the still and this is important to increase the productivity; b) there is no temperature gradient along the glass cover thickness and in water depth; c) the free convection heat transfer from water surface to the air–vapor mixture is negligible and neglected. Fig. 1 shows the thermal processes occurring in the system.

The energy equation for the absorber plate can be written as:

$$M_P C_P A_P \frac{\mathrm{d}T_P}{\mathrm{d}t} = \left(I_{\text{Tot}}\tau_w \tau_g \alpha_P A_P\right) - Q_{\text{conv},p-w} A_p - Q_{Ins,p-a} A_p \quad (1)$$

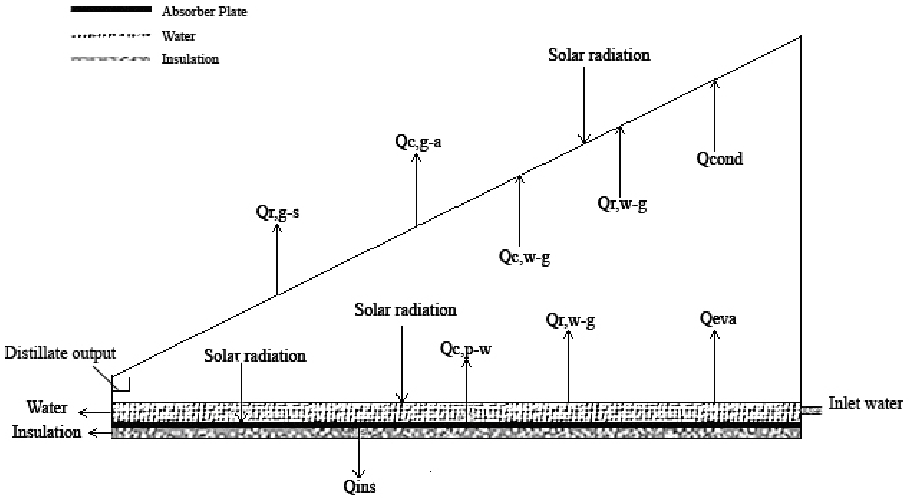

Fig. 1. Thermal processes occurring in the unit.

where M_p is the mass of absorber plate per 1 m^2, C_p is the specific heat of absorber plate, A_p is the area of plate, T_p is the temperature of the absorber plate, I_{Tot}, τ_g, τ_w, α_p are total incident solar radiation, transmissivity of the glass cover, transmissivity of water and absorptivity of the absorber plate, respectively. The heat flux terms $Q_{\text{conv},p\text{-}g}$ and Q_{ins} represent the convective heat transfer between plate and water and heat loss through the bottom of the plate and insulation to the ambient air respectively.

$$Q_{\text{conv},p-w} = h_{c,p-w}\left(T_p - T_w\right) \tag{2}$$

$$Q_{\text{Ins}} = U_{p-a}\Delta T,\ U_{P-a} = \frac{1}{\left(\dfrac{th_{ins}}{k_{ins}A_p} + \dfrac{1}{h_a A_p}\right)A_p} \tag{3}$$

where th_{ins} is thickness of the insulation, k_{ins} is thermal conductivity of the insulation and h_a is the convective heat transfer coefficient between the glass cover and ambient temperature. $h_{c,p\text{-}w}$ is free convection heat transfer coefficient between the absorber plate and water and is evaluated as:

$$h_{c,p-w} = 0.54\frac{k\text{Ra}_L^{1/4}}{\delta_l} \quad \text{if Ra} = 10^4\text{–}10^7 \tag{4}$$

$$h_{c,p-w} = 0.15\frac{k\text{Ra}_L^{1/3}}{\delta_l} \quad \text{if Ra} = 10^7\text{–}10^{11} \tag{5}$$

where Ra_L is Rayleigh number, k is thermal conductivity of the water and δ_l is characteristic length.

The energy equation for water mass in the basin can be written as:

$$M_w C_w A_w \frac{\text{d}T_w}{\text{d}t} = \left(\dot{m}_{in} C_w T_{w,in} - \dot{m}_{ex} C_w T_{w,ex}\right) + \left(I_{\text{Tot}}\tau_g \alpha_w A_w\right) + Q_{\text{conv},p-w}A_p - Q_{\text{evap}}A_w - Q_{r,w-g}A_w \tag{6}$$

where M_w is the mass of water per 1 m^2, C_w is the specific heat of water, I_{Tot} is the total solar radiation, τ_g is the transmissivity of the glass cover and α_w is absorptivity of water and A_w is the water surface area, $T_{w,in}$ is inlet water temperature, $T_{w,ex}$ is water temperature, $\dot{m}_{in}$ and $\dot{m}_{ex}$ (kg/s) are inlet and outlet mass flow rates of water respectively. In this system, the exit mass flow rate of water is equal to the rate of condensation. Q_{evap} is evaporation heat transfer rate and $Q_{r\text{-}w\text{-}g}$ is radiative heat transfer from water surface to glass cover calculated as follow:

$$Q_{r,w-g} = 0.96\sigma\left(T_w^4 - T_g^4\right)\ [5] \tag{7}$$

$$Q_{\text{evap}} = 0.027.\Delta T^{1/3}.P_{\text{sat}}.(1-\varphi)\ [8] \tag{8}$$

where ΔT is the temperature difference between water temperature (T_w) and air vapor mixture (T_m), T_w and T_g are the temperatures of water and glass respectively and σ is the Boltzmann constant.

The energy balance equation used in simulation is written as:

$$M_g C_g A_g \frac{\text{d}T_g}{\text{d}t} = \left(I_{\text{Tot}}\alpha_g A_g\right) + Q_{\text{cond}}A_g + Q_{r,w-g}A_w - Q_{r,g-a}A_g - Q_{\text{conv},g-a}A_g \tag{9}$$

Q_{cond} is condensation heat flux occurring on the backside of glass cover and is evaluated as:

$$Q_{\text{cond}} = 85.0.\left(T_m - T_g\right).\varphi\ [8] \tag{10}$$

$Q_{r,w\text{-}g}$ is radiative heat flux from water surface to the glass cover. Radiative heat flux from glass to ambient air is:

$$Q_{r,g-a} = h_{r,g-a}(T_g - T_a) \tag{11}$$

while:

$$h_{r,g-a} = \varepsilon_g.\sigma.\left(T_g + T_a\right).\left(T_g^2 + T_a^2\right) \tag{12}$$

where ε_g is emissivity of the glass cover, T_g and T_a are temperatures of glass and ambient air. Convective heat flux from glass to ambient air is calculated as follows:

$$Q_{c,g-a} = h_{c,g-a}(T_g - T_a) \tag{13}$$

where $h_{c,g\text{-}a}$ is convection heat transfer coefficient and calculates as follows (Duffi and Beckman correlation 1980):

$$h_{c,g-a} = 2.8 + 3V \tag{14}$$

where V is wind speed, m/s. The condensation and evaporation mass flow rates are calculated as:

$$\dot{m}_{cond} = \frac{Q_{\text{cond}}}{h_{fg}},\quad \dot{m}_{evap} = \frac{Q_{\text{evap}}}{h_{fg}} \tag{15}$$

where h_{fg} is the latent heat of vaporization.

Vapor mass balance equation is written as:

$$\frac{\text{d}M_v}{\text{d}t} = \dot{m}_{\text{evap}}A_w - \dot{m}_{\text{cond}}A_g \tag{16}$$

The partial pressure of air and vapor and the total pressure are calculated as follows:

$$P_a = \frac{M_a R_a T_m}{V},\ P_v = \frac{M_v R_v T_m}{V},\quad P = P_a + P_v \tag{17}$$

where V is volume of the cavity, M_a and M_v are mass of air and vapor, R_a and R_v are gas constant of air and vapor respectively. The absolute humidity and relative humidity in the cavity are obtained from:

$$\omega = \frac{M_v}{M_a},\quad \varphi = \frac{P_v}{P_{\text{sat}}} \tag{18}$$

The saturation pressure is obtained using the stated equation of $P_{\text{sat}} = P\,(T_m)$ [8].

The incident beam and diffuse solar radiation on the inclined glass cover is also calculated [9] throughout a day in order to evaluate the total productivity of the solar still.

4. Results and discussion

The thermo-physical properties of the system, assumed constant in all simulation, are given in Table 1.

In order to show the underlying process in the system the simulation is done while the thickness of water film is taken 3 cm, with 700 W/m^2 solar radiations. Since the mathematical modeling is done with time-dependence, the system should go to steady state with time. The temperature of glass and plate is taken 28°C initially. Fig. 2 shows the temperature changes of glass, absorber plate and water in the basin. As is clear, the changes of temperatures reach steady-state condition with time.

The changes of evaporation and condensation rate with time are shown in Fig. 3 reaching steady state condition with time. Fig. 4 shows the changes of relative humidity. The relative humidity is zero initially since only air is in the cavity at first. The relative humidity increases dramatically in the first 500 s, since the rate of evaporation is higher than the rate of condensation as shown in Fig. 3, after that the rate of condensation becomes higher than the evaporation rate leading to a decrease of relative humidity, finally the rates of evaporation and condensation become equal, thereby the relative humidity reaches the steady state condition.

Table 1
Simulation parameter

Parameter	Value
Mass of absorber plate (M_p), kg/m^2	7.93
Specific heat of absorber plate (C_p), J/kg.K	477
Absorptivity of absorber plate (α_p)	0.96
Absorptivity of glass (α_g)	0.12
Absorptivity of water (α_w)	0.45
Specific heat of glass cover (C_g), J/kg.K	800
Density of water (ρ_w), kg/m^3	997
Specific heat of water (C_w), J/kg.K	4184
Latent heat of vaporization (h_{fg}), J/kg	2257×10^3
Emissivity of glass cover (ε_g)	0.88

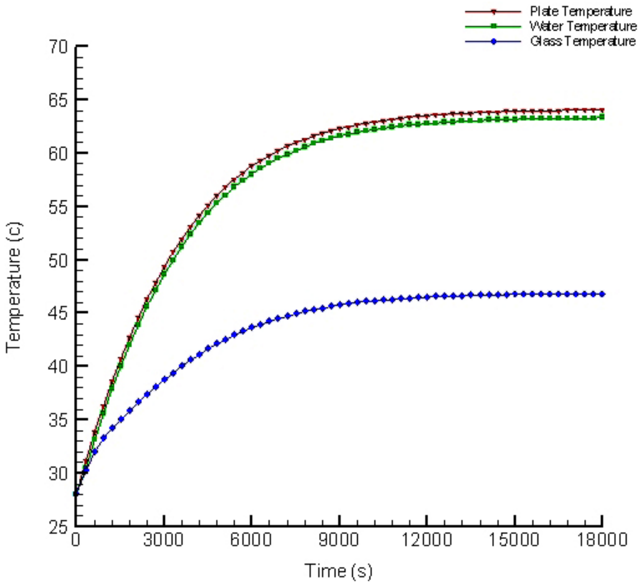

Fig. 2. Temperature changes of the plate, water and glass cover with time.

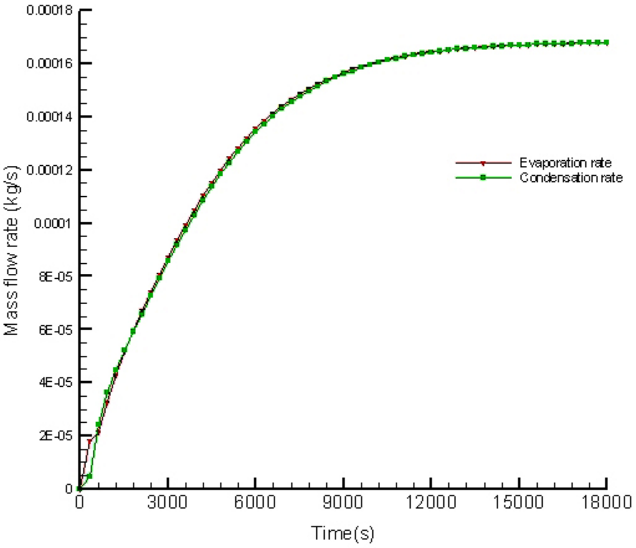

Fig. 3. Evaporation–condensation rates.

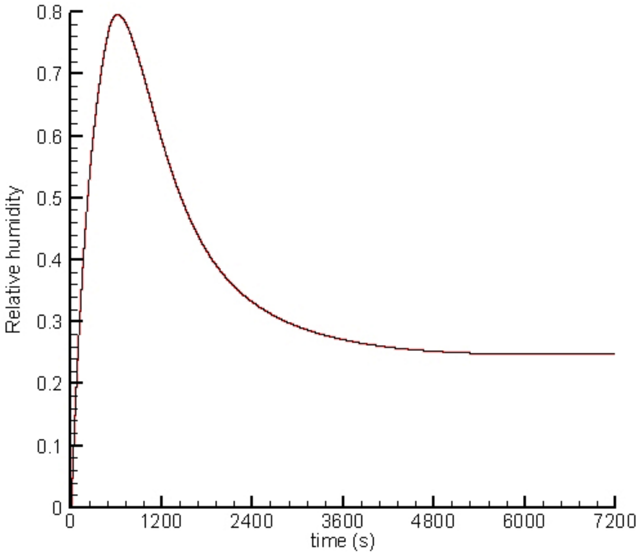

Fig. 4. Changes of relative humidity.

In order to investigate the effect of water depth on the productivity of the unit a parametric study was performed. The simulation is done with constant solar radiation of 700 W/m^2, the air temperature, water inlet temperature and initial temperature of water and glass

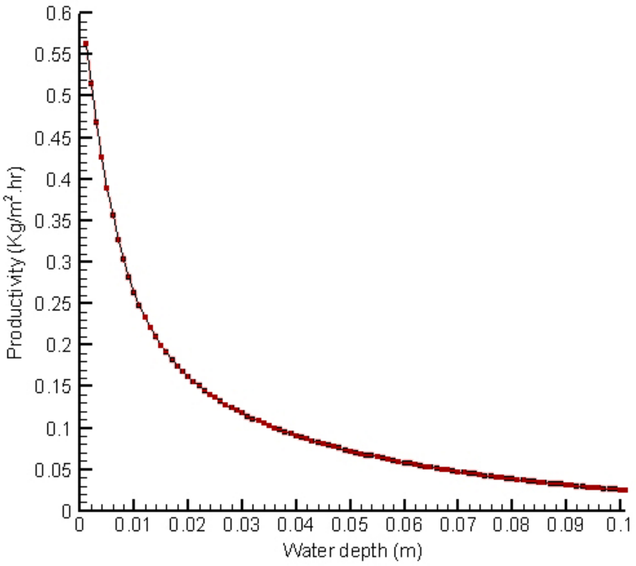

Fig. 5. Effect of water depth on the productivity.

are taken as 28°C [8]. As expected, the rate of productivity decreases with increase in water depth (Fig. 5). This is due to decrease in the rate of evaporation, since by increasing the thickness of water, the capacity of water to store heat (heat capacity of water) increases and as a result the rate of evaporation and thereby rate of condensation decreases.

The results of the inclination angle analysis are shown in Fig. 6. According to the results, the best inclination angle is 35° while the most solar radiation hits inclined glass cover, thereby the highest productivity rate occurs at this angle which is the latitude of N. Cyprus.

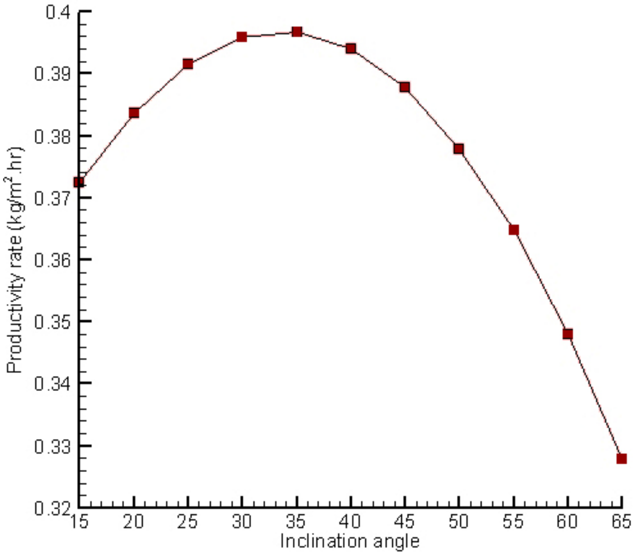

Fig. 6. Effect of the inclination angle on the productivity.

The simulation of the system was performed for a day under the climatic condition of N. Cyprus on 21st of March. Variable solar intensity through the day was calculated on the average temperature of 22°C. The rate of productivity through the day is shown in Fig. 7. The accumulated distilled water is 5.3 kg/m^2.d. As expected, the highest rate of productivity happens around noon when the solar radiation is at its highest rate. Moreover, the sunset hour is at 6:00 pm, while the system produces fresh water until 7:30 pm. This is due to the heat stored in water and absorber plate through the day.

In order to do the sensitivity analysis, the experimental setup of Badran [5] is chosen to be simulated with the explained equations and provided solar intensity and

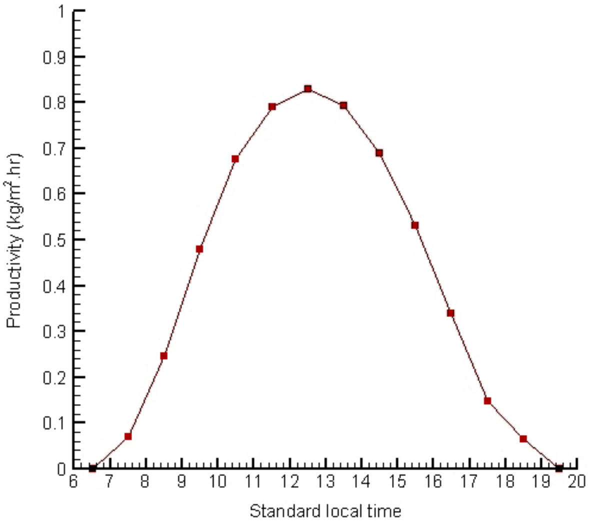

Fig. 7. Total productivity of the unit.

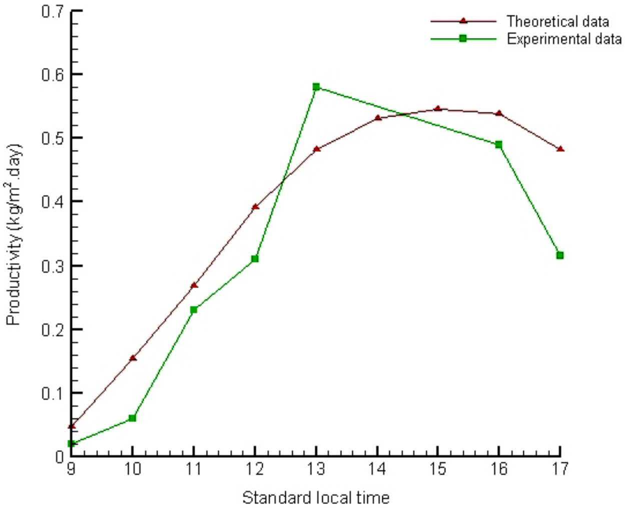

Fig. 8. Error analysis.

environmental parameters. The productivity rates of experimental and theoretical studies are shown in Fig. 8.

As is clear, the simulation results are in good agreement with the experimental results. Accumulated productivity of the experimental setup was 3.56 kg/m^2.d while the productivity evaluated by simulation was 3.44 kg/m^2.d. The total relative error of the simulation is 3.37%. The lower productivity of simulation compared to the experimental results could be the effect of negligence of reflected radiation inside the cavity.

5. Conclusion

A single-slope solar still is mathematically modeled using 4th order Runge–Kutta method in FORTRAN. It was found that the best water depth to have the highest productivity rate is the least water depth. Also, the best inclination angle of the glass cover is equal to the latitude of the place. Moreover, the total productivity of the system under the climatic condition of N. Cyprus was obtained 5.3 kg/m^2.d. The results of the written code are checked with the experimental results and the relative error of 3.37% is obtained.

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