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Performance comparison of a single slope solar still equipped with water heater and an external fan during summer and winter

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ABSTRACT

Desalination of the brackish water in a solar still enhances by increasing the evaporation and condensation rate. In this paper, a comparison is made for the productivity of a single slope solar still that is equipped with a water heater and an external fan in summer and winter, by both experimental and numerical techniques. Heater is used to enhance the evaporation and the fan is used to promote the condensation. When using a 500 W heater, it was shown that an increase of up to 370% in the fresh water yield was observed. The effect of external fan that induces 7 m/s and 9 m/s wind speeds was also studied. In addition, a thermal modeling was done to simulate the desalination process using the principles of heat and mass transfer. Numerical results were validated by the experimental measurements. It is concluded that using water heater significantly enhances the productivity during both the summer and winter. However, employing an external fan increases the productivity in the summer, but decreases it slightly in the winter.

Keywords: Solar still; Water heater; Cooling fan; Performance analysis

1. Introduction

Clean water is essential for life on the Earth. Only 3% of all the available water on the planet Earth is fresh and drinkable. Furthermore, only 1% of this fresh water is available for human use and the rest is in the ice form. With the ever-increasing population, there is a strong demand to satisfy the needs for the human consumption. Desalination of water is one of such methods that is used to obtain pure water from the salty or raw water. The dependence on non-renewable energy sources for desalination of water will lead to the depletion of these resources. Hence there is a global focus on the utilization of solar and renewable energy resources for the desalination of water. Distillation of water using solar energy is a viable option to provide clean water for small communities living in remote areas. Solar stills are one of the devices which use solar energy to obtain pure water. There are a number of parameters that affect the productivity of solar still. Some of these parameters are glass slope angle, depth of water, solar radiation, surrounding temperature and speed of the wind.

Many experimental and numerical studies have been performed in the past using different kinds of solar stills. Numerical modeling of a multi stage stacked tray solar still was done by Adhikari et al. [1] to analyze the steady state performance of the still. They used an immersion type water heater to simulate the experiments. Hongfei et al. [2] presented a number of heat and mass transfer correlations in multi stage stacked tray still. They performed indoor simulations to validate the correlation using two immersion type water heaters. Murugavel et al. [3] tried to improve the yield of solar still by conducting indoor experiments using various wick materials. They used an electric heater having capacity of 2 kW in their simulations. Mahian et al. [4] studied the evaporation rate in a solar still equipped with a heat exchanger. Their results showed that using the heat exchanger at temperatures lower than 60°C is not advantageous and the corresponding yield is smaller than that of solar still without the heat exchanger.

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To improve the fresh water yield of solar still, many attempts have been made by researchers. An experimental analysis of solar still was done by Abu-Hijleh et al. [5] in which sponge cubes are used in the basin water. The basin water rises through the sponge cubes by capillary forces and thus the evaporation rate is increased. It was reported that the fresh water yield increased by 18% to 273% when sponge cubes were used. Abed et al. [6] studied the performance improvement of a passive solar still in a water desalination. They found that their system had 87% distillation efficiency and 26% of the overall efficiency due to heat losses in the system.

Rajvanshi [7] performed an experiment work on a single slope solar still in order to study the effect of adding dyes in the water. Dye solution is found to increase the productivity of the still by 29%. The best dye in his study was found to be black napthylamine. Badran [8] studied the effect of using asphalt and sprinkler. He concluded that an increase of 29% in still productivity is obtained when asphalt was used. A further 22% increase in the yield was observed if the sprinkler was combined with asphalt.

Abdenacer et al. [9] carried out an numerical analysis to study the effect of difference in the temperature between the glass surface and the basin water. It was reported that the productivity increases as the temperature difference increases. Ali [10] conducted experiments to study the effect of the air circulation inside solar still. He used a fan to circulate the air inside the solar still and found the productivity to increase significantly. In their attempt to increase the productivity, Zurigat et al. [11] performed a numerical study in which flowing water was used in order to reduce the temperature of the glass surface of the solar still. They found the yield to increase by 20% when using water to cool the glass surface. They also studied the effect of the wind velocity found the productivity to increase by 50% as the wind velocity was changed from 0 to 10 m/s.

El-Sebaii [12] performed a numerical study to reveal the effect of wind velocity on the yield of solar still. He found that the yield is independent of still shape and it increases with wind velocity up to a certain value. The threshold velocity up to which the productivity increases significantly was found to be 10 m/s for summer and 8 m/s for winter. Farid et al. [13] did a study on various parameters that affect the productivity of the solar still. They found that the yield increases with the temperature of the ambient and decreases with wind speed.

Several authors such as Garg et al. [14], Cooper [15], and Soliman [16] have noted that the productivity increases with the wind speed. However, Yeh et al. [17,18] and Hollands [19] found that the distilled water production decreases with the speed of the wind. Furthermore, Morse et al. [20] found that the yield is not affected by change in wind speed. Hence, the effect of the wind velocity on the yield of solar still is not very clear. Other detail information on the performance of solar still can be found in [21] and [22].

The mechanism of water distillation in summer climatic conditions differs from that in winter climatic conditions. That is why there are conflicting reports in the literature on the effect of wind velocity on the amount of distillation. Thus, the effects of the wind speed and that of the water heater on the yield of solar still need to be clarified. In light of the above literature, an attempt is made in the present study to examine the effects of the water heater and the wind velocity induced by an external fan for cooling the outer glass surface of a solar still in both summer and winter climatic conditions. Water heater was used by many researchers [1–3] in order to simulate the solar radiation. In the present study, a water heater is used in addition to the available solar radiation. Both the external fan and the water heater used in this study are electrically powered and solar PV cells can be accommodated to power these accessories. The effects of using water heater and external fan on the productivity of the solar still are studied and compared. The present study is partial implementation of two patents [23,24].

2. Mathematical modeling

A schematic representation of a single slope solar still is given in Fig. 1. Different heat transfer mechanisms are indicated in the figure.

In the present thermal and heat transfer model, the assumptions made are as follows [25]:

1) The surface temperature of the glass is uniform.
2) The basin temperature and that of the water inside the basin is uniform.
3) The sides and the bottom of the basin are adiabatic; therefore $\dot{Q}_l, \dot{Q}_{cond}$ and $\dot{Q}_{sides}$ are negligible.
4) The reflection of the solar radiation from the surface of the water and the basin material is negligible, therefore $\dot{Q}_{ref(w,b)}$ can be neglected.

In the numerical simulations for the use of water heater, the ambient wind velocity is taken into consideration. Whereas, when studying the effect of the external fan, the term $\dot{Q}_{heater}$ is set to zero in the heat transfer analysis.

The conservation of mass is given by [25] ,

$$\dot{m}_d = \dot{m}_{fw} - \dot{m}_{bd} \quad (1)$$

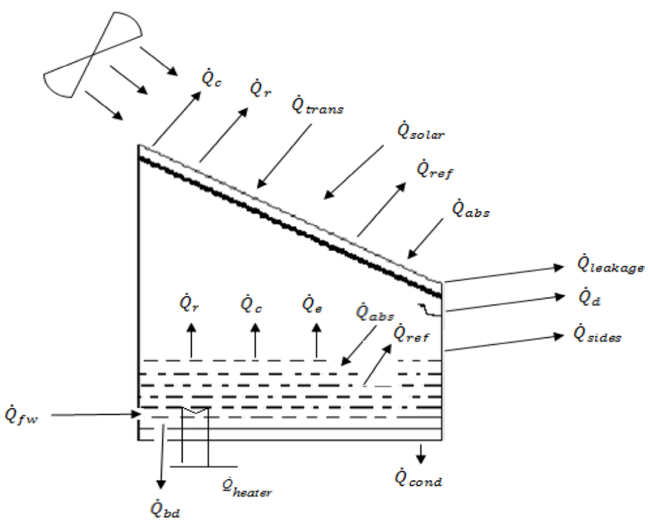

Fig. 1. Various mechanisms of heat transfer in the solar still equipped with a water heater and an external fan.

The conservation of energy for the glass cover can be written as [26],

$$\left(\frac{dE_g}{dt}\right) = \dot{Q}_{abs,g} + \dot{Q}_{e(w-g)} + \dot{Q}_{c(w-g)} + \dot{Q}_{r(w-g)} - \dot{Q}_{c(g-a)} - \dot{Q}_{r(g-a)} - \dot{Q}_{ref(g-a)} \tag{2}$$

$$\left(\frac{dE_g}{dt}\right) = m_g C_g \left(\frac{dT_g}{dt}\right) \tag{3}$$

The conservation of energy for the basin that contains water can be written as [26],

$$\left(\frac{dE_{w,b}}{dt}\right) = \dot{Q}_{heater} + \dot{Q}_{abs,w} + \dot{Q}_{fw} - Q_{e(w-g)} - \dot{Q}_{c(w-g)} - \dot{Q}_{r(w-g)} - \dot{Q}_{ref(w,b)} - \dot{Q}_d - \dot{Q}_{bd} - \dot{Q}_l - \dot{Q}_{cond} - \dot{Q}_{sides} \tag{4}$$

$$\left(\frac{dE_{w,b}}{dt}\right) = \left(m_w C_w + m_b C_b\right)\left(\frac{dT_w}{dt}\right) \tag{5}$$

Eqs. (2) and (4) can be solved to obtain T_w and T_g.
The rate of water distillation is given by [25] ,

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

The solar irradiation on a surface is given by [27],

$$I_{Tilted} = I_{beam} R_{beam} + I_{diffuse}\left(\frac{1+cos\beta}{2}\right) + I\rho_{gr}\left(\frac{1-cos\beta}{2}\right) \tag{7}$$

where the geometric factor R_{beam} for the northern hemisphere is given by [27],

$$R_{beam} = \frac{\cos(\phi-\beta)cos\delta cos\omega + \sin(\phi-\beta)sin\delta}{cos\phi cos\delta cos\omega + sin\phi sin\delta} \tag{8}$$

In which the declination angle is [27],

$$\delta = (23.45)\sin\left[\frac{360(284+n)}{365}\right] \tag{9}$$

The heat transfer associated with the convection, evaporation and radiation from the surface of water, respectively, given by [25],

$$\dot{Q}_{c(w-g)} = h_{c(w-g)} A_b \left(T_w - T_g\right) \tag{10}$$

$$\dot{Q}_{e(w-g)} = h_{e(w-g)} A_b \left(P_w - P_g\right) \tag{11}$$

$$\dot{Q}_{r(w-g)} = \sigma\varepsilon_{w-g} A_b \left(T_w^{\ 4} - T_g^{\ 4}\right) \tag{12}$$

The convection and evaporation coefficients of heat transfer from the water surface can be evaluated, respectively, [25,26]

$$h_{c(w-g)} = 0.884\left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)T_w}{268900 - P_w}\right]^{1/3} \tag{13}$$

$$h_{e(w-g)} = \frac{M_w h_{fg} P_T h_{c(w-g)}}{M_a C_{pa}\left(P_T - P_w\right)\left(P_T - P_g\right)} \tag{14}$$

The partial pressure of vapor is evaluated by the empirical relations as [28],

$$P_w = 7235 - 431.45T_w + 10.76T_w^{\ 2} \tag{15}$$

$$C_{pa} = 999.2 + \left(0.14339T_{av}\right) + \left(0.0001101T_{av}^{\ 2}\right) - \left(0.67581x10^{-7}T_{av}^{\ 3}\right) \tag{16}$$

The air specific heat inside the solar still can be evaluated by [29],

$$C_{pa} = 999.2 + \left(0.14339T_{av}\right) + \left(0.0001101T_{av}^{\ 2}\right) - \left(0.67581x10^{-7}T_{av}^{\ 3}\right) \tag{17}$$

where

$$T_{av} = \frac{\left(T_w + T_g\right)}{2} \tag{18}$$

The latent heat of evaporation for the water is estimated as [30]

$$h_{fg} = \left(2503.3 - 2.398T_w\right) \times 1000 \tag{19}$$

Part of the incident solar radiation that is absorbed by the glass which can be evaluated as [31],

$$\dot{Q}_{abs,g} = \alpha_g \dot{Q}_s = \alpha_{g,S} A_g I_S \tag{20}$$

On the other hand, the solar radiation that is absorbed by the basin and the water can be estimated by [31]

$$\dot{Q}_{abs,w} = \alpha_w \dot{Q}_\tau = \alpha_w \tau_S A_{g,S} I_S \tag{21}$$

The heat transfer from the glass cover through convection and radiation, respectively, is [25],

$$\dot{Q}_{c(g-a)} = h_{c(g-a)} A_g \left(T_g - T_{atm}\right) \tag{22}$$

$$\dot{Q}_{r(g-a)} = \sigma\varepsilon_g A_g \left(T_g^{\ 4} - T_{atm}^{\ 4}\right) \tag{23}$$

where the coefficient of the convective heat transfer from the surface of the glass cover to the atmosphere is given by [32]

$$h_{c(g-a)} = 5.7 + 3.8V \quad (24)$$

The heat gain by the system through the feed water supply can be written as [25]

$$\dot{Q}_{fw} = \dot{m}_{fw} C_w \left(T_{atm} - T_w\right) \quad (25)$$

The loss of heat from the system as a result of the distillate leaving the system is [25]

$$\dot{Q}_d = \dot{m}_d C_w \left(T_w - T_{atm}\right) \quad (26)$$

The heat transfer associated with the blow down in the base of the tank is [25]

$$\dot{Q}_{bd} = \dot{m}_{bd} C_w \left(T_w - T_{atm}\right) \quad (27)$$

3. Description of experimental setup

For the experimental investigation, a single slope solar still is designed and constructed. The solar still has a 35° glass slope angle. The dimensions of the base tank of the solar still are 0.5 m × 1 m × 0.06 m. The basin of the still is made of 3 mm thick Galvanized steel that has good formability characteristics. In order to improve the absorption in the basin and in the water that it contains, the inner and the outer sides of the basin were painted in black color.

The level of water in the basin of the solar still is maintained to be 1 cm. In order to extract the distilled water, a hole is made in the basin. Bottles are used under the basin to collect the water extracted. L shaped aluminum profiles are used around the solar still to provide rigidity for the glass cover. The constructed single slope solar still is shown in Fig. 2.

Experimental measurements were conducted in the campus of KFUPM, Dhahran (26°16′N, 50°10′E), Saudi Arabia. The orientation of the solar still is placed to face the southern direction. Experiments were carried out starting from the sunrise until the sunset. The following reading were recorded on an hourly basis: the glass surface temperature, temperature of the basin water, and the amount of distillate water. In addition, speed and direction of the wind, and the ambient temperature were recorded. The basin water temperature was measured by using calibrated K-type thermocouples (with a range of 0–100°C and ±0.1°C accuracy) attached to the basin of the still and a digital temperature indicator. The ambient temperature measurement was done by using calibrated mercury thermometer with a range of 0–100°C and accuracy of ± 0.1°C. The amount of distillate water was measured by using a measuring container. On the other hand, the speed and direction of the wind were measured using an electronic digital anemometer that has a range of 0–15 m/s and accuracy of ± 0.1°C.

Fig. 2. The experimental setup.

3.1. Experimental measurements

Experimental investigation of the effect of the water heater and the external fan for a typical summer day were reported earlier in [33]. Therefore, in the present study the experimental results obtained for a typical winter day are reported. In addition, a comparison for the productivity of the solar still is made between the summer and winter days.

3.1.1 Effect of water heater

Fig. 3 shows a comparison of temperature profiles in the solar still during a typical winter day with and without water heater placed in the basin of the solar still. When the water heater is used, the maximum temperature of the basin water and the glass surface reaches 63°C and 53°C respectively. The highest temperature of the basin water and the glass without the heater were measured to be 47.2°C and 43.4°C respectively. The temperature rises sharply when water heater is used. The peak value of the solar still temperature occurs at 12 PM when water heater is used while it occurs one hour later in the case of no water heater. This delay is due to the low ambient temperatures during the morning hours. When water heater is used in the basin of the solar still the temperature of the water increases faster.

As can be seen from Fig. 3 that the temperature of the glass is also increasing together with the water temperature increase. The rate of increase of the glass temperature is due

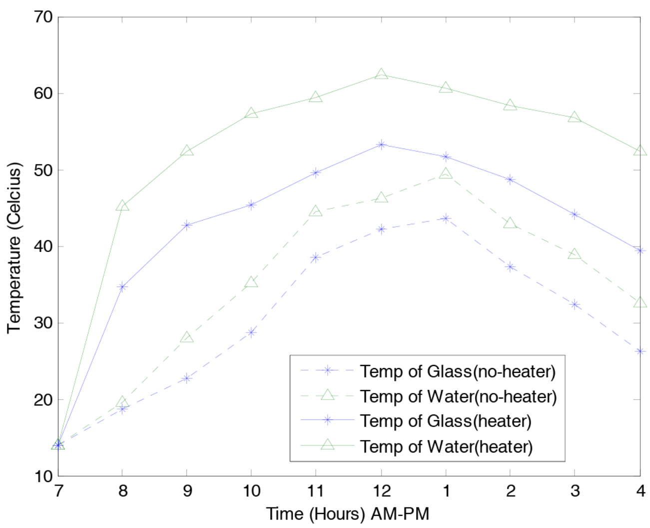

Fig. 3. Temperature measurement in the solar still.

to the water evaporation and the subsequent condensation on the surface of the glass surface. Moreover, the temperature difference between the basin water and the surface of the glass is also increased which results in high yield of desalinated water.

It can be observed in Fig. 4 that the rate of increase in the distilled water in the solar still much higher when water heater is used in the basin. The daily distilled water production in the solar still is found to be 5.405 L when water heater is used, while that is found to be 1.15 L when no water heater is used. Thus, the water heater enhances the productivity by 370%.

3.1.2 The effect of the external fan

A very little reduction in the glass and basin water temperatures was observed as the wind speed increases. It can be seen from Fig 7 that as the wind speed is increased to 7 m/s and 9 m/s by using the external fan, the glass temperature decreases from 37.4°C to 36.2°C and 33.3°C respectively. The outer surface of the glass cover is cooled as a result of forced convection and thus the temperature of the inner glass decreases. It can be noted that the glass temperature is already low during winter, and any further cooling of glass surface will make it cooler. This is due the fact that the rate of the heat transfer from the water in the basin to the glass surface increases. Therefore, the water temperature reduces as can be observed from Fig. 5 which will result in decreasing the evaporation rate of water. This will ultimately decrease the productivity of the still.

Fig. 7 shows that the distilled water production in the solar still for various wind speeds. As can be seen from the figure, the daily distilled water production from the solar still with wind speeds of 7 m/s and 9 m/s are 1.104 and 1.058 L, respectively. A decrease of about 4% is observed when the wind speed increases to 7 m/s. Similarly, a decrease in the daily distilled water production of 8% occurs when the speed increases to 9 m/s. The productivity decreases because the wind speed increases the top loss from the still [19]. This result agrees with the observations presented in [19,20,23]. Fig. 8 shows a comparison of the experimental measurements with

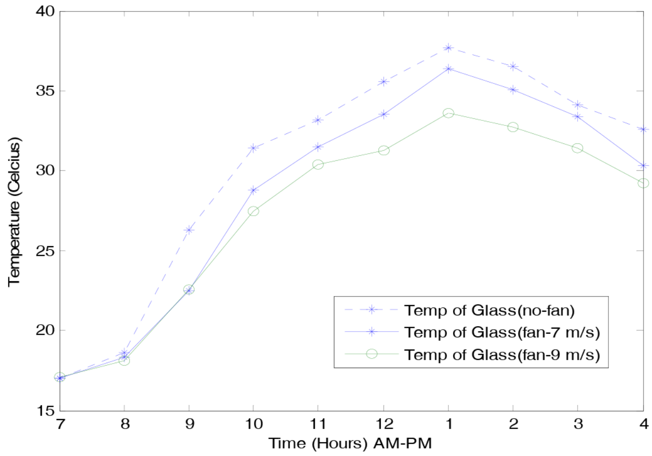

Fig. 5. The effect of fan speed on the glass temperatures in the solar still.

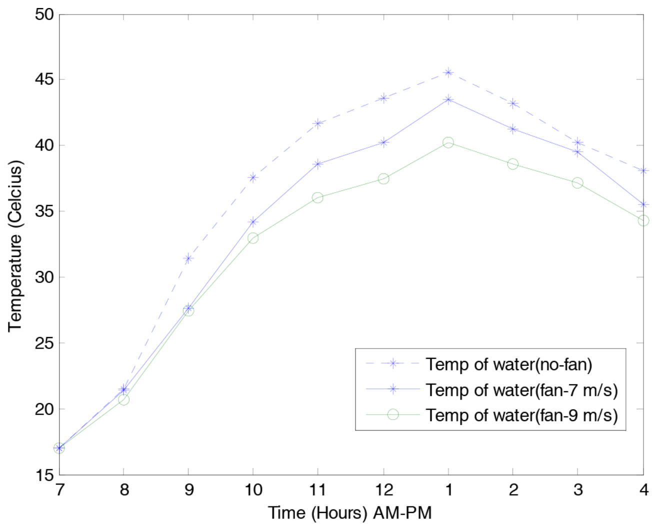

Fig. 6. The effect of fan speed on the water temperatures in the solar still.

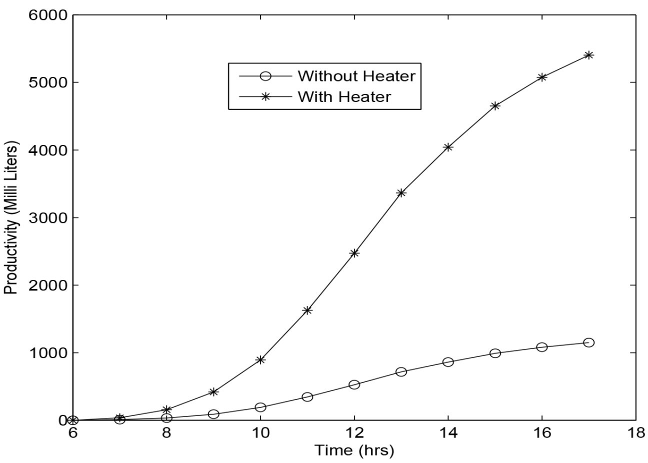

Fig. 4. Distilled water production in the solar still with time.

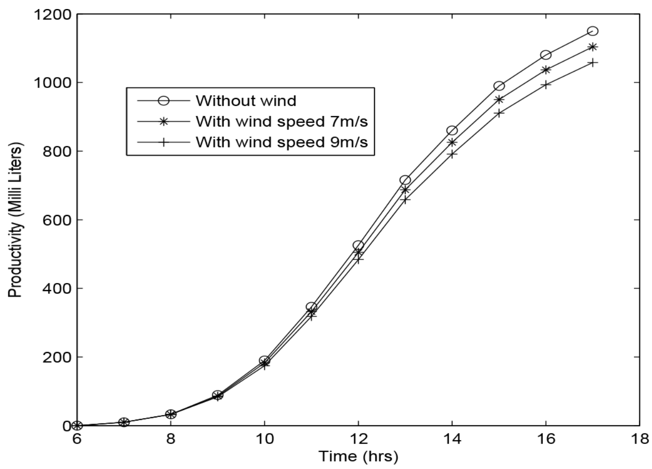

Fig. 7. The effect of the fan speed on the productivity of solar still.

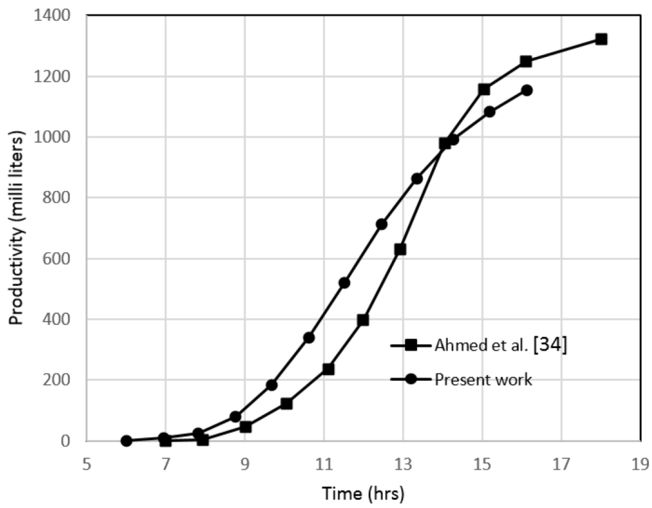

Fig. 8. Comparison of experimental measurements.

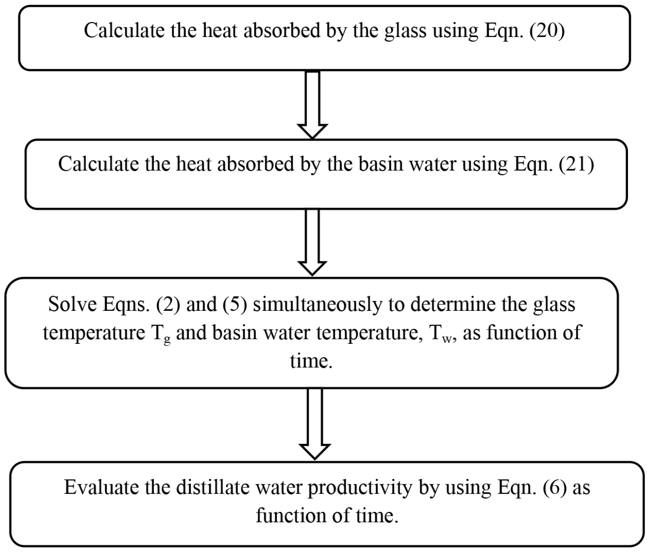

Fig. 9. Flow diagram for the numerical modeling.

a previous study [34] done in Bahrain that has similar environmental conditions as the present location where the current experimental measurements were done. The cumulative productivity in both measurements follow a similar trend with a small deviation due to difference in settings and size of experiments as well as environments. The results from the present model have been compared with the experimental measurements in the following section.

4. Numerical modelling

MATLAB software program is used to simulate the distillation process and to solve the differential equations by using 'ode23' function. The effect of water heater has been considered in the energy conservation equations and the thermal analysis of the solar still. The parameters used in the simulations are given in Table 1. The hour angle ω varies at 15°/h from morning to evening.

Figs. 10–12 shows the numerical and the experimental temperature variations for the basin water and glass surface for a typical winter day. It can be seed that the peak values for the water and the glass temperatures occur between 12 PM to 1 PM. Figs. 13, 14 and 15 show a com-

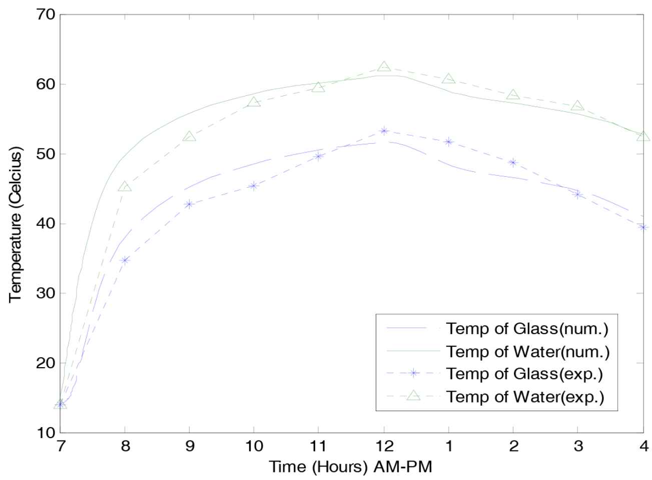

Fig. 10. Comparison of the numerical and the experimental temperature variations in the solar still with water heater.

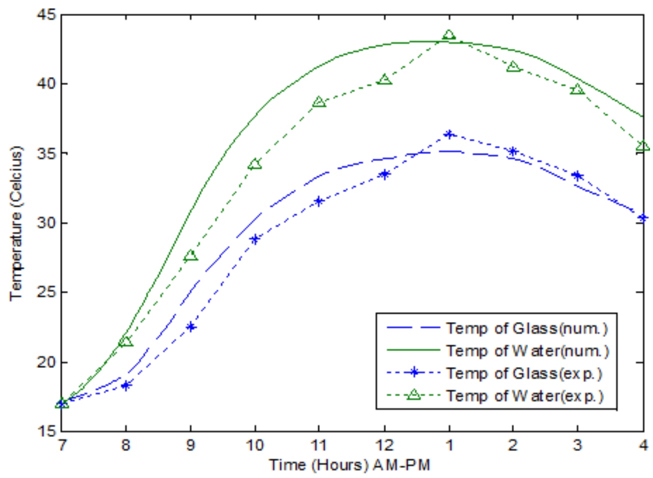

Fig. 11. Comparison of the numerical and the experimental temperature profiles in the solar still using the cooling fan (7 m/s).

Table 1
Parameters used in the numerical modelling and simulations.

A_g = 0.6 (m^2)	mw = 5 (kg)
A_b = 0.5(m^2)	mb = 12 (kg)
C_b = 486 (J/kgK)	Cg = 840 (J/kgK)
C_w = 4178 (J/kgK)	ρ_w = 1000 (kg/m^3)
τ_S = 0.835	τ_N = 0.835
α_{gS} = 0.127	α_{gN} = 0.127
α_w = 0.69	ρ_{gr} = 0.5
ε_g = 0.9	ε_{wg} = 0.9

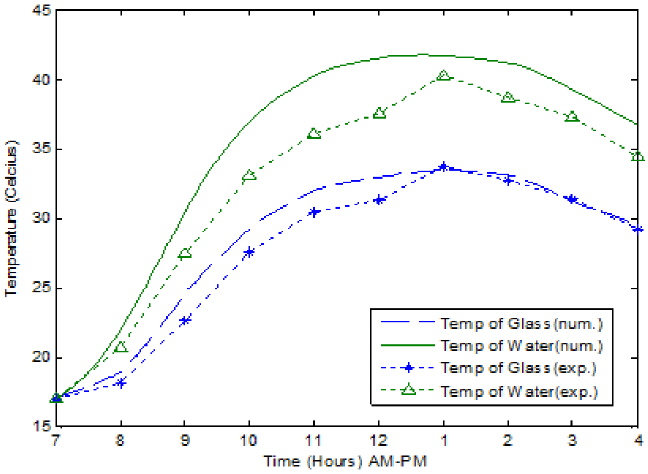

Fig. 12. Comparison of numerical and experimental temperature profiles in the solar still with cooling fan (9 m/s).

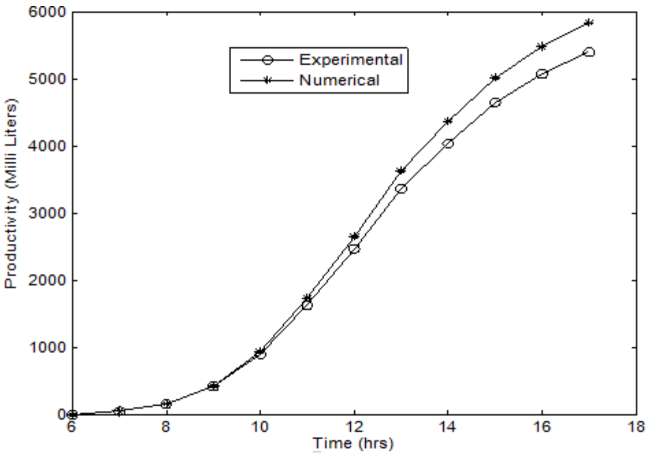

Fig. 13. Comparison of numerical and experimental distilled water production for the solar still with the water heater.

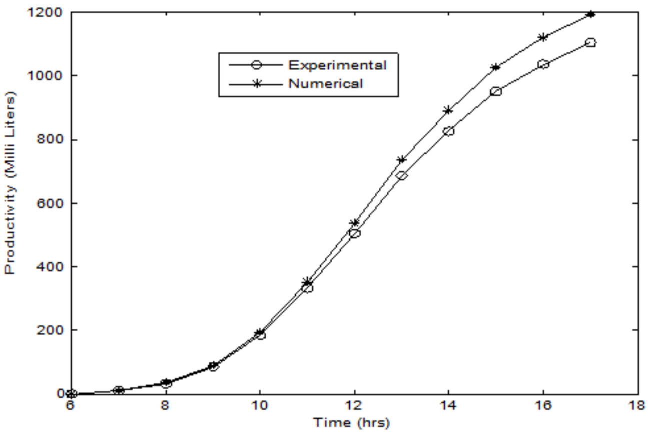

Fig. 14. Comparison of the numerical and the experimental results for the daily production by using external fan (7 m/s)

parison of daily distilled water productivities obtained for the water heater and two different cases of the external fan. The numerical results and the corresponding experimental results are found to be in a reasonable agreement. The differences between the numerical predictions and the experimental results could be due to the effect of the reflection of the solar radiation from the glass surface to the surrounding.

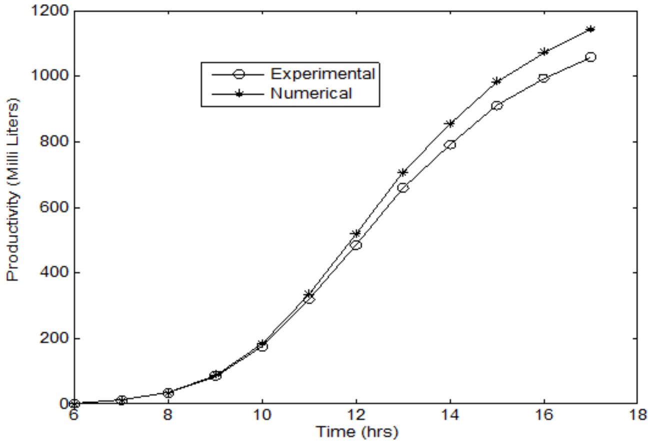

Fig. 15. Comparison of numerical and experimental daily production from the solar still with external fan (9 m/s).

5. Comparison of results for summer and winter days

Table 2 shows a summary of the experimental measurements for the summer and winter days. The experimental data for the typical summer day were obtained from the earlier study [33]. For both summer and winter days, the productivity is enhanced significantly (250% = 6.05 L/d in summer and 370% = 4.2 L/d in the winter) by using water heater. This is due to the promoting of the evaporation from the water in the basin and subsequent condensation on the inner surface of the glass cover. However, for the case of using external fan the productivity in summer and winter days shows different behavior. The use of external fan during the summer days enhances the productivity by small amount (up to 10.3% = 0.25 L/d for wind speed of 9 m/s), but when using the external fan in the winter, the productivity is observed to decrease by small amount (up to 8% = 0.092 L/d for wind speed of 9 m/s). This is because the enthalpy of evaporation of water increases as the temperature decreases, at the same time the specific heats of water vapor and air vary with temperature and the density of the air is also inversely proportional with temperature. That means, more heat transfer is needed to evaporate the water at lower temperatures in winter, which is not sufficient in the case when using the external fan in the winter. Although, the temperature difference between the glass and the water in the basin increases, the temperature of the water in the basin decreases, consequently larger amount of heat transfer is needed for the water to evaporate and to depart from the surface of water and thus a decrease of productivity by small amount in the winter for the case of using fan. This is in agreement with several studies [14–16], and in disagreement with some other studies [17–19]. This dispute among these studies may be due to the small amount of change in the productivity, which may be within the experimental uncertainty.

Table 2
Experimental data for summer and winter days

			Maximum basin water temperature (°C)	Maximum glass temperature (°C)	Desalinated water productivity (L/day)	Change of water productivity from the base case (L/day)/%
Summer	Base case (without heater and fan)		57.0	52.3	2.421	–
	With heater		78	71	8.471	6.05/250%
	With fan	7 m/s	60	55	2.541	0.12/4.9%
		9 m/s	59	53	2.671	0.25/10.3%
Winter	Base case (without heater and fan)		47.2	43.4	1.15	–
	With heater		63	53	5.405	4.255/370%
	With fan	7 m/s	43	36.2	1.104	−0.046/−4%
		9 m/s	40	33.3	1.058	−0.092/−8%

6. Conclusions

The effect of a water heater and the external cooling fan on the distilled water production from the single slope solar still is investigated using experimental and numerical techniques. The results obtained in typical summer and winter conditions are then compared. It is found that using water heater in the basin of the solar still increases the water temperature sharply and increases the distilled water productivity considerably as high as 370%. An external fan is used for cooling the outer glass surface of the solar still and found to decrease the distilled water production in winter by 4% and 8% for the wind speeds 7 m/s and 9 m/s, respectively. The comparison of the productivity for the typical days of summer and winter reveals that using external fan increases the productivity in the summer but decreases it in the winter by small amount. The numerical model results are found to agree with the experimental results within an error of 5–8%.

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Symbols

A – Area (m^2)
C – Specific heat capacity (J/kg K)
h – Heat transfer coefficient (W/m^2 K)
hfg – Latent heat of water (J/kg)
I – Total solar radiation (W/m^2)
M – Molecular weight
m – Mass (kg)
$\dot{m}$ – Mass flow rate (kg/s)
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 – Temperature (°C)
t – Time (s)
V – Wind speed (m/s)

Greek

α – Absorptivity
σ – Stefan Boltzmann constant (5.67 × 10^{-8} W/m^{2}K^4)
τ – Transmissivity
ε – Emissivity
δ – Declination angle (degree)
ω – Hour angle (degree)
Φ – Latitude (degree)
β – Glass tilt angle (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	–	South
s	–	Solar
T	–	Total
w	–	Water

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