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Productivity enhancement of single slope solar still using immersion-type water heater and external cooling fan during summer

Ahmed Z. Al-Garni

Aerospace Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), PO Box 842, Dhahran 31261, Saudi Arabia
Tel. +966 3 860 4656; Fax: +966 3 860 4626; email: algarni@kfupm.edu.sa

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ABSTRACT

In this paper, an attempt is made to study the productivity enhancement of a single-slope solar still using an immersion-type water heater and external cooling fan. Experiments were carried out at KFUPM campus in Dhahran (26°16′N Latitude and 50°10′E Longitude) during the summer. A solar still with glass tilt angle of 35° and water depth of 1 cm was chosen in our study. The experimental results showed that the productivity increased by 250% when a water heater of 500 W capacity was used in the base tank. An external cooling fan was used to cool the outer glass surface of the solar still and an increase in productivity by 5.2 and 10.3% was observed with wind speeds of 7 and 9 m/s, respectively. The energy and mass balance equations were used to numerically study the effect of water heater and external cooling fan and were validated with the experimental results. It is found that there is a good match between the experimental and numerical results. The present study is partial implementation of the two patents in the field of solar distillation.

Keywords: Single-slope solar still; Productivity enhancement; Water heater; External cooling fan

1. Introduction

Solar distillation is considered as a feasible option for water distillation. Due to the low productivity of solar still, studies are always focused on ways to improve the productivity of a solar still. Hongfei et al. [1] used two immersion type water heaters having resistance 75 ohms to conduct indoor simulations in order to validate the correlations developed. Murugavel et al. [2] performed indoor experiments and used wick materials like light cotton cloth, light jute cloth, sponge sheet, porous materials like washed natural rock and quartzite rock. A 2-kW electric heater was used by him to simulate the actual solar radiation conditions. Adhikari et al. [3] presented a numerical model for studying the steady-state performance of a multi stage stacked tray solar still using immersion-type water heater as the heating source. After establishing a group of improved heat and mass transfer relations in multi stage stacked tray still.

Various methods were used by researchers to enhance the productivity of solar still. Abu-Hijleh et al. [4] carried out an experimental study of single-slope solar still which was focused on placing sponge cubes in the basin water to enhance the productivity. He found that there was a significant increase in production in the range of 18–273% when compared with a reference still without sponge cubes. El-Sebaii [5] studied the effect of wind speed on the productivity of solar still. He concluded that the productivity increases with increase in wind speed up to a typical velocity beyond which the increase in productivity becomes insignificant. This typical velocity was 10 and 8 m/s for summer and winter, respectively. Farid et al. [6] made a study on the parameters affecting the productivity of a single basin solar still. Their results showed that the productivity increases with increase in ambient temperature and decrease in wind velocity.

Garg et al. [7], Cooper [8], and Soliman [9] have found that the productivity of solar still increases with increase in wind speed. However, Yeh et al. [10,11] and Hollands [12] concluded that the productivity decreases with increase in wind speed. Moreover, Morse et al. [13] stated that the wind speed has no significant effect on the productivity. Due to the above conflicts, the effect of wind speed on the productivity of solar still is not clearly known as yet. Abdenacer et al. [14] carried out a numerical study to examine the impact of temperature difference between the basin water and the glass surface. He found that efficiency increases with increase in temperature difference. Ali [15] experimentally studied the effect of air motion inside the solar still. A fan was placed inside the solar still for this purpose, and a significant increase in productivity was observed. Zurigat and Abu-Arabi [16] studied the effect of flowing water in-order to cool the glass surface of a solar still and increase the productivity. His numerical results show that the productivity increased by 20% when the glass surface was cooled using flowing water. The effect of wind speed was also studied and he concluded that the productivity increased by 50% when the wind speed was increased from 0 to 10 m/s.

After reviewing the above literature, the present study deals with examining the effect of wind speed and cooling the outer glass surface of solar still by using an external fan. Several researchers [1–3] have made the use of water heater to simulate the actual solar radiation conditions. In the present study, the effect of using water heater along with the available external solar radiation is examined, while keeping an eye on the future where PV cells can be used to power the water heater and the external cooling fan. The present study is partial implementation of two patents [17] and [18] in this field of solar distillation.

2. Mathematical modeling

The schematic diagram for the single-slope solar still with various heat transfer mechanisms is shown in Fig. 1.

The following assumptions are made while solving the energy balance equations.

(1) The temperature of glass is uniform over the glass cover.
(2) The temperature of water is uniform over the water and the basin material.
(3) Bottom and sides of the basin are well insulated; thus $\dot{Q}_1$, $\dot{Q}_{\mathrm{cond}}$ and $\dot{Q}_{\mathrm{sides}}$ are negligible.
(4) Reflection of heat from water surface and the energy storage material used in the basin is negligible, thus $\dot{Q}_{\mathrm{ref}}(w, b)$ is negligible. Heat reflected from glass to air is also negligible.

It is to be noted that the water heater and the external cooling fan are not used in conjunction with each other. Therefore, the ambient wind speed is taken into account while performing numerical simulations for the still with water heater. When the effect of using external cooling fan is examined, the term $\dot{Q}_{\mathrm{heater}}$ is taken as zero in the energy balance Eq. (4).

The equation for conservation of mass is written as [19],

$$\dot{m}_{\mathrm{d}} = \dot{m}_{\mathrm{fw}} - \dot{m}_{\mathrm{bd}} \tag{1}$$

The energy balance equation for the glass cover is given by Dunkle [20],

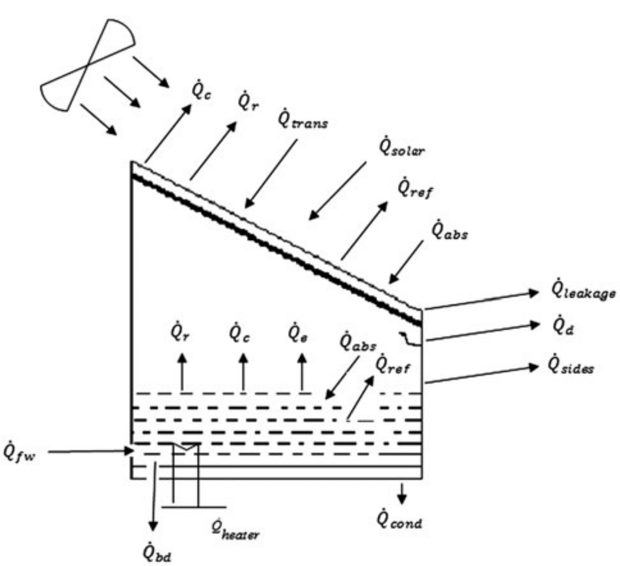

Fig. 1. Various heat transfer modes in a solar still with immersed water heater and external fan.

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

$$\left(\frac{dE_g}{dt}\right) = \dot{m}_g C_g (dT_g/dt) \quad (3)$$

The energy balance equation for the basin and the water contained in it is given by Dunkle [20],

$$\left(\frac{dE_{w,b}}{dt}\right) = \dot{Q}_{heater} + \dot{Q}_{abs,w} + \dot{Q}_{fw} + \dot{Q}_{e(w-g)} - \dot{Q}_{c(w-g)} - \dot{Q}_{r(w-g)} - \dot{Q}_{ref(w-b)} - \dot{Q}_{d} - \dot{Q}_{bd} - \dot{Q}_{1} - \dot{Q}_{cond} - \dot{Q}_{sides} - \dot{Q}_{abs,b} \quad (4)$$

$$(dE_{w,b}/dt) = (m_w C_w + m_b C_b)(dT_w/dt) \quad (5)$$

Eqs. (2) and (4) are solved simultaneously for T_w and T_g.

The distilled water production rate is calculated by [19],

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

The details of the various terms used in the above equations are given below:

The solar radiation on a tilted surface is a combination of three components and is calculated using Liu and Jordan relation given by [21],

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

for northern hemisphere, the geometric factor R_{beam} is calculated using [21],

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

The declination angle is found using the equation of Cooper given by [21],

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

heat is transferred from water to the glass surface by convection of air trapped inside the still, evaporation of water, and radiation of heat from the water surface. This heat transfer is estimated by [19],

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

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

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

The evaporative and convective heat transfer coefficients for water to glass surface are calculated by Malik [19] and Dunkle [20], respectively,

$$h_{c(w-g)} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)T_w}{268,900 - P_w}\right]^{1/3} \quad (13)$$

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

The partial vapor pressure at a given basin water temperature and glass surface is found by the relation [22],

$$P_w = 7,235 - 431.45 T_w + 10.76 T_w^2 \quad (15)$$

$$P_g = 7,235 - 431.45 T_g + 10.76 T_g^2 \quad (16)$$

The specific heat of the air trapped inside the solar still is written in terms of the average temperature of basin water and glass and is known by Zurigat and Abu-Arabi [16],

$$C_{pa} = 999.2 + (0.14339 T_{av} + (0.0001101 T_{av}^2) - (0.67581 \times 10^{-7} T_{av}^3)) \quad (17)$$

$$T_{av} = (T_w + T_g)/2 \quad (18)$$

The latent heat of evaporation of water is found using [23],

$$h_{fg} = (2503.3 - 2.398 T_w) \times 1,000 \quad (19)$$

Some amount of heat is absorbed by the glass due to the incident solar radiation falling on the glass surface. This can be calculated by [24],

$$\dot{Q}_{abs,g} = \alpha_g (1 - Re_g) \quad (20)$$

The solar radiation incident on the still is absorbed in huge amounts by the blackened base and water. The heat absorbed by water is estimated using [25],

$$\dot{Q}_{\text{abs,w}} = \alpha_{\text{w}}\dot{Q}_{\tau} = \alpha_{\text{w}}\tau_{\text{S}}A_{\text{g,S}}I_{\text{S}} \quad (21)$$

The heat absorbed by the basin is estimated by [24]

$$\dot{Q}_{abs,b} = \alpha_{\text{b}}(1-\alpha_{\text{w}})\sum\mu_{\text{j}}\exp(-\eta_{\text{j}}L)(1-\text{Re}_{\text{w}})(1-\alpha_{\text{g}}) \times (1-\text{Re}_{\text{g}}) \quad (22)$$

where $\sum\mu_{\text{j}}\exp(-\eta_{\text{j}}L)$ is the attenuation factor for water depth L.

Heat is absorbed by the glass surface due to evaporation, convection, and radiation from the water surface. Heat is lost from the glass cover to the atmosphere by convection and radiation and is found by [19],

$$\dot{Q}_{\text{c}(g-a)} = h_{\text{c}(g-a)\,A_{\text{g}}(T_{\text{g}}-T_{\text{atm}})} \quad (23)$$

$$\dot{Q}_{r(g-a)} = \sigma\varepsilon_{\text{g}}A_{\text{g}}(T_{\text{g}}^4 - T_{\text{atm}}^4) \quad (24)$$

The convective heat transfer coefficient from glass cover to atmosphere (due atmospheric wind velocity) is given by [26],

$$h_{\text{c}(g-a)} = 5.7 + 3.8V \quad (25)$$

The convective heat transfer coefficient when fan is used is given by [27],

For wind velocity, $V \leqslant 5\,\text{m/s}$

$$h_{\text{c}(g-a)} = 2.8 + 3V \quad (26)$$

For wind velocity, $V > 5\,\text{m/s}$

$$h_{\text{c}(g-a)} = 6.15V^{0.8} \quad (27)$$

The heat added to the system by the supply of feed water is written as [19],

$$\dot{Q}_{\text{fw}} = \dot{m}_{\text{fw}}C_{\text{w}}(T_{\text{atm}} - T_{\text{w}}) \quad (28)$$

The heat loss from the system due to the distillate leaving the still is estimated by [19],

$$\dot{Q}_{\text{d}} = \dot{m}_{\text{d}}C_{\text{w}}(T_{\text{w}} - T_{\text{atm}}) \quad (29)$$

The heat due to salt water blowdown in the base tank is given as [19],

$$\dot{Q}_{\text{bd}} = \dot{m}_{\text{bd}}C_{\text{w}}(T_{\text{w}} - T_{\text{atm}}) \quad (30)$$

3. Experimental work

Four single-slope solar still with glass cover angles of 25°, 30°, 35°, and 40° are designed and constructed. All the single-slope solar stills were tested and on comparison, the still with glass cover angle 35° gave the best output (productivity). The still with glass cover slope angle was selected for conducting the experiments. Minimum water depth of 1 cm is maintained in the base tank of the solar still. The base tank was made of the dimension 0.5 m × 1 m × 0.06 m. Galvanized Iron steel having 3 mm thickness was used to manufacture the base tank of the still since it has good formability. In order to increase the absorptivity of the water and the base tank, black paint was applied on the inner and outer surfaces.

A hole is provided in the base tank which allows the flow of distilled water into the measurable water bottles kept beneath the still. Aluminum strips were fixed on the edges of the still to make the glass cover rigid. Fig. 2 shows the fabricated solar still with all the parts.

An immersion type water heater having 500 W capacity is used in the study. The water heater which is electrically powered was placed in the base tank of the still and then the still was completely sealed again. The heater was completely immersed in the basin water at all times to improve the evaporation rate of water. An external cooling fan with variable speeds was used to cool the top glass cover of the solar still. Two speeds of 7 and 9 m/s were examined in our study. The external fan that is electrically powered was placed in such a way that the breeze flows along the surface of the top glass cover.

Outdoor experiments for summer season were done in KFUPM campus, Dhahran (26°16´N, 50°10´E),

Fig. 2. Single slope solar still with 35° glass tilt angle.

a city in the Eastern Province of Saudi Arabia. Since the experimental site is in Northern hemisphere, the still was placed in South-North orientation. The experiments were performed from sunrise to sunset and hourly recordings for glass temperature, basin water temperature, and the distillate water was done. The ambient temperature, wind speed and wind direction were also noted.

4. Experimental results

4.1. Effect of water heater

Fig. 3 shows a comparison of temperature profiles for summer season when water heater is immersed in the base tank of the solar still. It can be seen that a maximum water temperature of 78.0˚C is obtained while the peak value of glass temperature is found to be 71˚C. The maximum values of water and glass temperatures for the still without the heater were found to be 57 and 52.3˚C, respectively. The water heater in the base tank of the solar still increased the water temperature quite significantly. This rise in water and glass temperature was observed after an hour of experiment.

As seen in Fig. 4, there is a significant increase in the total productivity of the solar still when water heater is used in the base tank. The productivity of the solar still with immersed water heater is found to be 8.47 l in comparison to 2.42 l obtained for the still without the heater. An increase in productivity of 250% was observed.

4.2. Effect of external cooling fan

As seen in Fig. 5, when external fan is used to increase the wind speed to 7 m/s and 9 m/s, there is a

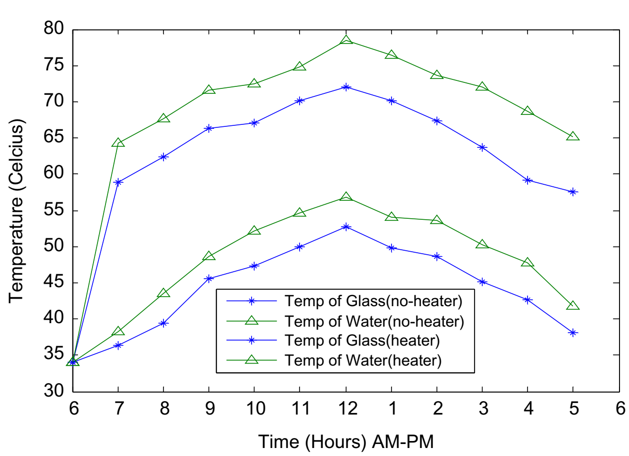

Fig. 3. Temperature profiles for solar still with and without water heater.

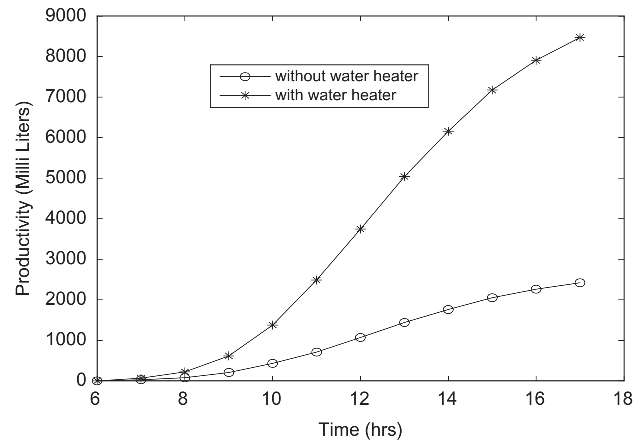

Fig. 4. Productivity of solar still with and without water heater.

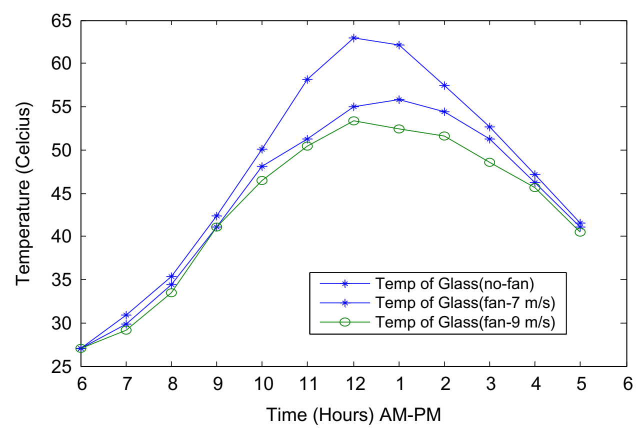

Fig. 5. Glass temperatures of solar still for different fan speeds.

reduction in the glass temperature from 62.6 to 55˚C and 53.0˚C, respectively. With the increase in the wind speed, the outer glass is cooled by forced convection thus reducing the inner glass temperature. As the glass temperature decreases, the rate of heat transfer from basin water to the glass surface increases. Subsequently, a reduction in water temperature was observed as can be seen in Fig. 6.

The productivity of solar still increased with the wind speed and is shown in Fig. 7. It can be observed that the daily productivities of solar still with wind speed 7 and 9 m/s are 2.54 l and 2.67 l, respectively. There is an increase by about 5.2% when the wind speed is increased to 7 m/s. An increase in productivity by 10.3% was observed when the speed is increased to 9 m/s. This increase in output is due to better heat transfer from glass cover to the atmosphere [5].

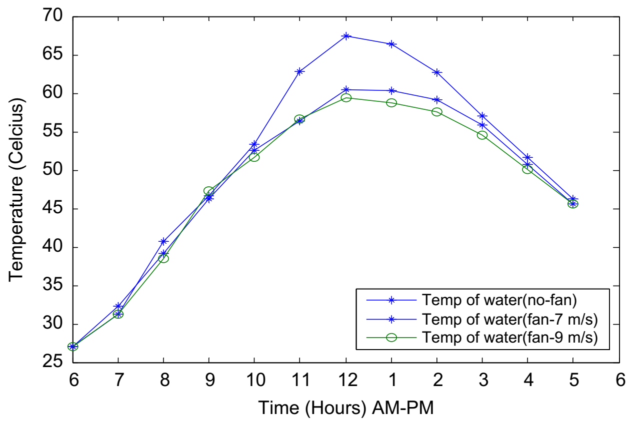

Fig. 6. Water temperatures of solar still for different fan speeds.

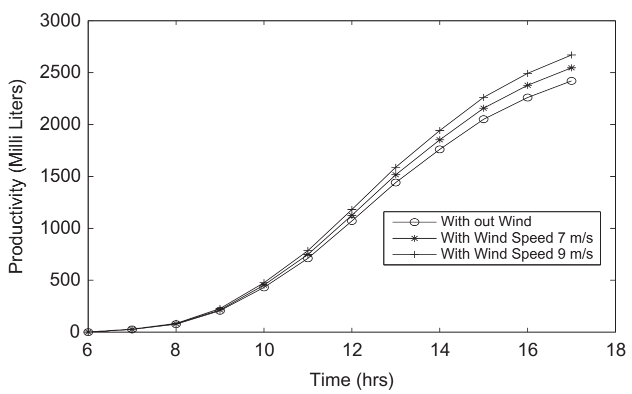

Fig. 7. Productivity of solar still for different fan speeds.

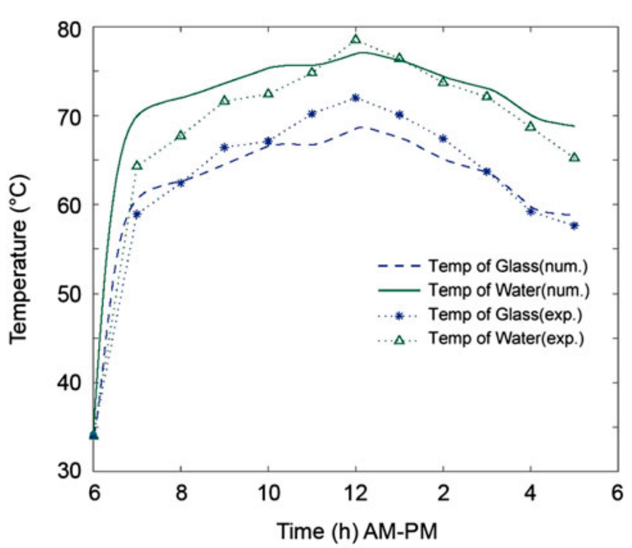

Fig. 8. Comparison of experimental and numerical temperature profiles for solar still with immersed water heater.

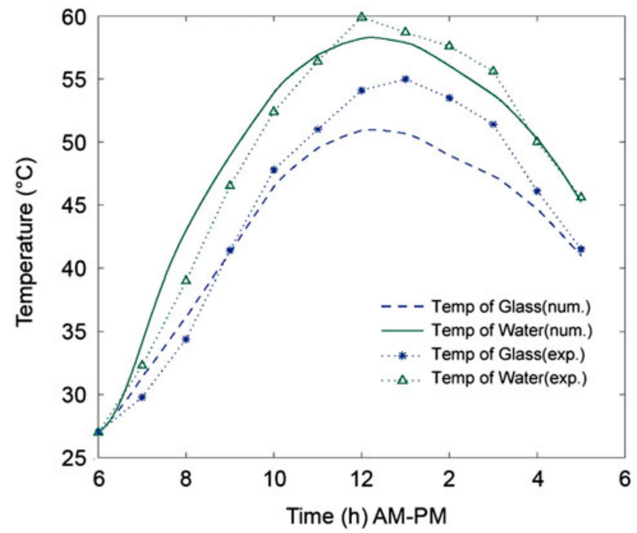

Fig. 9. Comparison of experimental and numerical temperature profiles for solar still with external cooling fan (7 m/s).

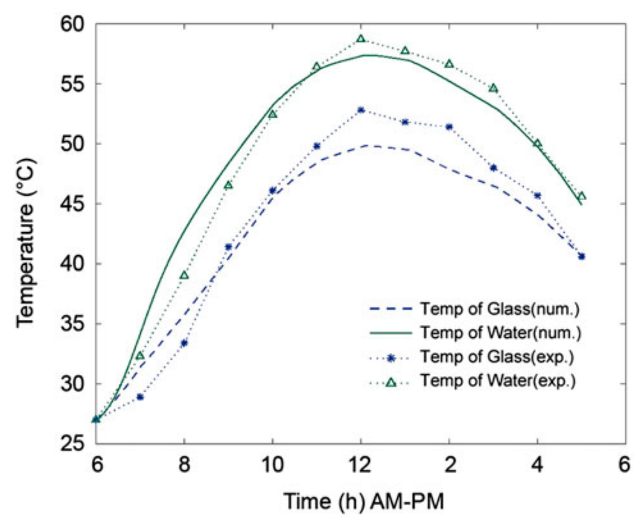

Fig. 10. Comparison of experimental and numerical temperature profiles for solar still with external cooling fan (9 m/s).

It can be noted that with increase in wind speed, there is an increase in the temperature difference between water and glass surface due of which the productivity increases. Although the basin water and glass temperature is found to decrease with increase in wind speed, the increase in water-glass temperature difference is more than compensated for the fall in both the temperatures. This increase in temperature difference was found to be greater during the afternoon hours. This result is in agreement with the

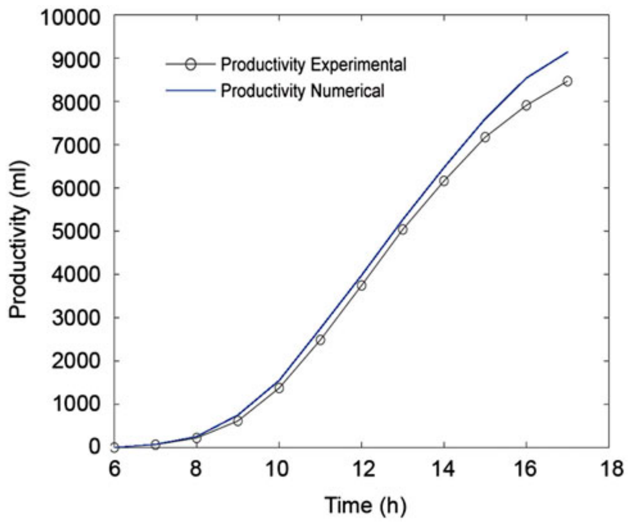

Fig. 11. Comparison of experimental and numerical productivities for solar still with immersed water heater.

results obtained by [7–9] who found the productivity to increase with increase in wind speed.

5. Numerical results

5.1. Design parameters

MATLAB software was used for numerical calculation. A comparison between the experimental and numerical temperature profiles for basin water temperature and glass temperature is shown in Figs. 8–10 for summer season. It can be observed that a peak value for water and glass temperatures is obtained between 12 and 1 PM. Figs. 11–13 show the comparison of cumulative productivity for different modes of operation of the still. Fig. 14 shows the domination of $Q_{c(g-a)}$ over $Q_{r(g-a)}$ at fans speeds 7 and 9 m/s. It is found that the simulation results are in good agreement with the experimental results.

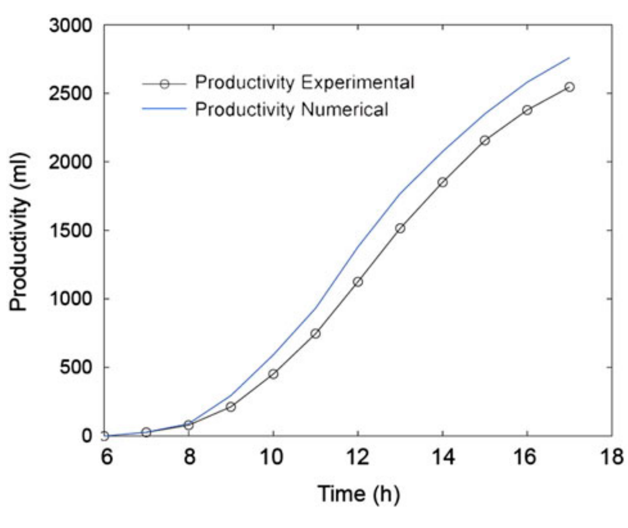

Fig. 12. Comparison of experimental and numerical daily productivities for solar still with external cooling fan (7 m/s).

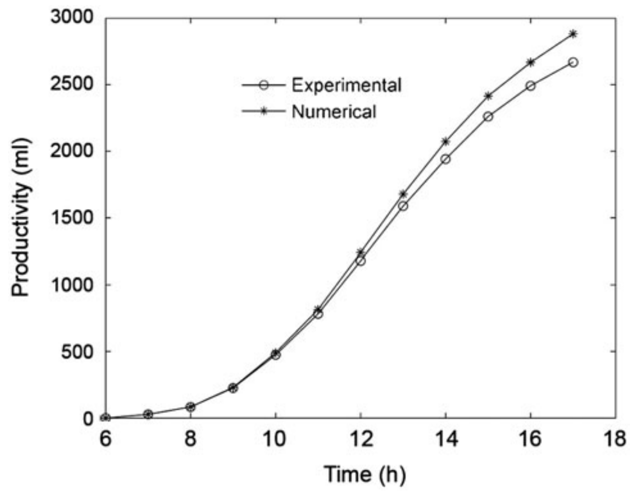

Fig. 13. Comparison of experimental and numerical daily productivities for solar still with external cooling fan (9 m/s).

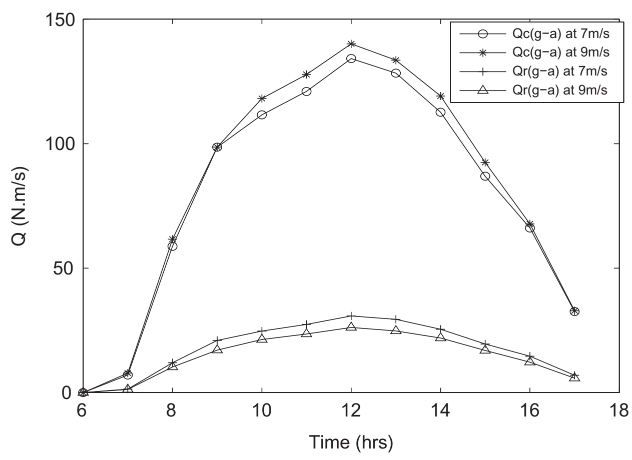

Fig. 14. Comparison of $Q_{c(g-a)}$ and $Q_{r(g-a)}$ at different fan speeds.

The differences between the experimental and numerical results obtained for the productivity, glass and water temperatures could be because of neglecting the reflected radiation from glass to atmosphere. The theoretical values of constants used in our calculations are listed below.

$A_g = 0.6$ (m^2) $\dot{m}_w = 5$ (kg)
$A_b = 0.5$ (m^2) $\dot{m}_b = 12$ (kg)

$C_b = 486$ (J/kgK) $C_g = 840$ (J/kgK)
$C_w = 4{,}178$ (J/kgK) $\rho_w = 1000\left(\frac{kg}{m^3}\right)$
$\tau_S = 0.835$ $\tau_N = 0.835$
$\alpha_g = 0.05$ $Re_g = 0.05$
$\alpha_w = 0.69$ $\rho_{gr} = 0.5$
$\varepsilon_g = 0.9$ $\varepsilon_{wg} = 0.9$

6. Concluding remarks

The following conclusions can be made based on the results presented in this paper.

The use of water heater in the base tank of a solar still boosts the water temperature rapidly and enhances the productivity significantly by around 250%. Wind speed has an increasing effect on the productivity of solar still. External cooling fan used to cool the glass surface of the solar still enhances the productivity by 5.2 and 10.3% for wind speeds 7 and 9 m/s, respectively. Based on the assumptions made in this study, the numerical model is found to predict the experimental results with an error of 6–9%.

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Symbols

A — area (m^2)
C — specific heat capacity (J/kg K)
h — heat transfer coefficient (W/m^2K)
h_{fg} — latent heat of water (J/kg)
I — total solar radiation (W/m^2)
L — water depth (m)
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
Re — reflectivity
T — temperature (°C)
t — time (s)
V — wind speed (m/s)

Greek

α — absorptivity
σ — Stefan Boltzmann constant (5.67×10^{-8} W/m^2K^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)
μ_j — fraction of solar radiation having extinction coefficient η_j

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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