PARABOLIC TYPE SOLAR STILL

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ABSTRACT

A complete design and fabrication procedure for a distilled water apparatus is given. The design is based on a line concentrator of parabolic reflector type, which can be used for sea water distillation. A steady state theoretical model based on energy balance is presented. The experimental results are compared with the theoretical as well as with the available data. The comparison shows a satisfactory agreement. The maximum fraction that can be evaporated from water flow rate is investigated and recommendations are given.

INTRODUCTION

The idea of using solar energy for distillation is quite important, since the need for fresh water is increasing and the energy resources are decreasing. Many studies have been conducted on solar still [1-8]. The main objective of each of these studies was to gather information which may lead to the reduction the cost of the produced water either by increasing the efficiency of the still or by reducing the costs of the plant, including those of construction, operation, and maintenance.

Several different solar still designs have been investigated theoretically and experimentally by Hirschman [1] and Bloemer et al [2]. A single type solar still having optimum effective height (0.24 m) well sealed and with well insulated base was constructed by Soliman [3]. Observations for temperatures of water, cover, and ambient air together with solar intensity were recorded. Sharif and Kiss [4] had introduced a numerical simulation procedure to predict the daily fresh water production of a solar still.

In an attempt to increase the productivity of a basin type solar still, Hegazy [5] used two flat booster reflectors in order to increase the quantity of solar radiation incident into the evaporator. The effect of such reflectors on the still's performance over a year had been studied.

A solar collector consisting of thin film, inclined, free flow, flat plate had been studied both experimentally and theoretically by Lesson and Bootebila [6]. As their objective was distillation applications, a condensing system was introduced in their experimental rig.

A study of the factors affecting the productivity of the solar still by Akinsete et al [7], showed that the solar radiation is the critical and the most important one. However, Morse and Read [8] have shown that an ambient temperature change from 26.7°C to 37.8°C causes an 11% increase in the output, and a change from 26.7°C to 15.6°C causes a 14% drop. This emphasizes that the ambient temperature is also an important factor affecting the productivity of solar still.

The aim of the present work is to introduce a system utilizing a line concentrator of parabolic type, to produce distilled water of reasonable quality. A complete model for steady state conditions for the proposed system is given.

EXPERIMENTAL SET-UP

A schematic diagram for the experimental set-up, constructed at Mu'tah University, Jordan, is shown in Figure (1), and a flow diagram is given in Figure (2). The apparatus consist mainly of a parabolic concentrator, a separation and condensation unit, and two heat exchanger. The specification of the parabolic reflector used in the present study is given in Table 1.

Table 1. Specification of the parabolic reflector.

Focal length	36.5 cm
Width of line concentrator (calculated from equation given in Ref. [9] page 132.)	8.71 cm
Width of reflector	70 cm
Rim angle	44.5 degrees
Acceptance angle	1 degree
Concentration factor	20.5
Concentration ratio	57.3
Length of the parabolic reflector	1.4 meter

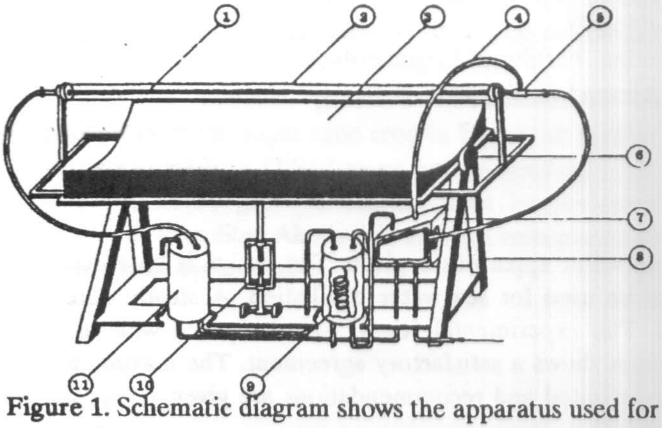

Figure 1. Schematic diagram shows the apparatus used for water distillation 1: collector tube; 2: glass cover; 3: parabolic reflector; 4: flexable tube; 5: T connection 6: bearing; 7: separation and condansation unit 8; frame; 9: frist exchanger; 10: tilting mechanism; 11: second heat exchanger.

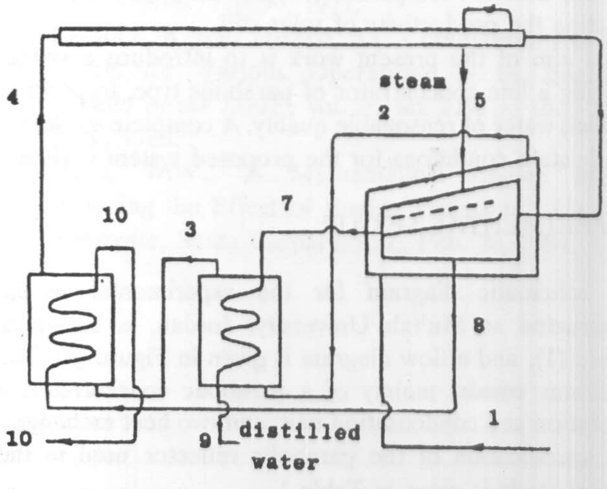

Figure 2. Flow diagram showing the flow of water and the loaction of thermocouples.

In the separation and condensation unit, the steam coming through point 5 [see Figure (2)] in addition to that which may be combined with hot water through point 6 is condensed on the surface of the two inclined plated inside the unit. Then it is collected to flow through point 7. Meanwhile, the non-distilled water comes out from point 8. The upper inclined plate has a gap near its lower end to allow the condensed water to fall down on the lower plate. The separation and condensation unit is fabricated from galvanized steel. It is preferable to fabricate the unit from either glass or stainless steel, but unfortunately, this was not possible at Mu'tah University.

In the first heat exchanger, the raw water makes use of the sensible heat contained in the condensed steam. The water that exits from the first heat exchanger (point 3) enters the second heat exchanger, in which the raw water temperature increases once again due to the sensible heat contained in the non-distilled water.

The beam radiation at the site of the experiment was measured using normal incidence Pyrheliometer (NIP) instrument. The system is provided with a tilting mechanism as well as with four wheels at the bottom of the carrying frame, in order to allow manual adjustment to the normal radiation.

The temperature at different locations where measured using ten K type thermocouple (Ni-Cr/Ni-Al), inserted at the corresponding points as shown in Figure (2).

It is to be emphasized that the elevation level of the separation and condensation unit must be higher than the top of the heat exchanger, which means that, the elevations of points 6 and 7 must be higher that those of point 3 and 10.

THEORETICAL ANALYSIS

The amount of energy received by reflector can be given as:

$$E_1 = A_o I_b \tag{1}$$

while the energy reflected by reflector is given as:

$$E_2 = \rho E_1 \tag{2}$$

and the energy absorbed by the collector can be given as:

$$E_3 = \gamma \tau \alpha E_2 \tag{3}$$

The combined effect of radiation q_{r4} and convection q_{c4} losses from the absorber to the cover can be given as:

$$E_4 = q_{r4} + q_{c5} \tag{4}$$

Similarly, the total heat losses due to wind effect and sky radiation from the collector cover can be calculated as:

$$E_5 = q_{r5} + q_{c5} \tag{5}$$

where the heat flux components q_{r4}, q_{c4}, q_{r5} and q_{c5} are given in appendix A.

For a thin glass cover the heat balance for the glass cover can be simplified to $E_4 = E_5$. This will give the temperature of the glass cover T_c. The Energy balance for the separation unit gives (after canceling the mass flow rate):

$$xh_g + (1-x)h_f + c_pT_1 = xc_p T_7 + (1-x)c_p T_8 + c_p T_2 \tag{6}$$

On canceling $\dot{m}$ and c_p; the energy balance for the two heat exchanger gives:

For heat exchanger I:

$$xT_7 + T_2 = T_3 + xT_9 \tag{7}$$

For heat exchanger II:

$$T_3 + (1\text{-}x)T_8 = T_4 + (1\text{-}x)T_{10} \tag{8}$$

Heat balance for the collector tube gives:

$$E_3 - E_4 + \dot{m}c_p\,T_4 = x\,\dot{m}h_g + (1\text{-}x)\,\dot{m}h_f \tag{9}$$

Additional assumptions used as boundary conditions are:

$$T_5 = T_6 = T_s \tag{10}$$
$$T_7 = T_8 = T_s - \Delta T_1 \tag{11}$$
$$T_9 = T_3 + \Delta T_2 \tag{12}$$
$$T_{10} = T_4 + \Delta T_3 \tag{13}$$

Where ΔT_1, ΔT_2 and ΔT_3 are the allowable temperatures drops in the separation and condensation unit and the two heat exchanger respectively. All These temperature drops were considered to be 3°C. The system of equations (6 - 8) together with equations (10 - 13) can be solved to get the temperature distributions, then equation (9) can predict the mass flow rate. The efficiency of the collector can be defined as:

$$\eta_1 = \frac{E_3 - E_4 - E_5}{E_1} \tag{14}$$

The efficiency of the plant can then be defined as:

$$\eta_2 = \frac{x\dot{m}\,h_g}{E_1} \tag{15}$$

RESULTS AND DISCUSSION

The solution of the system of equations 1 through 14 has been carried out analytically. The set of results obtained at $T_1 = 20°C$, and beam radiation 900 W/m², are tabulated in Table 2 and plotted in Figure (3). It is clear that as x (the ratio of distilled water to the total mass flow rates) increases, each of T_2, T_3, T_4, T_9 and T_{10} increases linearly, that is because as x increases, more latent heat can be used to heat the inlet water. It is clear from Table 3 that a decrease of $\dot{m}$corresponds to an increase of x.

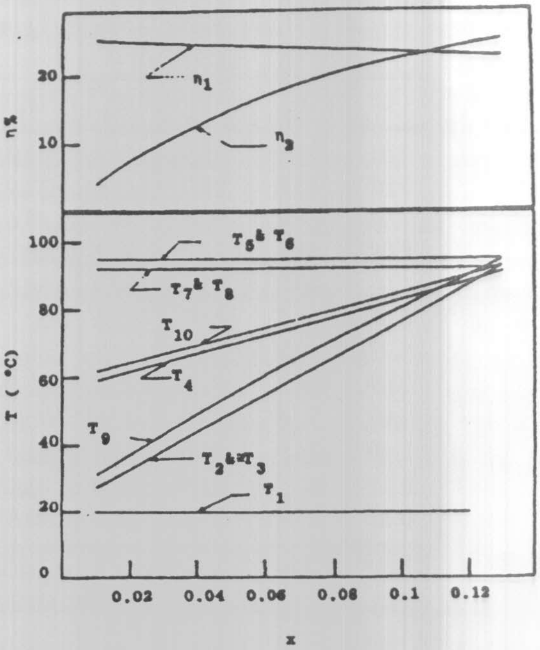

Figure 3. Shows the effect of on x temperatures distribution and on the efficiency.

This may be understood as we have the same amount of solar energy input to the system and consequently as $\dot{m}$ decreases more vapor is produced.

It is very important to mention that not any value of x can satisfy the solution of equation 6 as during condensation, the amount of heat contained in the steam must be less or equal to the amount of sensible heat that can be gained by the inlet water flow. The amount of steam will be a small fraction of the water flow (see Table 3), since the latent heat of steam per unit mass is much greater than the sensible heat per unit mass. This observation is quite important especially if the raw water used comes directly from sea or unclean source. In such a case a reasonable amount of unevaporated water (in the collector tube) is needed to flow in the system for the removal of deposited matter; otherwise a fouling problem will occur.

An Investigation to find the maximum fraction of water flow that can be evaporated (x_{max})has been done using the system of equations mentioned above. Starting with a small value of x (0.001), the solution gives the temperatures and the mass flow rate. Then the calculation is repeated with a higher value of x (increment of 0.001) until the calculations is self terminated when the temperature T_2 and/or T_3 reaches the saturation temperature T_s. At this situation, x_{max} is obtained. The results are tabulated in

Table 3 and plotted in Figure (4).

Table 2. The Effect of x on Temperatures Distribution and Mass Flow Rate.
(T_1 = 20°C, $T_5 = T_6 = T_s$ = 95°C + , $T_7 = T_8$ = 92°C)

x	T_2	T_3	T_4	T_9	T_{10}	$\dot{m}$	$x\dot{m}$	T_c	η_1	η_2
0.01	28.4	28.9	58.8	32.0	61.8	6.90	.069	53.3	37.0	5.6
0.02	33.8	34.9	61.6	37.9	64.7	6.47	.129	54.2	36.9	10.6
0.03	39.2	40.6	64.4	43.6	67.4	6.10	.183	55.0	36.8	15.0
0.04	44.6	46.2	67.2	49.2	70.2	5.70	.228	55.9	36.7	18.8
0.05	49.9	51.8	69.9	54.8	72.9	5.40	.270	56.7	36.6	22.3
0.06	55.3	57.2	72.6	60.2	75.6	5.16	.309	57.6	36.5	25.4
0.07	60.7	62.6	75.3	65.6	78.3	4.90	.343	58.4	36.4	28.1
0.08	66.1	67.8	78.0	70.8	81.0	4.67	.373	59.3	36.3	30.6
0.09	71.5	73.0	80.6	76.0	83.6	4.45	.400	60.1	36.2	32.8
0.10	76.9	78.0	83.2	81.0	86.2	4.25	.425	61.0	36.1	34.8
0.11	82.3	82.9	85.8	85.9	88.8	4.07	.447	61.8	36.0	36.6
0.12	87.7	87.8	88.4	90.8	91.4	3.89	.467	62.7	35.9	38.2

+ Mu'tah is located at an altitude of about 1100 meters above sea level,
where the pressure is less than atmospheric.

Table 3. The Effect of Inlet Water Temperature on x_{max}, and m.

T_1 °C	10	15	20	25	30	35	40
x_{max}	0.152	0.142	0.133	0.124	0.115	0.105	0.096
$\dot{m}$(kg/m²hr)	3.072	3.281	3.496	3.742	4.034	4.401	4.802
$x\dot{m}$(kg/m²hr)	0.467	0.466	0.465	0.464	0.463	0.462	0.461

Table 4. The Experimental Results Carried out at Mu'tah University, Jordan.

date	Time	T_1	T_2	T_3	T_4	T_5	T_7	T_8	I_b	$x\dot{m}$	$(1-x)\dot{m}$	x	η_1	η_2
31/8	9:30	27.2	28.5	27.2	45.4	46.1	26.2	28.5						
	10:30	35.1	43.1	32.4	33.7	96.1	38.3	41.6	840	.185	1.575	.105	23.8	13.0
	11:30	39.1	57.3	34.1	54.1	99.8	35.2	48.0	850	.190	1.575	.107	24.2	13.4
	12:30	38.6	54.6	39.6	64.6	95.6	40.6	45.7	850	.205	1.545	.117	24.7	14.6
	13:30	43.7	53.2	48.3	50.1	99.5	38.7	50.0	840	.200	1.580	.112	24.4	14.3
5/9	11:00	35.6	56.6	39.3	49.6	100.3	35.0	45.5						
	12:00	36.5	56.1	39.6	66.1	99.8	36.0	47.5	930	.182	1.506	.108	21.7	11.7
	13:00	43.7	53.2	48.3	40.0	99.5	38.7	50.0	930	.196	1.492	.116	21.4	12.7
26/9	10:30	32.9	40.1	29.0	33.2	85.9	28.1	46.5	970					
	11:30	37.9	49.0	30.2	47.8	96.3	30.9	45.8	975	.175	1.800	.089	21.2	10.8
	12:30	43.6	49.5	37.0	69.4	99.2	34.9	56.5	975	.195	1.780	.099	21.8	12.0
	13:30	38.9	49.6	35.3	59.5	96.3	34.7	49.1	975	.198	1.775	.100	22.4	12.4

Figure (4) shows that as T_1 increases x_{max} decreases, this is due to the fact that an increasing of T_1 leads to a less tendency of gaining heat from the condensation and separation unit. Therefore more $\dot{m}$ must be supplied and as a result we obtain less x_{max}. The calculated data show that the predicted values of the product of x_{max} and its corresponding $\dot{m}$ are very nearly constant independent of T_1 as it should be.

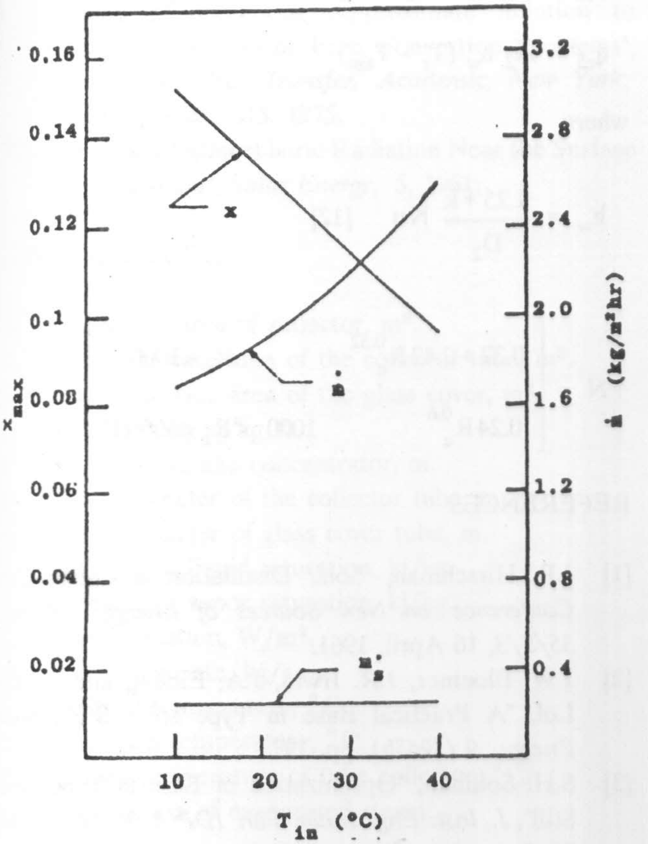

Figure 4. Shows the effect of inlet temperature on x_{max}, m and the amount of distilled water, m_x (=xm).

The results of an experimental run carried out during September, 1989 at Mu'tah University, Jordan, are tabulated in Table 4. It can be seen that the calculated temperatures are far away from the experimental results. That is because the initial volume of water contained in the system (each heat exchanger has a volume of about 10 litres and that of the separation unit is around 2 litres) needs too much energy to be stored as sensible heat before it reaches the steady state conditions which is difficult to achieve in proper time.

Since the flow rate during the experimental runs was very small (around 2 litre/hr.), it was not practically possible to record the temperatures T_9 and T_{10}. As the flow pattern was in the form of very small drops, one at a time, therefore there was no enough water to fill the surrounding of the copper tube in which the thermocouple is inserted. Furthermore, due to the very low flow rate and the energy gained by the inlet tube directly from solar radiation, T_1 increases with time with a result of non-steady conditions.

In Table 5, a comparison between the present experimental results with those reported by some other investigators, are given. It is clear that the productivity of the present work is slightly higher than all that reported in similar works. In addition, it was possible to get the maximum value for a period of 4 hours as compared to a period of one hour in basin type [4 and 11]. This is due to the facility given in the apparatus which is the manual tracking of the sun.

Table 5. The Maximum Productivity Comparison. (kg/m²hr.)

Present work	Ref.[4]	Ref.[5]	Ref.[11]
0.17	0.16	0.13	0.15

The plane efficiency η_2 was found experimentally to be 12.76% on the average, while similar efficiency found by Zuhair [11] was 10%.

A collected sample of distilled water was tested in the Chemistry Department at Mu'tah University, Jordan. The following results where obtained:

Test type	PH	Electrical conductance Ω^{-1}
Sample	7.4	2.6×10^{-4}
Tap water	7.9	1.0×10^{-3}
Distilled water*	7.2	3.4×10^{-5}

* Sample of distilled water was obtained from an automatic water stills apparatus, manufactured by GFL company, W. Germany, Model 2002.

These results show that the properties of the product water obtained from the solar still are closer to those of distilled water. The discrepancy in the electrical conductance may be due to the contamination of the product water as it is in permanent contact with the welded galvanized steel. Also the product water remains a long period of time in the steel tubes connected to the heat exchanger due to the small flow rate. Therefore a recommended modification for such apparatus is to use plastic tubes in all connections and smaller heat exchanger, of concentric type with an inner glass tube. Also the separation and condensation unit should be fabricated from glass or stainless steel.

CONCLUSIONS

The following remarks can be concluded with:

1. The proposed apparatus is an efficient and acceptable method to obtain distilled water of reasonable properties at an isolated area.
2. The proposed apparatus can work as double purpose for heating and/or distillating water.
3. More modification can be done, such as manufacturing the separation unit from glass and using plastic tubes. Also a smaller heat exchanger must be used.

ACKNOWLEDGMENT

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APPENDIX A

$$q_{r4} = \frac{\sigma(T_{su}^4 - T_c^4)}{\frac{1-\epsilon_1}{A_1 \epsilon_1} + \frac{1}{A_1 F_{1-2}} + \frac{1-\epsilon_2}{\epsilon_2 A_2}}$$

where F_{1-2} is the shape factor ($F_{1-2} = 1$)

$$q_{c4} = \frac{2\pi k_{eff} L}{\ln D_2/D_1} (T_{su} - T_c) \quad [11]$$

where T_{su} is the average surface temperature [$T_{su} = (T_4 + T_5)/2$],

$$\frac{k_{eff}}{k} = 0.386 \left(\frac{P_r}{0.861 + P_r}\right)^{1/4} R_a^{*1/4}$$

$$R_a^{*1/4} = \frac{\ln D_2/D_1}{\delta^{3/4}(D_1^{-3/5} + D_2^{-3/5})^{5/4}} R_a^{1/4}$$

$$R_a = \frac{g\beta(T_{su} - T_c)\delta^3}{\gamma^2} P_r$$

$$\delta = 1/2\,(D_2 - D_1)$$

for $10^2 < R_a{}^* < 10^7$

$$q_{r5} = A_2\, \epsilon_2\, \sigma(T_c^4 - T_a^4)$$

$$q_{c5} = A_2\, h_w\, (T_c - T_{am})$$

where

$$h_w = \frac{1.25 * k}{D_2} Nu \quad [12]$$

$$N = \begin{bmatrix} 0.32 + 0.43 R_e^{0.52} & R_e < 1000 \\ 0.24 R_e^{0.6} & 1000 < R_e < 50000 \end{bmatrix}$$

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NOMENCLATURE

A_0	Projected area of reflector, m^2.
A_1	Outer surface area of the collector tube, m^2.
A_2	Outer surface area of the glass cover, m^2.
c_p	Specific heat, kj/kg K.
d	Width of the line concentrator, m.
d_1	Outer diameter of the collector tube, m.
d_2	Outer diameter of glass cover tube, m.
h_f	Enthalpy of liquid saturation, kj/kg.
h_g	Enthalpy of vapor saturation, kj/kg.
I_b	Beam radiation, W/m^2.
m	Water flow rate, kg/s.
T_{am}	Ambient temperature, °C.
T_s	Saturation temperature, °C.
T_{su}	Surface temperature of tube collector, °C.
x	The fraction of evaporated steam.

Greek Symbols

ρ	Reflectivity of the reflector = 0.55
α	Absorbitivity of the collector tube = 0.9
τ	Transmissivity of the glass tube = 0.9
γ	Shape factor = 1.0
ϵ	Emissivity of the collector tube = 0.9
σ	Stefan-Boltzman constant = 5.68×10^{-8} W/m^2K^4