EVALUATION AND ENERGY BALANCE STUDY OF A SOLAR STILL WITH AN INTERNAL CONDENSER☆

Abdul - Jabbar N. Khalifa
Solar Energy Research Center
Scientific Research Council
P.O.Box 13026, Jaderyiah, Baghdad

ABSTRACT :

An experimental study was carried out to evaluate the effect of using an internal condenser on the performance of a basin type solar still. The condenser was tested in two different ways: first it was used for water preheating and water vapor condensation, and second it was used for water vapor condensation only.

The still was single - sloped with an internal condenser, its effective base area was 0.55 m^2 and its cover slope was 30°.

The results showed that combining an internal condenser with the basin type solar still caused an improvement in the still performance. The still daily productivity was increased from 5.086 to 5.811 kg / m^2. day for the first test and to 5.617 kg / m^2. day for the second test.

An energy balance study on the solar still for different tests was also included.

LIST OF SYMBOLS:

A: Refers to test A
a_g: Absorptivity of transparent cover for radiation
a_w: Absorptivity of water to radiation
B: Refers to test B.
C: Refers to test C.
C_{gs}: Heat capacity of transparent cover and supports per unit basin area, (kJ / m^2. K).
C_{wb}: Heat capacity of water basin and contents per unit basin area, (kJ / m^2. K).
E_d, E_h: Daily and hourly efficiency, respectively.
E_w: Efficiency through working hours.
Ih: Incident solar radiation on a horizontal surface, (kJ / hr. m^2).
Lh: Latent heat of evaporation, (kJ / kg).

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$\dot{m}$: Mass flow rate, (kg / min).
P_w: Vapor pressure of water at temperature of water surface, (N / m^2).
P_{wg}: Vapor pressure of water at temperature of transparent cover, (N / m^2).
q_c: Heat flux by convection from water surface to transparent cover (kJ / hr.m^2).
q_{cond}: Heat lost to the circulated water, (kJ / hr.m^2).
q_e: Heat flux by evaporation / condensation from water surface to transparent cover, (kJ / hr.m^2).
q_{ga}: Heat flux from transparent cover to air, (kJ / hr.m^2).
q_r: Heat flux by radiation from cover to air, (kJ / hr.m^2).
t: time, (sec).
T_a: Ambient temperature, (K).
T_g: Temperature of transparent cover, (K).
T_w: Water temperature (K).
τ: Transmissivity of transparent cover for radiation.
Y: Still productivity, (kg / hr.m^2).

1 . INTRODUCTION:

Most existing desalination plants use fossil fuel as a source of energy. The conventional distillation processes such as multieffect evaporation, multistage flash evaporation, thin film distillation, reverse osmossis, and electrodialysis are not only energy intensive but also uneconomical when the demand of fresh water is small. The maximization of water production rate of the basin type solar still is therefore a prime objective in the development of solar distillation.

Many attempts had been made to improve the performance of the basin type solar still. Collins et al(1), and Grune et al(2) made tests on a simple solar still coupled with an external condenser. An air vapor mixture was circulated from the still to an external water cooled condenser, where the condensate was extracted. The latent heat of condensation was utilized to preheat the feed water. Malik et al(3) reported that Bartali et al developed a simple still coupled with a chimney containing a heat exchanger. The saline water entered the chimney, flowed through the heat exchanger and then entered the still. The water evaporated and diffused into the chimney and condensed on the external fins of the heat exchanger. The latent heat released in the heat exchanger preheated the feed water. Abed(4) made tests on a simple still coupled with an internal condenser, the condenser was fixed on the back wall of the still.

In this work, a basin type solar still with an internal condenser was constructed, and an investigation with the following objectives has been carried out:

1 - To study the performance of a basin type solar still combined with an internal condenser from the standpoint of energy utilization and overall efficiency.

2 - To explore design modification for increasing the productivity of a desalination unit.
3 - To explore design modification for the reuse of latent heat of evaporation.

2 . ENERGY CONSIDERATIONS:

The amount of distillate produced in a solar still depends primarily on the amount of solar radiation available, but it is affected by several other factors. On the other hand, the efficiencyof utilization of energy in the solar still is affected by various modes of heat and mass transfer that take place as a result of the total incident solar radiation. Löf(5) identified the energy leaving the basin as follows:
1 - Thermal radiation from water and basin bottom to cover.
2 - Sensible heat transferred from water surface to cover by circulating air in the enclosure.
3 - Conduction losses to the ground or other surroundings, which could be neglected in well insulated stills(6).
4 - Sensible heat in effluent distillate and feeding water.
5 - Enthalpy in any vapor or liquid streams which might escape from the enclosure, (assumed negligible).

With these factors in mind, the energy flow diagram for the basin type solar still is presented in Figure (1). By calculating the above mentioned components, it was possible to locate losses in the still, to appraise their importance, and to gain insight as to improvements that might be made in still design.

The values of the above factors were influenced by the temperatures of the basin (T_w), the cover (T_g) and the ambient air (T_a). The basin temperature influenced the thermal radiation from the basin to the cover and the sensible heat transfer between the water and cover which accompanied the useful transfer of water vapor. The cover temperature affected the distillation rate and efficiency. All the heat transferred to the underside plus the solar absorption in it ought to be dissipated by convection and radiation to the surroundings. Ambient air temperature and other factors such as wind velocity and atmospheric clarity all affect the heat transfer rate from the distiller.

Referring to Figure (1), heat balance equations could be written for several conditions(5-10) as shown below:

1 - Heat balance for basin water:

$$a_w \cdot \tau \cdot Ih = q_b + C_{wb} \cdot \frac{dT_w}{dt} + q_e + q_r + q_c \qquad \text{............. (1)}$$

2 - Heat balance for glass cover:

$$q_e + q_c + q_r + a_g \cdot Ih = q_{ga} + C_{gs} \cdot \frac{dT_g}{dt} \qquad \text{............. (2)}$$

3 - Heat balance of the basin and cover assembly:

$$a_g . Ih + a_w . \tau . Ih = q_{ga} + q_b + C_{wb} . \frac{dT_w}{dt} + C_{gs} . \frac{dT_g}{dt} \qquad .... (3)$$

The predominant modes of heat transfer in a solar still are convection, evaporation and radiation, which could be approximated as that between two parallel planes (6,7,8), using following equations to describe those modes:

$$q_r = 18.371 \times 10^{-8} (T_w^4 - T_g^4) \qquad .... (4)$$

$$q_c = 3.1824 \left[(Tw - Tg) + \frac{P_w - P_{wg} . T_w}{2.65 \times 10^5 - P_w}\right]^{1/3} (T_w - T_g) \qquad .... (5)$$

$$q_e = 16.276 \times 10^{-3} \times q_c \frac{P_w - P_{wg}}{(T_w - T_g)} \qquad .... (6)$$

The heat flux due to condensation is assumed equal to that by evaporation and is given by:

$$q_e = Y.Lh \qquad .... (7)$$

Heat lost to the circulated water could also be calculated from equation (7).

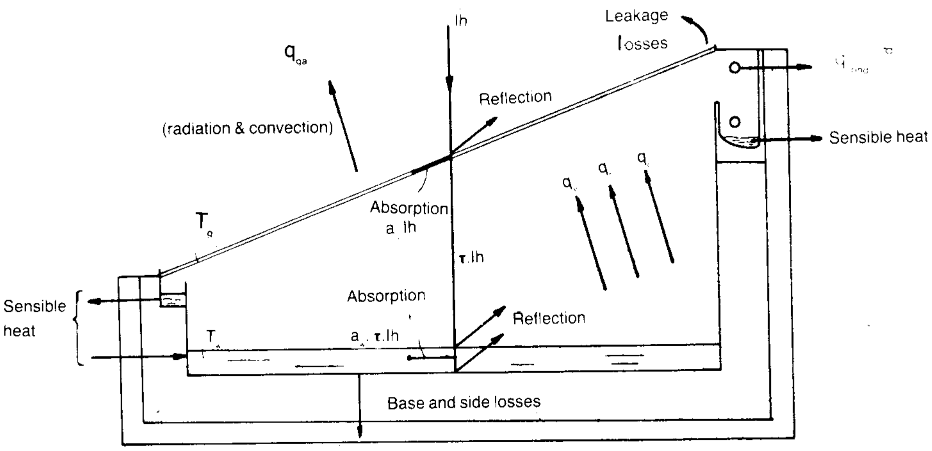


Fig (1) Energy flow diagram for the solar still

3 - EXPERIMENTAL CONSIDERATIONS:

3.1 Construction of the still:

Galvanized steel sheet of 1 mm thick was folded to form a single - sloped tray with a depth of 8 cm, cover slope of 30°, and effective base area of 100 × 55 cm. A galvanized steel trough of 100 cm length was fixed to the tray for the collection of distillate, (Figure · 2).

The condenser shell was constructed to have the dimensions of 100 cm length, 10 cm height and 4 cm width. A copper tube 1 cm in diameter and 205 cm long was bent to form a double - pass heat exchanger.

The base was painted black, a 4mm glass sheet was used as a condensation surface, silicon rubber joint sealant was used to insure vapor tightness. The base and sides of the still were insulated with 5cm thick polystyrene. Finally the entire structure was encased in a wooden container made of 2cm thick wooden sheet.

3.2 Test procedure:

To collect maximum energy, the still was oriented south. The amounts of condensate from both the glass cover and condenser were measured separately by means of glass bottles with 1 liter capacity each, and with divisions of 10 mililiters. Temperatures of the basin water, glass cover, and air - vapor mixture were

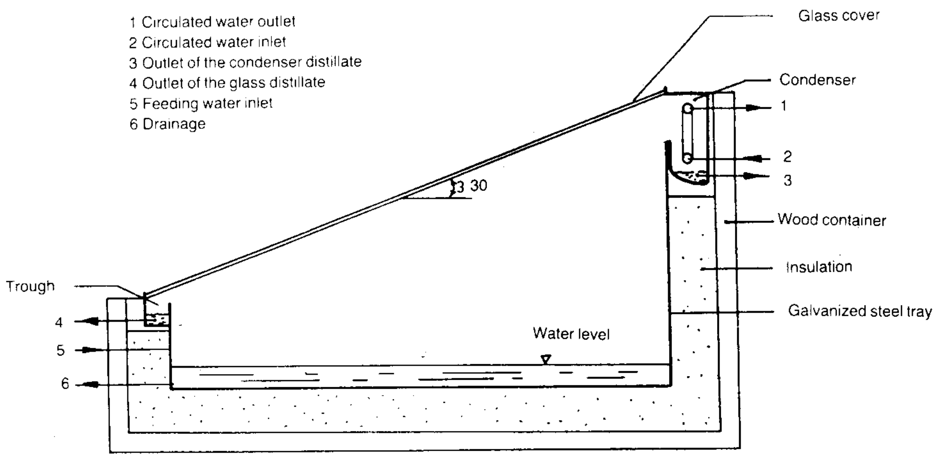


Fig (2) The experimental solar still

taken in degrees centigrade by means of copper - constantan thermocouples, using a digital electronic thermometer with divisions of 0.5°C. A rotameter was used to read the mass flow rate. Incident solar radiation on a horizontal surface was measured in the field using a solar intensity meter.

The above readings were taken at hourly intervals starting from 8 a.m up to 4 p.m (Summer time) during the period of April to June 1983.

The same still was operated successively in the following modes using fresh water through all the tests:

TEST A: the still was tested with an initial water depth of 1 cm without using the condenser.

TEST B: the still was tested starting with very shallow water depth, using the condenser for the purpose of condensing water vapor and preheating the feeding water. As soon as the water temperature increased enough to insure considerable evaporation (at about 10 a.m), cooling water was circulated through the condenser into the basin, and as soon as the temperature of the cooling water in the condenser began to decrease (at about 4 p.m) no more water was fed into the basin. The make - up water during this period was controlled to be almost sufficient to replace that lost by evaporation and to maintain a water depth of about 1 cm after mid - day.

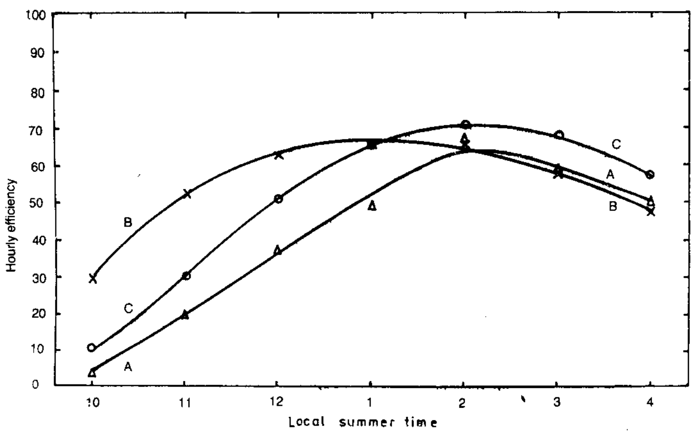
TEST C: the still was tested with an initial water depth of 1 cm with the condenser in use, throughout the period 10 a.m to 4 p.m, for condensation only. The cooling water circulated through the condenser was thrown away. Different mass flow rates were examined ($\dot{m}$ = 0.1, 0.5, 1.0, 1.5 and 2.5 kg / min).

In tests B and C the still was left after 4 p.m to operate as a normal one. Refilling (in the case of test A and C) and blowingdown (in the case of test B) was carried out at about 8 a.m. Only clear - day readings were used to determine the performance curves. Also, each test was repeated four times, and the average values were presented in Figures (3 - 6).

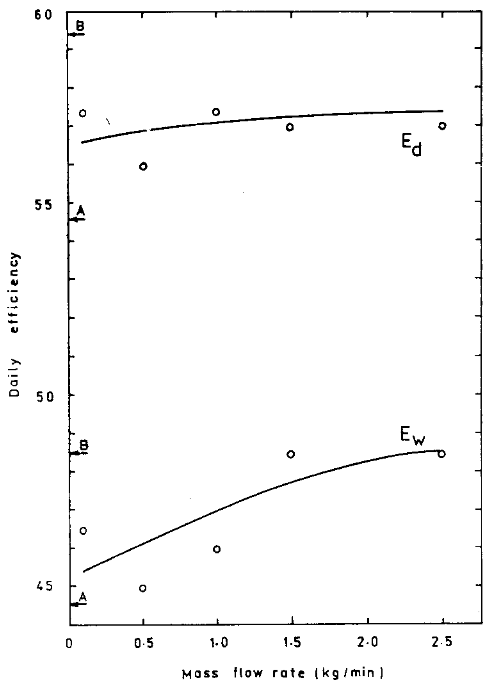
4 . RESULTS AND DISCUSSION:

The hourly efficiency is calculated using the relation $E = Lh. Y / Ih$, the daily efficiency and the efficiency through working hours are calculated using the relation $E = Lh. \Sigma Y / \Sigma Ih$.

The variation of the hourly efficiency with local time for the different tests is shown in Figure (3). The curve C in this graph was established by using the values of hourly efficiency at the various flow rates considered and detailed values of efficiency for different mass flow rates are given in Figure (4). It was observed from Figure (3) that test B gave the highest hourly efficiency up to about 1 p.m due to the shallow basin in the morning hours and the preheated water



Fig(3) Variation of hourly efficiency with local time for the different tests carried out on the



Fig(4) Variation of daily efficiency and efficiency through working hours with mass flow rate for test C fed into the basin. After 2 p.m the test gave the lowest efficiency because the additional cooling water fed to the still did not permit the temperature of the basin to rise to the level expected in the normal operation (test A.). This could be demonstrated by comparing the water temperatures during the period 1 to 4 p.m. The preheated water in test B was fed into the basin of the still at an average temperature of about 50°C, during the same period, the average temperature of the basin water for test A was about 66°C, while that for B was about 60°C. It was observed from Figure (3) that test C gave a higher average efficiency compared to test A, this was due to the additional amount of distillate produced at the condenser. The average glass productivity for tests A and C were 5.086 and 4.313 kg / m^2. day respectively, and the average condenser productivity for test C was 1.304 kg / m^2. day.

The efficiency through working hours (10 a.m to 4 p.m) and the daily efficiency for the different tests are shown in Figure (4). It was observed that test B gave the highest efficiency through working hours. This could be explained from Figure (3), where it is seen that the area under curve B is greater than that under curves A and C.

An optimum operation could be obtained by using test B up to about 1 p.m and then circulating cooling water through the condenser. The daily efficiency of test B was higher compared to test C. This difference could be attributed to the decrease in the mean temperatures of the still, in the case of test C, due to the heat taken by the circulated water. The average water vapor temperature at 4 p.m for test B was 62 °C, while that for test C was 58 °C. Increasing the mass flow rate did not appear to have a signifcant effect on the daily efficiency of test C.

Figure (5) shows the variation of the incident solar energy, the heat flux by evaporation, radiation and convection with local time for tests A,B and C. The amounts of the incident solar radiation through the working hours (10 a.m to 4 p.m), the heat utilized to produce distillate, the heat lost by radiation, and the heat lost by convection through the same period were obtained by calculating the area under the curves shown in graphs A and B of Figure (5). Similar values were obtained for the different flows of test C from similar graphs (not inclu - ded). The values obtained from such results are shown in Figure (6), which gives the ratio of q_e, q_r, q_c and q_{cond} as a percentage of the total incident solar radiation through the working hours for different tests. The amount of heat taken by the circulated water was also calculated and presented in the Figure. For example, for the case of 1.5 kg / min flow rate, 56 per cent of the total incident solar energy through the period 10 a. m to 4 p.m was utilized to produce the distillate, 14 per cent was lost by radiation, 5 per cent by convection, and 23 per cent to the circulated water. It is observed from Figure (6) that increasing the mass flow rate and using different operations has no significant effect on the percentage of q_r and q_c, while a more noticeable effect is found on the percentage of q_e and q_{cond}.

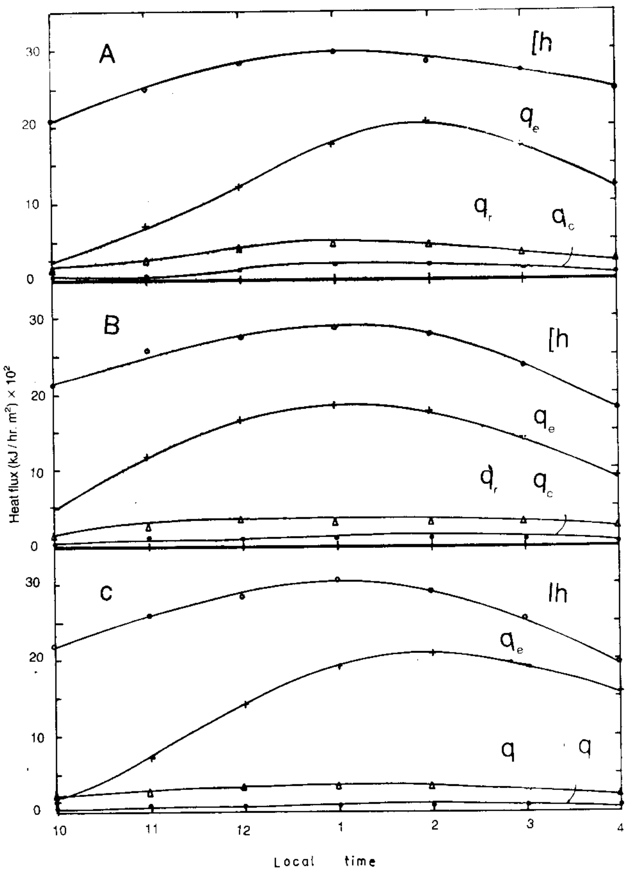


Fig (5) Average variation of incident solar radiation and heat flux by evaporation, radiation and convection with local time for tests A, B & C.

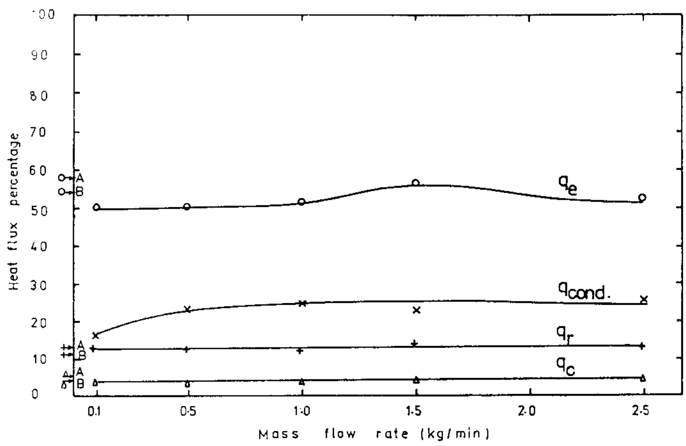


Fig (6) Variation of heat flux percentage with mass flow rate for test C

5. CONCLUSIONS:

1 - The efficiency of a basin type solar still could be increased by adding to it an internal condenser. A normal basin type solar still (TEST A) gave an average daily efficiency of 48. 5 %. When the condenser was used for condensing water vapor and preheating the feed water (TEST B), an average daily efficiency of 59. 35 % was obtained. On the other hand, when the condenser was only used for condensing water vapor by circulating different mass flow rates of cooling water (TEST C), an average daily efficiency of 57. 5% was obtained.

2 - An increase in the average total still productivity was observed for tests B and C compared to test A as shown below:

TEST	Y_c	Y_g	Y_t	
A	-	5.086	5. 086	kg / m^2 day
B	0.578	5.233	5.811	kg / m^2 day
C	1.304	4.313	5.617	kg/m^2. day

3 - It was found that increasing the mass flow rate in the case of test C, and using different operations had no significant effect on the percentage of heat flux by radiation and convection, while a more noticeable effect was observed on the percentage of heat flux by evaporation and heat lost with the circulated water.

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تقييم مقطر شمسي ذي مكثف داخلي ودراسة توازنه الحراري

عبد الجبار نعمة خليفة

مركز بحوث الطاقة الشمسية
مجلس البحث العلمي
ص.ب. 13026 بغداد

المستخلص

يتضمن البحث دراسة تجريبية حول تأثير اضافة مكثف داخلي الى المقطر الشمسي البسيط على إداء المقطر. لهذا الغرض تم تصنيع مقطر شمسي بسيط مفرد الميل مساحة قاعدته 0.55 متر مربع وبغطاء زجاجي ذو ميل 30 درجة مجهز بمكثف داخلي، وقد تم فحص الجهاز بطرق مختلفة حيث فحص بدون استعمال المكثف (فحص A)، وفحص باستعمال المكثف لاغراض تكثيف بخار الماء وتسخين الماء قبل تغذيته الى المقطر (فحص B)، ثم فحص باستعمال المكثف لاغراض التكثيف فقط (فحص C) وذلك بأمرار ماء بمعدلات جريان مختلفة خلال المكثف، وقد اظهرت نتائج الفحوصات ان اضافة مكثف داخلي ادت الى تحسين في اداء المقطر الشمسي، حيث ازدادت انتاجية المقطر الشمسي من 5.086 الى 5.811 (كغم / م^{2} يوم) نتيجة للفحص B والى 5.617 (كغم / م^{2} يوم) نتيجة للفحص C. كما يتضمن البحث دراسة التوازن الحراري للمقطر الشمسي في كل من الحالات المذكورة اعلاه.