

A Numerical Simulation of Solar Distillation for Installation in Chabahar-Iran

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Abstract—The world demand for potable water is increasing every day with growing population. Desalination using solar energy is suitable for potable water production from brackish and seawater. In this paper, we present a theoretical study of solar distillation in a single basin under the open environmental conditions of Chabahar-Iran. The still has a base area of 2000mm×500mm with a glass cover inclined at 25° in order to obtain extra solar energy. We model the still and conduct its energy balance equations under minor assumptions. We computed the temperatures of glass cover, seawater interface, moist air and bottom using numerical method. The investigation addressed the following: The still productivity, distilled water salinity and still performance in terms of the still efficiency. Calculated still productivity in July was higher than December. So in this paper, we show that still productivity is directly functioning of solar radiation.

Keywords—Inclined Solar still, Solar energy, Solar desalination, Numerical Simulation.

I. INTRODUCTION

THE availability of drinking water is reducing day by day; where as the requirement of drinking water is increasing rapidly. To overcome this problem there is a need for some sustainable source for the water distillation. Solar still is a useful device that can be used for the distilling of brackish water for the drinking purposes [1]. Solar Distillation is particularly important for locations where solar intensity is high and there is a scarcity of fresh water classified into: direct (passive) and indirect (active) regimes. The direct solar distillation systems collect solar energy to produce the still water directly compared to the indirect systems categories. passive solar stills is recommended as it is economical to provide potable water and active solar distillation system from a commercial point of view compared to the active stills [2,3], Abdel-Ghafar [4] investigated a passive solar basin still type

in Alexandria, Egypt. The still was fabricated from simple available materials (i.e. wood, corks, galvanized steel, glass pane and mirrors). The still was sloped by 30°; it was oriented toward the south direction, It had area of 1.2 m² with a projected area of 1,1 m². A mirror of 0.7 m² was fitted on the still side walls. The maximum obtained basin water temperatures were found 53°C and 56°C at the experiments in June and July, respectively as the distilled water of 2 liter/m².day was obtained. Fath *et al.* [5] found that the single slope still was slightly more efficient than the pyramid-shape one. The solar energy received by the single slope still was 8% higher than that received by the pyramid in winter while it was 5% lower in summer. Due to the larger radiation losses from the cover surface of the pyramid, while the daily yield of the single slope still of 30% higher than that of the pyramid in winter and 3% higher in summer was performed. The slope of solar still cover on the production rate was investigated by Pınar İlker Ayay and Gürbüz Atagündüz [6] done Theoretical and experimental investigations on solar distillation of IZTECH campus area seawater. They done a theoretical and experimental study of solar distillation in a single basin constructed at İzmir Institute of Technology Urla Campus. The still has had a base area of 2100 mm × 700 mm with a glass cover inclined at 38°. In order to obtain extra solar energy, an aluminum reflector (2100 mm × 500 mm) is also assembled to the still. They modeled the still and conducted its energy balance equations under minor assumptions. They compared the theoretical and experimental results and shown the benefits of the proposed model of the still and the efficacy of its energy balance equations.

According to in literature review mentioned, it seems that many studies were done for some countries. The aim of this study was to investigate a single basin solar still with a glass cover inclined at 25° of south direction in Iran. So we conducted a theoretical model of the solar still under consideration to describe the energy balances for the glass cover, seawater interface, black plate at the bottom and overall still and also to find still productivity. The main contribution of this paper is, therefore, the energy balance equations of the still. To our best knowledge, our study seems more comprehensive than other similar studies in the literature.

II. PROBLEM STATEMENT

In a simple solar still, solar radiation passes through the glass cover. This solar energy is almost entirely absorbed by

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the black cover on the basin while it is partially absorbed in the thin seawater layer. Thus, seawater and basin are heated by the solar energy. The heat is conducted from the black surface into the seawater and the temperature of the seawater increases. Vaporization takes place at the interface, seawater surface and air inside of the solar still, at the interface temperature, T_i . At the interface, the saturated air at the temperature, T_i , is transported by diffusion due to the partial pressure difference and convection due to the natural convection of the humid air from the interface into the air inside of the solar still with the temperature, T_r . In steady state or quasi-steady state conditions, the air inside of the solar still is also saturated at the temperature, T_r . Therefore, the humid saturated air inside of the solar still will condense at the glass cover, which has a lower temperature, T_g , then the air temperature inside solar still, T_r . Heat of condensation heats the glass cover. The glass cover is in heat exchange with surrounding and air inside of the still by convection and radiation. The condensate flows down, collecting along the glass cover and then in a channel at the end of the glass cover. Finally, it collects in a storage bottle outside of the still. The schematic view of the solar still can be seen in Fig. 1.

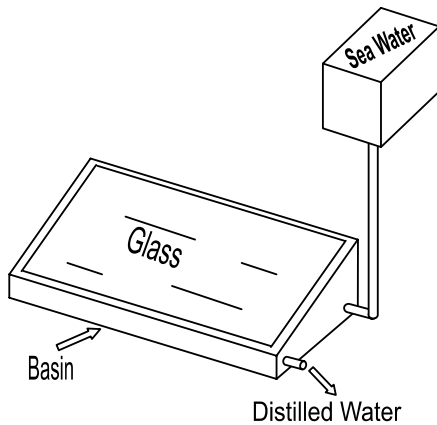


Fig. 1 Scheme of single basin solar still
(for the inclined 25° of south direction)

In order to be able to calculate the daily produced condensed water, we apply the energy balance method by making the following assumptions [6]:

- The whole system is in a quasi-steady state condition.
- Heat loss by radiation from the circumferential area is neglected.
- At the base of the still, temperatures of the walls equal to the water temperature, and the
- water temperature is the average of the interface temperature, T_i and the bottom temperature, T_b .
- The wind speed is assumed to be constant.

According to ref [6], maximum of received radiation is for the inclined 25° of south direction (for Chabahar).

The performance of a solar still is generally expressed as the quantity of water evaporated by unit area of the basin in

one day, i.e. cubic meters or liters of water per square meter of the basin area per day. This performance of a solar still can be predicted by deploying the energy and mass balance equations on the various components of the still. The whole system is in a quasi-steady state condition and the temperatures are assumed not to change in one hour interval of time. The energy balance equations for the whole still, glass cover, seawater interface and black plate at the bottom will be given next.

III. ENERGY BALANCE EQUATION

A. Energy balance for the whole still

We first consider the energy balance of the whole still. The input energy to the still and the heat transfer from the still to the atmosphere, are illustrated in Fig. 2. Hence, the energy balance equation can be written as:

$$I_s^* A_g = I_s^* r_g A_g + q_{g,s}^* A_g + q_{h,g}^* A_g + q_{k,air}^* A_{k,air} + q_{k,l}^* A_{k,l} + q_{k,b}^* A_b + (m_{cw}^* h_{sat,f}) \left[\frac{J}{S} \right] \quad (1)$$

In Eq. (1), I_s^* is the solar radiation intensity, r_g is the reflectivity of the glass cover for visible light, $h_{sat,f}$ is the enthalpy of water at saturation temperature T_g , m_{cw}^* is the mass flow rate of condensed water, A_g is the glass cover surface area and A_b is the bottom area covered by the seawater, The rate of heat transfer from the cover to the atmosphere by convection (caused by the wind):

$$q_{h,g}^* = h_g (T_g - T_a) \quad (2)$$

Where T_g , T_a and h_g are the glass cover temperature, ambient air temperature and convective heat transfer coefficient, respectively. The convective heat transfer coefficient (h_g) depends up on the prevailing wind speed it was given by McAdams [7] as:

$$h_g = 5.7 + 3.8w \quad (3)$$

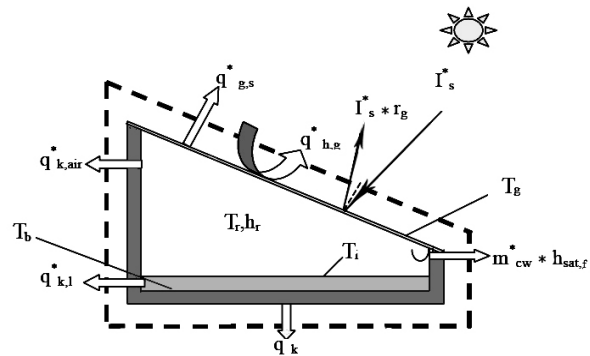


Fig. 2 Illustration of the overall energy balance.[6]

Where, w is the wind speed in m/s.

Radiative heat transfer from the glass cover to the atmospheric air is given as:

$$q_{g,s}^* = \varepsilon_g \sigma [(T_g)^4 - (T_{sky})^4] \quad (4)$$

where ε_g is the emissivity of the glass for infrared radiation, σ is $5.667 \times 10^{-8} \text{ W/m}^2\text{K}^4$, T_{sky} is the sky temperature in K and generally the average sky temperature during the operating hours is given by Swinbank [8] i.e.

$$T_{sky} = 0.0552 T_a^{1.5} \quad (5)$$

The conductive heat transfer from the bottom to the atmosphere can be formulated as:

$$q_{k,b}^* = k_b (T_b - T_a) \quad (6)$$

Where:

$$\frac{1}{k_b} = \frac{1}{h_{in}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{h_a}$$

considering the heat transfer from the circumferential area of the still by conduction. From inside moist air to the atmosphere,

$$q_{k,air}^* = k_r (T_r - T_a) \quad (7)$$

Where:

$$\frac{1}{k_r} = \frac{1}{h_r} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{h_a}$$

From liquid to atmosphere,

$$q_{k,l}^* = k_l (T_l - T_a) \quad (8)$$

Where:

$$\frac{1}{k_l} = \frac{1}{\infty} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{h_a}$$

and $T_l = (T_i + T_b)/2$ where T_i is the liquid seawater temperature.

B. Energy balance for glass cover

By following Fig. 3, the energy balance equation of glass cover is written as:

$$\begin{aligned} & I_s^* A_g + q_{i,g}^* A_g \cos \beta + q_{h,r}^* A_g + m_{m,air}^* h_{m,air,r} \\ & = I_s^* r_g A_g + I_s^* d_g A_g + q_{g,s}^* A_g + q_{h,g}^* A_g + \\ & q_{\lambda,gh}^* A_{\lambda,gh} + q_{h,gf}^* A_{h,gf} + (m_{cw}^* h_{sat,f}) \left[\frac{J}{S} \right] \end{aligned} \quad (9)$$

heat flux from the water surface to the glass and $h_{m,air,r}$ is the enthalpy of the water at saturation temperature T_r . $q_{\lambda,gh}^*$ and $q_{h,gf}^*$ are the heat losses from the back and front borders of the glass and they can be neglected for the sake of clarity.

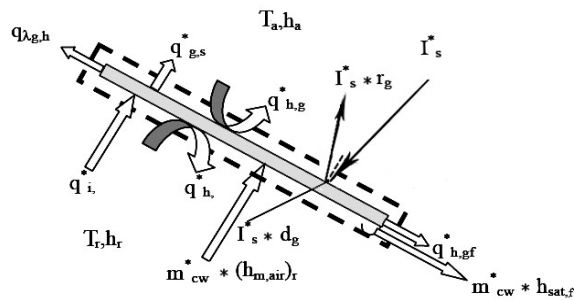


Fig. 3 Energy balance for glass cover.[6]

Between the optical permeable and non-permeable walls (water surface is assumed to be a non-permeable wall because transmittance of water equals to zero for infrared radiation), radiation heat transfer from the water to the glass is [9]:

$$q_{i,g}^* = \frac{\left[\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_g}{100} \right)^4 \right] + \left(\frac{1-\varepsilon}{\varepsilon_g} \right) \times D_g \times \left(\frac{T_i}{100} \right)^4}{\frac{1}{\varepsilon_g C_s} + \frac{1}{\varepsilon_w C_s} - \frac{1}{C_s} + \frac{1-\varepsilon_p - \varepsilon_g}{\varepsilon_w \varepsilon_g C_s} d_g} \quad (10)$$

where ε_w is the emissivity of water and d_g is the transmittance of glass for infrared radiation.

Convective heat transfer from the water to the glass is:

$$q_{h,r}^* = h_r (T_r - T_g) \quad (11)$$

where h_r is the convective heat transfer coefficient. it is given by Dunkle [10] in the following expression:

$$h_r = 0.884 \left[(T_i - T_g) + \frac{P_i - P_g}{268900 - P_i} (T_i) \right]^{1/3} \quad (12)$$

Where P_i and P_g , are the partial pressures in (N/m^2) for water vapor at water and the glass cover temperatures within the still which are given by Fernandez and Chargooy [11] as:

$$P_{partial} = \exp \left[25.317 - \left(\frac{5144}{T} \right) \right] \quad (13)$$

C. Energy balance for seawater interface

By referring to Fig. 4, the energy balance for seawater interface can be written as:

$$\begin{aligned} & I_s^* d_g A_g + q_{\lambda}^* A_b = I_s^* d_g r_w A_b + I_s^* d_g d_w A_b \\ & + q_{i,g}^* A_b + q_{h,r}^* A_b + m_{m,air}^* h_{m,air,i} \left[\frac{J}{S} \right] \end{aligned} \quad (14)$$

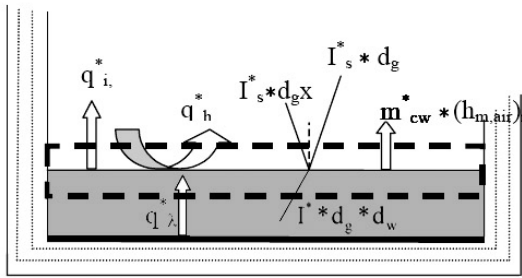


Fig. 4 Heat transfer modes for seawater interface.[6]

where d_w is the transmittance of water, r_w is the reflectivity of water for visible light. $h_{m,air,i}$ is the enthalpy of water at saturation temperature T_i . The conductive heat transfer from the bottom to the seawater interface is:

$$q_\lambda = \frac{\lambda_w}{\delta_w} (T_b - T_i) \quad (15)$$

and the heat transfer from seawater interface to the glass cover is:

$$q_{h,r} = h_r (T_i - T_r) \quad (16)$$

D. Energy balance for black plate

According to Fig. 5, the energy balance for black plate can be written as:

$$I_s^* d_g d_w A_b - I_s^* d_g d_w r_b A_b = q_\lambda^* A_b + q_{k,b}^* A_b - q_{c,b}^* A_b \quad \left[\frac{J}{S} \right] \quad (17)$$

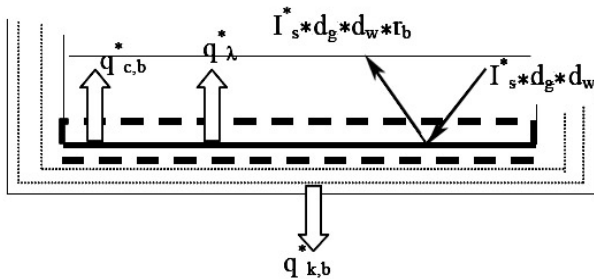


Fig. 5 Energy balance for black plate.[6]

Where r_b is the reflectivity of the black plate. $q_{c,b}^*$ is the convective heat transfer from bottom to the seawater, i.e.

$$q_{c,b}^* = h_{cb} (T_b - T_i) \quad (18)$$

Since the seawater depth in the still is very thin, the convective heat transfer from the black plate to the seawater can be neglected. The mass transfer coefficient is:

$$h_M = \frac{h}{\rho C_p} \quad [m/s] \quad (19)$$

The mass flow rate of the evaporated water mass will be calculated according to the semi-permeable plane theory. For this purpose, first of all, we calculate the mass flux for a non-permeable plane according to the Reynolds analogy. By using this value, the mass transfer coefficient for semi permeable plane becomes:

$$h_{M,h} = h_M \frac{P}{P_i - P_r} \ln \frac{P - P_r}{P - P_i} \quad (20)$$

Hence, the mass flow rate of the evaporated water mass is [6]:

$$m_{vapor}^* = h_{M,h} \frac{1}{RT} (P_i - P_r) A_b \quad [kg/s] \quad (21)$$

R denotes the universal gas constant in Nm/kgK and T denotes the moist air temperature in K.

The efficiency of a still can be calculated by the following equation[6]:

$$\eta = \frac{m^* \times L_v}{I_{s,t} \times A_g} \times 100\% \quad (22)$$

where m^* is the daily output (kg/m²s), L_v is the latent heat of evaporation of water (kJ/kg) and $I_{s,t}$ is the daily total solar radiation (kJ/m²s).

IV. NUMERICAL METHOD

We developed a computer program that implements appropriate numerical analysis methods in order to solve the energy balance equations. This program allows us to calculate the temperatures of the glass cover, the inside moist air, the bottom and the interface, depending on the amount of the radiation and various other parameters given as the input to evaluate theoretically the amount of evaporated water for a given solar radiation, ambient temperature and other parameters. In this program, we utilize the newton method to solve four non-linear equations.

V. RESULTS AND DISCUSSION

A. Validation

The accuracy of results is verified with available data by Pinar İlker Ayav et al.[6] and is depicted in table 1. As shown the current results are in good agreement with Pinar İlker Ayav's results.

TABLE I HOURLY VARIATION OF THEORETICAL TEMPERATURE VALUES ON 28.04.2003

Time	Pinar İlker Ayav's Work[6]			
	T_{bottom}	$T_{moistair}$	$T_{interface}$	T_{glass}
9--10	47.14	25.85	39.67	21.1
10--11	62.26	45.01	53.47	25.97
11--12	73.91	58.19	64.12	28.65

12--13	89.06	76.38	79.12	35.98
13--14	94	83.3	84.88	37.87
14--15	89.84	80.24	81.81	35.62
15--16	82.72	77.2	77.38	34.28
16--17	76.98	74.78	73.66	29.76
Present Work				
Time	T _{bottom}	T _{moistair}	T _{interface}	T _{glass}
9--10	48.50	26.51	40.53	21.51
10--11	64.03	46.18	54.45	26.34
11--12	76.41	59.83	64.61	28.97
12--13	91.60	78.82	80.12	36.35
13--14	96.92	84.46	85.88	38.42
14--15	92.30	82.34	82.67	35.80
15--16	85.45	78.51	79.45	34.62
16--17	76.33	75.36	75.82	30.09

B. Effect of amount of radiation on the solar still temperatures

Fig. 6 presents the theoretical hourly solar radiation values on tilted surface ($\beta=25^\circ$) on the 6th day of July and on the 6th day of December. As shown that solar radiation in July was higher than December. So this had the maximum amount at noon for both.

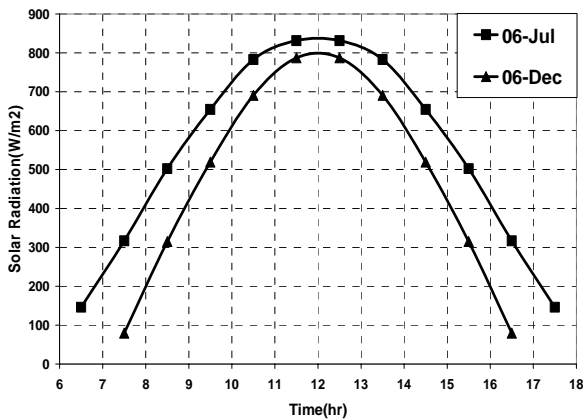


Fig. 6 Hourly solar Radiation values on tilted surface ($\beta=25^\circ$)

Figs. 7 and 8 present the theoretical hourly variation of temperatures on the 6th day of July and December. These calculations were performed with known solar radiation and ambient air temperature (30°C on the 6th day of July and 10°C on the 6th day of December). According to these figures, variation of temperatures matches with variation of solar radiation.

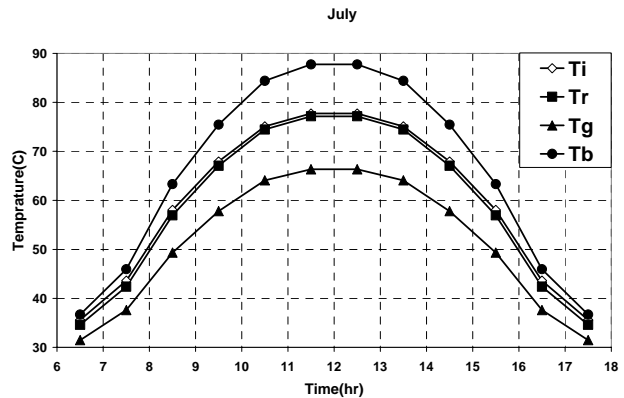


Fig. 7 Hourly variation of temperature values on solar still (6th July)

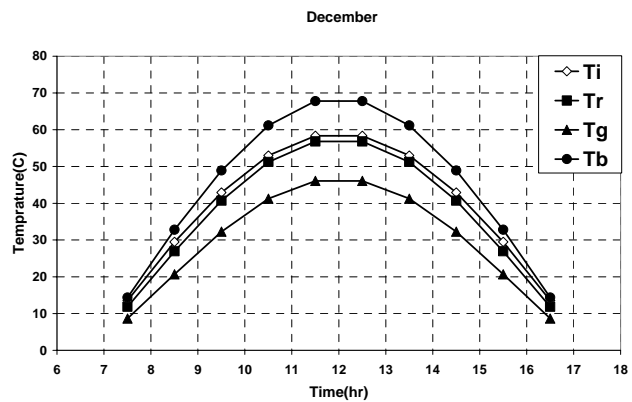


Fig. 8 Hourly variation of temperature values on solar still (6th December)

C. Effect of amount of radiation on the productivity of the distilled water and efficiency of solar still

Fig. 9 presents hourly productivity of the distilled water values. According to the figure maximum of productivity of the distilled water is occurred at noon in July and December. Variation of productivity of the distilled water matches with variation of solar radiation.

Hourly variation of the distilled water values is given in Fig. 10. According to the figure, the amount of distilled water calculated theoretically for July is 4.81 Lit/m^2 and the amount of distilled water calculated for December is 3.67 Lit/m^2 .

The hourly variation of the still efficiency for 6th of July and December is shown in Fig. 11, which indicates the efficiency of the still increases to a maximum value at noon. So this figure shows that variation of efficiency follows than amount of radiation.

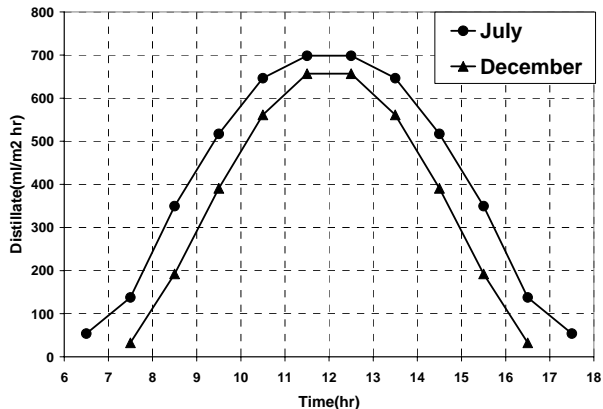


Fig. 9 Hourly productivity of the distilled water values

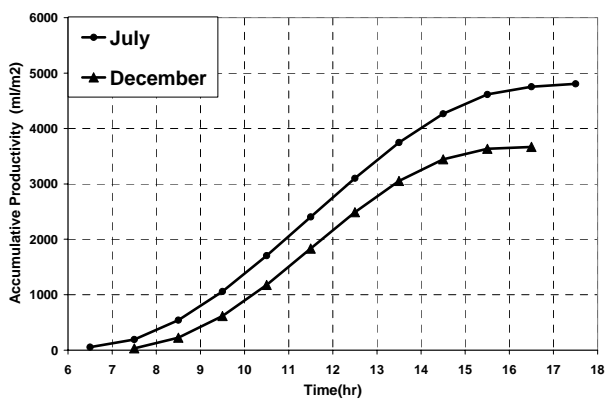


Fig. 10 Hourly variation of the distilled water values

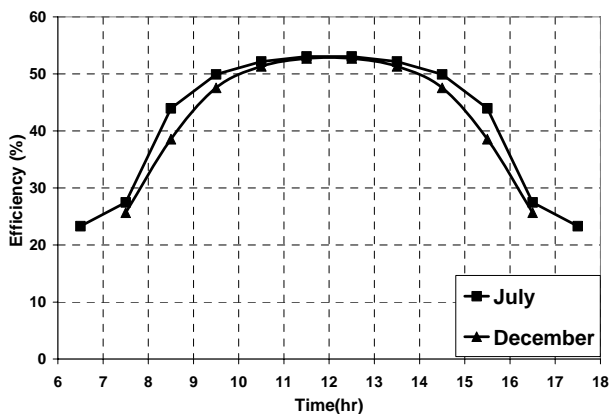


Fig. 11 Hourly variation of the still efficiency

VI. CONCLUSION

In this work, we developed a theoretical framework of a typical single basin solar still. This framework enabled us to establish the numerical solutions of the basic heat and mass transfer equations of the solar still. We compared results of July with results of December. These comparisons show that the amount of distilled water in July is more than December. We showed that the developed model can be very useful for designing and analyzing the solar stills. So we found out the efficiency of the solar still was maximum at noon and variation of efficiency follows that amount of radiation. Appropriate accommodation between efficiency's amount in July and December represent accuracy of single basin solar still operation and calculation performed. More comparisons show that still productivity is directly function of solar radiation..

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