Condensation Heat Recycle in Solar Stills

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***Abstract*—A solar still of 1 m^2 area consists of upper and lower chambers separated by a thin cupper sheet that was built for indoor experimental purposes. The solar still has the advantage, over the conventional basin and tilted wick type solar stills of recycling the condensation heat of distillate to heat up the saline water feed and the wet tilted wick. The tilted still surface was covered with black thin textile. The feed water is fed to the lower chamber in a serpentine tube to the upper chamber of the still where water is collected in a weir from which is distributed on the textile. While water is descending down the still; is heated up by solar radiation and evaporated.**

A stream of air is blown to the upper chamber counter currently to the descending water and used to carry up the water vapor and circulated to the bottom of the solar heated surface where it loses its energy to heat up the middle sheet still surface as well as the serpentine tube carrying the saline feed water. Large part of water vapor is condensed at lower part of the still and collected in a container outside of the lower chamber. The vapor remained in air stream is further condenses in an external heat exchanger. The steady state distillate yield and temperature variations as a function of air flow rate were determined experimentally for single, double glass, metal cover and metal cover covered with glass.

The productivity of the still at 670 W/m^2.h simulated incident radiation; For condensation energy recycled is around, 1 kg./m^2.h for double glass cover, 0.75 for single glass cover, 0.7 kg./m^2.h for metal cover and 0.98 kg./m^2.h for metal cover covered further by glass cover. For no recycling of the condensation energy, the productivity is around, 0.5 kg/m^2.h for double glass, 0.45 kg/m^2.h for single glass cover, 0.36 kg/m^2.h for metal cover, and 0.425 kg./m^2.h for metal cover covered further by glass cover.

***Index Terms* — Solar energy, Solar distillation, Energy recycle.**

I. Introduction

In many small communities, the natural supply of fresh water is inadequate. The worldwide problem of the rapidly dwindling resources of inadequate fresh water supply for an increasing population intensifies. The task of providing adequate supplies of fresh water may indeed become the most serious problem facing the world. New sources of fresh water supplies must be found and two of the most likely sources are the great oceans and the vast reserves of brackish inland water. All the above discussed reasons provide sample evidence of the necessity of solving the problem of water shortage especially in arid and other less publicized areas by concerted efforts both nationally and internationally.

In many regions of the world, solar energy offers the only hope for obtaining inexpensive fresh water from saline or brackish water. This method has its application for arid and remote isolated desert areas in which abundance of solar energy (sunshine) coincides with water needs (suffers from deficiency in fresh water). In these areas no other economical means of obtaining fresh water are available from other freshening methods like ion exchange (IE), electro-dialysis (ED), reverse osmosis (RO), refrigeration, vapor compression cycle (VCC), multiple-effect evaporation (ME) and multiple-stage flash distillation (MSF), since these methods, require highly sophisticated technologies and highly trained operation and maintenance teams that are not available in arid remote isolated areas. The advantages of using solar energy for distillation are; [1] easy technology, [2] simple and easy operation and maintenance, [3] free source of energy and [4] environmentally clean energy that improves the quality of life in the areas where it is used.

The use of direct solar energy for the production of potable water from saline water represents a promising option, particularly when the demand for fresh water is small. The basic process of solar distillation involves utilizing heat from the sun to evaporate saline water and condensing the vapor to fresh water product. This is conventionally done in a device in which evaporation and condensation takes place in one enclosure known as a basin-type solar still. This still utilizes the greenhouse effect and operates below the normal boiling point of water.

Different design shapes and construction materials have been attempted to maximize the productivity of fresh water. The development went on from the simple conventional solar stills of high thermal capacity to designs of systems of low thermal capacities such as tilted-wick still, multiple-ledge tilted still, cascade tilted still, and those that recycle heat such as multiple-effect diffusion still, multiple-effect tilted still, multiple- effect basin type still. In some of the still designs, evaporation and condensation take place in the same enclosure, in others evaporation and condensation occur in separate enclosures. Also, some of the stills recycle energy through the latent heat of condensation either in counter-current flow of an air-vapor mixture with the inlet feed or directly to another solar still, like in double-basin solar stills. Solar stills that reject the heat of condensation to the atmosphere are termed as single-effect solar stills, but those that provide the reuse of latent heat of condensation to some or more extent, are termed as multiple-effect solar stills.

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Such a design has its technical problems, such as the leak-proof junction of dissimilar materials and the rejection of condensation energy.

The present paper summarizes the results obtained by a study of a laboratory scale air blown tilted-wick solar still that recycles energy of condensation of vapor for preheating the feed water and further evaporation in the upper part of the still. Thus, the variation of the yields and the steady-state local temperatures with the flow rate of the air and the feedstock is discussed for glass glazing cover and metallic cover.

II. METHODOLOGY

A. The Solar Still Module and The Experimental Arrangement

A schematic diagram is shown in Fig.1. The still body is a thin rectangular box (1850x540x25 mm), constructed from copper sheets of 1mm thickness and insulated externally with 5 cm thick polystyrene foam. The still window is double glazed, with 20 mm spacing. The body is separated into two chambers by a central metal sheet connected on three sides to the still walls, whereas there is a slot between the metal sheet and the fourth wall connecting the two chambers to each other allowing feed water to pour to the upper chamber and air carrying vapor to pass to the lower chamber.

This solar still operates in the following:

- The feedstock enters the still via a serpentine conduit attached to the backside of the metal sheet and preheated by the condensation of the counter flowing hot saturated air coming from the top chamber, i.e., the evaporation chamber.
- The feedstock exits the serpentine conduit into the overflow weir at the top of the central metal sheet, which is covered with a black wick. The feedstock then wets the surface of the wick and flows by gravity to the outlet at the bottom of the metal sheet.
- Ambient air enters at the bottom of the upper chamber and flows by forced circulation in the space between the metal plate and the double glazing in the direction opposite to the flow of the feedstock. As the air flows in the upper chamber it is heated and becomes saturated with water vapor. It reaches its maximum temperature (T5) at the top of the upper chamber, i.e., in the slot connecting the two chambers.
- At the top of the upper chamber, the direction of the air flow turns around and enters the lower chamber, viz., the condensing chamber, through the slot. In the lower chamber, a considerable portion of the enthalpy of the hot, saturated air is transferred to the entering feedstock and to the backside of the central sheet. As a result, the saturated air is cooled and most of its water content condenses.
- The air stream exiting from the lower chamber enters a gas-liquid separator (SEP1), and then an external heat exchanger, where it cools down close to ambient. The second separator (SEP2) serves for collecting the water condensed outside the still.

B. Experimental Conditions

Feedstock was introduced in a two- to fourfold excess in the experiments herein. Ambient air circulation was achieved using a low pressure variable speed ventilator. The exposed wick surface area was 1.0 m^2 and thermal energy was supplied by a solar simulator. The yield of fresh water, as well as the relevant temperatures (T(0)- T(15)) were measured and recorded using magnetic valves M1 and M2, an electric balance and calibrated thermostats connected on-line to a PC via multi channel A/D card.

The flow rate of air was measured by a mechanical gas flow meter of $12m^3/h$ range.
The tilt angle was 20 degree. The feedstock was led into the module at ambient.
The location of the thermostats utilized to monitor the temperatures within the system were shown in Fig.1 and defined as:

T(0): The temperature of the feedstock entering the top of the central metal sheet(in the weir).
T(1)-T(5): the temperatures of the air stream close to the its inlet, alongside of the upper chamber and above the slot.
T(6)-T(10): the temperatures of the air stream below the slot, at the middle of the lower chamber and in the vicinity of its outlet, respectively;
T(11)-T(14): the temperatures of the air flow outside the still, of which T(12) and T(13) are the temperatures in separators 1 and 2.
T(15): The temperature of the brine at the outlet.

The software developed for these experiments enabled to monitor and store the temperature data from the fifteen thermostats and to calculate differential and cumulative (integral) yields at variable time intervals. Thus, the approach to the steady-state conditions with regard to both temperatures and yield could be noticed clearly during operation.

C. Operation Modes

The experimental setup allowed to run the system in two operation modes:

- Operation with heat recycling. In this case VALVE 1 is closed, VALVE2 is opened, and the direction of air flow is the same as shown in Fig.1.
- Operation without heat recycling. In this case VALVE 1 is opened, VALVE 2 is closed, and a long tube of 1" diameter (not shown in Fig.1) is used to make connection between VALVE 1 and separator 1, i.e. the air flow does not passes through the lower chamber, because is directly lead out at the top of the upper chamber. This arrangement refers to an air-blown tilted-wick type still with external condensation of the distillate.

III. RESULTS AND DISCUSSION

A. General Observations

Under steady-state conditions the following temperature correlations were observed:

T(0) > T(6) >> T(amb) a result of the preheating of the feedstock in the lower chamber, where T(amb) stands for ambient temperature;
T(5) > T(4) > T(3) > T(2) > T(1) > T(amb) as a result of the heating of air stream in the upper chamber;
T(5) > T(6) > T(7) > T(8) > T(9) > T(10) > T(amb) a result of the cooling of the saturated air stream in the lower chamber;
T(7) > T(4); T(8) > T(3); T(9) > T(2); T(10) > T(1).

These temperature gradients are the driving forces for the heat transfer from the lower to the upper chamber or in other words the heart of the thermal energy recycle process.

B. Attainment of The Quasi-Steady-State

As a result of the low thermal mass of the system, quasi-steady-state temperatures and yields were achieved after approximately one hour of operation. The progress of the most characteristic temperatures with the time of "insolation" are shown in Fig. 2, in energy recycling operation mode and without energy recycling, respectively.

In Figure 2 it is also seen, that energy recycling starts after about 30 min operation, when T(10) becomes higher then T(1), i.e. after the temperature of lower chamber exceeded that of the upper chamber.

A comparison of these figures clearly shows that energy recycling results in a significantly higher operation temperature. Another result of the heat recycling is that after the lamps were switched off at 120 min, but the air pump was left working, the system cooled down more slowly.

Figure 3 shows that in both operation modes, increasing flow rate of air pumped in results in a monotonous decrease of T(5), the highest local temperature of the still.

Figure 4 shows the increase of the cumulative yields collected in vessel 1 and 2 (cf.SEP1 and 2 in Fig.1), and the total yield, the sum of these two, as a function of the time of insolation. It is seen that quasi-steady productivity rates (constant slopes) are achieved after about 60 min operation. As discussed earlier, the amount of the distillate collected in vessel 1 refers to that water which was condensed inside the lower chamber. This amount is much greater than that, collected in vessel 2 after external cooling of the outlet air. If we assume that the heat losses through the side walls and the bottom of the still are negligible, we conclude that a major fraction of the enthalpy of the hot saturated air that entered the lower chamber through the slot was successfully recycled and used for evaporation.

A comparison of the progress of cumulative yields with time is given in Fig.5. In this figure it is also seen that, in spite of the low thermal mass of the unit, energy recycling results also a considerable increase of yield even after "sunset", i.e. after the solar simulator was switched off.

The effect of air flow rate on the steady state productivity rates is shown in Figure 6 for double glass cover and Fig.7 for single and double glass cover . Air flow rate means the flow rate of ambient temperature saturated air, which is measured after separator 2). It could be seen that, heat recycling resulted in a considerable increase of productivity. As it was expected, in both operation modes the curves had a local maximum, since at zero flow rate and at very high flow rates of air yields close to zero could be expected. As shown in Fig.6, in energy recycling operation mode the optimum is in the vicinity of $2m^3/m^2h$, where not only the total productivity rate but the differential yield collected in vessel 1 also exhibits a local maximum. Also, the productivity obtained from double glass solar stills is higher than that from single glass solar still.

Figure 8 compares the steady state productivity for copper metallic cover solar still with and without energy recycle. It shows that the productivity is higher for energy recycling operation mode.

Figures 9 and 10 compares the productivity of solar stills at operation modes, with energy recycle and without energy recycle for different solar still covers, Double glass(dg), single glass(sg), metallic cover(mc) and single metallic covered with single glass(sm+sg).

C. Heat And Mass Transfer In The Vicinity of Optimum

As the system is not isothermal and its operation based on the heat and mass transfer of counter-current flowing fluids of different temperature and water vapor content, our calculations are based on the only measurable gas flow rate, the flow rate of saturated air pumped in at ambient temperature. To feed "saturated air at ambient temperature" does not mean technical problem, as the outlet air that leaves our system is always saturated, its temperature is close to ambient, and it can be directly lead to the air inlet of the module.

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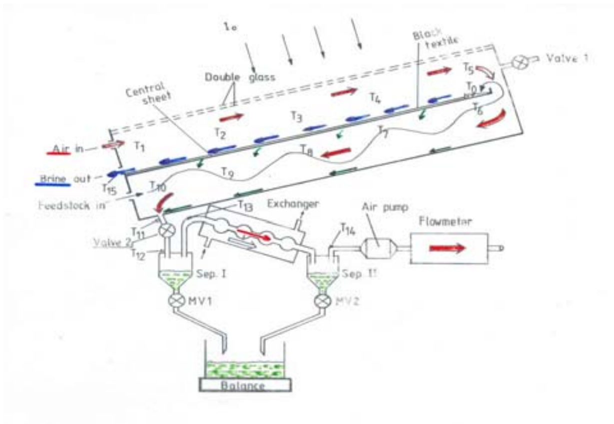

Figure 1. Schematic diagram of the air blown tilted-wick solar still module.

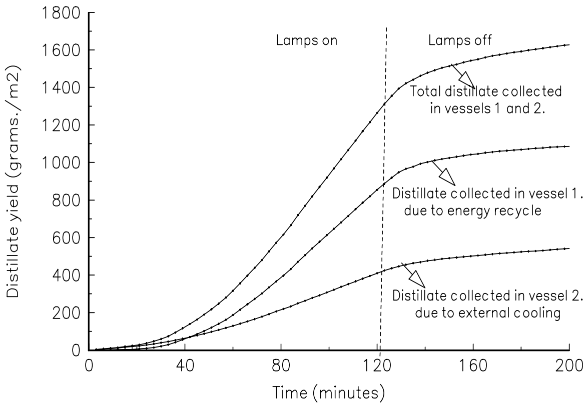

Figure 4. Cumulative yields versus time with energy recycling. Glazing: Double Glass; water flow rate = 2.281 l/h.; measured air flow rate = 3.2 m^3/h . Irradiation = 670 W/m^2.

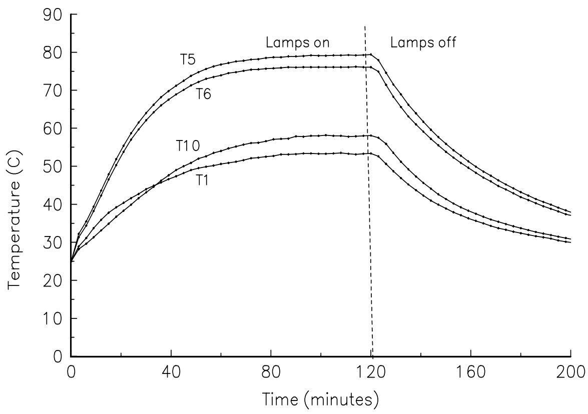

Figure 2. Attainment of steady state temperatures in energy recycling operation mode. Glazing: Double Glass; measured water flow rate = 2.281 l/h; measured air flow rate = 3.2 m^3/h. Irradiation = 670 W/m^2.

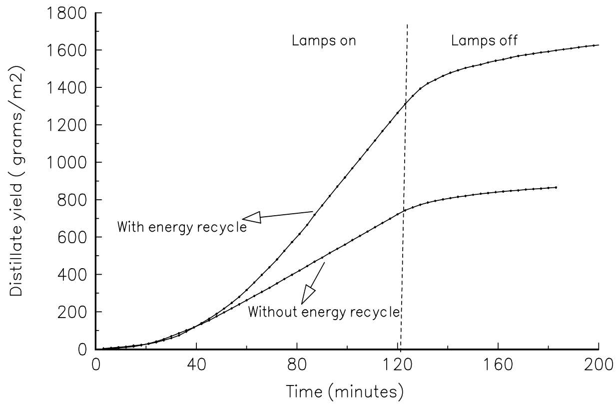

Figure 5. Cumulative total yields versus time with and without energy recycling. Glazing: Double Glass; measured water flow rate = 2.281 l/h; measured air flow rate = 3.2 m^3/h. Irradiation = 670 W/m^2.

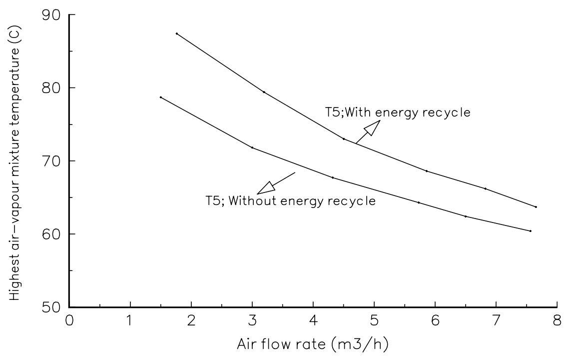

Figure 3. The steady state values of T5, the highest local temperature at different measured flow rates of ambient air pumped in, with and without energy recycling. Glazing: Double Glass; measured water flow rate = 2.281 l/h. Irradiation = 670 W/m^2.

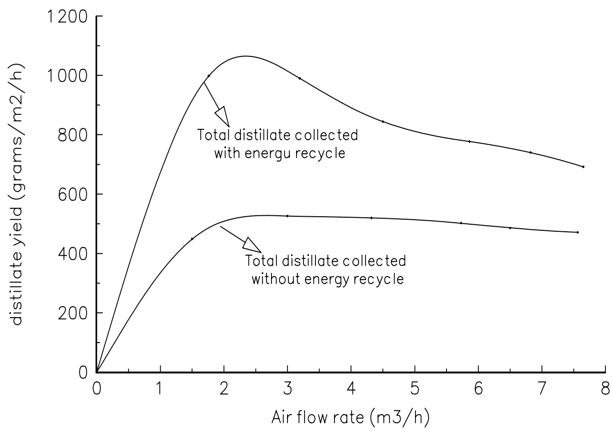

Figure 6. Steady state productivity rates versus measured air flow rate, with and without energy recycling. Glazing: Double glass; measured water flow rate = 2.281 l/h. Irradiation = 670 W/m^2.

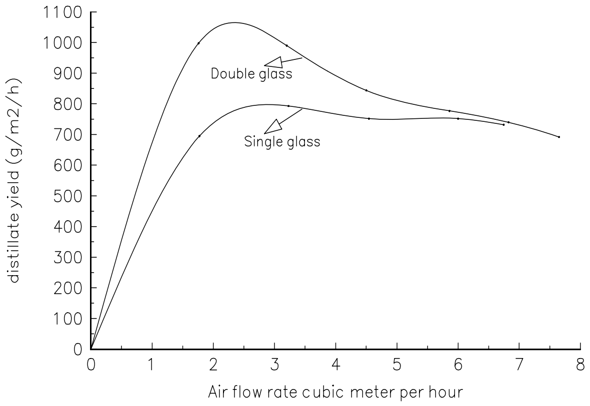

Figure 7. Steady state productivity rates versus measured air flow rate in energy recycling operation mode. Glazing: Double Glass and Single Glass; measured water flow rate = 2.281 l/h. Irradiation = 670 W/m^2.

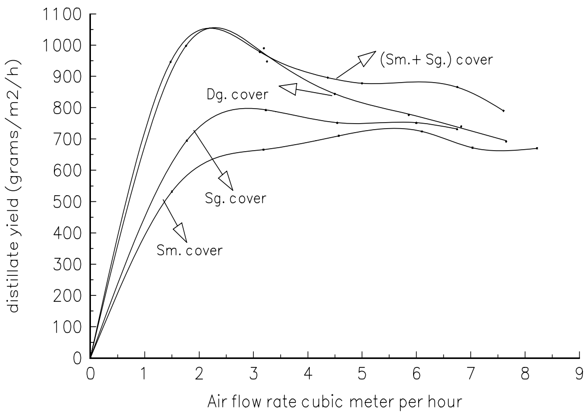

Figure 9. Steady state productivity rate (I + II) versus air flow rate, in energy recycling operation mode. Glazing: Dg. = Double glass; (Sm. + Sg.) = Single metal plus Single glass cover; Sg. = Single glass; Sm. = Single metal; water flow rate = 2.281 l/h.

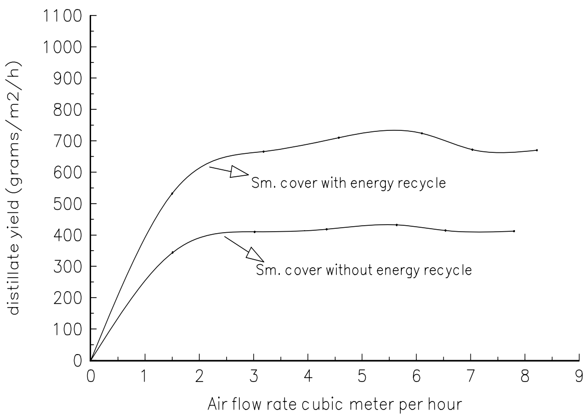

Figure 8. Steady state productivity rate (I + II) versus air flow rate, with and without energy recycling operation mode. Glazing: Sm. = Single metal; water flow rate = 2.281 l/h.

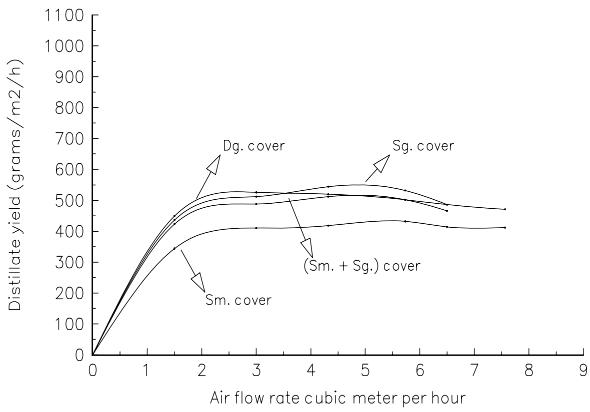

Figure 10. Steady state productivity rate (I + II) versus air flow rate, without energy recycling operation mode. Glazing: Dg. = Double glass; (Sm. + Sg.) = Single metal plus Single glass cover; Sg. = Single glass; Sm. = Single metal; water flow rate = 2.281 l/h.