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Thermal-economic analysis of modular solar still under Algerian climatic conditions: effect of collector and condensation chamber area

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ABSTRACT

In this paper, a thermal-economic analysis of a modular solar still was investigated. For that, a modular solar still was designed. The collector area and the condensation chamber area effect on the productivity and distilled water cost were examined. Simulations were performed according to meteorological data of Algiers (Algeria) using Liu Jordan method. Results show that the surface area of collector increase increases the evaporated water and distilled water production at the same time. The average annual production passed from 482.35 L for 2 m^2 of solar collector to 2083.65 L for 10 m^2 of solar collector. On the other side, increasing surface of solar collector decreases the cost of distilled water. The cost of liter of distilled water varies between 0.12 and 0.04$ for 2 and 10 m^2 of collector, respectively. Also, when the condensation chamber area increases, the amount of the distillate water produced decreases.

Keywords: Condensation; Evaporation; Distillate; Natural convection; Modeling

1. Introduction

Fresh water is an essential element for the well being of the population, since it participates to the socioeconomic development of nations. The semi-arid or arid countries are characterized by a low annual rainfall. As well, the water resources are low and irregular. The semi-arid regions have a significant sunshine duration which is suitable for the production of drinking water by solar distillation process. Besides, the desalination of seawater and brackish water by different processes (thermal, membrane filtration, etc.) is a good alternative to face the water needs in the short and long term. Thus, different techniques have been used to improve the daily water production of the direct solar desalination. For instance, the coupling of the basin solar still with a flat-plate collector increased production until 36% [1]. A comparative study shows that efficiency of a basin solar still operating with a parabolic concentrator was higher than that of a still operating with a flat-plate collector [2]. Sampathkumar et al. concluded that coupling a basin solar still with a solar water heater using evacuated tube collector enhanced the production. In fact, the

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experiments conducted on the system shows that productivity was doubled when the solar collector was coupled with a 24 h period [3]. Adding a vertical reflector to the basin solar still contributes to the increase of the solar flux absorbed by solar still and consequently increases the amount of distillate water [4]. Tanaka determined the optimum inclination of the external reflector of each month along the year. They confirmed that the increase of the annual production of the basin solar still with inclined external reflector varies between 29 and 67% [5]. The reuse of the latent heat of condensation by adding a second effect above the basin solar still leads to a production rate greater than the conventional still by 20% [6]. The use of fan for cooling one side of glass cover of pyramid still increased the distillated water production by 25% compared to the still operating under free convection [7]. It will be noted that the addition of a condenser with fins on the class cover of double slope basin solar still increased the production [8]. Also, the same method was used for the evaporation surface, which is modified with the addition of sponge cubes and fins on the bottom of the basin [9,10].

The separation of the evaporation chamber from the condensation one leads to a higher temperature difference between the glass cover and the brackish water. A water vapors pressure decrease compared to that of a conventional still results. The absence of condensed water on the cover increases the solar radiation absorbed by the bottom of the still, thus generating an increase in the distilled water amount. Coupling the basin solar still with an additional condenser increases the yield and efficiency of the still by 70 and 75%, respectively [11]. Madhlopa and Johnstone concluded that the distillate water production of solar still with a separate condenser increased by 62% compared to a conventional still [12].

This paper is concerned with the effect of the collector and the condensation chamber surface of indirect modular still on the amount and the cost of fresh water. The simulation of solar still was conducted under Algerian weather conditions. The Liu Jordan method was used for modeling the solar radiation.

2. Description of the still

The indirect solar still consists of a solar flat-plate collector connected to a condensation chamber. A schematic view of the system is presented in Fig. 1. The main feature of this still is the increase of the difference between the evaporator temperature and the condenser one. The evaporator is a solar plate collector which is an insulated box with a black sheet steel absorber (1,000 × 2,000 × 0.4 mm) and a glass cover (1,000 × 2,000 × 4 mm). In order to solve the problem of heat losses, the absorber is insulated with 20-mm-thick glass wool. The solar collector is tilted at an angle equal to the latitude (36°N) of Algiers (Algeria). The brackish water streams along the absorber under the gravity force and absorbs heat which increases its temperature until evaporation. The difference between the absorber temperature, the cover one, and the wall side's temperature of the solar collector generates a natural ascending convection flow. Thus, the air moves across the solar collector and the condenser by natural convection. This flow combined to the effect of the solar radiation absorbed by the brackish water. Consequently, its temperature increased until evaporation one.

The condenser chamber consists of a vertical rectangular channel composed of three compartments. One of the walls of the first compartment is cooled by the brackish water pumped from a tank and flowing along the outside of this wall which is one part of a channel (2,000 × 2,000 × 25 mm) insulated with 20-mm-thick glass wool. At the exit of this channel, the brackish water goes into the flat-plate solar collector and streams along the absorber gaining heat energy from the solar radiation and the natural convection flow. Part of this water evaporates and the remaining is collected in the brackish water tank. The amount of water vapor produced by the evaporation of the brackish flows upwards the first compartment which dissipates the heat of condensation to the brackish water flowing down as described above. In order to increase the natural convection flow across the collector and consequently the rate of evaporation of the brackish water, the second and the third compartments are connected to the first one. The second compartment consists of a flat-plate solar collector composed of a glass cover (400 × 2,000 × 4 mm), a galvanized steel sheet (400 × 2,000 × 0.4 mm) painted in black and insulated with glass wool (20 mm thickness). The third compartment is an open rectangular channel in which the plane walls are composed of galvanized steel sheet.

3. Heat and mass transfer in the still

The mathematical model for the flat-plate solar collector and the condenser unit is constructed on thermal and mass balance over the various component of the still. This method is based on the electric analogy relative to a section perpendicular to the air flow rate direction across the collector and the condenser [13].

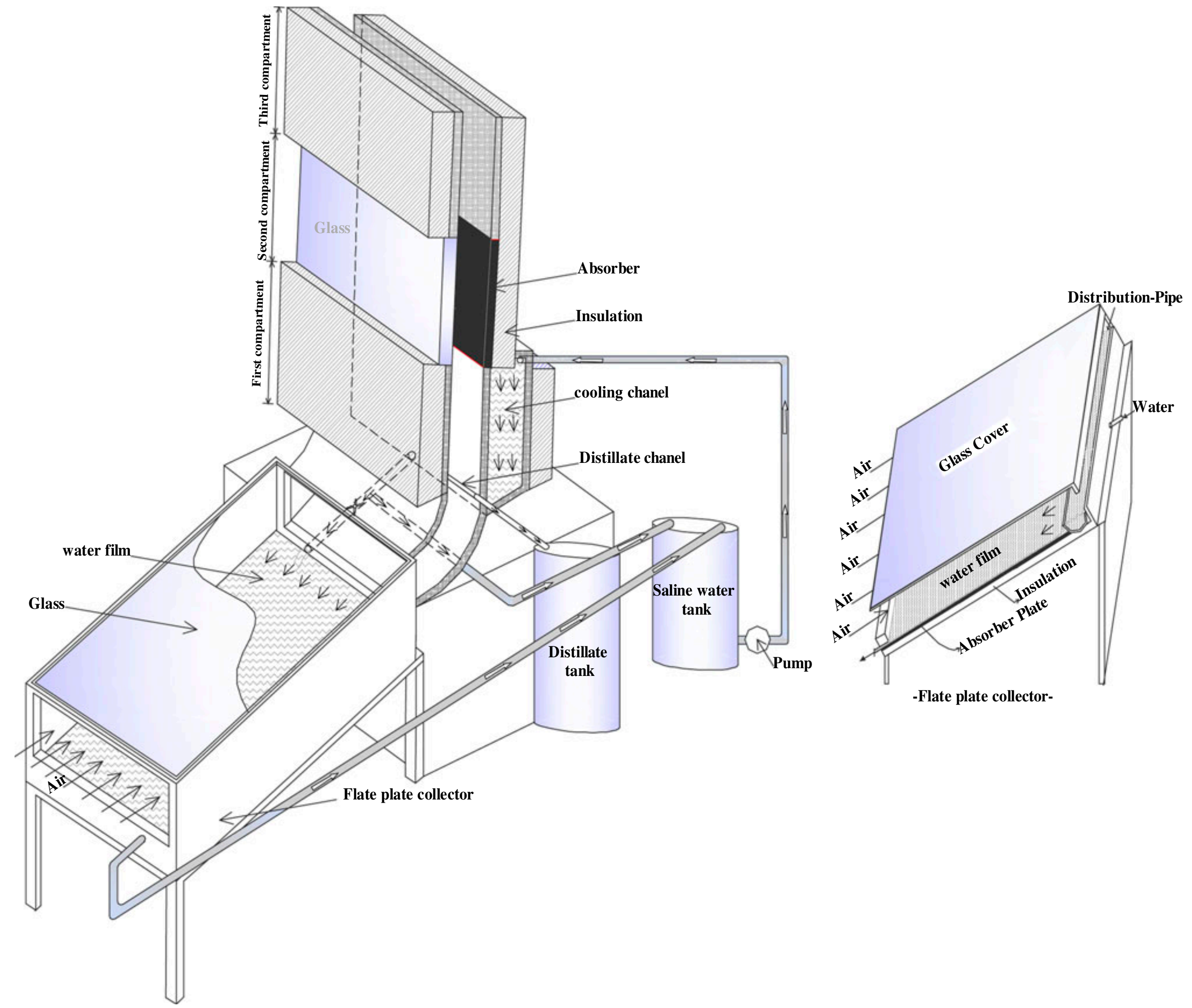

Fig. 1. A schematic view of the still.

For every node the energy balance is written as:

$$\frac{M_i Cp_i}{A_i} \times \frac{\partial T_i}{\partial t} = \alpha_i \dot{q}_i + \sum_{i=1}^{n} \sum_{x} h_{x,i,j}(T_i - T_j) + \dot{q}_k \quad (1)$$

$h_{x,i,j}$—coefficient of heat exchanged between components media i and j by transfer mode x: conduction, convection, or radiation (W m^2 K^{-1}).

The coefficients of heat transfer by radiation and natural convection are computed using correlations [13–16].

For the brackish water streaming along the absorber of the flat-plate collector

$$\dot{q}_k = \dot{m}_{eV} L_V \quad (2)$$

where L_V—specific latent heat of vaporization (J kg^{-1}); $\dot{m}_{eV}$—rate of evaporation (kg s^{-1} m^{-2}).

For the first compartment of the condenser chamber

$$\dot{q}_k = \dot{m}_c L_c \quad (3)$$

L_c—specific latent heat of condensation (J kg^{-1}); $\dot{m}_c$—rate of condensation (kg s^{-1} m^{-2}).

The rate of evaporation is determined using the following relationships [17]:

$$\dot{m}_{eV} = \left(0.002198 + 0.0398 \quad V_a^{0.5756}\right)(P_S - P_a) \quad \text{With} \quad 0 < V_a \leq 5.36 \quad (4)$$

The saturation pressure is determined by [18]:

$$P_S = 10^5 10^{\left(17.443 - \frac{2,795}{T} - 3.686 \log(T)\right)} \quad (5)$$

The rate of condensation is determined using the following relationships [19]:

$$\dot{m}_c = \frac{85.0(T_a - T_P)\varphi}{L_V} \quad (6)$$

With:

$$L_V = 3.141\ 10^6\ \left(1 - 7.6\ 10^{-4}\ T\right) \quad (7)$$

4. Numerical methodology

Transfer equations are solved using a numerical implicit finite-difference scheme method. An iterative calculation is necessary because the heat and mass transfer coefficients depend on the temperatures of the different media which are unknown. Moreover, the air flow through the still depends on the air temperature at the still outlet. It is also necessary to use an iterative method for the calculation of this flow [13].

5. Economic analysis

Unit dimensions, site location, feed water properties, and the qualified staff availability are the main factors affecting the cost of the distillate water. The economic advantages of solar distillation are as follows: simple design and installation, easy to operate and maintain, and it does not require much infrastructure.

The best economic return on the economic investment depends on the production cost of the distilled water and its applicability. The economical analysis of a distillation unit is given as in [20]:

$$\mathrm{CRF} = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (8)$$

with CRF—capital recovery factor; n—number of life years (n = 10 years); i—interest per year (i = 8%).

- First annual cost is calculated using the equation below:

$$\mathrm{FAC} = \mathrm{CC(CRF)} \quad (9)$$

with CC—capital cost of the still.

- Annual salvage value is determined as:

$$\mathrm{ASV} = \mathrm{SFF} \cdot S \quad (10)$$

with S—salvage value of the system (20% of the capital cost of the still); SFF—sinking fund factor:

$$\mathrm{SFF} = \frac{i}{(i+1)^n - 1} \quad (11)$$

- Annual maintenance operational cost is equal to 15% of the first annual cost.

$$\mathrm{AMC} = 0.15\mathrm{FAC} \quad (12)$$

- Annual cost of the distillation system is determined using the equation below:

$$\mathrm{AC} = \mathrm{FAC} + \mathrm{AMC} - \mathrm{ASV} \quad (13)$$

- Cost of distilled water per litter can be calculated as:

$$\mathrm{CPL} = \frac{\mathrm{AC}}{M} \quad (14)$$

M—is average annual productivity of the distillation system (kg).

Prices of different materials are taken according to the Algerian market.

6. Results and discussion

Fig. 2 illustrates the evolution of the monthly average solar radiation during a year collected by a horizontal plane. It presents a bell curve where the maximum is recorded during June. It can be observed that the average ambient temperature profile is similar to the daily average solar radiation one with a maximum value in August.

Results obtained with a surface of condensation chamber equal to 4 m^2 were presented. In all other cases, the same variations were obtained.

Fig. 3 shows the effect of the collector's area on the daily mass of evaporated water. For each month, the amount of evaporated water increase with the collector's area increase. In fact, increasing the collector surface will increase the solar flux absorbed by the collector this contribute to a great difference of temperature of water vapor between the inlet and outlet

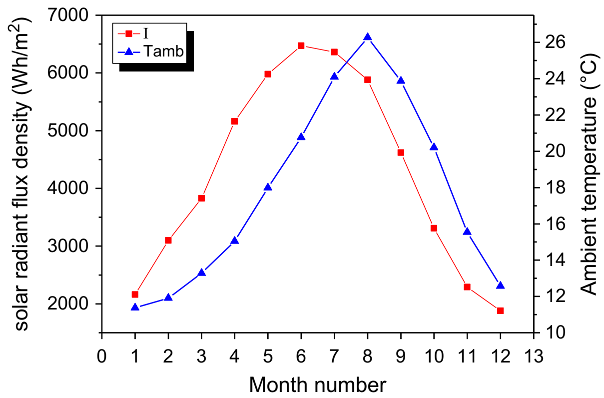

Fig. 2. Annual variation of average daily solar radiation and ambient temperature.

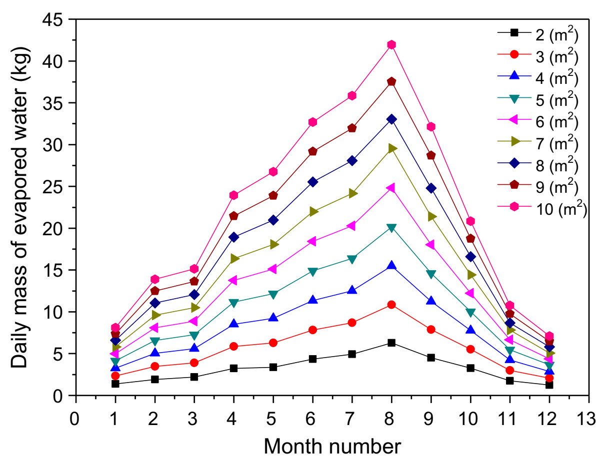

Fig. 3. Effect of the collector area on the daily mass of evaporated water (A_{ch} = 4 m^2).

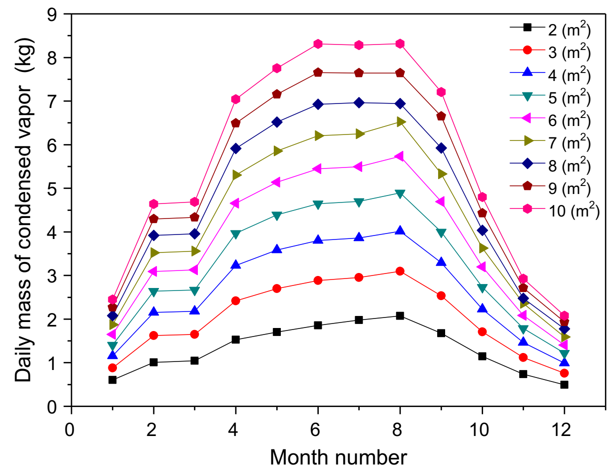

Fig. 4. Effect of the collector area on the daily mass of condensed vapor (A_{ch} = 4 m^2).

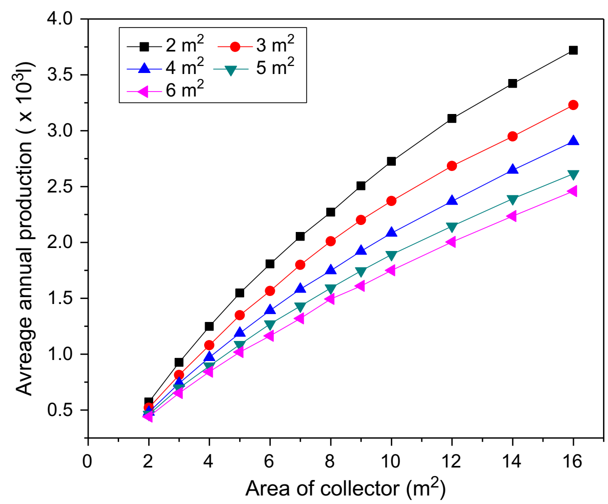

Fig. 5. Average annual production of different area of solar collector and condensation chamber.

of the still. And consequently increasing vapor flow rate across the still which leads to a great amount of evaporated water. For all surfaces, the maximum of evaporated water is recorded during August and the minimum during December.

Daily condensed vapor increase with increasing surface of collector (Fig. 4). The increase of collector's surface leads to a great amount of water vapor. Also, it increases the difference between temperature of water vapor and temperature of the wall on which the water vapor condenses. This increase gives a larger amount of condensed water vapor. Similarly as water vapor, for all collector's surfaces, the maximum of production rate of the still is recorded during August and minimum during December.

The average annual production of the still for different surface of solar collector and condensation chamber is presented in Fig. 5. For all the surfaces of condensation chamber, the annual production of the still increases with increasing collector surface. Also, increasing the surface of the condensation chamber contributes to decrease average annual production of distillate. This difference becomes progressively more significant that the surface of the solar collector increases. The amount of average annual water production varies between 484 (all surface condensation chamber) and 2,084 L (A_{ch} = 2 m^2) for 2 m^2 and 10 m^2 of collector, respectively.

Fig. 6 shows the distilled water cost variation per liter with different area of collector for different area

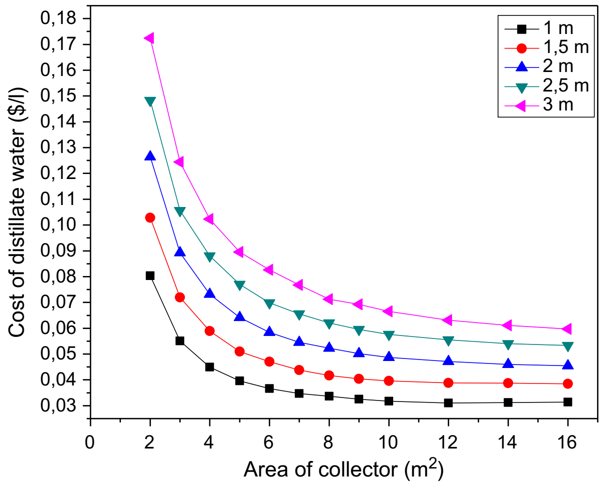

Fig. 6. Cost of distilled water per liter of different area of collector and condensation chamber.

of condensation chamber. The cost of distilled water decreases with the increase of the solar collector surface for all area of condensation chamber. The collector surface increase leads to a great amount of condensed water. At the same time, the cost increase of the still is not high. Therefore, the distilled water cost decreased with increasing surface of collector. In addition, increasing the condensation chamber surface increases the cost of the distillate water. The cost of distilled water of liter varies between 0.08$ and 0.03$ for 2 m^2 (A_{ch} = 2 m^2) and 16 m^2 (A_{ch} = 2 m^2) of collector, respectively.

7. Conclusion

The operation of a modular solar still has been examined above. Also, the effect of the collector's areas of the solar collector on the amount and cost of distilled water has been examined. The outcome of the analysis can be summarized as:

- The maximum of daily water vapor and distilled water production is observed during August for all collector's surfaces.
- The amount of evaporated water increase with the increase of solar collector area.
- Increasing solar collector surface leads to a great yield of distilled water.
- Increasing the condensation chamber surface decrease the annual average production of distillate water.
- The cost of distilled water decreased with increase collector's area and increase with the condensation chamber surface increase.

Symbols

A	—	area (m^2)
AC	—	annual cost of the distillation system ($)
AMC	—	annual maintenance operational cost ($)
ASV	—	annual salvage value ($)
CC	—	capital cost of the still ($)
Cp	—	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
CPL	—	cost of distilled water per litter ($/l)
CRF	—	capital recovery factor
FAC	—	first annual cost ($)
h	—	coefficient of heat transfer (W m^{-2} K^{-1})
i	—	interest per year (%)
I	—	solar radiation density (Wh/m^2)
L_V	—	specific latent heat of vaporization (J kg^{-1})
M	—	mass, average annual productivity (kg)
$\dot{m}$	—	mass flow rate (kg s^{-1} m^{-2})
n	—	number of life years
P	—	pressure (Pa)
$\dot{q}$	—	flux density (W m^{-2})
S	—	salvage value of the system ($)
SFF	—	sinking fund factor
T	—	temperature (K)
t	—	time
V	—	flow velocity (m s^{-1})
Greek symbols		
α	—	absorptance
φ	—	relative humidity (%)
Subscripts		
A	—	air water vapor mixture
amb	—	ambient
c	—	condensed
ch	—	condensation chamber
eV	—	evaporated
i,j	—	index
p	—	wall
s	—	saturation

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