Mathematical modeling and analysis of a solar still with multiple-effect cover cooling

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***Abstract*— This paper presents a theoretical study of the thermal performance of a double-sloped basin still coupling with multiple-effect cover cooling. The still was built so that one of its cover sides (the multiple-stage) is tilted to be parallel to sun rays and, therefore, be in the shaded area. Direct solar radiation heated the saline water and evaporated it. A fraction of the resulting vapor condensed on the inner glass cover surface while the rest was condenser to the outer first partition to be condensed there. The distiller was double-slope with a double pass capillary film distiller. Is effective base area was 1m2 and its cover slope was 65° to the horizontal. The results showed that combining a capillary film distiller with basin type solar still caused an improvement in the still performance. The proposed still of two parallel cells with 50-mm gaps is theoretically predicted to produce 11.8 kgm^{-2}d^{-1} on a sunny day of daily solar radiation of 42.5 MJ m^{-2}d^{-1} on the glass cover.**

Keywords*— *Solar, distillation, capillary, modeling

I. INTRODUCTION

In many parts of the world, the production of fresh water is often a serious problem. Especially in the arid regions, desalination has becomes a reliable source of fresh water. In these regions, solar energy received on a horizontal surface is nearly constant in intensity throughout the year.

The different methods used in desalination are based on thermal or membrane principles. In these methods use electrical power which is an environmental concern because a large portion of this power is generated by coal or gas based power plants.

Solar distillation can be a good solution for production of fresh water. In operation, the greenhouse effect of the transparent cover during sunny hours increases the water temperature, causing some of it to air contained within the enclosure. Moreover, it's low operating and maintenance costs made it an attractive method in areas remote from the electricity supply grid.

In some early publications on this subject, [1] constructed and test a three-effect-type still consisting of a glass cover on top, a solar absorber plate and three partition which are all parallel with gaps. The still was tilted so that the solar absorber faced upwards to the sun and received solar energy. Saline soaked wicks were in contact with the bottom surfaces of a solar absorber plate and parallel partitions except the bottom partition. Water vapor evaporated from the saline-soaked wick, diffused across the gap downwards and condensed on the uncovered top surface of the facing partition. The latent heat of the condensation penetrated the partition to the wick underneath contributing to further evaporation. In this manner the latent heat of condensation is recovered and recycled to increase the total amount of distillate. [2], in a continuation of this study, simulated a solar still coupled with an evaporator-condenser, which operated in an indirect mode. [3] Have reported on a solar based desalination process based upon a multiple evaporation-condensation cycle, in which some components of the system were fabricated from polypropylene. [4] Proposed a new simple design for a solar still coupled with vertical multiple effect narrow gap distillation cells. [5] and [6].

Several researchers have suggested improvements to the passive solar still with separate condenser and natural circulation of water vapor. [7] Developed a double-effect solar still, with the second-effect component on the shaded side of a basin solar still. It was found that the daily productivity improved. [8] Studied a solar still with one glass cover, and a separate condenser. A vertical steel reflector fitted in the top part of the evaporator cast a shadow over the condenser system. It was found that the solar still with a condenser performed better than the one which had no condenser. The tilted-wick still, another type of solar still designed to operate at very low heat capacities [9]. The wick solar still is made up of wicks located on a feed tank and one on the inside of the still. [10] Studied a double-slope still joined to a capillary film condenser cell. It was found that the performance improved. [11] Analyzed the effect of integrating passive condenser on the performance of a solar still. The proposed passive condenser connected to the still in the shaded zone of a single-slope still.

An objective of the paper is to improvement of the efficiency and production rate of fresh water from solar distillation with multiple-effect cover cooling. The device used for this purpose is the Capillary Film Distiller (CFD), and an investigation with the following objectives has been carried out:

1. To study the performance of a basin-type solar still combined with a multiple-effect partitions condenser.

2. To explore design modification for increasing the productivity of a desalination unit.

3. To make a computer model to the distiller which can predict theoretically the effect of number of distillation cells and ratio of feed rates of brackish water to wicks to distillate rate with feed rate brackish water on the performance of the distiller.

II. DESCRIPTION OF THE MODIFIER STILL

In this work we propose a new configuration design for conventional solar still (CSS) with a triangular cross-section consisting of a sloping glass cover facing the sun, a horizontal basin and a number of incline partitions in contact with saline-soaked wicks as shown in Fig. 1. The incline partition may have small deformations, but any fibers protruding from the wicks absorb saline water, become heavier and are gradually suppressed by gravity.

The solar radiation after being transmitted through the glass cover is absorbed in the basin and the reflected first plate partition, P, and water vapor from the basin diffuses in the humid air and condenses under the surface of the glass cover and on P. the latent heat of condensation and the solar energy absorbed on P enter the multiple-effect distillation section and are recycled to increase the production of distillate.

Heat of the condense resultants through on the front surface of the first plate causes evaporation saline water in the wick attached to the rear surface of the first plate. Water vapor diffuses through the narrow humid air layer between the first and second partition and condenses on the front surface of the second partition. Latent heat of condensation contribution to further evaporation of saline water in the wick attached to the rear surface of the second partition.Maintaining the Integrity of the Specifications.

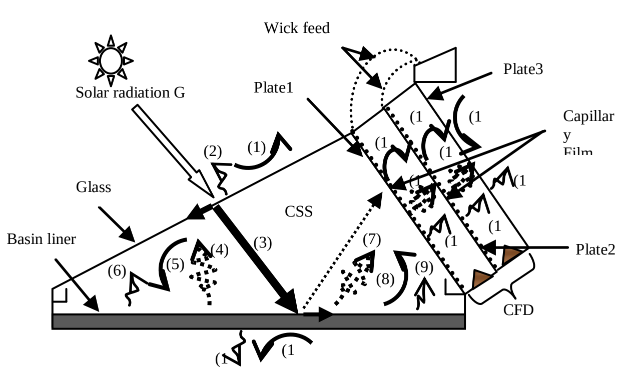

FIGURE I. PRINCIPE OF CSS AND CFD.

(1) Q_{cga}, (2) Q_{rgsky}, (3) τ_g G, (4) Q_{ewg}, (5) Q_{cwg}, (6) Q_{rwg}, (7) Q_{ewp1}, (8) Q_{cwp1}, (9) Q_{rwp1}, (10) Q_{rwa}, (11) Q_{cwa}, (12) Q_{rp1p2}, (13) Q_{ep1p2}, (14) Q_{cp1p2}, (15) Q_{rp2p3}, (16) Q_{ep2p3}, (17) Q_{cp2p3}, (18) Q_{rgp3a}, (19) Q_{cp3sky}

III. MATHEMATICAL MODEL

A mathematical model was developed in order to simulate the performance of the proposed still under local meteorological conditions in Adrar which is located in Algerian Sahara at 27° 53'N latitude, an 262m altitude and 0° 17'W longitude. Fig. 2 illustrates the still overall heat balance. The transient energy equations can be written as follows:

Glass cover

$$M_g\ C_g\ \frac{dT_g}{dt} = \alpha_g\ G\ S_g + Q_{wg} - Q_{cga} - Q_{rgsky} \tag{1}$$

Basin water

$$M_w\ C_w\ \frac{dT_w}{dt} = \left(\alpha_w\ \tau_g + \alpha_b\ \alpha_w\ \tau_g\right) G\ S_g - Q_{wg} - Q_{wp1} + Q_{cbw} - Q_{db} \tag{2}$$

Where

$$U_{db} = h_{cba} + h_{rba} + \left(\frac{1}{E_b/\lambda_b} + \frac{1}{E_{isu}/\lambda_{isu}} + \frac{1}{1/h_{cbw}}\right)^{-1}$$

First plate cover (condenser/evaporator)

$$M_{p1}\ C_{p1}\ \frac{dT_{p1}}{dt} = \Re_{p1} G\ S_{p1} + Q_{wp1} - Q_{p1p2} + q_{ap1}^{in} - q_{p1a}^{out} \tag{3}$$

Second plate (condenser/evaporator)

$$M_{p2} C_{p2} \frac{dT_{p2}}{dt} = q_{ap2}^{in} - q_{p2a}^{out} - Q_{p2p3} \tag{4}$$

Three plate (condenser)

$$M_{p3} C_{p3} \frac{dT_{p3}}{dt} = Q_{p2p3} - Q_{cp3a} - Q_{rp3sky} \tag{5}$$

Where

$$Q_{wg} = Q_{cwg} + \dot{m}_{ewg}\ S_w\ hf_w + Q_{rwg}$$

$$Q_{wp1} = Q_{cwp1} + \dot{m}_{ewp1}\ S_{p1}\ hf_w + Q_{rwp1}$$

$$Q_{p1p2} = Q_{cp1p2} + \dot{m}_{ep1p2}\ S_{p1}\ hf_w + Q_{rp1p2}$$

$$Q_{p2p3} = Q_{cp2p3} + \dot{m}_{ep2p3}\ S_{p1}\ hf_{p1} + Q_{rp2p3}$$

For the heat transfer rates and mass fluxes by the natural convection in the basin section, the heat or mass transfer coefficients on the three inner surfaces of the basin section are given by the following equation of rate of evaporation

$$\dot{m}_T = \dot{m}_e + \dot{m}_p \tag{6}$$

$$\dot{m}_e = \frac{h_{ewg}\ (T_w - T_g)}{hf_w} + \frac{h_{ewp1}\ (T_w - T_{p1})}{hf_w} \quad (7)$$

$$\dot{m}_p = h_{me}\ (\rho_{p2} - \rho_{p1}) + h_{mp}\ (\rho_{p3} - \rho_{p2}) \quad (8)$$

IV. RESULTS AND DISCUSSION

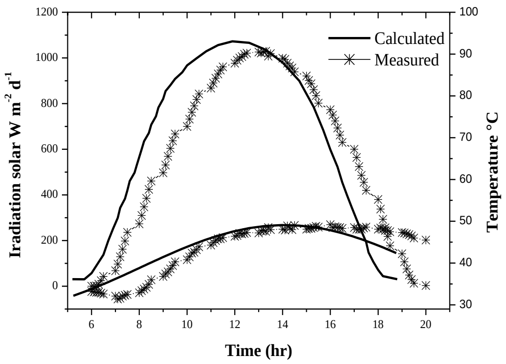

FIGURE II. VARIATION OF CALCULATED IRRADIATION, AND MEASURED RADIATION IN THE PRESENT STILL

The simulation was carried out for typical day (one in July 15th) with the climatic conductions of Adrar, Algeria. The global solar radiation for this day is shown in Fig. 2, the variation of calculated and measured total radiation with time. It is seen that the calculated radiation is concord than the measured radiation. It should be mentioned that solar radiation is the most influence environmental parameter in distillate production [12]. Distillate production increases with the magnitude of solar radiation.

It is seen that ambient air temperature was relatively high; varying between 40 and 50°C during the test period is presented in Fig. 3. Distillate production tends to increase with temperature. Consequently, production of distilled water would also be adversely affected on such a day in spite of satisfactory levels of solar radiation.

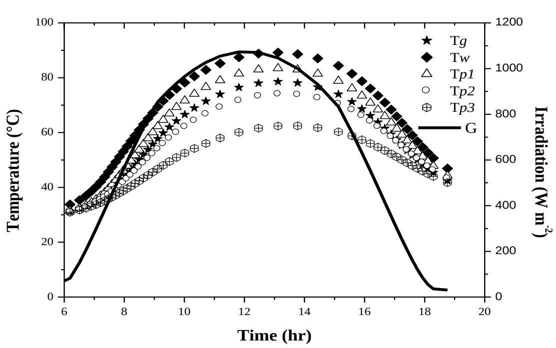

FIGURE III. TEMPERATURE DISTRIBUTION OF STILL DIFFERENT ELEMENTS

The temperature of the basin water glass cover, plate partition cover and ambient temperature vs. time are shown in Fig.3 where we can easily see the small difference between the brine and condenser plate temperature, i.e., the quantity of heat transfers to the condenser plate by evaporation (which depends on the condenser plate temperature difference) will be decreased and consequently more vapor transfers to the plate cover condenser where its temperature is much higher than that of the glass, showing good thermal insulation.

The temperature of first partition is higher than that in the glass cover in the evaporator basin of the CSS during the most part of the day, with the difference (3.30°C) being maximum around 14:00 h. this trend is attributed to the heat transfer modes from water in the evaporator basins (first partition) of the systems. in the proposed still, heat is lost to ambient environment through the glass cover, bottom and side walls while heat is transferred by reuse of latent heat of steam condensed in the first plate, for water evaporation in the subsequent stage, in addition to heat loses through the last plate. It is nevertheless pleasing to note that the values of Tw are comparable with experimental data reported in literature [13].

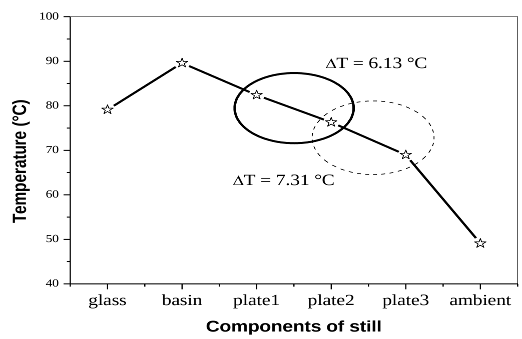

FIGURE IV. TEMPERATURE DİSTRİBUTİON İN THE PROPOSED STİLL

The temperature distribution in the proposed still at the peak of the overall production rats is shown in Fig. 4. The temperature is highest at the basin and water, and decreases as going through the multiple-effect cover cooling and glass cover to the ambient air. There is a large temperature drop through three partitions, a 4.58°C from first partition, and 4.34°C from second partition, showing good thermal insulation. The thermal resistance is smaller through the second partition than the first partition, and therefore the temperature is lower at the outer plate than the inner plate partition. The drop in temperature through a single distillation cell increases from the first to the last cell since the heat transfer rate by evaporation and condensation, Q_e, rapidly decreases with a decrease in mean temperature of a cell, and the thermal resistance through the cell rapidly increases. The temperature of the last plate is higher than the ambient air temperature.

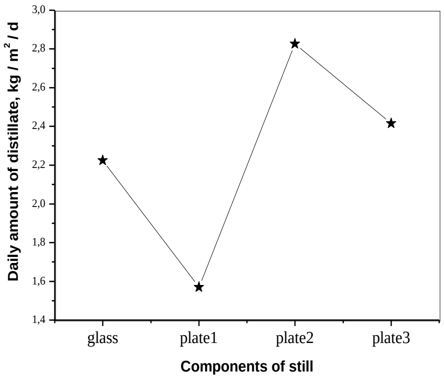

FIGURE V. DİSTRİBUTİONS OF DAİLY AMOUNTS OF DİSTİLLATE İN THE PROPOSED STİLL AT THE PEAK OF THE OVERALL PRODUCTİON RATE

Fig. 5 shows the daily amounts of distillate on the glass cover and all partition in the still and the instant distillate production rates on glass and first plate 1 all partitions at the peak of the overall production rate. The daily amounts and the instant production rate of distillate are largest on the second partition plate 2, and decrease as going from plate 2 to the last partition. The latent heat of condensation and the solar energy reflected absorbed on the first partition plate 1 cause the large amount of evaporation from the wick of plate 1, which condenses on plate 2. The evaporation and condensation rate in the cell decreases with a decrease in the mean temperature of the cell (see Fig.4).

V. CONCLUSIONS

The theoretical performance of a novel design solar still consisting of a pyramid an asymmetric basin-type distillation coupled with a slope multiple-sections cover cooling. The mathematical model is developed using a heat balance analysis of the different elements of the present still. Computer simulation studies were conducted to predict behavior of the additives cells partitions under transient conditions. The results of this work are summarized as:

1- Using an multiple-effect cover cooling in a simple basin double-slope solar still improves daily about 53% and the productivity of the still

2- The proposed still of three partitions with 50-mm diffusions gaps is theoretically predicted to 15.83 kg m^{-2} d-1, an sunny summer day of daily solar radiation of 86.4MJ m^{-2} d^{-1}.

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