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Experimental and numerical study of solar still with varying glass cover slopes

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ABSTRACT

The current work presents an experimental study on the distilled water yield in a single slope solar still with varying glass cover angle and basin water depths. The experiments were carried out with different cover angles (25°, 30°, 35°, and 40°) and various depths of water (1, 2, and 3 cm). In addition to the experimental measurements, a numerical model was developed to analyze the effect of different depths of water and various inclination angles of glass cover on the distilled water yield. The numerical results were then validated by the experimental measurements. The shallower the layer of water in the basin the higher the daily productivity. The production of distilled water dropped with an increase in slope of the cover beyond 35°, highest productivity being for the cover slope of 35°.

Keywords: Water depth; Slope of glass cover; Solar still; Performance

1. Introduction

Demand for drinking water is increasing because of the world population increase. On the other hand, the environmental pollution causes decrease in the sources of clean water. Thus, it has become a necessary to develop methods for purifying brackish or seawater. One of the promising and inexpensive methods of purifying water is using solar still [1].

One of the most economical method for producing drinking water is the distillation by solar still. However, the amount of clean water that is produced through the solar still is relatively less as compared with that of other methods. Therefore, a considerable amount of work has been carried out to improve the performance of the solar stills. Single slope solar stills are common type of solar stills. Among the many experimental studies, Akash et al. [2] investigated the effect of various light absorbing materials on the performance of the solar still. They found a considerable improvement in fresh water yield by 60%, 45%, and 38% when using black dye, black ink, and black rubber, respectively. In another experimental study, Ahsan et al. [3] considered various essential parameters such as solar insolation, wind velocity ambient air temperature, brine depth, and glass angle and their effect on the performance using four different sets of solar still under the same atmospheric conditions. They also developed an empirical equation for the productivity of the solar still with time. Estahbanati et al. [4] carried out both theoretical and experimental investigation for the effect of the glass cover angle on the performance. Similarly, Kumar and Tiwari [5] investigated the glass cover in an effort to maximize the fresh water yield in a single slope solar still in Indian climatic conditions.

Sharshir et al. [6] experimentally studied the effect of using a perforated aluminum sheet to heat the water in

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order to increase the evaporation and the fresh water yield in the solar still. They concluded that the yield of fresh water increased when the depth of water is increased in their study. The effect of wind speed on the daily drinking water production was studied by El-Sebaii [7] in both active and passive solar stills. They found that the yield of fresh water increased with wind speed up to a certain value. In a numerical study, Morad et al. [8] studied the glass cover temperature effect on the productivity of the solar still. The used a water film cooling technique to decrease the temperature of the glass cover. The found that a performance improvement of 20% was possible when cooling the glass cover using water film cooling. Khalifa and Hamood [9] carried out a computational and experimental study to investigate the effects of glass inclination and the orientation of the solar still on the performance of the solar still. They found out that a 12.5° of glass cover tilting yielded a maximum fresh water yield. They also concluded that east–west orientation is more sensitive to the productivity when compared with north–west orientation. Sharshir et al. [10] analyzed both the single and double slope solar stills from the perspective of the design parameters, atmospheric conditions, and operational parameters. They concluded that the water yield increased with solar insolation, ambient temperature, and the wind speed. The also noted that the higher depth of basin water yielded lower rate of productivity.

2. Experimental setup

In the present study, four sets of single slope solar stills of various glass cover angles were constructed as shown in Fig. 1. All the four sets were made identical, except the glass cover angles were 25°, 30°, 35°, and 40°, respectively. Their basins were made of galvanized iron of 3 mm thickness. The sizes of the basins were 0.5 m × 1 m × 0.06 m. The base of the basins was painted in black color to increase absorption. A scale is used in the basin water to measure the depth of the water in the basin. A small glass water through is placed at end of glass cover to collect the condensate water on the inside the glass cover and thus the water condensed is directed to a water container. The glass covers used are made of high transmittance and low reflectance glass of thickness 6 mm. They are fixed to the solar still by using aluminum frames and silicon rubber.

Experimental measurements were carried out in Dhahran (26°16′ N Latitude and 50°10′ E Longitude) during both the summer and the winter seasons. The solar stills were places in north–south direction such that the glass covers were facing the south. Experimental measurements were done daily from the sunrise until the sunset. The following measurements were recorded: amount of desalinated water produced, glass cover temperatures, and the temperature of the basin water. In addition, the ambient pressure and temperature, the wind speed, and its direction were measured on an hourly basis.

3. Mathematical modeling

Mathematical modeling for the distillation process is summarized below. The solution is done using MATLAB program. Fig. 2 shows the various energy quantities.

The following simplifying assumptions were made for the modeling of the distillation process:

- The glass cover temperature is uniform across the glass cover thickness.
- Water temperature is assumed to be uniform along the depth of the water and water level is kept constant.
- The basin is well-insulated from all sides and there is no leakage from the solar still.
- The reflectivity of the surface of water and that of the basin are assumed to be negligible.

Under the above-mentioned assumptions, the conservation of energy for the glass cover [11] can be written as:

$$\frac{dE_g}{dt} = \dot{Q}_{\text{abs},g} + \dot{Q}_{e(w-g)} + \dot{Q}_{c(w-g)} + \dot{Q}_{r(w-g)} - \dot{Q}_{c(g-a)} - \dot{Q}_{r(g-a)} - \dot{Q}_{\text{ref}(g-a)} \quad (1)$$

Fig. 1. Four sets of solar stills for experimental measurements. The slopes of glass covers are 25°, 30°, 35°, and 40° respectively.

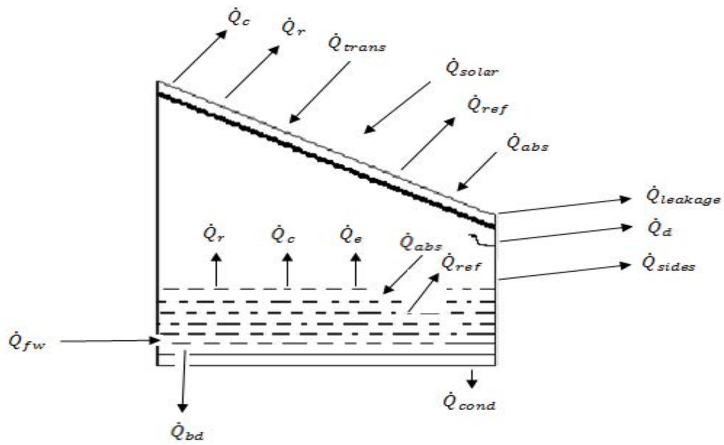

Fig. 2. Various heat transfer mechanisms taking place in a solar still.

$$\frac{dE_g}{dt} = m_g C_g \frac{dT_g}{dt} \tag{2}$$

On the other hand, the conservation of energy for the water and the basin [11] is:

$$\frac{dE_{w,b}}{dt} = \dot{Q}_{\text{abs},w} + \dot{Q}_{fw} + \dot{Q}_{e(w-g)} + \dot{Q}_{e(w-g)} - \dot{Q}_{r(w-g)} - \dot{Q}_{\text{ref}(w,b)} - \dot{Q}_d - \dot{Q}_{bd} - \dot{Q}_l - \dot{Q}_{\text{cond}} - \dot{Q}_{\text{sides}} \tag{3}$$

$$\frac{dE_g}{dt} = \left(m_w C_w + m_b C_b\right) \frac{dT_w}{dt} \tag{4}$$

The conservation of mass for water in the solar still [1] is given as:

$$\dot{m}_d = \dot{m}_{fw} - \dot{m}_{bd} \tag{5}$$

Solving Eqs. (1) and (3) simultaneously, one can obtain T_w and T_g. Accordingly, the rate of drinking water that is produced by the solar still is given by:

$$\dot{m}_d = \frac{\dot{Q}_{e(w-g)}}{h_{fg}} \tag{6}$$

The various terms in Eqs. (1) and (3) as evaluated as follows:

The convection heat transfer from the surface of the water to the inner surface of the glass [1] is:

$$\dot{Q}_{c(w-g)} = h_{c(w-g)} A_b \left(T_w - T_g\right) \tag{7}$$

where the convective heat transfer coefficient from the water surface to the glass is:

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

The radiation heat transfer from the surface of the water to the inner surface of the glass is:

$$\dot{Q}_{r(w-g)} = \sigma \in_{(w-g)} A_b \left(T_w^4 - T_g^4\right) \tag{9}$$

The evaporative heat transfer from the water surface to the glass inner surface is:

$$\dot{Q}_{e(w-g)} = h_{e(w-g)} A_b \left(P_w - P_g\right) \tag{10}$$

where the evaporative heat transfer coefficient from the water surface to the inner surface of the glass is:

$$h_{e(w-g)} = \frac{M_w h_{fg} P_T h_{c(w-g)}}{M_w c_{pa} \left(P_T - P_w\right)\left(P_T - P_g\right)} \tag{11}$$

in which:

$$P_w = 7235 - 431.45 T_w + 10.76 T_w^2 \tag{12}$$

and that for the glass cover inner surface temperature [12] is:

$$P_g = 7235 - 431.45 T_g + 10.76 T_g^2 \tag{13}$$

The specific heat of air in the solar still [13] is:

$$C_{pa} = 999.2 + 0.14339 T_{av} + 0.0001 T_{av}^2 - 0.000000067581 T_{av}^3 \tag{14}$$

where:

$$T_{av} = \frac{T_w + T_g}{2} \tag{15}$$

The latent heat of evaporation of the basin water is a function of temperature [14] and is given:

$$h_{fg} = \left(2503.3 - 2.398T\right) \times 1{,}000 \tag{16}$$

On the other hand, the convective heat transfer losses from the outer surface of the glass cover to the atmosphere [15] is:

$$\dot{Q}_{c(g-a)} = h_{c(g-a)} A_g \left(T_g - T_{\text{atm}}\right) \quad (17)$$

where the convection heat transfer coefficient on the outer surface of the glass surface is:

$$h_{c(g-a)} = 5.7 + 3.8V \quad (18)$$

The radiative heat losses from the outer surface of the glass cover to the surroundings is:

$$\dot{Q}_{r(g-a)} = \sigma \in_g A_g (T_g^4 - T_{\text{atm}}^4) \quad (19)$$

The amount of absorption of the solar radiation by the glass cover is given by:

$$\dot{Q}_{\text{abs},g} = \alpha_g \dot{Q}_s = \alpha_{g,S} A_g I_S \quad (20)$$

and the amount of heat absorption by the water and the material of the basin is given by:

$$\dot{Q}_{\text{abs},w} = \alpha_g \dot{Q}_\tau = \alpha_w \tau_S A_{g,S} I_S \quad (21)$$

The amount of energy entering in the form of heat by the supply of water is:

$$\dot{Q}_{fw} = \dot{m}_{fw} C_w \left(T_{\text{atm}} - T_w\right) \quad (22)$$

The amount of heat lost through the distillate is:

$$\dot{Q}_d = \dot{m}_d C_w \left(T_w - T_{\text{atm}}\right) \quad (23)$$

The amount of heat lost through blow down is:

$$\dot{Q}_{bd} = \dot{m}_{bd} C_w \left(T_w - T_{\text{atm}}\right) \quad (24)$$

4. Results and discussion

4.1. Experimental measurements

4.1.1. Effect of glass cover slope on the performance

Four different glass cover slopes were considered for comparison [16]. The effect of the slope of the glass cover on the yield of distilled water for a typical summer day of June is shown in Fig. 3.

The depth of water was 1 cm. As can be seen from this Fig. 3, the productivity of fresh water increased as the slope of the glass cover is increased from 25° to 35° and then decreased for the case of glass cover slope of 40°. A maximum distilled water productivity of 2.4 L/d was reached when the cover slope was 35°. This was an increase of 9.0% as compared with the case of cover slope of 25°. The productivity at 30° was 2.8% higher than that of 25°. The productivity decreased by 3.0% when the glass cover angle is increased from 35° to 40°.

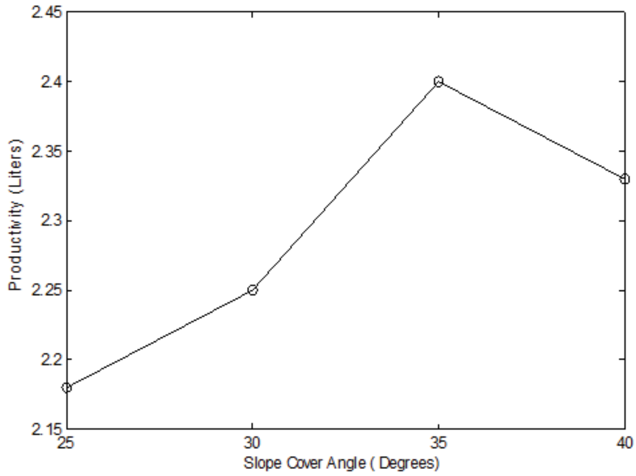

Fig. 3. Fresh water yield in the solar still during a typical summer day.

Similarly, Fig. 4 shows the effect of glass cover slope on the yield of distilled water for a typical day of December (summer). Again, the depth of water was 1 cm. As can be seen from Fig. 4 the productivity of fresh water increased as the slope of the glass cover is increased from 25° to 35° and then decreased for the case of glass cover slope of 40°. A maximum distilled water productivity of 1.15 L/d was reached when the cover slope was the optimum 35°. This was an increase of 11.0% as compared with the case of cover slope of 25°. The productivity at 30° was 3.0% higher than that of 25°. The productivity decreased by 2.5% when the glass cover angle is increased from 35° to 40°.

4.1.2. Effect of water depth

Three cases of basin water depth were considered for comparison. These were 1, 2, and 3 cm. The variation of the productivity for a summer day of June with varying the depth of water is shown in Fig. 5. In all cases of glass cover angles, the productivity decreased as the water depth is increased. Higher productivity of water was observed when the water depth was small, that is, 1 cm. This is due to the fact that as the water level is higher, the time required is longer for the temperature to rise and evaporate the water from the surface [17–20]. This slows down the process and thus the productivity turns out to be less for the cases of higher depths of basin water. When all the cases considered, the optimum conditions for producing the maximum distilled water were 35° of glass cover and 1 cm of basin water depth. For the case of glass cover angle of 35°, the water yield decreases by 11.3% when the level of water is increased to 3 cm.

The same experiment with different depths of basin water and different slopes of glass cover was repeated in December and the results are shown in Fig. 6. A similar trend is observed in the productivity; that is, when the water depth is increased, the productivity of the distilled water decreased for the case of winter, too. The highest output of 1.15 L was obtained for a 35° slope of glass cover and basin

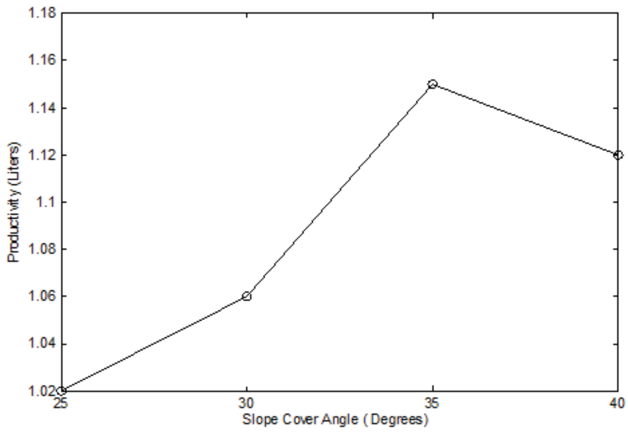

Fig. 4. Fresh water yield in the solar still during a typical winter day.

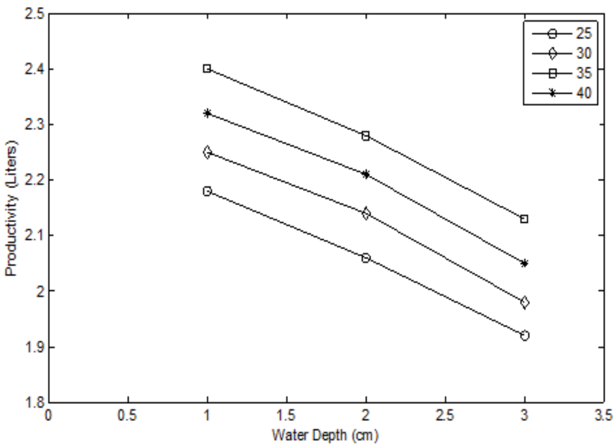

Fig. 5. Distilled water production of the solar still with varying water depths and four different cases of glass cover angles during a typical day of summer.

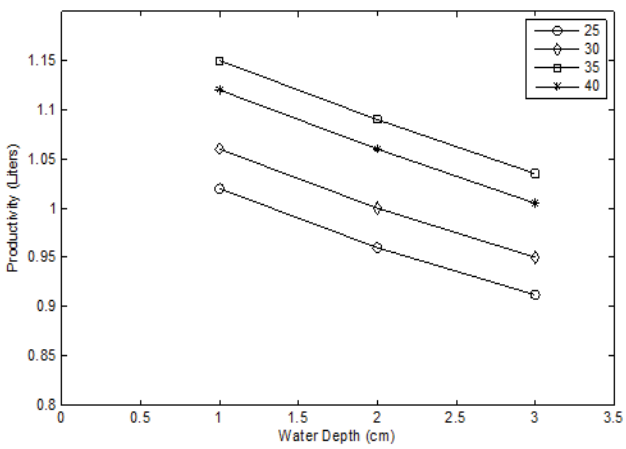

Fig. 6. Distilled water production of the solar still with varying water depths and four different cases of glass cover angles during a typical day of winter.

water depth of 1 cm. A decrease of 5.3% and 5.1% in output was observed for the cases of 2 and 3 cm depths of water, respectively.

The rate of distilled water production during a typical summer day of June on an hourly basis is in Fig. 7. The fresh water yield increased during the morning hours reaching a peak at around 1:00 PM in the afternoon and then the productivity decreased. The highest output per hour was obtained between 12 noon and 1 PM.

Fig. 8 shows the hourly rate of distilled water production during a typical day of December (winter). As was the case of summer, the peak value of rate of water productivity was observed to take place between 12 noon and 1 PM. Because the days are shorter during the winter and the solar radiation is low, the rate of fresh water productivity is lower in the winter that that in the summer. It takes more time to warm up the water in the basing to help evaporate it during the winter. As the ambient air temperature and solar radiation increases during the day, the water productivity increases until 1:00 PM, and then it decreases during the afternoon hours.

4.2. Numerical results

The MATLAB software (ode23 stiff function) was used for numerical simulation. Simulations were performed using all the cases of glass cover angles and basin water depts as mentioned above. However, for the sake of space limitations, only the results for the glass cover angle of 35° were reported. As for the water depts, cases of 1 and 3 cm were considered. The hourly glass cover and basin water temperatures for a typical summer day for water depths of 1 and 3 cm are shown in Figs. 9 and 10, respectively. A good agreement is observed between the temperature profiles of numerical simulation and the experimental measurements. Similarly, the experimental and the numerical results for the hourly glass cover and basin water temperatures during a typical winter day for water depths of 1 and 3 cm were compared in Figs. 11 and 12, respectively.

Both the experimental measurements and numerical simulation results indicate that, in the summer, both the glass cover and the basin water temperatures reach their peak at around 1 PM. In the winter, the peak value of temperatures for the solar still with 3 cm water depth is obtained between 1 and 2 PM. This delay may be attributed to a shorter day length wherein the ambient temperature is not very high in the morning hours. The variation in glass tilt angle considered in this study did not show a considerable effect on the glass cover and basin water temperatures. The discrepancy between the numerical results and experimental measurements of temperatures is attributed to the modeling assumptions that the reflections from the outer glass cover and that from the surface of the basin water are assumed negligible.

The comparison of experimental and numerical profiles of distilled water productivity for a typical summer day and water depths of 1 and 3 cm are shown in Figs. 13 and 14, respectively. Similarly, the comparison of experimental and numerical profiles of distilled water productivity for a typical winter day and water depths of 1 and 3 cm are shown in Figs. 15 and 16, respectively.

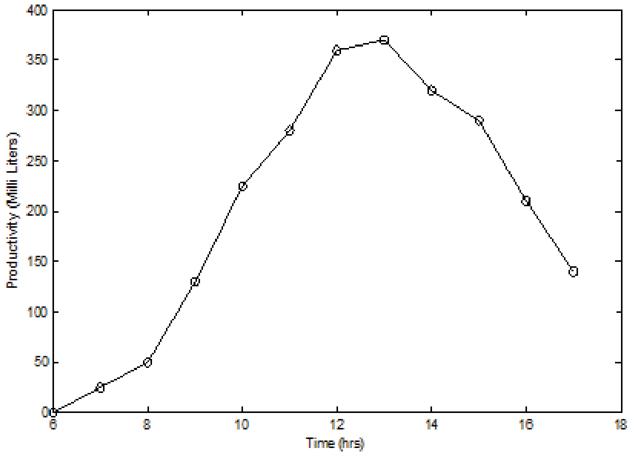

Fig. 7. Hourly rate of distilled water production in the solar still during a typical day of summer.

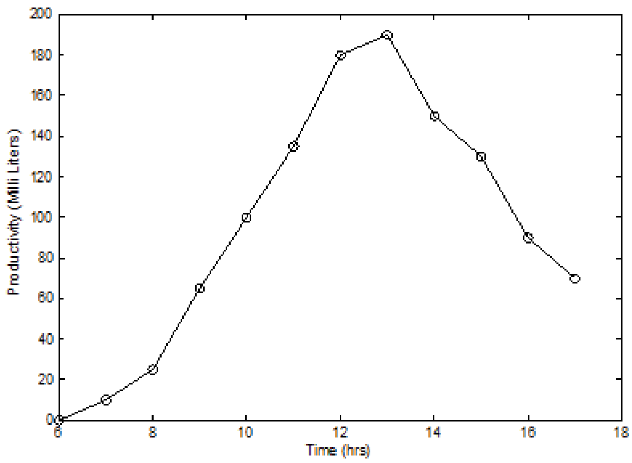

Fig. 8. Hourly rate of distilled water production in the solar still during a typical day of winter.

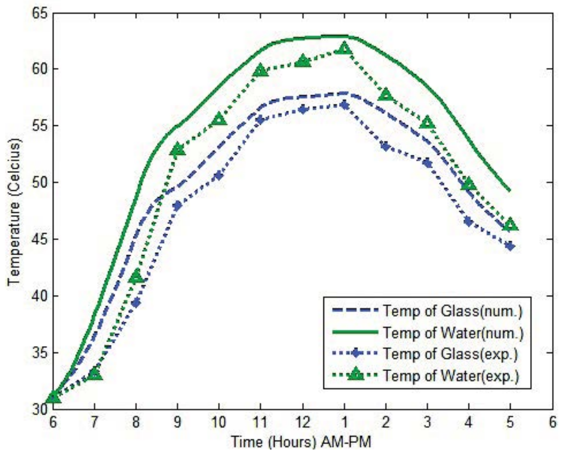

Fig. 9. Numerical and experimental measurements of the cover glass and basin water temperatures for 1 cm water depth and a cover slope angle 35° for summer.

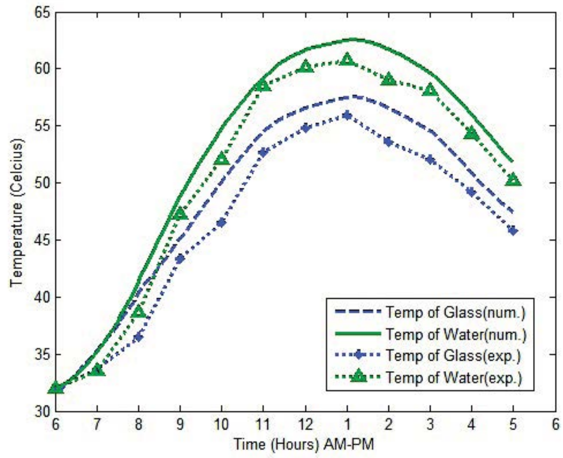

Fig. 10. Numerical and experimental measurements of the cover glass and basin water temperatures for 3 cm water depth and a cover slope angle 35° for summer.

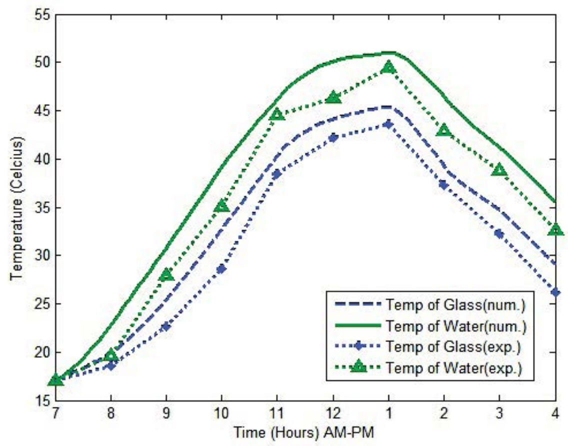

Fig. 11. Numerical and experimental measurements of the cover glass and basin water temperatures for 1 cm water depth and a cover slope angle 35° for winter.

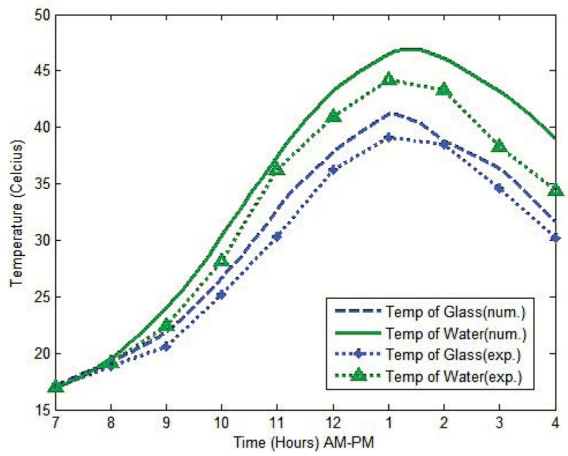

Fig. 12. Numerical and experimental measurements of the cover glass and basin water temperatures for 3 cm water depth and a cover slope angle 35° for winter.

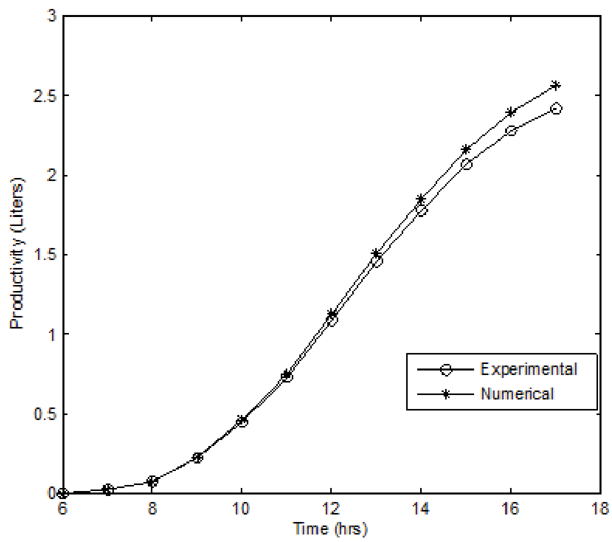

Fig. 13. Experimental and numerical comparison of productivity for 1 cm water depth and a cover slope angle 35° for summer.

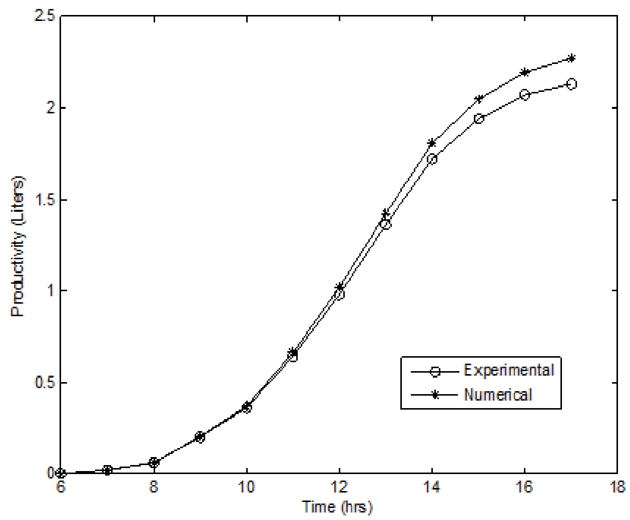

Fig. 14. Experimental and numerical comparison of productivity for 3 cm water depth and a cover slope angle 35° for summer.

When the basin water temperatures of 1 cm depth in the summer and that in the winter are compared, a decrease of 20% is observed in the winter. The decrease of basin water temperature in the winter for the case 3 cm water depth when compared with the summer case is 27%.

The productivity of the distilled water per day with 1 cm depth was reduced by 55% from summer to winter and for the same still with higher water depth (3 cm), there was a decrease in the productivity by 62%. These significant decreases in distilled water during the winter days are attributed to the decrease in the solar radiation and the prevailing climatic conditions during the winter in the test site. From the above results, it can be stated that the distilled

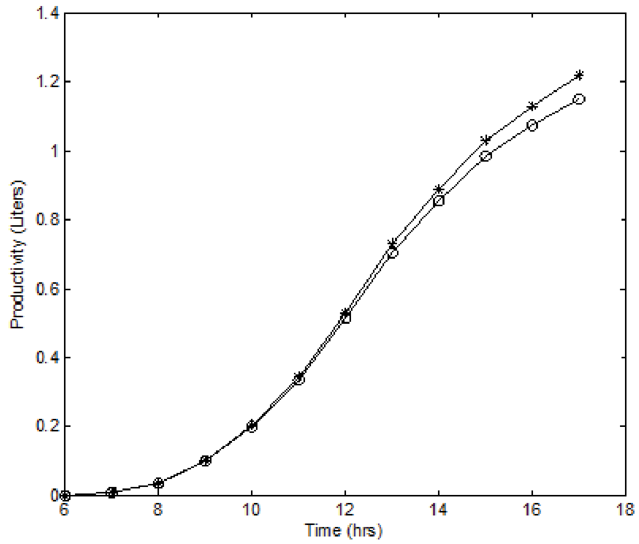

Fig. 15. Experimental and numerical comparison of productivity for 1 cm water depth and a cover slope angle 35° for winter.

water productivity in the summer is more than that of the winter roughly by a factor of 2.

5. Conclusion

The effects of tilt angle of the glass cover and the depth of the basin water in a solar still on the distilled water yield were analyzed by both experimental measurements and numerical modeling simulations. The following conclusions can be derived from the current work:

- Among the considered tilt angles considered in this study, 35° is found to be an optimum glass cover slope for both the summer and the winter climatic conditions in Dhahran, Saudi Arabia.
- It was observed that the lower the depth of the basin water, the higher the distilled water yield for both the summer and the winter conditions. The optimum depth of the basin water is found to be 1 cm among the water depths considered in this study.
- The maximum amount of distilled water productivity for the typical summer day was found to be 2.4 L/d for the case of 35° glass cover angle and 1 cm depth of basin water. The maximum amount of distilled water productivity for the typical winter day was 1.15 L/d for the same cases as mentioned for summer.
- The distilled water production increased during the morning hours until it reached a peak at around 1:00 PM in the afternoon and then the productivity decreased. The distillation rate was highest between 12 noon and 1 PM.
- The numerical modeling results and the experimental measurements are found to be in a good agreement.
- The distilled water yield per day with 1 cm depth decreased by 55% in the winter as compared with that for summer. There was a decrease of 62% in the yield when the water depth is increased from 1 to 3 cm.

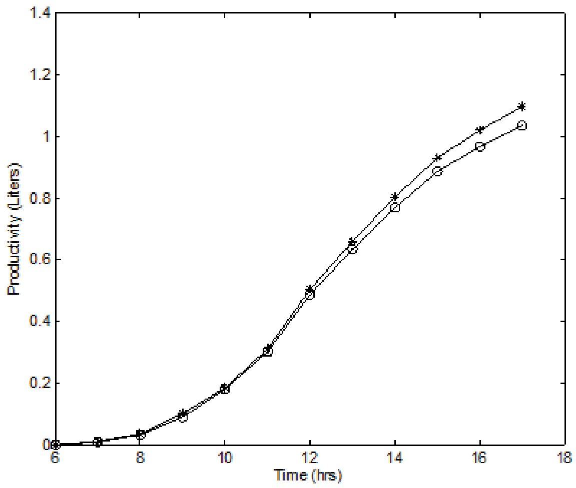

Fig. 16. Experimental and numerical comparison of productivity for 3 cm water depth and a cover slope angle 35° for winter.

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Symbols

A	—	Area, m^2
C	—	Specific heat capacity, J/kg K
h	—	Heat transfer coefficient, W/m^2 K
h_{fg}	—	Latent heat of water, J/kg
I	—	Total solar radiation, W/m^2
m	—	Mass, kg
$\dot{m}$	—	Mass flow rate, kg/s
M	—	Molecular weight
n	—	Day number in a year
P	—	Partial pressure of water vapor, N/m^2
Q	—	Heat energy, W
$\dot{Q}$	—	Rate of heat energy transfer, W/s
R	—	Ratio of beam radiation on tilted surface to that on horizontal surface
t	—	Time, s
T	—	Temperature, °C
V	—	Wind speed, m/s

Greek

α	—	Absorptivity
β	—	Glass tilt angle, degree
δ	—	Declination angle, degree
ε	—	Emissivity
σ	—	Stefan Boltzmann constant, 5.67 × 10^{-8} W/m^2 K^4
τ	—	Transmissivity
ω	—	Hour angle, degree
ϕ	—	Latitude, degree
ρ_{gr}	—	Ground reflectivity
ρ	—	Density, kg/m^3

Subscripts

a	—	Air
abs	—	Absorb
av	—	Average
b	—	Basin
bd	—	Blow down
c	—	Convection
d	—	Distillate
e	—	Evaporation
fw	—	Feed water
g	—	Glass
gr	—	Ground
l	—	Leakage
N	—	North
r	—	Radiation
ref	—	Reflection
s	—	Solar
S	—	South
T	—	Total
w	—	Water

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