# Theoretical and Experimental Comparison Between The Thermal Performance of A Solar Evaporator and A Solar Distiller

Ragab I. A. Murad[1]

## ABSTRACT

**Both of a solar evaporator and a single slope solar distiller were designed and constructed to present the experimental and theoretical comparison between their thermal behaviors. The thermal comparison showed that, evaporation in both systems is the major heat loss and is larger than the other three modes together (radiation, convection and conduction). Also, the thermal results showed that, the higher heat loss by convection of the solar evaporator is due to the wind effect. The maximum thermal efficiency of the solar evaporator and the solar distiller was 72.3 and 64.6% respectively.**

## INTRODUCTION

Solar evaporation pan (solar evaporator) can be used for roof ponds, swimming pools, salt production, etc. Evaporation pan or free water surface are also names related to the same system. Most existent works are of experimental order deal with the estimation of the evaporation rate (e.g. Chow and Chung, 1983; Brighton, 1985). These works, however, were preceded by Bowen (1926), who related the convective to the evaporative heat transfer rate from any water surface. Recently, with the growing interest on solar energy engineering many articles considering the heat balances on free water surface in steady state and in transient heat transfer have been published(e.g. Czarnecki, 1978; Govaer and Zarmi, 1981; 1983; Rakopoulos and Vazeos, 1987; Sartori, 1987a; 1990a; 1990b; 1991).

Hot-box, basin type, conventional solar still and solar distiller are names of one the most ancient application the solar energy field. Since a little more than one century of its conception, several theoretical and experimental efforts have been dedicated to its development, mainly in the sixties and nowadays the complex processes and effects of the combinations of several parameters involved in solar distillation are well known. Numerous publications are found in the literature on the subject (e.g. El-Sebaii, 2004; Tripathi and Tiwari, 2006 and Tsilingiris, 2011)

The main physical difference between solar evaporator and solar distiller with equivalent condition and construction is the existence of a cover in the distiller system. The cover causes the free convection process inside the distiller and the created greenhouse effect considerably increases its water temperature. On the other hand, the solar evaporator remains open to the atmosphere and its water layer suffers direct influence from the wind velocity, relative humidity, ambient temperature, etc. originating water temperatures lower than those from solar distillers.

So those, the theoretical and experimental comparison of the thermal performance between the solar evaporator and solar distiller are the main goals of this work.

## MATERIALS AND METHODS

The experimental work was carried out through June, July and August, 2010, under West of Alexandria metrological conditions.

**System setup:**

The schematic configuration of the proposed solar evaporator and single slope solar distiller are illustrated in Figure 1(a and b). Basically (Fig. 1a), it is a direct heated solar evaporation pan, which mainly comprises an evaporation unit. It consists of a square wooden box of 1.12 m x 1.12 m and depth of 0.16 m. Also, a square steel box of 1.0 m x 1.0 m and 0.10 m depth was put inside the wooden box. A fibber insulation of 0.04 m thickness was put between the wooden and the steel. A steel ruler was fixed on a side of steel for water leveling (initial depth of salty water equal 0.05 m). The solar distiller model (Fig. 1b) has the same format and dimensional of the solar evaporator, but the glass cover (4 mm thickness) was fixed over the wooden box at inclined angle of 15$^o$ on the horizontal, as suitable for the experimental location and date. The lower side of the distiller was oriented to face the south direction. A plastic channel was fixed under the lower side of the cover glass to collect the distillation water in the external vessel.

The ambient ($T_a$, $^o$C) and water tempe-ratures ($T_w$ , $^o$C) were recorded at each hour, using a digital thermometer VE310 (with accuracy of ± 0.10 C$^o$). Solar intensity ($I$, W/m$^2$), wind velocity ($\upsilon$, m/s) and relative humidity (Rh, %) were measured using MC11 digital pyrometer (with accuracy of ± 10 W/m$^2$), Vane type digital anemometer (with accuracy of ± 0.1 m/s) and digital hygrometer (with accuracy of ± 0.1%), respectively.

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[1]Agric. Eng., Fac. of Agric., Fayoum University, A.R.E.
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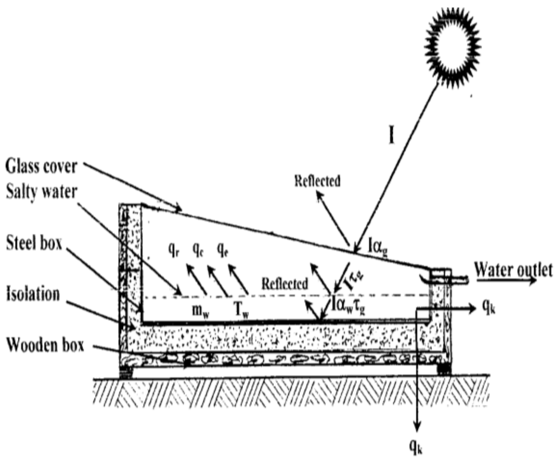


**Fig. 1a. Schematic drawing of a solar evaporator and its heat balance**

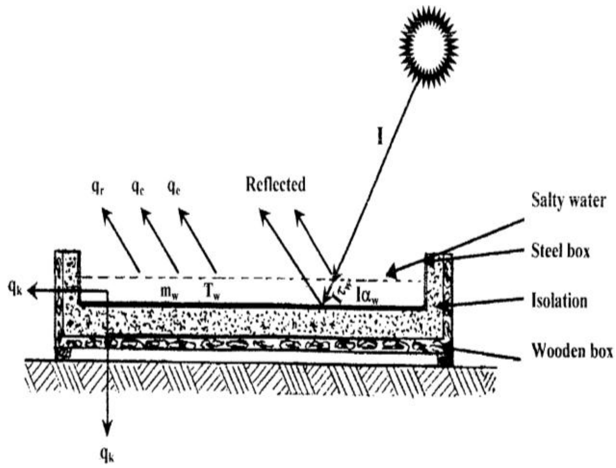


**Fig. 1b. Schematic drawing of a solar distiller and its heat balance**

A salty sea water sample was taken to measure the saline concentration. The electrical conductivity of salty water sample was 48 mmohs/cm (48 ds/m) at 25 °C.

**Theoretical heat balance of the evaporator:**

The steady state energy balance around the overall solar evaporation pan is given by:

$$A\,\alpha_w\,I = q_r + q_c + q_e + q_k + C_{ev}\,\frac{dt_w}{d\theta_h} \quad \text{….(1)}$$

Where, A (m$^2$) is the plan area of evaporator, $\alpha_w$ is the water solar absorbance, $C_{ev}$ is the thermal capacity (kJ/m$^2$K), $q_r$, $q_c$, $q_e$ and $q_k$ are heat transfer rates by radiation, convection, evaporation and conduction, respectively (W/m$^2$).

The first term in the previous equation is the solar radiation absorbed by the water, which is equal to the input energy to the evaporation pan. The right hand side shows the radiation, convective, evaporation and conduction and the thermal capacity of the pan as a function of time, where the heat transfer terms are given by Sartori, (1987a), in SI units:

$$q_r = \epsilon_w\,\sigma\,(T_w^4 - T_{sky}^4) \quad \text{……………………………....(2)}$$

Where, $\epsilon_w$ is the water emittance, $\sigma$ is Stefan-Boltzmann constant (56.7 x 10$^{-9}$ W/m$^2$K$^4$) and $T_{sky}$ is given by Duffie and Beckman (1991),

$$T_{sky} = (T_a + 273.15)\,[(T_d + 200)/250]^{1/4} - 273.15 \quad \text{…………........................……… (3)}$$

$$q_c = 3.9183\,V^{0.5}\,(T_w - T_a) \quad \text{………………………......…… (4)}$$

$$q_k = k_b\,(T_w - T_a) \quad \text{…………………………………...... (5)}$$

Where, $k_b$ (W/m$^2$K) for a soil elevated pan as considered here, and is determined through the over-all heat transfer coefficient for a multi-layer wall.

$$q_e = 2.6639\,v^{0.5}\,(P_w - P_d)\,L_w / P \quad \text{………….....……..…. (6)}$$

Where, P is atmospheric pressure (Pa) and water vapor partial pressure at water $P_w$ (Pa) and at dew point $P_d$ (Pa) and latent heat $L_w$ (kJ/kg) are calculated by Fernandez and Chargoy (1990) as follows:

$$P_{w,d} = Exp\,(25.317 - 5144/T_{w,d}) \quad \text{………………..….. (7)}$$

$$L_w = (2501.67 - 2.389\,T_w) \times 10^3 \quad \text{…………………...….. (8)}$$

The hourly evaporation rate is obtained through;

$$m_h = \int_0^{\theta_h} q_e\,d\theta_h\,/L_w \quad \text{……..……….............. (9)}$$

The thermal efficiency ($\eta_{Ev}$) of the solar evaporator can be calculating as follows:

$$\eta_{Ev} = q_e / q_e + q_c + q_r \quad \text{…………………………….... (10)}$$

**Theoretical heat balance of the distiller:**

The solar distiller operation is similar to that of the solar evaporator, but with transient cover. Excluding cover interferences, the processes of heating the water and loss of heat from the system are the same as that for the evaporator. Figure 1b shows the main thermal processes involved in the solar distiller.

The energy balance for the solar distiller can be expressed by:

$$\alpha_g\,I + \alpha_w\,\tau_g I = q_{ga}A + q_k + C_{st}\,\frac{dt_w}{d\theta_h} \quad \text{…...(11)}$$

Where, $\alpha_g$ is the glass absorbance, $\tau_g$ glass transmittance, $C_{st}$ is the thermal capacity, (kJ/m$^2$K).

The heat transfer between the water and the glass is given by the heat transfer rates by radiation, convection and evaporation whereas the heat flux to the ambient is the summation of such quantities plus the solar energy absorbed by the cover, i.e.

$$q_{ga} A = q_r + q_c + q_e + \alpha_g I \quad (12)$$

The internal heat transfer rates expressed in SI units by (Sartori, 1987b) as follows:

$$q_r = 0.9\sigma (T_w^4 - T_g^4) \quad (13)$$

$$q_c = 0.884 [T_w - T_g + (P_w - P_g/267.7 \times 10^3 - P_w) T_w^{1/3}(T_w - T_g)] \quad (14)$$

$$q_e = 60.78 \times 10^{-7} \times [T_w - T_g + (P_w - P_g/267.7 \times 10^3 - P_w). T_w^{1/3}(P_w - P_g).L_w \quad (15)$$

Where $T_g$ is the glass cover temperature, ºC, and $P_g$ is the water vapor partial pressure at glass temperature, Pa.

The heat dissipation ($q_{ga}$) from the glass to the surroundings is given by the radiation plus the convective heat transfer is:

$$q_{ga} = \epsilon_g \sigma (T_g^4 - T_{sky}^4) + h_{ca} (T_g - T_a) \quad (16)$$

$T_{sky}$ calculated as eq. 3.

$q_k$ calculated as eq. 5.

The thermal efficiency ($\eta_{st}$) of the solar distiller can be calculating as;

$$\eta_{st} = q_e / q_e + q_c + q_r \quad (17)$$

**Numerical calculations:**

Both of The solar evaporation pan and the solar distiller described in the previous section were simulated at steady state using excel spread sheet software on an IBM personal computer. The considered system used for experimental tests (Sartori, 1987a & 1987b). Besides the hourly environmental parameters $I$, $T_a$, $T_d$, $v$ and $Rh$, the following physical properties are used as input data; $A$ = 1.0 m$^2$, $C_{ev}=167.60$ kJ/m$^2$K, $C_{st}= 174.44$ kJ/m$^2$K, $\alpha_w=0.90$, $\alpha_g=0.05$, $\tau_g 0.90$, $\epsilon_g =0.94$, and $\epsilon_w = 0.95$.

## RESULTS AND DISCUSSIONS

**Results of the solar evaporator:**

Figure 2 presents the general behavior of metrological parameters affecting evaporation rate of solar evaporator during the experimental period (June, July and August 2010 as an average values). In general, it is clear that, the evaporation rate increases with increasing of both of solar intensity and ambient air temperature, and decreases with decreasing the relative humidity and wind velocity.

Results also showed that, increasing of evaporation rate from 2.20 to 2.90 L/m$^2$.day (32% increasing) as decreasing relative humidity from 62.1 to 48.3% and decreasing the wind velocity from 3.7 to 1.5 m/s, while increasing of solar radiation from 400 to 700 W/m$^2$.day, and with increasing of water temperature from 30 to 40 ºC (33% increasing). Also, it shows that increasing of water temperature with increasing of ambient temperature in parallel trend as solar radiation intensity increases. The following showing has more details about the parameters affected on evaporation rate.

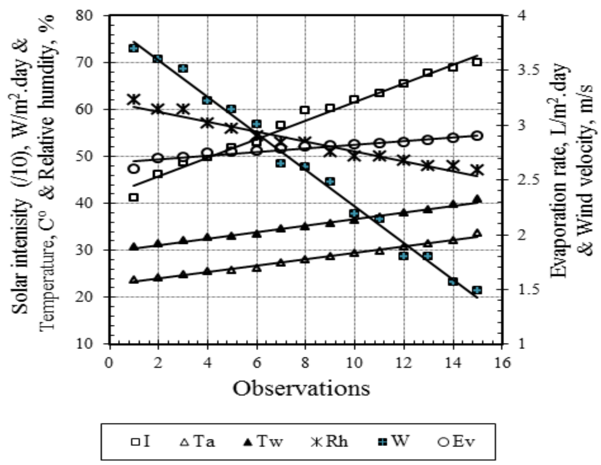


**Fig. 2. Behavior of solar radiation, ambient & water temperatures, relative humidity and wind velocity with evaporation rate**

Figures 3 & 4 present the corresponding properties from the solar evaporator during the solar time, together with the air temperature, solar radiation intensity and the dew point temperature. The major important parameter affecting the evaporation rate is the intensity of solar radiation. The evaporation rate increases by increasing of solar radiation intensity and vice versa, as shown in Figure 3. Also, it showed that, the behavior trend of water temperature increases by increasing the solar radiation and ambient temperature and vice versa. There is a little effect of dew point appeared through the solar time as shown in Figure 4.

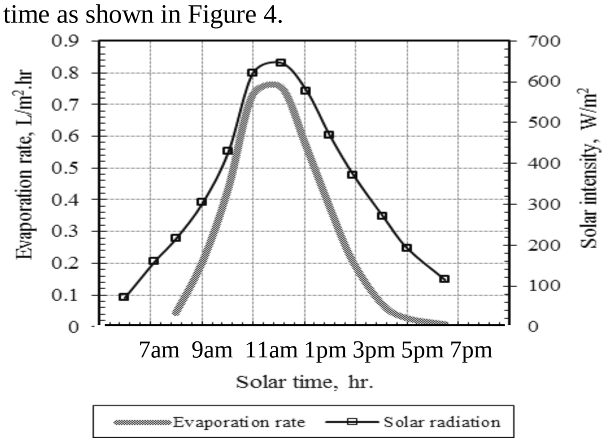


**Fig. 3. Solar radiation vs. evaporation rate during the solar time**

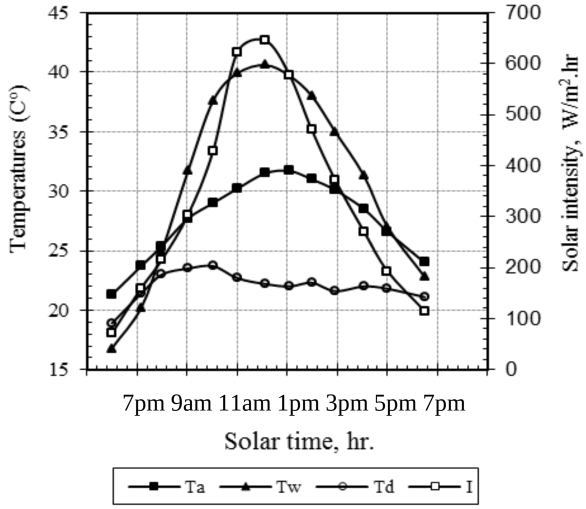


**Fig. 4.The relationship between ambient, dew point, water temperatures and solar intensity during the solar time**

Figure 5 shows the simulation results of the system hourly heat transfer rates by evaporation, radiation and convection. It is clear that, the evaporation is the major heat loss and is greater than the other two modes together. $q_k$ was negligible, where it has a very small value due to the insolation, so its curve disappeared from Figure 5. Also, it is clear that, the increasing of solar evaporator efficiency as heat transfer of evaporation increases, and vice versa.

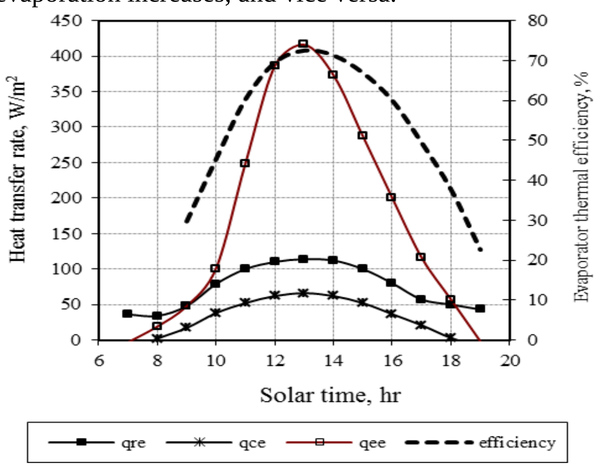


**Fig. 5. Heat transfer rates and evaporator efficiency during the solar time**

## Results of the solar distiller:

Fig. 6 shows the water temperature ($T_w$)and the glass cover temperature ($T_g$) from the solar distiller together with the ambient temperature ($T_a$) and the solar radiation (I) during the solar time. It is clear that, increasing the water temperature as solar radiation increases, as expected, that the solar distiller operation has the same general nature to that of the solar evaporator (and vice versa), irrespective of the existence of transparent cover.

Fig. 7 presents the simulated results of the distiller hourly heat transfer rates by evaporation, radiation and convection. As expected, that the evaporation heat transfer rate has the maximum values and it is greater than the radiation and convection heat transfer together. Also, it shows that, the increasing of solar distiller efficiency as heat transfer of evaporation increases, and vice versa.

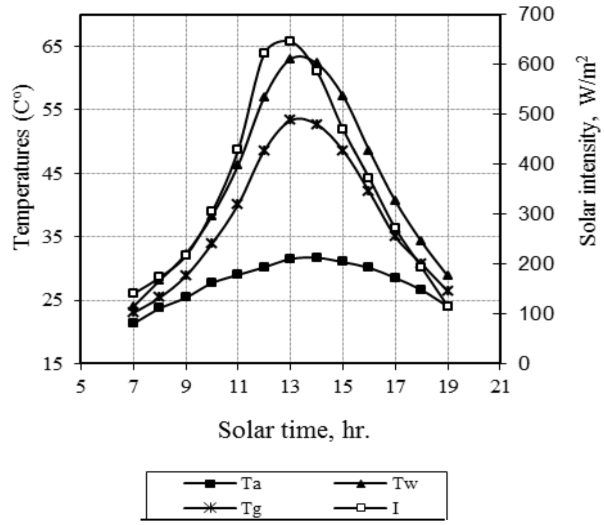


**Fig. 6: The relationship between ambient, water, cover temperatures and solar radiation during the solar time**

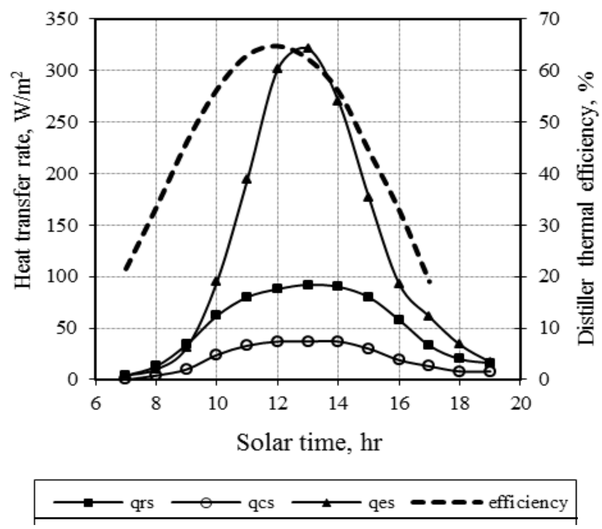


**Fig. 7: Heat transfer rates and evaporator efficiency during the solar time**

**Thermal comparison between the solar evaporator and the solar distiller:**

Fig. 8 shows the water temperature behavior inside the solar evaporator and the solar distiller. It showed that, for the same environmental conditions, the solar distiller reaches water temperatures higher than those the solar evaporator, caused by the greenhouse effect inside the distiller. Although evaporation is a strong function of the water temperature, the rate of evaporation in the solar distiller is much less than that in the open evaporation as can be seen in Fig. 9.

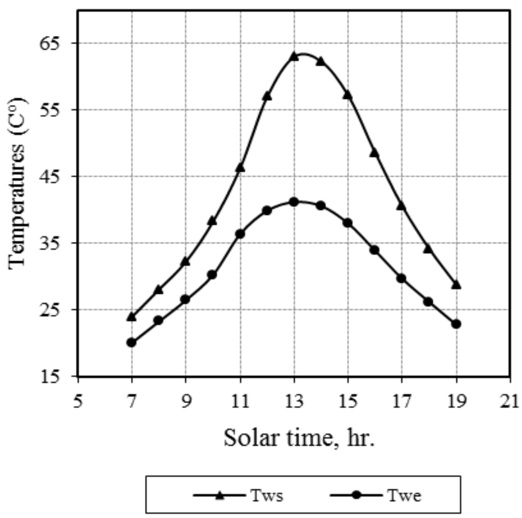


**Fig. 8. Behavior of water temperature inside the solar evaporator and the distiller during the solar time**

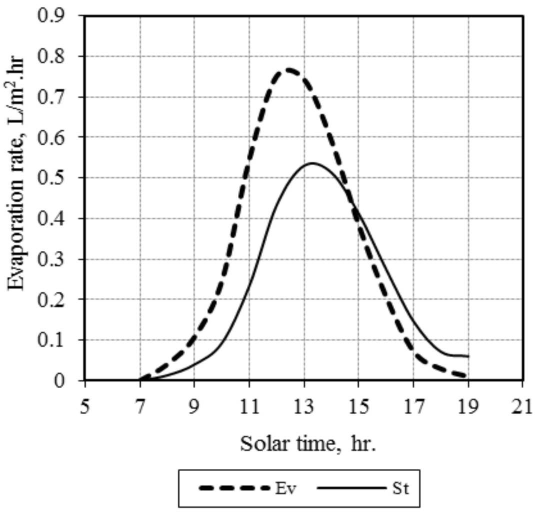


**Fig. 9. Evaporation rate from the solar evaporator and the solar distiller**

Fig. 10 shows the thermal comparison between the heat transfer of the solar evaporator and the solar distiller. It is clear that, the success of heat loss by evaporation from the evaporator on the solar distiller, so that the vapor productivity of the evaporator is higher than the solar distiller. Also, the higher heat loss by convection of the evaporator is due to the wind effect. On the other hand, there are an approximately behavior and values of radiation heat losses from the solar evaporator and the solar distiller.

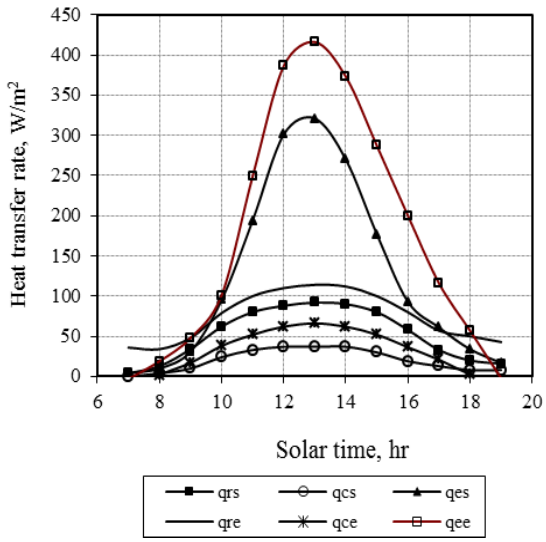


**Fig. 10. Heat transfer rates from the solar evaporator and the solar distiller**

## CONCLUSION

It is shown that, the evaporation in solar distiller is much less than that in open evaporation despite the higher water temperatures in the former system. This is also true even when the water temperature of both systems is same. Evaporation in both systems is the major heat loss and larger than the other three modes together (radiation, convection and conduction). There is a little effect of dew point appeared through the solar time in evaporator system, and there is zero effect for distiller system. The heat loss by convection of the evaporator is higher than the distiller due to the wind effect.

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## الملخص العربي

# مقارنة نظرية وتجريبية بين الأداء الحراري لكل من المبخر والمقطر الشمسي

رجب إسماعيل أحمد مراد

أجريت هذه الدراسة بغرض استخدم نموذجين لمبخر شمسي ذو سطح حر معرض مباشرة للأشعة الشمسية والآخر لمقطر شمسي ذو غطاء من الزجاج الشفاف، وذلك لإجراء مقارنة نظرية وعملية للأداء الحراري بينهما. حيث أوضحت النتائج وجود تأثير قوي لكل من شدة الإشعاع الشمسي ودرجة حرارة المياه المالحة علي عملية التبخير، كما لم تظهر النتائج تأثيرا قويا وواضحا لدرجة حرارة نقطة الندي علي معدل التبخير أثناء ساعات النهار (من سطوع الشمس لغروبها) بالنسبة للمبخر الشمسي. درس الإتزان الحراري لكل من المبخر والمقطر من أجل حساب قيم الفقد الحراري بالتبخير والإشعاع والحمل، وكذلك الحصول علي الكفاءة الحرارية لكل منهما، حيث أظهرت النتائج أن الفقد الحراري الأعظم كان بالتبخير في كلا النظامين مع تفوق الفقد بالتبخير للمبخر علي المقطر، كما أوضحت النتائج كبر قيم الفقد الحراري بالحمل للمبخر عن المقطر وذلك كنتيجة لوقوع المبخر تحت تأثير الهواء الجوي المباشر. بينما سجلت الحسابات القيم العظمي للكفاءة الحرارية للمبخر والمقطر ٧٢,٣ و ٦٤,٦% علي الترتيب.