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Modelling and simulation of a modular solar still constituted of a streaming plate collector and a condensation chamber

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Nomenclature

A - cross sectional area, m^2; *Cd* - coefficient of discharge of air channel; *Cp* - specific heat capacity at constant pressure, J/kg K; *g* - gravitational constant, m/s^2; *h* - coefficient of heat transfer, W/m^{2}K; *HR* - relative humidity, %; *L* - still length, m; L_v - specific latent heat of vaporization, J/kg; *M* - mass, kg; $\dot{m}$ - rate of mass flow, kg/s m^2; *P* - pressure, Pa; *Pu* - output power, W; Q_m - volumetric air flow rate, m^3/s; *T* - temperature, K; *V* - flow velocity, m/s; α_i - absorptivity; φ - flux density, W/m^2; η - efficiency, %;
index–
a - humid air; *amb* - ambient; *c* - condensed; *ca* - collector; *cd* - conduction; *ch* - chamber, change of state; *cv* - convection; *e* - water; *ev* - evaporated; *en* - inlet; *ij* - *i* - wall number; *j* - level number; *p* - wall; *r* - radiation; *s* - saturation; *sr* - outlet; *soi* - solar; *v* - glass.

1. Introduction

Desalination of seawater and brackish water by different processes (thermal, filtering membranes), knows an important development following the increase of population, industrial activities and agriculture. Although of simple design, the basin solar still gives a low daily production. So many techniques have been used to improve the performance of such still. For instance, by coupling the basin solar still with a flat plate collector we can increase daily production of distilled water compared to that of a conventional distiller by 24% to 35% [1, 2]. Parabolic concentrator collector can be coupled to the basin still to increase the distillate productivity of the still [3, 4]. Coupling the still with hot water storage tank ensures a continuous alimentation of the still contributing to a steady production and a larger amount of distilled water. It has been found that the water production is more important during the night, since the ambient temperature is lower than by day [5-9]. The increase in energy input of the still using a reflector which may be vertical placed outside or inside the still, leads to increased production of the distilled water compared to that obtained with a conventional still [10, 11]. However, it is noted that the use of a fixed reflector does not improve significantly the production of distilled water. In fact, using a vertical flat plate external reflector increase the daily amount of distillate of a tilted-wick solar still only by 9% [12]. The reuse of the latent heat of condensation also increases the amount of distilled water from 40% to 55%, compared to a simple still [13, 14]. It has been shown that by cooling the glass cover or the four sides of the still walls by flowing water, the amount of condensate can be increased [15, 16]. Similarly increased condensing surface by fins increased the yield of condensation by 55% compared to that of a still using a flat condensing surface [17]. It is the same for the evaporation surface, which is modified for example with the addition of sponge cubes and fins on the bottom of the basin [18, 19]. The addition of stones, coal, red brick pieces, iron pieces and sand in brackish water can store energy in sensible heat form [20-23]. Thus Kalidassa et al showed that the use of quartzite rock leads to a better performance than that obtained with washed rock, iron pieces or red brick [21]. Among black rubber, sand, pebbles, sponge and sponge and sand, sand and sponge lead to a maximum amount of condensate [24]. Thus the heat storage in the sand and sponge immersed in brackish water allows increase the amount of condensate compared to that obtained by coupling the still with a flat plate collector, or using a floating black plate.

The separation of the evaporation chamber from the condensation leads to a higher temperature difference between the glass cover and the brackish water. A decrease in pressure of water vapours compared to that of a conventional still results. The absence of condensate on the cover increases the solar radiation absorbed by the bottom of the still, thus generating an increase in the distilled water amount [25-29]. This article is concerned with the modelling and simulation of modular solar still constituted of streaming solar collector, sit of the evaporation of a brackish water film and condensation chamber.

2. Description of the still

The still consists of a streaming plane solar collector and a condensing chamber (Fig. 1). The solar collector is a parallelepiped enclosure, in which the absorber is a sheet steel (2 m x 1 m x 0.4 mm), the cover is made of glass (2 m x 1 m x 4 mm). The absorber is insulated by a layer of glass wool of 2 cm thickness. The evaporation of water film is produced by natural convection; thus the movement of water and humid air is in counter current.

The condensing chamber is a vertical channel of rectangular section composed of three compartments. In the first, the water vapour, which is generated by the evaporation of water film in the solar streaming collector, condenses on a plane wall cooled from the outside by forced water flow. This forced flow circulates in a channel (2 m x 1 m x 2.5 cm) insulated from the ambient medium by a layer of glass wool (2 cm thick). To reject the non-condensed water vapour to the atmosphere, the device contains above the condensing chamber, a compartment comparable to a solar air heater, composed of an glass cover (0.4 m x 1 m x 4 mm), a sheet steel galvanized (0.4 m x 1 m x 0.4 mm) painted in black and insulated by a layer of glass wool (2 cm thick). The third compartment which appeared as a channel. It is used to increase the chimney effect.

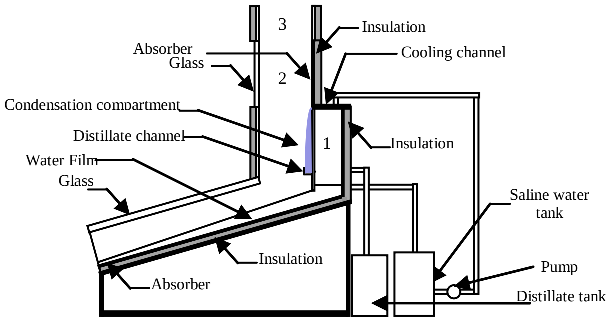

Fig. 1 A schematic view of still

3. Thermal analysis

3.1. Simplifying assumption

- Transfers are one-dimensional.
- Air is perfectly transparent to solar radiation.
- Materials are assimilated to grey bodies.
- Sky is assimilated to a black body.
- The ground temperature is equal to the ambient temperature.
- The effect of the condensing chamber's shadow on the collector is neglected.
- The insulator glass internal side is not a condensation seat.

3.2. Transfer equations

The still is divided to perpendicular fictive parts in the flow's direction. Based on the electrical analogy, a heat balance is established in each part, in order to describe the transfer equations.

By considering each part as an independent entity, it is possible to describe the evolution of thermal transfer in the still (Fig. 2). The instantaneous energy variation in a part (i) of the still is equal to the algebraic sum of the exchanged flow densities inside each part

$$\frac{M_i Cp_i}{S}\frac{\partial T_i}{\partial t} = \varphi_{soi} + \sum_{i=1}^{n}\sum_{x}\phi_{ij} + \varphi_{ch} \tag{1}$$

where ϕ_{ij} is exchanged heat flux density by the transfer mode x (conduction, convection or radiation) between elements i and j (w/m^2).

$$\varphi_{soi} = \alpha_i \phi_i \tag{2}$$

$$\eta_{ca,ch} = \frac{M_{ev,c}}{Pu}\frac{L_v}{3600} \tag{3}$$

The heat flux density (ϕ_{xij}) by the transfer mode x (convection, conduction and radiation) can be written as

$$\phi_{xij} = h_{xij}\left(T_j - T_i\right) \tag{4}$$

Thus, Eq. (1) can be reduced to

$$\frac{M_i Cp_i}{S}\frac{\partial T_i}{\partial t} = \varphi_{soi} + \sum_{i=1}^{n}\sum_{x} h_{xij}\left(T_j - T_i\right) + \dot{m}L_V \tag{5}$$

The radiation heat transfer coefficients between, on the one hand, the external surface of the cover and sky, and the other hand, the insulation and the ground, are deduced from [30]. The natural convection heat transfer coefficients between the external sides of the collector glass, of the condensing chamber, the glass of the condensation chamber, the external sides of insulators and the ambient air (h_{cvent}) are calculated from their correlations [30]. The natural convection heat transfer coefficient of the collector inlet glass and the air (h_{cvav}) are calculated from correlations [30]. We note that we used the same correlations for the heat transfer coefficient between the water film and air (h_{cvae}).

In order to determine the heat transfer coefficients (P_{11}, P_{21}, P_{12}, V_{ich}, P_{13}, P_{23}) and the humid air ($h_{cvap_{11}}, h_{cvp_{21}}, h_{cvap_{12}}, h_{cvavch}, h_{cvap_{13}}, h_{cvap_{23}}$), we used the correlations reported in [31, 32]. The forced convection heat transfer coefficients between on the one hand, the film water and absorber (h_{cvep}), and on the other hand the cooling water and the channel walls ($h_{cvep_{21}}, h_{cvep_{31}}$) are deduced by the reported correlations in [33].

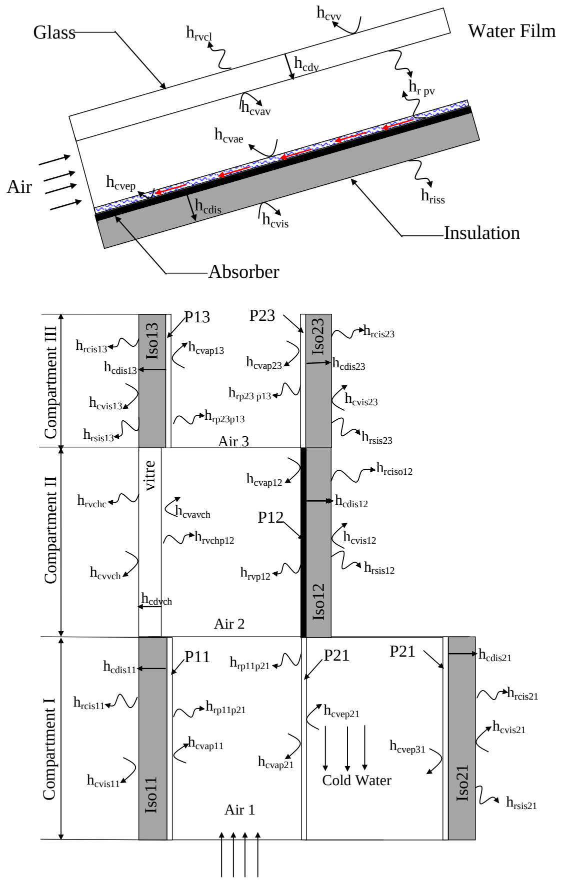

Fig. 2 A schematic view of heat and mass transfer in still

The mass calculation of the evaporated water and the vapour mass of the condensed water is obtained respectively from [34, 35]

$$\dot{m}_{ev} = \left(0.002198 + 0.0398 \quad V_a^{0.5756}\right)\left(P_S - P_a\right) \qquad (7)$$

With $0 \le V \le 5.36$

$$\dot{m}_c = \frac{85.0\left(T_a - T_P\right)HR}{L_v} \qquad (8)$$

The air flow is deduced from the expression below [36]

$$Q_m = Cd\,A\left[g\,L\left(\frac{T_{asr} - T_{aen}}{T_{aen}}\right)\right]^{1/2} \qquad (9)$$

We define the efficiency of the collector and the condensation chamber as follows

$$\eta_{ca,ch} = \frac{M_{ev,c} \quad L_v}{Pu \quad 3600}\,. \qquad (10)$$

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.

5. Results and discussions

Simulations have been conducted by using the weather data of Bouzareah region (Algeria). Liu Jordan method and the typical day concept used. We consider water flows in the adjacent channel at the condensation chamber and the streaming film along the absorber equal to 0.03 m^3/s and 6 x 10^{-6} m^3/s respectively.

Fig. 3 illustrates the evolution of average daily solar intensity during the year upon horizontal surface. It presents a bell figure where the maximum is recorded during the typical day of June. The average ambient temperature variation of Bouzareah region is similar to the solar intensity variation except that the maximum is recorded during the typical day of August.

The Annual average relative humidity varies between 68% during August (typical day) and 74% during December (Fig. 4).

Fig. 5 shows the hourly variation of the solar radiation collected by the still during a typical day of April. The incident solar radiation over the inclined collector (36.8°) is superior to that captured by the condensation chamber inside. Thus an augmentation of the inclination angle causes an increase in the incidence angle. A decreasing in the global solar radiation is the more important when the inclination angle is bigger.

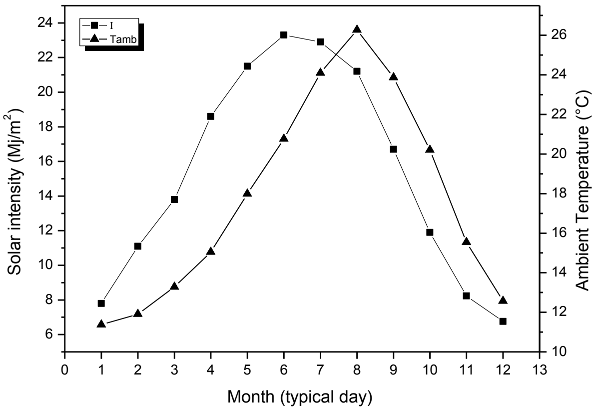

Fig. 3 Annual variation of average daily solar intensity and ambient temperature

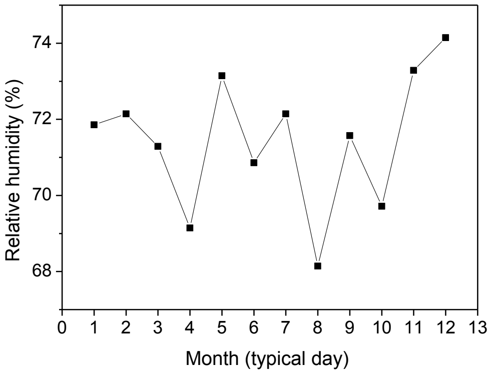

Fig. 4 Annual variation of average daily relative humidity

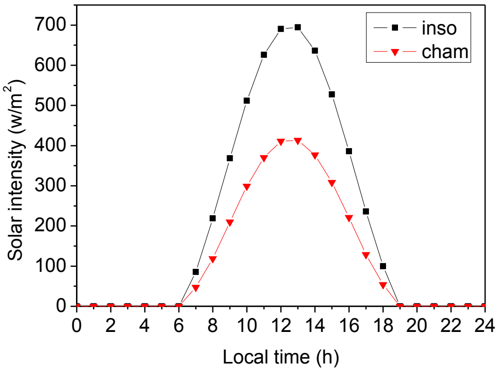

Fig. 5 Hourly variation of solar radiation during typical day of April

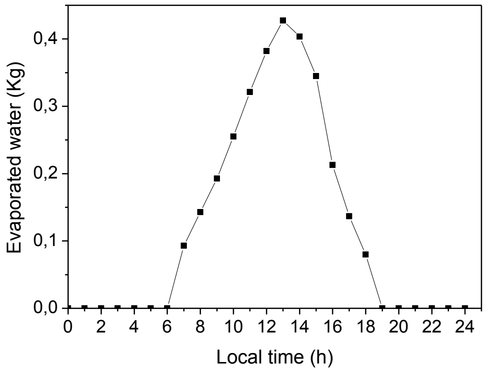

Fig. 6 Hourly variation of evaporated water during typical day of April

The evaporated water mass and the condensed vapour mass increase with time similarly to that of solar radiation (Figs. 6 and 7). We remark that the condensation starts at 8h00, because the inside temperature on which the vapour is condensed is superior to the dew temperature. The hourly variation of the water temperature at the collector outlet, the air and the air flow at the condensation chamber are represented in Figs. 8, 9 and 10. Their evolutions are equally similar to that of the solar radiation with a temporal phase lay of a few minutes due to the thermal inertia of the materials of the condensation chamber.

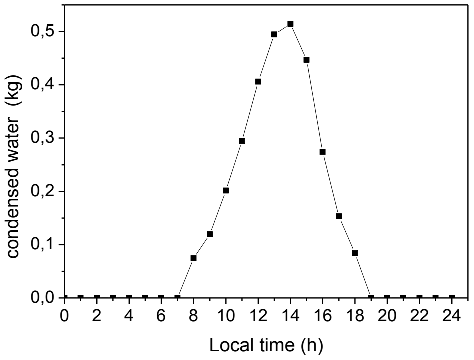

Fig. 7 Hourly variation of condensed water during typical day of April

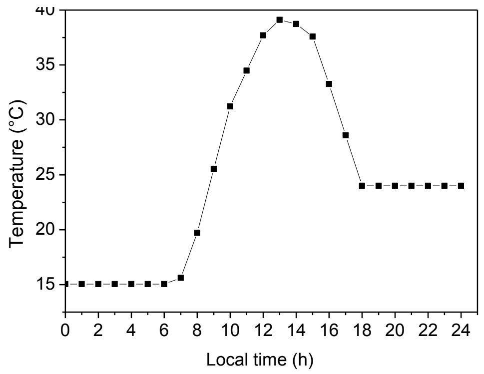

Fig. 8 Hourly variation of water temperatures at the collector outlet during typical day of April

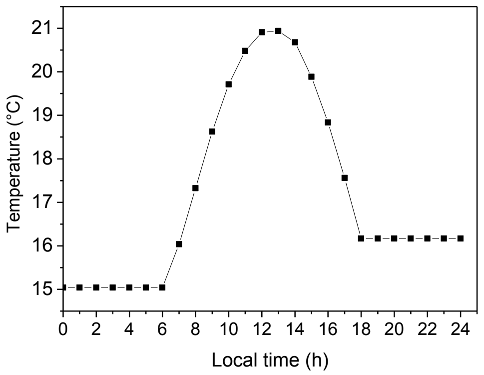

Fig. 9 Hourly variation of air temperatures at the chamber outlet during typical day of April

For weak solar radiation values, notably at the beginning and the end of the day, the collector's efficiency reaches maximum values (Fig. 11). Indeed during these periods the solar radiation is weak, the evaporation depends on the vapour concentration gradient between water-air interface and air. This gradient is notably greater in the collector entrance zone where the relative humidity is weak.

The time evolution of the efficiency of the condensation chamber is similar to that of the solar radiation and temperatures (Fig. 12).

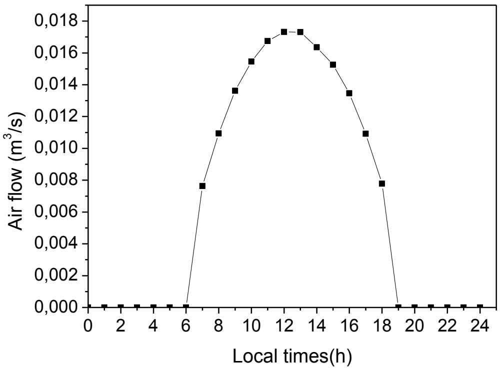

Fig. 10 Hourly variation of air flow during typical day of April

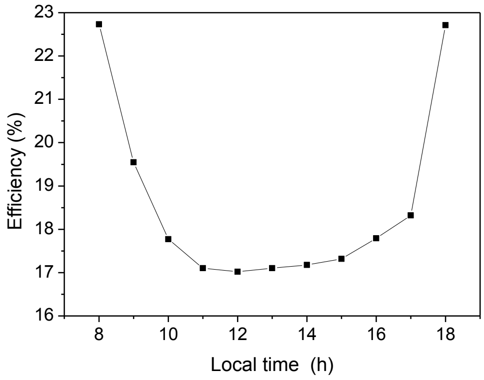

Fig. 11 Hourly variation of collector efficiency during typical day of April

The annual mass of the evaporated water is maximal during the typical day of August where the weather conditions (solar radiation, relative humidity and ambient temperature) favor evaporation (Fig. 13).

Fig. 14 shows the annual variation of the condensed water. The system produces a maximum of distillate during the typical day of August. This day is characterised by a maximal production of the water vapour. The variation of the water mass recovered during the typical days of June and July are weak because the weather conditions during these days were practically similar.

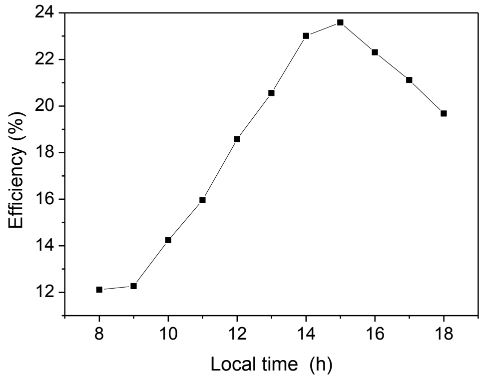

Fig. 12 Hourly variation of condensation chamber efficiency during typical day of April

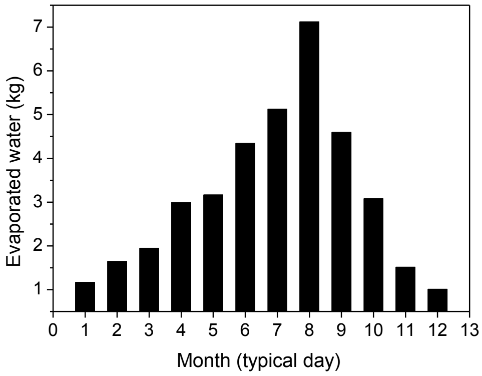

Fig. 13 Annual variation of evaporated water

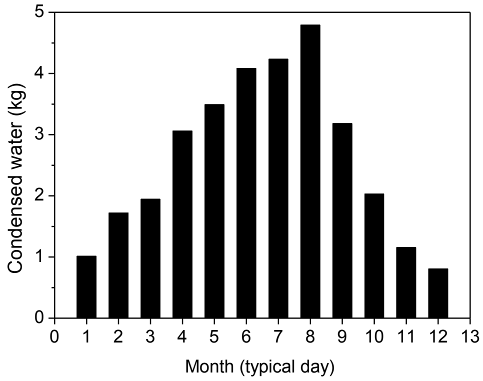

Fig. 14 Annual variation of condensed water

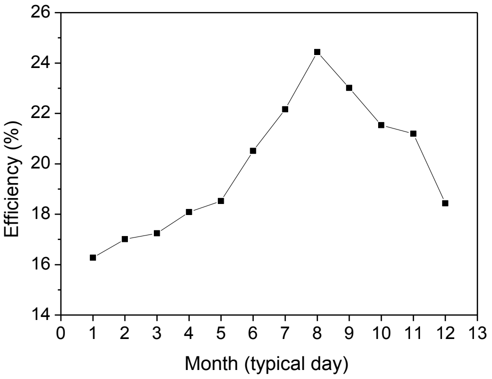

Fig. 15 Annual variation of collector efficiency

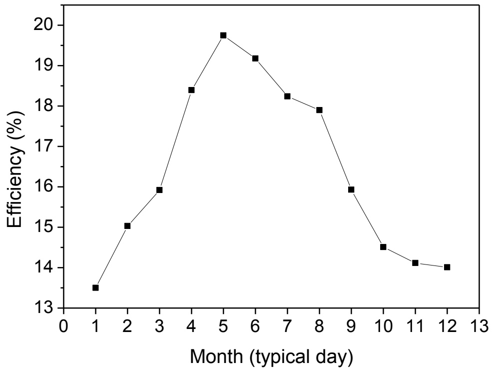

Fig. 16 Annual variation of condensation chamber efficiency

The variation of the average daily efficiency of the collector during the year is similar to that of the evaporated mass variation. Indeed, the maximal efficiency is observed during the typical day of August, characterised by a maximal production of water vapour (Fig. 15). While the maximal average daily efficiency of the condensation chamber is obtained during the typical day of May (Fig. 16). This day is characterised by too weak ambient temperature to permit a good cooling to the water vapour produced by the collector.

6. Conclusion

We have modelled and simulated a modular still constituted of a plane streaming solar collector and a condensation chamber. Our simulations were carried out by using the weather data (10 years) of the region of Bouzareah (Algeria), and the typical day concept based on Lui Jordan method. The obtained results through this research show that:

- solar radiation is the major factor of the system because distillation occurs through natural;
- the distillation system has a maximal production during the typical day of August.
- the maximum average daily efficiency of the solar collector is reached during the typical day of August;
- the maximum average daily efficiency of the condensation chamber is recorded during the typical day of May.

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MODULINIO SAULĖS DISTILIATORIAUS SUSIDEDANČIO IŠ PLAUNAMOS KOLEKTORIAUS PLOKŠTĖS IR KONDENSACINĖS KAMEROS, MODELIAVIMAS IR IMITAVIMAS

Reziumė

Straipsnyje pristatomas modulinės saulės distiliavimo sistemos, veikiančios natūralios konvekcijos būdu, skaitmeninis tyrimas. Šis distiliatoriaus susideda iš plaunamo saulės kolektoriaus sistemos ir kondensacijos kameros. Svarbiausios šilumos ir masės kitimo lygybės yra sudarytos taikant mazgų metodą. Imituojamas tipinės mėnesio dienos distiliatoriaus darbas Alžyro sąlygomis. Rezultatai rodo, kad svarbiausias yra sistemos darbo parametras saulės radiacija. Nustatyta, kad didžiausia distiliato masė tenka tipinei rugpjūčio dienai, o geriausias kondensavimo kameros rezultatas gautas gegužės mėnesį.

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MODELLING AND SIMULATION OF A MODULAR SOLAR STILL CONSTITUTED OF A STREAMING PLATE COLLECTOR AND A CONDENSATION CHAMBER

Summary

In this paper, we present a numerical study of a modular solar distillation system working in natural convection mode. This still is constituted of a streaming plan solar collector and a condensing chamber. Equations governing the heat and mass exchange are established using the nodal method. The operation of the still is simulated for a typical day of the month with the weather conditions of Algiers (Algeria). Results show that solar radiation is the most important parameter of the system operation. The obtained distillate mass is maximum during the typical day of August, while the best performance of the condensing chamber is recorded during May.

Keywords: modular solar still, streaming plate collector, condensation chamber.

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