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Summer and winter comparison of productivity improvement in a single slope solar still by using external mirrors

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ABSTRACT

Production of distilled water from a single slope solar still, which is equipped with external reflectors of four sides, has been investigated for typical summer and winter conditions using experimental and numerical techniques. Mass and heat transfer inside the solar still have been considered in modelling the distillation process. Numerical results have been validated with the experimental measurements. It was found that using external reflectors can increase the distilled water production significantly. The enhancement of the production by using the external reflectors is measured to be 40% in the summer and 85% in the winter as compared with the solar still without the reflectors.

Keywords: Single slope solar still; Solar distillation; Productivity improvement; External reflectors

1. Introduction

Only 1% of the total water available on the Earth is suitable for drinking. On the other hand, the world population is increasing exponentially. Thus, there is a need for developing methods for utilizing waste water to produce sweet water for the life on Earth. Distillation is a method that is used to produce clean water and is an energy intensive process. Using renewable energy sources for the desalination is preferable and causes no environmental pollution.

Performance of solar still has been studied extensively in the literature and a number of design modifications has been studied [1,2]. Abdallah et al. [3] studied the single solar still equipped with internal mirrors. They showed that the mirrors provided an increase in the efficiency by 180%. Tanaka and Nakatake [4,5]; and Tanaka [6] carried out theoretical studies for the basin-type solar distillation unit using internal and external reflecting mirrors and achieved 48% improvement in the productivity.

Tamimi [7] and El-Sebaii [8] considered using inner and outer mirrors, respectively. The main disadvantage in using internal mirrors was the fast deterioration of the inner mirrors inside the solar still. Therefore, Khan [9] studied the solar distillation unit with a mirror at the back placed vertically and found the water yield to be 4.68 L/m^2 per day.

Omara et al. [10,11] studied the stepped solar distillation unit performance enhancement through the use of both the internal and the external reflectors. They found that the productivity of their solar still is improved as high as 125% as compared with the conventional one. They also carried out an economic feasibility analysis. In an earlier experimental study, Al-Garni [12] considered a double slope solar still and studied the effect of the external reflectors on the performance. He observed an 82% improvement in the winter when using external reflectors. El-Samadony et al. [13] investigated experimentally the effect of the reflectors on the productivity of a solar still. They placed the reflectors both externally and internally. They also added an external

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condenser in their experimental setup. They found a 165% increase in the productivity when using the reflectors and the condenser. Omara et al. [14] studied corrugated absorber solar still experimentally. They used a double layer wick material and reflectors in their experimental setup. They studied the performance of the solar still considering various depths of saline water. They obtained 145.5% higher productivity when using the wick layer and the reflectors as compared with conventional solar stills. Omara et al. [15] presented a detail review on the solar stills with reflectors. More information on the performance analysis of solar still can be found in references [16–18].

Although there are a number of studies done on the performance of the solar still and can be found in the literature, utilizing external mirrors has not received much attention. Therefore, in the current work, an experimental study is performed using a single slope solar still and a set of four external mirrors to determine the effect of the mirrors on the performance. This arrangement is found to be low cost and easy to implement. Significant performance improvement is found in employing external mirrors and the yield of fresh drinking water increased. In addition to the experimental measurements, a mathematical model [19,20] has also been developed and validated with the experimental measurements.

2. Mathematical modelling

Fig. 1 shows a schematic diagram with various heat transfer mechanisms association with the solar still while the experimental setup is shown in Fig. 2.

The conservation of mass is [21]:

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

where m_d is the distillate water flow rate, m_{fw} is the flow rate of feedwater and m_{bd} is the flow rate of blow down water.

On the other hand [22],

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

where the terms on the right-side of the equation are the rate of heat absorbed by the glass, the rate of heat transfer associated with the evaporation of water, the rate of

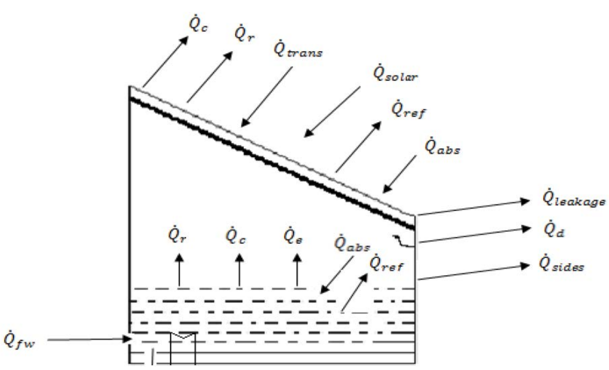

Fig. 1. Modes of heat transfer in solar still.

Fig. 2. Experimental setup.

convective heat transfer from the surface of the water, the rate of radiative heat transfer, the rate of convective heat transfer from outer surface of the glass, the rate of heat transfer between the glass outer surface and the ambient air, and the rate of reflective heat transfer from the glass outer surface and the ambient, respectively. The rate of change of energy of the glass given on the left-side of Eq. (2) can be written explicitly as function of the glass temperature as

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

Similarly, for the water contained in the basin [22],

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

where the rate of change of energy of the water and the basin is

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

The terms on the right-side of Eq. (4) are the rate of heat absorbed by the water, the rate of energy flow by the feedwater, the rate of evaporative heat transfer from the surface of the water, the rate of convective heat transfer, the rate of radiative heat transfer, the rate of the reflective heat transfer, the rate of heat transfer accompanied by the distilled water, the rate of energy flow accompanied by the blow down water, the heat transfer rate through leakage as a result of poor insulation, heat transfer rate through conduction, and the heat transfer loss rate from the sides, respectively.

Eqs. (2) and (4) are solved to evaluate the water temperature T_w and that of the glass T_g.

Accordingly [21],

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

where h_{fg} is the enthalpy of evaporation of water.

The various heat transfer terms are [20],

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

$$\dot{Q}_{e(w-g)} = h_{e(w-g)} A_b \left(P_w - P_g\right) \tag{8}$$

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

where h_c is the convective coefficient of heat transfer, h_e is the mass transport coefficient, σ is the Stefan–Boltzmann coefficient, and ε is emissivity, A_b is the surface area of basin, P_w is the partial pressure on the surface of water and P_g is partial pressure of water at surface of glass.

In Eqs. (7)–(9), the heat transfer coefficients are given as [22] follows:

$$h_{c(w-g)} = 0.884[\Delta T']^{1/3} \tag{10}$$

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

where the term $\Delta T'$ is given as follows:

$$\Delta T' = \left(T_w - T_g\right) + \frac{\left(P_w - P_g\right) T_w}{268900 - P_w} \tag{12}$$

in which

$$P_w = 7235 - 431.45 T_w + 10.76 T_w^2 \tag{13}$$

$$P_g = 7235 - 431.45 T_g + 10.76 T_g^2 \tag{14}$$

The air specific heat is given by Toure and Meukam [23],

$$C_{pa} = 999.2 + \left(0.14339 T_{av}\right) + \left(0.0001101 T_{av}^2\right) - \left(0.67581 \times 10^{-7} T_{av}^3\right) \tag{15}$$

where $T_{av} = (T_w + T_g)/2$.

On the other hand [24],

$$h_{fg} = \left(2503.3 - 2.398 T_w\right) \times 1000 \tag{16}$$

The heat absorption in the glass cover is [25] given as follows:

$$\dot{Q}_{abs,g} = \alpha_g \dot{Q}_S = \alpha_{g,S} A_{g,S} I_S \tag{17}$$

where α is the absorption coefficient of the glass, A_g is the surface area of the glass and I_S is the solar insolation.

The absorption of heat in the water is [26] given as follows:

$$\dot{Q}_{abs,w} = \alpha_w \dot{Q}_\tau = \alpha_w \left(\tau_S A_{g,S} I_S\right) \tag{18}$$

where τ is the radiation transmission coefficient of the glass.

On the other hand,

$$\dot{Q}_{c(g-a)} = h_{c(g-a)} A_g \left(T_g - T_{atm}\right) \tag{19}$$

$$\dot{Q}_{r(g-a)} = \sigma \varepsilon_g A_g \left(T_g^4 - T_{atm}^4\right) \tag{20}$$

where T_{atm} is the atmospheric (ambient) temperature and [27],

$$h_{c(g-a)} = 5.7 + 3.8V \tag{21}$$

in which V is the wind speed.

Various heat transfer terms are given by Malik et al. [21],

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

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

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

$$\dot{Q}_{cond} = \frac{S_g K_g \left(T_w - T_{atm}\right)}{L_{gw}} \tag{25}$$

where K_g is the thermal conductivity, and L_{gw} is the least width of the solar still.

The solar radiation on a tilted surface is [28],

$$I_{Tilted} = I_{beam} R_{beam} + I_{diffuse} \left(\frac{1 + \cos\beta}{2}\right) + I \rho_{gr} \left(\frac{1 - \cos\beta}{2}\right) \tag{26}$$

where R_{beam} is the ratio of beam radiation on the inclined surface, beta is glass inclination angle, and ρ_{gr} is reflectivity of the ground.

In equation (26) [28],

$$R_{beam} = \frac{\cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \tag{27}$$

where ϕ is the latitude (degree), δ is the declination angle (degree) and ω is the hour angle (degree).

The declination angle is [28],

$$\delta = (23.45)\sin\left[\frac{360(284 + n)}{365}\right] \tag{28}$$

The total incident solar radiation including the reflections from the external mirrors is given as follows:

$$I_{total} = I_S + I_{rmi,N} + I_{rmi,N} + I_{rmi,E} + I_{rmi,W} \tag{29}$$

where

$$I_{rmi,S} = \frac{I_{mi,S} \rho_{mi} F_{mg} A_{mi}}{\left(\frac{A_g}{2}\right)} \tag{30}$$

$$I_{\text{rmi},N} = \frac{I_{\text{mi},N}\rho_{\text{mi}}F_{\text{mg}}A_{\text{mi}}}{\left(\frac{A_g}{2}\right)} \quad (31)$$

$$I_{\text{rmi},E} = \frac{I_{\text{mi},E}\rho_{\text{mi}}F_{\text{mg}}A_{\text{mi}}}{\left(\frac{A_g}{2}\right)} \quad (32)$$

$$I_{\text{rmi},W} = \frac{I_{\text{mi},W}\rho_{\text{mi}}F_{\text{mg}}A_{\text{mi}}}{\left(\frac{A_g}{2}\right)} \quad (33)$$

The view factor is [29],

$$F_{\text{mg}} = \frac{\left(\text{cc} + \text{rr} - \text{ss}\right)}{2\text{rr}} \quad (34)$$

$$\left(\text{ss}\right)^2 = \left(\text{cc}^2 + \text{rr}^2 - 2\left(\text{cc}\right)\left(\text{rr}\right)\cos\psi\right) \quad (35)$$

where cc is the height of the mirrors, rr is the width of the glass cover, ss is the distance from upper edge of mirror to outer edge of glass cover, and ψ is the angle between the still glass top and mirror top.

The efficiency of desalination system is defined as the ratio of the total energy used for the evaporating the distilled water during the whole duration of a day to the total solar energy received by the glass cover over the same period of time.

$$\eta = \frac{\int \dot{m}_d h_{\text{fg}} dt}{A_{g,s}\int I_s dt} \quad (36)$$

where the integration is performed over the duration of a whole day.

3. Experimental procedure

The solar still used for the experimental investigation is shown in Fig. 2. The dimensions of the base tank were 0.5 m × 1 m × 0.06 m. The base tank of the solar still was made of galvanized iron (GI) having 3 mm thickness because it has good formability. Black paint was applied on the inner and outer surfaces of the base tank in order to increase the absorptivity of the water and the base tank. The distilled water is collected in the measurable water bottles placed under the solar still. A hole is provided in the base tank to extract the distilled water from the solar still. In order to make the glass cover rigid aluminum strips were fixed on the edges of the still. Experiments were carried out in Dhahran, a city in the eastern province of Saudi Arabia at latitude 26°N. Four inclined mirrors were placed around the still to reflect extra solar irradiance onto the solar still. Minimum water depth of 1 cm is maintained in the base tank of the solar still. The overall cost of the solar still unit was around \$400. However, the cost was not a main concern in the current study. The experimental measurement error is estimated to be within 10% which is due to the sensitivity of the temperature sensors and the evaporation of water that is accumulated in the measuring container.

Outdoor experiments were done in KFUPM campus, Dhahran (26°16′N, 50°10′E), 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.

3.1. Cost analysis

The unit cost of the distilled water UCW is

$$\text{UCW} = \frac{C_{\text{total}}}{\int \dot{m}_d dt} \quad (37)$$

where the total cost of the solar still unit C_{total} includes the capital cost, operation and maintenance costs

$$C_{\text{total}} = f_C C_C + C_O + C_M \quad (38)$$

where C_C, C_O and C_M are the capital cost, operational cost and the maintenance cost, respectively. f_C is the capital recovery factor which is given by

$$f_C = \frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1} \quad (39)$$

in which i is the annual rate of interest and n is the expected life of the solar still in years. The expected life of the solar still is 10 years. Therefore, the integral in Eq. (37) is performed over the total life of the solar still by considering the availability of the unit during the same period.

4. Results and discussion

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.

Table 1
Parameters used in the numerical modelling and simulations

A_g = 0.6 (m²)	m_w = 5 (kg)
A_b = 0.5 (m²)	m_b = 12 (kg)
C_b = 486 (J/kg K)	C_g = 840 (J/kg K)
C_w = 4,178 (J/kg K)	$\rho_w = 1000\left(\frac{\text{kg}}{m^3}\right)$
τ_S = 0.835	τ_N = 0.835
α_{gS} = 0.127	α_{gN} = 0.127
α_w = 0.6	ρ_{gr} = 0.5
ϵ_g = 0.9	ϵ_{wg} = 0.9

Fig. 3 shows daily temperature variations for (a) summer and (b) winter seasons. For a typical summer day, the maximum temperature of basin water and glass surface with the external mirrors reaches 68.4°C and 62.8°C, respectively. However, for the typical winter day, they reach 51.2°C and 42.2°C, respectively. This shows that the basin water and glass surface temperatures for winter are less by about 25% and 33% than those for the summer, respectively.

The maximum temperatures for water and glass without the external mirrors for the typical summer day were found to be 61.4°C and 56.6°C, respectively. However, for the typical winter day, they reach 44.5°C and 35.4°C, respectively. This shows that basin water and glass surface temperatures for winter are less by about 27% and 37% than those for the summer, respectively.

The cumulative distilled water production can be seen in Fig. 4 with and without mirror for (a) summer and (b) winter day. The water yield for the typical summer day is found to be 3.43 L/d. Without using external mirrors, the distilled water yield was 2.45 L/d. The total productivity of the still was found to enhance by around 40%.

For the typical winter day, the fresh water yield was 2.1 L/d. For the base case without the mirrors the yield was 1.2 L/d. The increase in the total distilled water yield was 75%. For both summer and winter cases, most of the water yield occurred around the noon time. This was due to the temperature difference between the water and glass that reaches a peak value between 12:00 PM and 1:00 PM.

Table 2 shows the comparison of the experimental measurements for both the summer and winter cases. When the productivity increase for both the summer and winter cases are compared, the percentage increase in the productivity in the winter appears to be higher, however, the amount of the productivity in the winter is lower. The amount of increase in the productivity in both summer (0.98 L/d) and winter (0.9 L/d) cases are comparable. This indicates that using external mirrors increases the productivity in both summer and winter and is preferable in both seasons. In summer, the efficiency of the solar still is estimated to be 42% and 58.8% for the base case (without mirrors) and for the case with external mirrors, respectively. On the other hand, during the winter, the efficiency of the unit is estimated to be 33% and 57% for the base case (without mirrors) and for the case with external mirrors, respectively. The increase of efficiency in winter season is higher than that of the summer season when using the external mirrors.

Fig. 5 shows a comparison of the numerical simulation for the glass and water temperatures of the single slope solar still for (a) summer and (b) winter. The numerical simulation

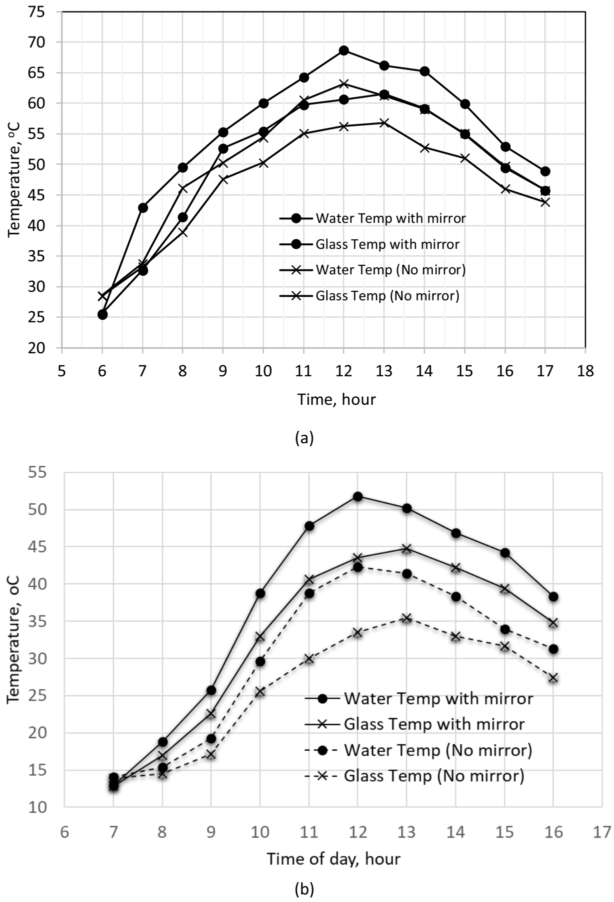

Fig. 3. Temperature variations throughout the day for (a) summer and (b) winter.

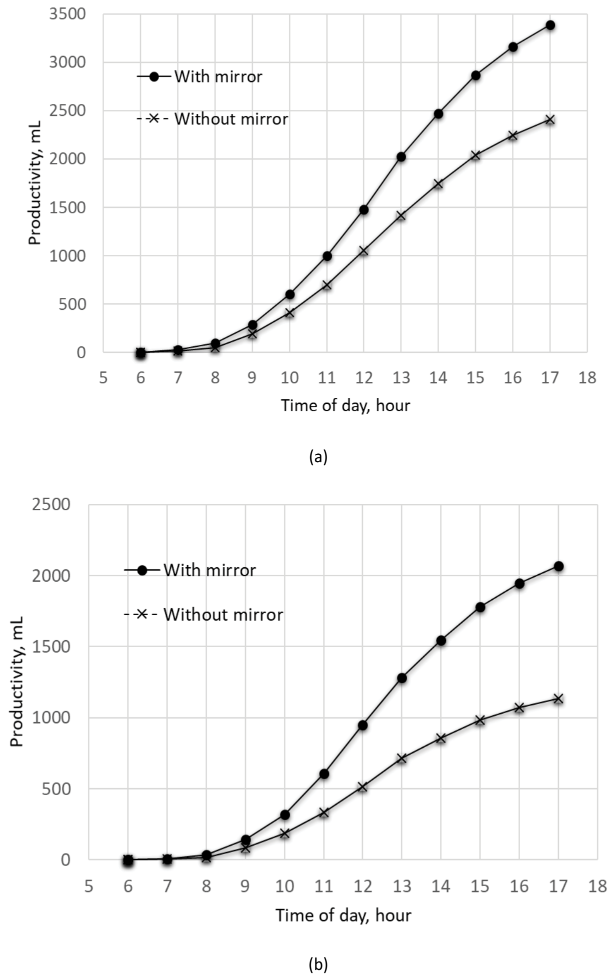

Fig. 4. Water yield during (a) summer and (b) winter.

Table 2
Experimental data for summer and winter days

		Maximum basin water temperature (°C)	Maximum glass temperature (°C)	Desalinated water productivity (L/d)	Change of water productivity from the base case (L/d)/%
Summer	Base case (without mirrors)	61.4	56.6	2.45	–
	With external mirrors	68.4	62.8	3.43	0.98/40%
Winter	Base case (without mirrors)	44.5	35.4	1.2	–
	With external mirrors	51.2	42.2	2.1	0.9/75%

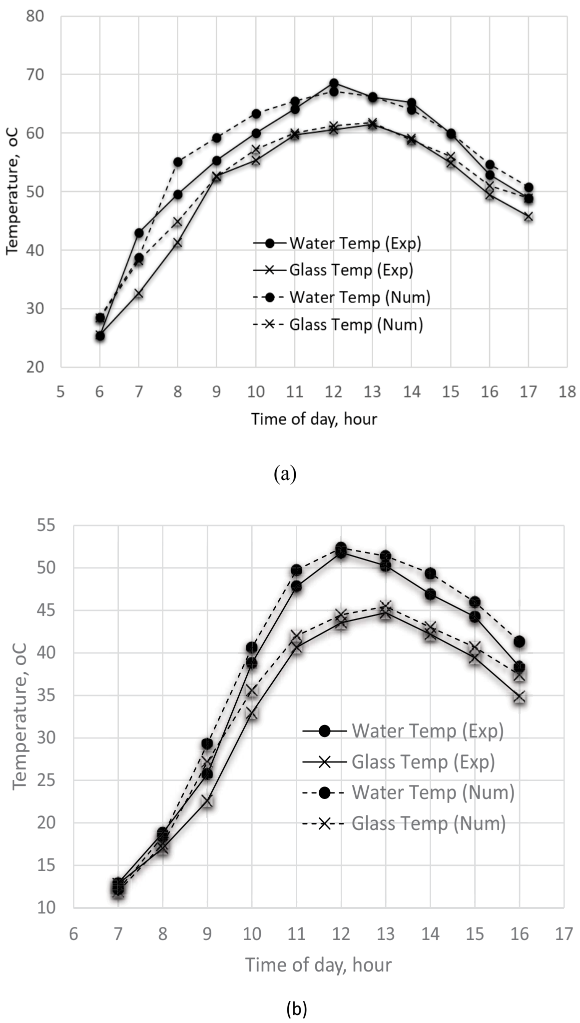

Fig. 5. Comparison of numerical and experimental temperature variations for (a) summer and (b) winter.

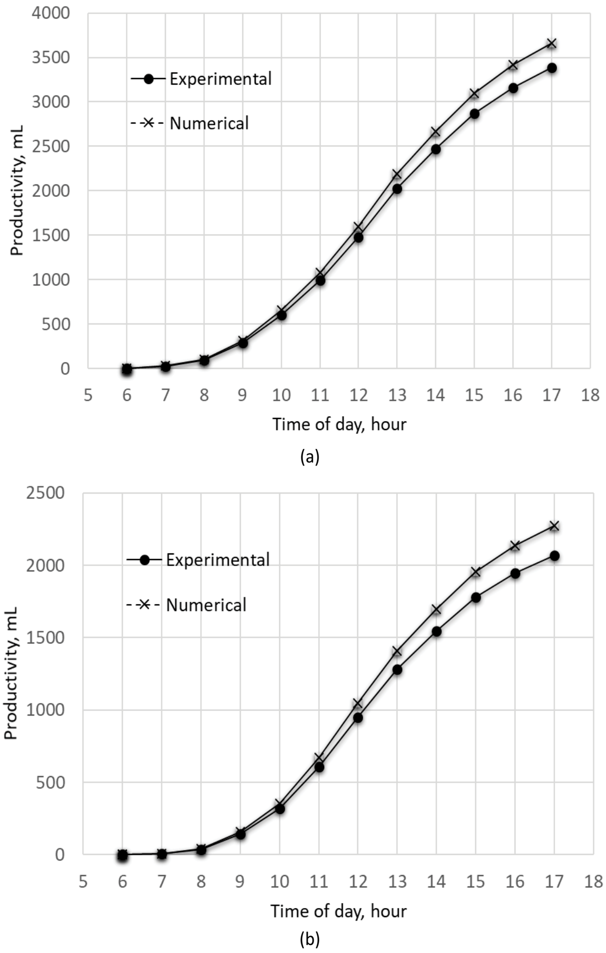

Fig. 6. Comparison of the numerical and experimental water productivity for (a) summer and (b) winter.

results agree with the experimental measurements within an 8% error.

The numerical simulation for the distilled water productivity with external mirrors for (a) summer and (b) winter is shown in Fig. 6. The numerical simulation overestimates the cumulative distilled water production; however, the error remains within 8% margin.

5. Conclusions

The following conclusions can be derived from the current work.

- External mirrors increased the water productivity by 40% for a typical summer day and 75% in a typical winter day for Saudi Arabian climatic conditions.
- External mirrors increase the water and glass temperatures in both summer and winter cases.

- The productivity reaches its maximum value between 12:00 PM and 1:00 PM in both summer and winter conditions. This is due to the maximum difference between the water and glass temperatures.
- Use of external mirrors is found to increase the productivity in both the summer and winter climatic conditions in a comparable amount, that is, approximately 0.9 L/d.
- The experimental results were simulated by the numerical predictions within a maximum error of 8%.
- Using external mirror with minimal cost it has been shown that the water productivity could be increased by as high as 75%.

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