HEFAT2008
6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
30 June to 2 July 2008
Pretoria, South Africa
Paper number: MM5

THERMOSYPHON SOLAR WATER DISTILLER FOR REMOTE AND ARID AREAS

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ABSTRACT

Two modifications of solar water distiller using cement and aluminum absorber are presented experimentally. The water basin of two modifications was constructed as a set of U channels section. The first modification used separated condenser to purge water vapor from the cement absorber to increase the condensation. The second modification used plate thermosyphon to increase the input energy to distiller from bottom, thus increasing the water vaporization and condensation. The optimum tilted angle of glazing surface was obtained theoretically between 10~20^o at latitude of 30^o north Egypt and longitude of 31.01^o. The daily productivity of cement absorber distiller was obtained of 2.08 L/(m^2.day) and increased with percentage of 18.7% by using separated condenser. For aluminum absorber distiller the average daily productivity was attained to 2.96 L/(m^2.day) and increased up to 3.49 L/(m^2.day) by using plate thermosyphon. The overall efficiency of two modifications was obtained from 50 % up to 65 %.

NOMENCLATURE

A	[Wm^{-2}]	Solar radiation intensity outside atmosphere
B	-	Weakness atmospheric factor
C	-	Diffuse radiation factor
F_{SS}	-	Angle factor between tilted surface and sky
F_{Sg}	-	Angle factor between tilted surface and ground surface
H_s	[Wm^{-2}]	Measured solar radiation incident on glazing surface
I_G	[Wm^{-2}]	Global solar radiation on horizontal surface
I_{ND}	[Wm^{-2}]	Normal direct intensity
I_{NS}	[Wm^{-2}]	Normal component on tilted surface
I_{TS}	[Wm^{-2}]	Total incident on tilted surface
L	^{o}	Latitude angle
L_g	^{o}	Longitude angle
LT	[Jkg^{-1}]	Latent heat of evaporation
$\dot{m}_w$	[kgm^{-2}hr^{-1}]	Hourly productivity
T_S	[hr]	Hour
Σ	^{o}	Tilted surface angle
β	^{o}	Solar altitude angle
ϕ	^{o}	Solar azimuth angle
γ	^{o}	Solar plan azimuth angle
η	-	Distiller efficiency
θ	^{o}	Solar incident angle
ρ_g	-	Reflection factor form earth
ψ	^{o}	Surface azimuth angle

INTRODUCTION

Fresh water is the source of life and corner stone of developing the modern civilization. Most of the human activities are intensively depending on the water resources such as underground water, rains, lakes and rivers for water requirements.

However, rapid industrial growth and the population explosion all over the world have resulted in a large escalation of demand for fresh water. Add to this, the problems of pollution of rivers and lakes by industrial wastes and large amounts of sewage discharged [1]. While water covers about three-quarters of the earth' surface, only 3 % is fresh water and not all of this limited quantity is suitable for drinking. Thus, water treatment is usually needed, and desalination is widely used for providing fresh water from brackish or seawater. Also, to supply the needed amount of portable water is already a problem in remote and arid areas which have a limited supply of conventional energy, but with a great potential for solar energy. Solar desalination could be promising for a cost effective solution.

The production of fresh water by solar distiller has been presented in many studies [2-4]. Several types of solar distiller exist, the simplest of which is the single-basin type, but the yield of this distiller is in the range of 2-4 L/day per m^2 of sun exposed glazing area. This distiller had the advantage of low installation cost and disadvantages of low efficiency and salt accumulation [5-7]. Many generations of solar systems and distiller had been developed but small numbers were tested. New approaches of solar desalination for small and medium size were used to enhance performance with using system of heat recovery [8]. Also, the solar distiller productivity was increased up to 33 % using a flat plate collector [9].

The recent works investigated similar solar distillation systems with heat-pipe solar collector [10-12]. Performance analysis of solar distiller coupled to a separated heat exchanger was presented [13-14]. The separated condenser was used to purge the water vapor to be condensed and the efficiency of the distiller was increased from 48 % to more than 70 %, and the proposed solar distiller worked perfectly with daily yield of 7 L/day per m^2.

The objective of the present study is to investigate the productivity of solar water distiller of cement and aluminum absorbers. Two modifications of auxiliary condenser and plate thermosyphon to increase the distiller productivity were conducted. The effect of glazing surface tilted angle and orientation to south or opposite sun has been carried out. Comparison between aluminum absorber productivity and efficiency without and with thermosyphon orientated to south has been performed.

MATHEMATICAL APPROACHES

The performance of solar distiller is related to the surface azimuth angle or orientation, ψ, and surface tilt angle, Σ.

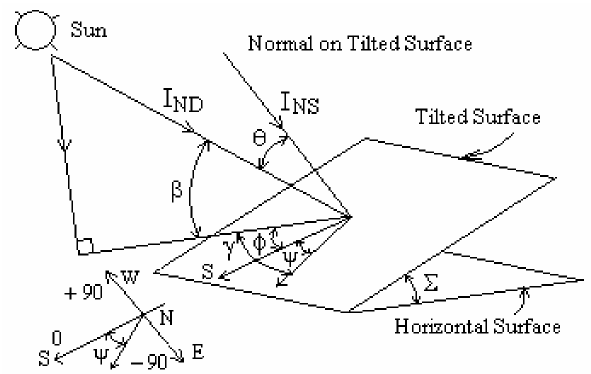

Fig. 1 Direct solar radiation and incident normal component on tilted surface.

To clarify the optimum tilt angle of solar collector at certain site, the *ASHARE* model [15] has been used to estimate the normal direct solar radiation, I_{ND}, the normal component on the tilted surface, I_{NS}, and solar incident angle, θ, which between the normal direct solar radiation and normal component on the tilted surface as shown in Fig. 1.

$$I_{ND} = A e^{-B/\sin\beta} \quad (1)$$

$$I_{NS} = I_{ND} \cos\theta \quad (2)$$

$$\theta = \cos^{-1}(\sin\beta\cos\Sigma + \cos\beta\cos\gamma\sin\Sigma) \quad (3)$$

Where the solar plane azimuth angle, $\gamma = \phi - \psi$, and ϕ is the solar azimuth angle. Thus, the global solar radiation, I_G, on the horizontal surface, $\Sigma=0$ is considered to be the sum of vertical component of the direct solar radiation and diffuse.

$$I_G = I_{ND}(\sin\beta + C) \quad (4)$$

Total solar radiation incident on the tilted surface with angle, Σ, is defined as,

$$I_{TS} = I_{NS} + I_{Ds} + I_{Rg} \quad (5)$$

Where the diffused radiation, I_{Ds}, and the reflection from the earth surface, I_{Rg}, are defined as,

$$I_{Ds} = C I_{ND} F_{SS} \quad (6)$$

$$I_{Rg} = \rho_g F_{Sg} I_{ND}(\sin\beta + C) \quad (7)$$

Where,

$$F_{SS} = (1 + \cos\Sigma)/2 \quad (8)$$

$$F_{Sg} = 1 - F_{SS} = (1 - \cos\Sigma)/2 \quad (9)$$

By compensate of Eqs. (2, 6-9) into Eq. (5), yields

$$I_{TS} = I_{ND}[\cos\theta + C\,F_{SS} + \rho_g F_{Sg}(\sin\beta + C)] \quad (10)$$

The solar radiation outside the atmosphere *A*, the constants, *B*, *C*, and formulas of solar angles are explained in reference [15]. A computer program has been developed using Eqs. (1-10) with the formulas of solar angles to estimate the normal direct solar radiation, the total solar radiation incident on the tilted surface at various tilt angle, Σ, and surface azimuth angle, ψ. To validate the accuracy of the program, the global solar radiation was measured at Minufiya University, Shebin El-kom, Egypt with EPPLEY Radiometer (PSP) and the data were taken every 15 min as shown in Fig 2 and 3. It can be seen that there is a regular variation from sunrise to sunset and peak radiation at noon, and the estimated values of global radiation are closed to the recorded data. It can be seen that the agreement is fairly good and the difference between measured and estimated global radiation, I_G^+ can be expressed by the following relation,

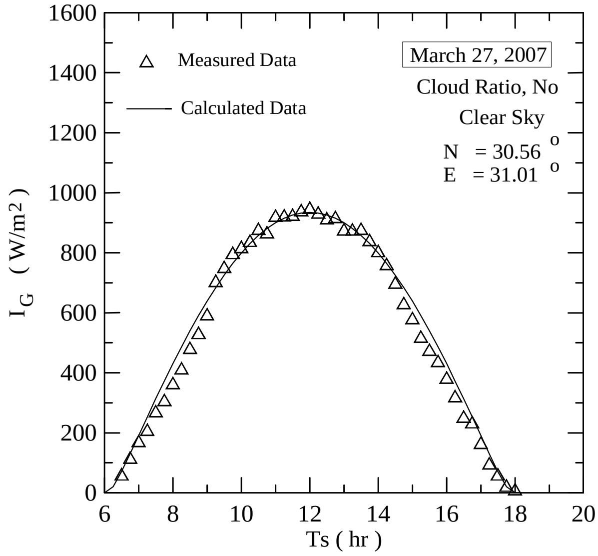

Fig. 2 Shebin El-kom at N 30° 33\ E 31°.

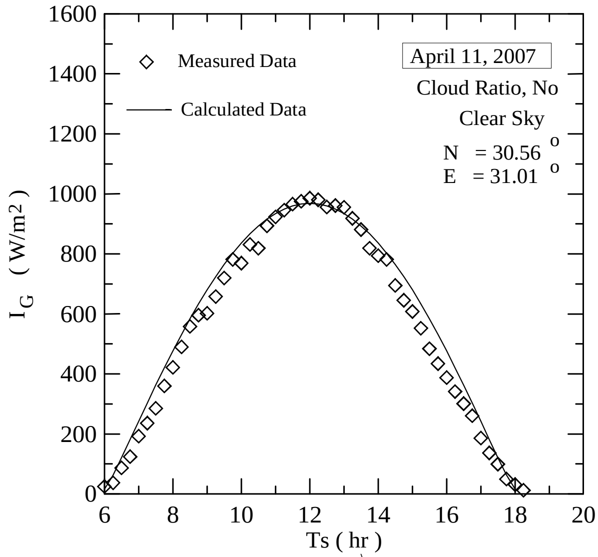

Fig. 3 Shebin El-kom at N 30° 33\ E 31°.

$$I_G^+ = (I_{G_{Estimated}} - I_{G_{Measured}}) / I_{G_{Measured}} \quad (11)$$

The standard deviation and root mean square deviation was employed to estimate the relative error of I_G^+ as the following,

$$SD = \sqrt{\sum_{i=1}^{i=n} (I_{G,i}^+)^2 / n} \quad (12)$$

The percentage deviation and root mean square of estimated global solar radiation relative to measured was illustrated in Fig. 4.

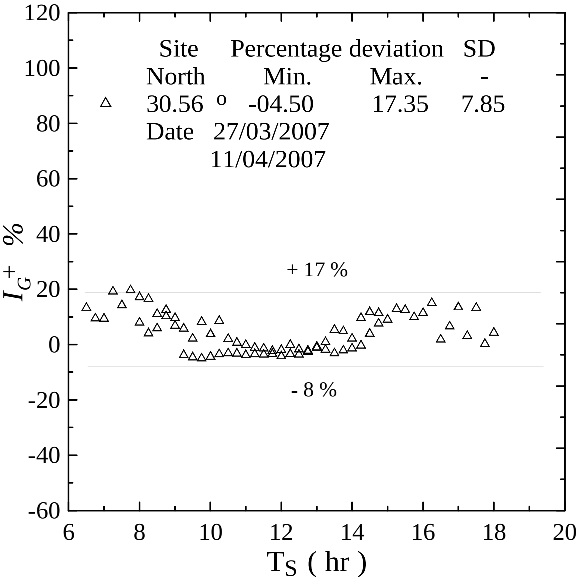

Fig. 4 Percentage deviation of global solar radiation.

It is observed that the agreement is satisfactory around noon from 9 ~ 15 O'clock. The percentage deviation from sunrise to 9 o'clock is positive of 0 ~ 17 %, because the global radiation estimated was higher than measured due to the effect of relative humidity in the morning. But the percentage deviation from 15 o'clock to sunset was negative of 0 ~ -8 %, because the global radiation measured is higher than estimated due to the increase of diffuse radiation. The root mean square was 5.02 ~ 7.85 %, and due to its low value clearly proves that the proposed mathematical approach can be used for estimation of global solar radiation on horizontal and tilted surface at any location with high confidence.

The prepared computer program is considered an effective tool to study the effect of surface azimuth and tilt angle on the solar radiation incident on the tilted surface. The effect of tilt angle was investigated from horizontal of $\Sigma = 0^o$ to vertical of $\Sigma = 90^o$, and surface azimuth from east to west in clock wise with step of 15^o as shown in Fig.1. The optimum tilt angle was found to be 10^o ~ 20^o facing south which the total solar incident on the tilted surface was maximum at noon of $\Sigma = 20^o$ as shown in Fig. 5. Thus, the surface tilted angle was used 20^o for glazing surface of the solar distiller in this study.

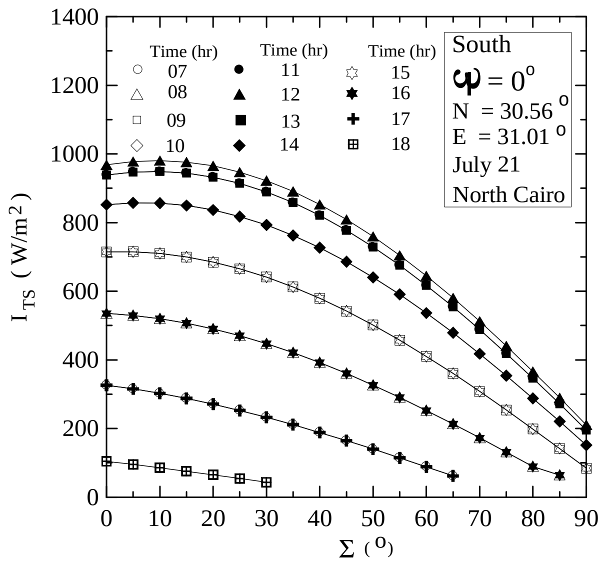

Fig. 5 Effect of surface tilted angle on incident solar radiation to south.

EXPERIMENTAL APPARATUS

The experimental apparatus was constructed from two models as shown in Fig. 6 and 7. The first model was made from wood basin of 1×1 *m* with 15 *cm* height and 1.2 *cm* wood thickness. The inside faces of wood basin were covered with cement layer of about 1.5 *cm* and divided into small channels of 4 *cm* deep and 8 *cm* width by ceramic slab of 5 *mm* thickness. The channels were formed to decrease the water deep in the basin and the thermal capacity of the distiller, also to increase the surface area of heat and mass transfer. The auxiliary condenser was made from galvanized steel of 0.25 *mm* thickness as a rectangular shape of 30×30×90 *cm* to increase the heat transfer area to accelerate the condensation of water vapor.

The second model was made from aluminum sheet of 1 *mm* thickness and consists of plate thermosyphon and glazing solar distiller. The plate thermosyphon was constructed from two plates of aluminum 1×2 *m* and the space between two plates was kept 2~3 *mm* by making small webs on the upper plate.

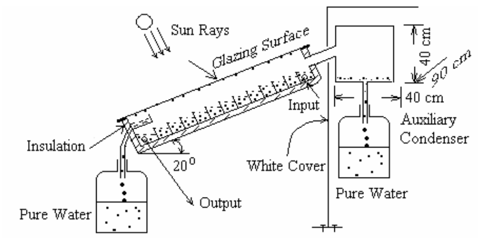

Fig. 6 Layout of cement model with auxiliary condenser.

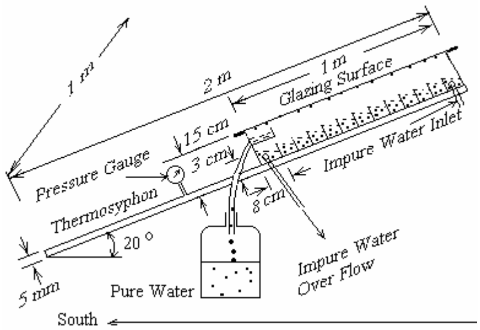

Fig. 7 Layout of aluminum model with thermosyphon.

The four edges of two plates welded together and examined before charging with Acetone. The dimension of glazing solar distiller was 1×1 *m* with 15 *cm* height and fixed on the upper half of the plate thermosyphon. Parallel channels of 4×8 *cm* were formed in amphitheater shape to keep the water on the tilted surface and to decrease the thermal capacity of the distiller. Suitable ways for distributing the impure water and collecting the pure water were arranged. The transparent surface was white glass of 1×1 *m* and 3 *mm* thickness and sealed to prevent the escape of water vapor. The two models were inclined 20^o to horizontal and all inside surfaces and channels were painted with heavy black color to absorb solar radiation. The two models were mounted on a woody frame and thermally insulated of base and all sides.

The solar radiation incident on the tilted surface was measured by EPPLEY Radiometer which fixed at the same level and tilt angle of glazing surface. The yields or productivity of fresh water was collected and measured by scaled over 1 hr. The plate thermosyphon was evacuated from air and charged with one Liter of acetone which is equal to three quarter of evaporator volume. The acetone as a working fluid was used because its boiling temperature is 57 ^oC at atmospheric pressure and it is convenient to this application.

RESULTS AND DISCUSSIONS

The experimental program was conducted using two models. First model is cement absorber distiller without and with separated condenser which orientated to south, and hourly and daily productivity was obtained as shown in Fig. 8 and 9. It can be seen that the productivity increased gradually to noon and reaching maximum at about 2 o clock due to the thermal capacity of the distiller. The experiments were repeated 2 days respectively to examine the data accuracy. The daily productivity of cement absorber model was 2.08 L/(m^2.day) without condenser and 2.388 L/(m^2.day) with separated condenser by percentage increase about 18 %. It is important to say that the cement absorber model has been used in this program because it is very cheap and easy to construct without any previous experience. Also, it is easy to build using local materials as bricks, cement and glass beside wells, rivers, lakes and sea beach to serve the people in arid and remote areas with fresh water.

The second model was aluminum absorber distiller and the experiments were conducted without thermosyphon which orientated to south. Thereafter, the distiller was rotated every 30 min facing the sun until its shadow underneath itself. In these experiments, the thermosyphon section is not charged with acetone and covered with thermal insulation to prevent the solar energy to strike this section. Hourly and daily productivity of aluminum absorber without thermosyphon were illustrated in Fig. 10 and 11. The daily productivity was 2.96 L/(m^2.day) when orientated to south, and 4.39 L/(m^2.day) when rotated faced sun with percentage increase about 48.6 %.

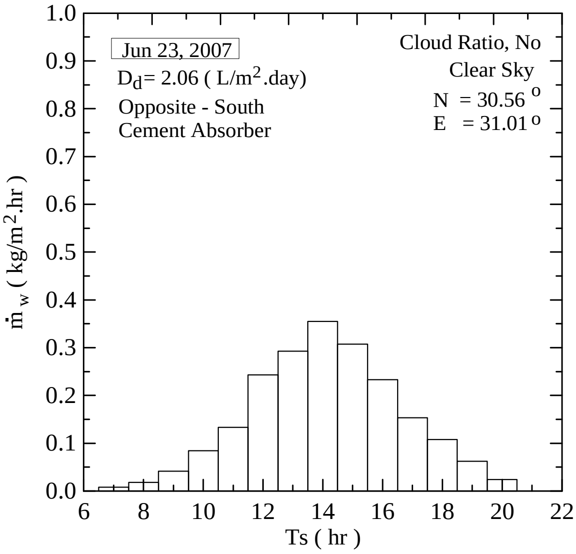

Fig. 8 Hourly productivity of cement model without condenser.

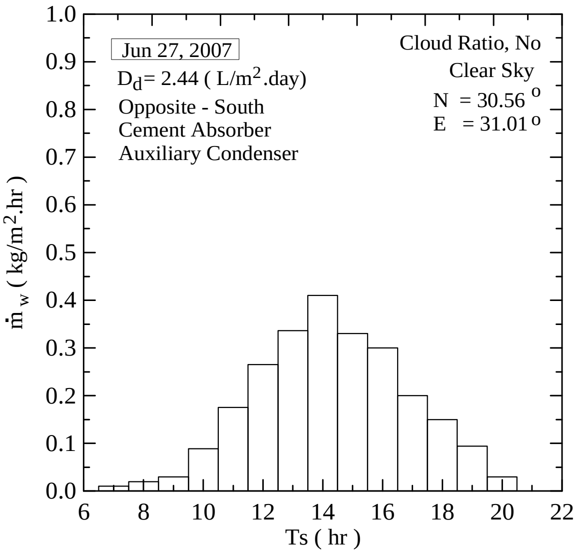

Fig. 9 Hourly productivity of cement model with condenser.

The daily productivity of aluminum absorber orientated to south is higher than the cement absorber by about 43.69 %. Because the aluminum absorber is making the temperature of black surfaces and basin water is homogenous and it accelerated the water evaporation. The plate thermosyphon was evacuated and charged with acetone. The daily productivity was 3.49 L/(m^2.day) when orientated to south as shown in Fig. 12. The daily productivity was increased by about 18 % than the distiller without thermosyphon. If the thermosyphon distiller orientated facing sun and its position changed every 30 min so that its shadow underneath itself, the daily productivity was increased up to 5.2 L/(m^2.day).

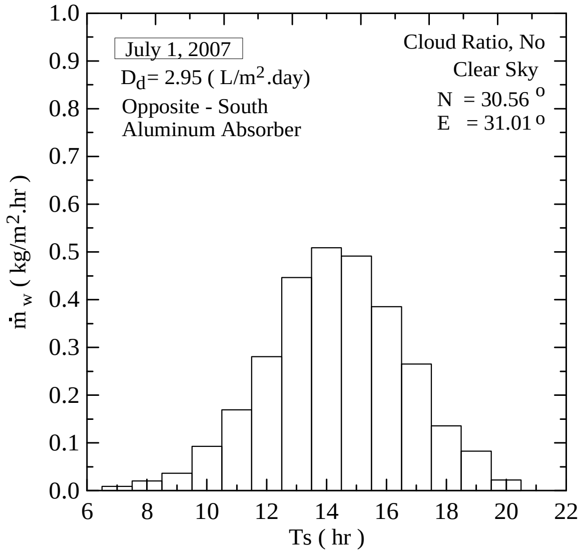

Fig. 10 Hourly productivity of aluminum model facing south.

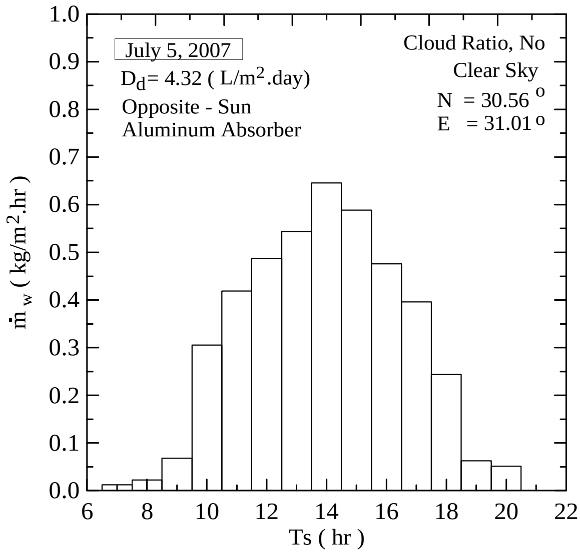

Fig. 11 Hourly productivity of aluminum model facing sun.

The distiller overall efficiency is dependent on incident solar energy and it is the ratio between solar energy utilized for water evaporation and the solar radiation incident on glazing surface as,

$$\eta = \frac{\dot{m}_w \times LT}{H_s} \quad (13)$$

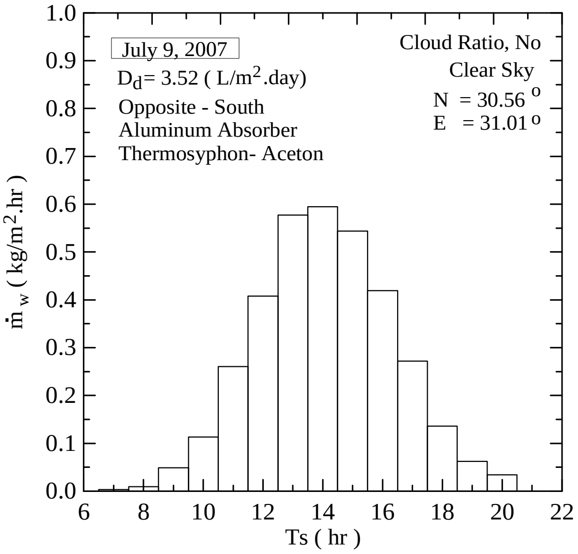

Fig. 12 Hourly productivity of aluminum model with thermosyphon.

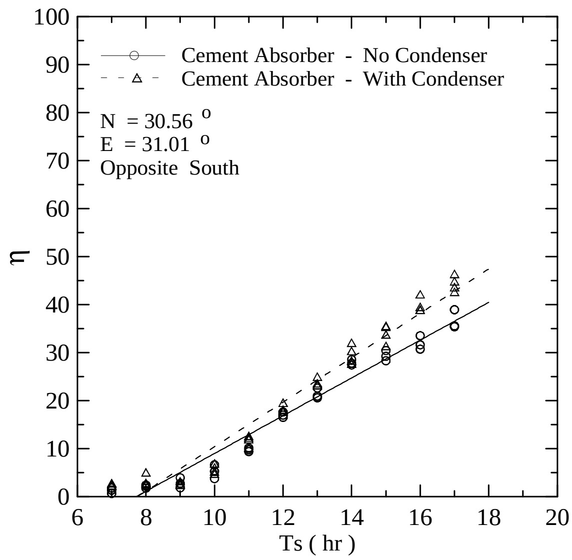

Fig. 13 Cement absorber distiller efficiency with and without condenser.

The overall efficiency of the previous cases was compared in Figs. 13-15. Obviously, the distiller efficiency was increased with increasing the solar energy until noon, but continued to increase because the thermal capacity of the distiller and energy stored in black surfaces and basin water. It is found that the efficiency of cement absorber with condenser is higher by about 5 % as shown in Fig. 13. While for aluminum absorber, the efficiency is higher than cement absorber by about of 15 % as shown in Fig. 14.

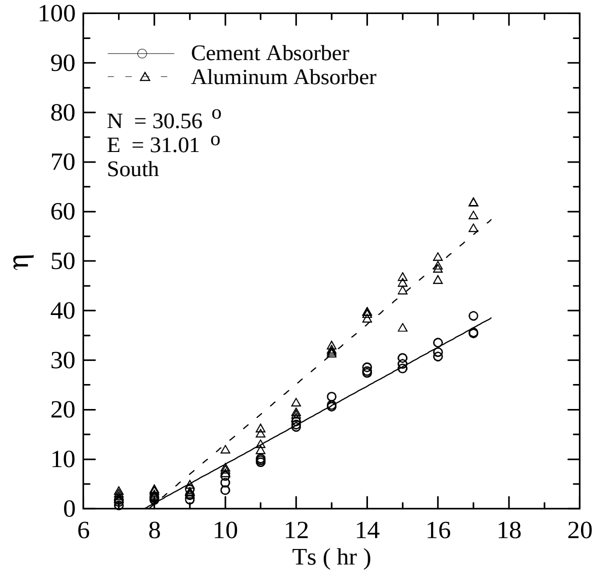

Fig. 14 Cement and aluminum absorber distiller efficiency.

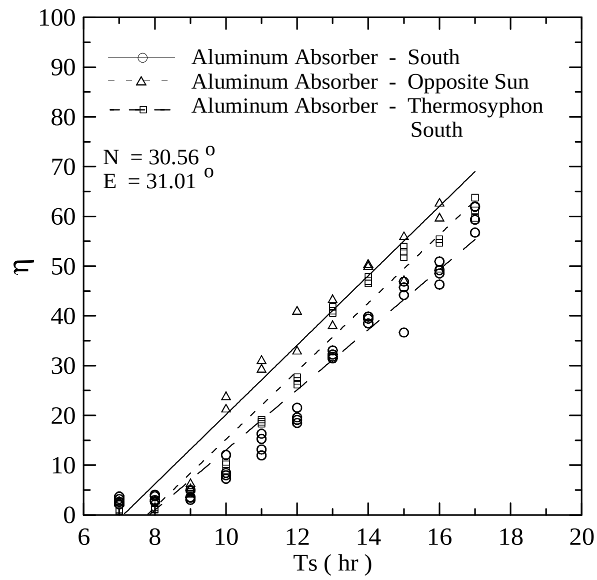

Fig. 15 Aluminum distiller efficiency with thermosyphon.

For aluminum absorber, the efficiency of plate thermosyphon is higher by about 8 % as illustrated in Fig. 15. But, when the aluminum absorber is rotating opposite the sun, the efficiency was increased by about 18 %. From these results, the two modifications of condenser in cement absorber and thermosyphon in aluminum absorber, the productivity was increased by about 18 % and overall efficiency by about 5 ~ 8 %.

CONCLUSIONS

An experimental study was performed to investigate the productivity and efficiency of solar distiller using cement and aluminum absorber. Two modifications were used to enhance the productivity of the distiller. For cement absorber, auxiliary condenser was used to purge the water vapor to increase the productivity. For aluminum absorber, plate thermosyphon charged with acetone was used to enhance the heat transfer underneath the water in the basin to increase the evaporation and productivity. The results are summarized as the followings:

1. The optimum tilted angle was theoretically estimated and it is found between 10~20^o at latitude of 30^o and longitude of 31^o, North East Cairo.
2. The average daily productivity of cement absorber distiller orientated to south was attained to 2.08 L/(m^2.day) with overall efficiency of 38 %. Since the productivity was increased to 2.39 L/(m^2.day) with overall efficiency of 45 % when using auxiliary condenser by percentage of increase about 18.7 % .
3. For aluminum absorber orientated to south, the average daily productivity was attained to 2.96 L/(m^2.day) with overall efficiency of 50 %.. But when plate thermosyphon was used the productivity attained to 3.49 L/(m^2.day) with overall efficiency up to 65 % by percentage of increase about 18 %.
4. For aluminum absorber positioned with respect to the direction of the sun, the average daily productivity was attained to 4.39 L/(m^2.day) with overall efficiency of 70 %.

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