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Simulation of the solar still under real operating conditions

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ABSTRACT

The present work is a contribution to reduce water deficiency in my country by using the solar distillation means. We propose a model of solar still planted under climatic conditions of the area of Constantine located at Eastern of Algeria. A theoretical approach is used to simulate the behavior of some internal and external parameters related to the solar-still with time, and their effects on the system performance during a sunny period. These parameters include the temperature difference between the evaporation surface and that of the condensation, internal heat transfer, water depth, wind velocity, solar radiation, ambient temperature, and external heat transfer. The obtained results show that the productivity is strongly related the solar radiation in the best direction of the still and a large temperature difference between the glass and the water surface improves the daily production. Moreover, shallow water of 0.02 m in basin of still gives higher production. Daily yield of still increases as wind speed increases up to critical value at 10 m/s where production reaches its maximum. The still productivity has increased by 57, 71% when the wind velocity increases from 2 to 10 m/s. The internal and the external heat transfers affect directly the performance of the still in relation with solar radiation.

Keywords: Solar still; Internal parameters; External parameters; Performance

1. Introduction

The production of water is an essential and most important component of life; it is used in many activities such as drinking, and irrigation etc. Solar still is one of the solar desalination processes that promising an alternative solution for converting the brackish water into potable water using solar energy because the reasonable cost of the system with cheap equipment. Therefore, the use of a simple solar still design that construction and maintenance with ease of operation, it is best suitable for regions of the world with high solar intensities, especially in the summer season. Many factors affect the performance of still such as internal and external parameters. The internal heat transfer of solar still is responsible for the transportation of pure water in the vapor form leaving behind all impurities in the basin, whereas the external heat transfer through a condensing cover is responsible for the condensation of pure vapor as distillate [1]. Several researches have been done to increase the productivity of the solar stills by studies the internal and external parameters such as solar intensity, wind velocity, ambient temperature, water–glass temperature difference, free surface area of water, absorber plate area, temperature of inlet water, glass angle, and depth of water [2–4]. In addition, Al-Hinai et al. [5] studied the effect of climatic, design and operational parameters on a conventional double-sloped single-basin solar, and was performed it to obtain an optimum design that gives higher production. Dunkle [6] developed mathematical expressions for convective, radiative and evaporative heat transfer coefficients for the solar Still. By considering the different factors affecting

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the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still. Murugavel et al. [7] reviewed the progress in improving the effectiveness of the single basin passive solar still. In the same way other researchers have investigated the effect of solar radiation on still productivity, and their results indicate that solar still productivity increases with increasing incident solar radiation [8]. According to El-Sebaii [9] the increase in wind speed causes an increase in productivity. Water depth is among important parameters affecting significantly the still productivity and the increase in the water depth leads to the decrease in the solar still production. The yield of a solar still mainly depends on the difference between water and glass cover temperatures which acts as a driving force of the distillation process.

The main objective of this work is to increase the solar still production by studying the effect of some internal and external parameters related to the system, under the climatic conditions of the area of Constantine located at Eastern of Algeria. In addition we look for the best cover tilt angle (10°, 20° and 40°) that received a maximum solar radiation.

2. Model of the solar still

The model of solar still used in this study is illustrated in Fig. 1. It consists of single basin with double slope, the simplest design which can be fabricated at much lower cost and with easily available materials. Aluminum is chosen as a material to construct the still because of its relatively low cost, good resistance to corrosion at low and medium temperatures, and low weight. The basin of the still has 1 m^2 of area (length = 1 m, width = 1 m), covered with 3 mm transparent glass. The height of the side of the solar still is taken at 0.15 m for the inclination angle of the condensing cover. The bottom and sides of the solar still is insulated from outside with 100 mm polystyrene and enclosed in a wooden box to minimize the heat loss with the surrounding. In addition, the solar still base is normally blackened at the inner side to enable the maximum absorption of solar radiation. In order to successfully perform the experimental investigation and to accurately evaluate the effect of water depth on the increased water productivity, it was necessary to investigate many depths of water under the same operational conditions. The operation of the still is very simple. The transparent glass cover allows the solar radiation to pass to the water and heats it. The evaporated water condenses on the inside of the glass cover and run down the cover towards its end (distillate outlet), where it will be collected.

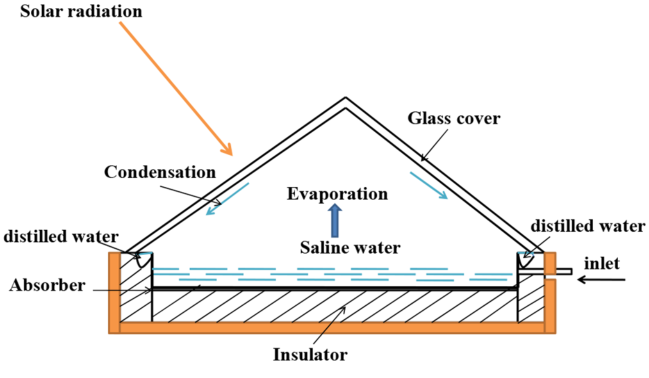

Fig. 1. Schematic diagram of the model of solar still.

3. Experimental set up

The experiment is supposed to be carried out on typical day in July 2013. The set-up is installed in the area of Constantine (northeast of Algeria) with latitude of 36° 22´ to the north, a longitude of 6° 37´ to the east. The glass cover of the solar still is fixed using a rubber gasket on the top of the vertical walls of each side and a silicon rubber is used to seal the glass covers and the basis since silicon has a good bonding between the glass and different materials. A channel was made adjacent to the smaller wall to collect the distilled water with a plastic pipe to drain it into an external measuring jar [10]. The all of experiments are to be started at 6.00 am local time and to be finished at 7.00 pm. The considered solar still is oriented to the best facing in order to receive the maximum possible solar radiation.

The various internal and external parameters of different component of still and environment that are measured every regular hour for the typical summer day are:

- Ambient temperature
- Solar insolation
- Wind velocity
- Outer and inner glass temperatures
- Water temperature
- Absorber temperature
- Hourly and a daily yield

3.1. Instrumentation and measurements

To measure the temperature of different elements of the solar still (cover, absorber, water, ambient), thermocouples (type-k) coupled to digital thermometer are connected to a multipoint recorder of the still. An external thermometer, pyranometer, and a digital anemometer are used to measure the ambient temperature, instantaneous values of solar radiation, and wind speed respectively. During the experimental work the wind speed was in the range of 2–14 m/s. A jar is used to measure the distillate and the hourly measured condensate is accumulated in a larger measuring tank. The total collected distillate during the day is the summed-up hourly values.

4. Mathematical modeling

The internal and the external parameters that enclosed and surroundings the solar still are considered the important element that affects the performance of the solar still. In this study the thermal model of a single basin double slope solar still is derived by the energy balance equations of its components, namely basin, water mass, and glass cover.

The following assumptions are taken into consideration when setting up the energy balance equations per unit area of the solar still components for the average temperature in a typical summer day.

1. The system is considered in a quasi-steady state condition.
2. There is no vapor leakage in the solar still.
3. It is an air tight basin, hence no heat loss.
4. Temperature-dependent heat transfer coefficients has been considered
5. The evaporated mass of water is continuously replaced.
7. The heat capacity and absorption of the glass cover and insulating material is negligible
8. Each component of the system, bottom/size and the sides are considered perfectly insulated.
9. Solar radiation absorbed by the walls is negligible.

The transient energy balance equation for the glass cover which exchanges heat with water and environment can be written is given as [10]:

$$m_g Cp_g \frac{\partial t_g}{\partial t} = \alpha'_g I(t) A_g + \left(Q_{c,w-g} + Q_{ev,w-g} + Q_{r,w-g}\right) - \left(Q_{r,g-sky}\right) - \left(Q_{c,g-a}\right) \quad (1)$$

For the water mass, the corresponding energy exchange, per unit area, taking place between the basin liner and the cover is:

$$m_w Cp_w \frac{\partial t_w}{\partial t} = \alpha'_w I(t) A_w + \left(Q_{c,b-w}\right) - \begin{pmatrix} Q_{c,w-g} + Q_{ev,w-g} \\ +Q_{r,w-g} \end{pmatrix} \quad (2)$$

The energy balance equation the basin liner per unit area is computed as follows:

$$m_b Cp_b \frac{\partial t_b}{\partial t} = \alpha'_b I(t) A_b - \left(Q_{c,b-w}\right) - \left(Q_{cd,b-in}\right) \quad (3)$$

The heat quantity exchanged by convection between the water and the absorber is:

$$Q_{c,b-w} = h_{c,b-w} A\left(T_b - T_w\right) \quad (4)$$

where the coefficient of heat transfer $h_{c,b-w}$ is given as [11]:

$$h_{c,b-w} = \frac{CK}{L}\left[Gr.Pr\right]^{1/4} \quad (5)$$

The heat loss by conduction, from the basin liner to the insulation is:

$$Q_{c,b-in} = h_{cd,b-in} A\left(T_b - T_{in}\right) \quad (6)$$

where the coefficient of heat transfer by conduction is [11]:

$$h_{cd,b-in} = \frac{K_b}{L_b} \quad (7)$$

The energy balance equation for the insulation per unit area of basin is:

$$m_{in} Cp_{in} \frac{\partial t_{in}}{\partial t} = \left(Q_{cd,b-in}\right) - \left(Q_{loss}\right) \quad (8)$$

The heat lost from the insulation to the environment can be written as:

$$Q_{loss} = U_{in} A\left(T_{in} - T_a\right) \quad (9)$$

The overall heat transfer coefficient is computed from the Fourier’s conduction equation [12]:

$$U_{in} = \left(\frac{L_{in}}{K_{in}} + \frac{1}{h_{in}}\right)^{-1} \quad (10)$$

The hourly yield per unit area depends on water and glass temperatures and is given by:

$$m_w = \frac{Q_{ev,w-g}}{L_V} \times 3600 \quad (11)$$

The total daily yield can be obtained through the following relation:

$$M_w = \sum m_w \quad (12)$$

4.1. Heat transfer in a solar still

The heat transfer process in a solar still can be broadly classified into internal and external heat transfer processes based on energy flow in and out of the enclosed space. The internal heat transfer is responsible for the transportation of pure water in the vapor form leaving behind impurities in the basin itself, whereas the external heat transfer through the condensing cover is responsible for the condensation of pure vapor as distillate [13]. Both these processes are briefly explained in the following sections:

4.1.1. Internal heat transfer

The internal heat transfer mode, that is, the heat exchange from evaporative surface to the glass cover inside the distillation unit is governed by radiation, convection and evaporation

$$Q_{r,w-g} = h_{r,w-g} A\left(T_w - T_g\right) \quad (13)$$

$$Q_{c,w-g} = h_{c,w-g} A\left(T_w - T_g\right) \quad (14)$$

$$Q_{ev,w-g} = h_{ev,w-g} A\left(T_w - T_g\right) \quad (15)$$

where the total heat transfer is expressed by [14]:

$$Q_1 = Qc,w-g + Qev,w-g + Qr,w-g \quad (16)$$

4.1.1.1. Convection heat transfer

The heat transfer per unit area per unit time due to convection is given by [11]**:**

$$Q_{c,w-g} = h_{c,w-g} A\left(T_w - T_g\right) \quad (17)$$

where the convective heat transfer coefficient between water mass and glass cover inner surface and can be calculated by Dunkle's relation [6]:

$$h_{c,w-g} = 0.884\left[\left(Tw - Tg\right)\frac{\left(P_w - P_g\right)}{268.9\times10^3 - P_w}T_w\right]^{1/3} \tag{18}$$

The partial pressure of water vapour at water and inner glass temperatures within the still are given by Fernandez and Chargoy [15]**:**

$$P_w = e^{\left(25.317 - 5.144/T_w\right)} \tag{19}$$

$$P_g = e^{\left(25.317 - 5.144/Tg\right)} \tag{20}$$

4.1.1.2. Radiation heat transfer

The radiative heat transfer occurs at inside of the solar still between water mass and glass cover inner surface can be obtained by the following relation:

$$Q_{r,w-g} = h_{r,w-g}A\left(T_w - T_g\right) \tag{21}$$

where $h_{r,w-gi}$ is the radiative heat transfer coefficient between water mass and glass cover inner surface and evaluated by:

$$h_{r,w-g} = \varepsilon_{eff}\times\sigma\left(T_w^2 + T_g^2\right)\left(T_w + T_g\right) \tag{22}$$

The effective emittance between water mass and glass cover is given as

$$\varepsilon_{eff} = \left(\frac{1}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1}\right)^{-1} \tag{23}$$

4.1.1.3. Evaporation heat transfer:

Evaporation occurs at the liquid-vapor interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature.

The rate of evaporative heat transfer between water mass and glass cover inner surface is given by:

$$Q_{ev} = h_{ev}A\left(T_w - T_g\right) \tag{24}$$

In the above expression, $h_{e,w-gi}$ represents the evaporative heat transfer coefficient between water mass and glass cover inner surface and it's determined by Dunkle's relation [6]:

$$h_{ev} = 16.276\times10^{-3}\times h_{c,w-g}\times\frac{P_w - P_g}{T_w - T_g} \tag{25}$$

The total internal heat transfer coefficient between water mass and glass cover inner surface ($h_{t,w-gi}$) is obtained by the following expression:

$$h_1 = h_{c,w-g} + h_{ev} + h_{r,w-g} \tag{26}$$

4.1.2. External heat transfer

4.1.2.1. Top loss heat transfer

The heat energy from the glass cover outer surface is lost to the atmosphere by convection and radiation heat transfer processes.

The convection heat loss from glass cover outer surface of the solar still to the atmosphere is given by:

$$Q_{c,g-a} = h_{c,g-a}A\left(T_g - T_a\right) \tag{27}$$

The coefficient of the convective heat transfer $h_{c,g-a}$ is a function of the wind speed, and is computed as follows [16]:

$$h_{g,c-a} = 2.8 + 3.0V \tag{28}$$

The radiation heat loss from glass cover outer surface of the solar still to the surroundings is given by:

$$Q_{r,g-sky} = h_{r,g-sky}A\left(T_g - T_{sky}\right) \tag{29}$$

The radiative heat transfer coefficient between the outer surface glass cover and the sky is given is given by Duffie Beckmann [17]:

$$h_{r,g-sky} = \varepsilon_g\times\sigma\left(T_g^2 + T_{sky}^2\right)\left(T_g + T_{sky}\right) \tag{30}$$

where the sky temperature T_{sky} is [18]:

$$T_{sky} = 0.0552T_a^{1.5} \tag{31}$$

The total external heat transfer (top heat loss) is the summation of convective and radiative heat losses which is given as:

$$Q_2 = Qc,g-a + Qr,g-sky \tag{32}$$

The total external heat transfer coefficient (h_2) is then:

$$h_2 = q_{r,g-sky} + q_{c,g-a} \tag{33}$$

5. Results and discussion

A computer program was written in MATLAB (version 7.0) to solve numerically the above nonlinear system related to differential equations by applying the Gauss–Seidel implicit iterative method [19] and a time step of one hour is used in the simulation. The simulations were carried out in summer typical day from July with the climatic conditions of Constantine, east of Algeria.

Fig. 2. indicates the change in solar radiation with time for south-north and east-west Orientations. The daily variation of solar radiation for solar still shows the same pattern of change for different orientations where the solar radiation increases till it reaches its maximum value, and then decreases till it reaches its minimum value. It can be observed, that at the east–west orientation the solar still receives the maximum solar radiation at (12:00 a.m.; 948,

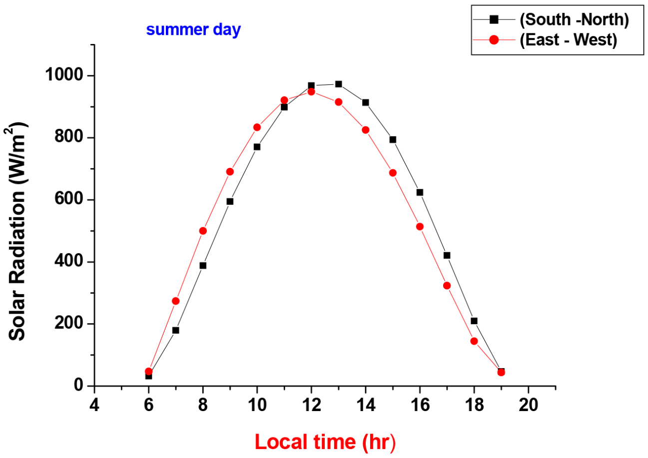

Fig. 2. Solar radiation change with time for south-north and east-west orientations.

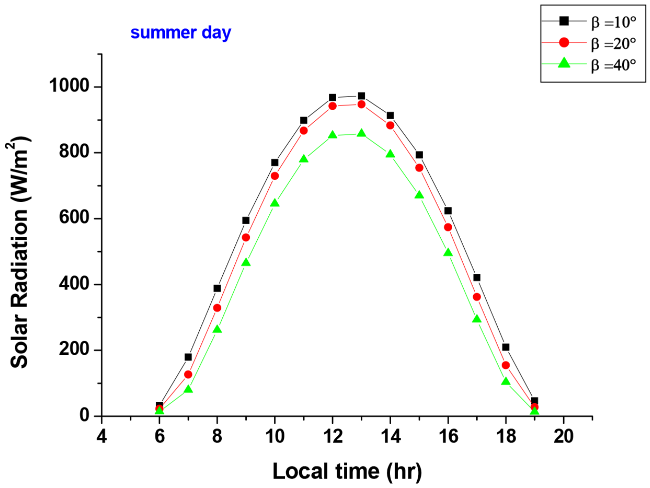

Fig. 3. Change solar radiation with time at different angle of inclination.

35 W/m^2) earlier than that received at the south–north orientation, with a maximum value (973, 10) at 13.00 pm). It's also noticed that at the south–north orientation and during the morning, the solar radiation reception by the still, starts slowly in comparison with east-west orientation and reversely at the afternoon where it is already at high levels. So we can conclude from this comparison, that solar radiation reception is the greatest at the south–north orientation. This can be explained by the concentration of the solar radiation in this orientation.

In order to fix the best angle of inclination of the cover of still that receives more solar radiation, the hourly variation of solar radiation at different angles of inclination is studied as shown in Fig. 3. The results indicate that the curves of the solar radiation at different angle of inclination have similar trend where it increases in the morning hours to reach maximum values of, respectively, 973, 10 W/m^2, 947, 57 W/ m^2, and 857, 91 W/m^2 at 13:00 p.m corresponding inclination angles of 10, 20° and 40°. It's obviously that 10° is the optimum angle to be used. It's well known that the smaller the glass cover angle, the smaller the distance between the cover and basin water (height of still) will be, and not only the faster solar radiation reaches the water basin but also the volume of air with vapor purges into the condenser area is maximum [20]. In addition the cover tilt angle is small in summer season [21].

The effect of the predicted solar radiation on the yield at south–north direction (the found best orientation) is shown in Fig. 4. The maximum yield occurred at 16:00 p.m, while the maximum insolation occurred at 13:00 p.m. The difference is due to the time lag of the system [5].

The variation of ambient temperature and the yield with time of a passive solar still in the considered summer day is shown in Fig. 5. From this figure, one can observe that there is a similar trend for both curves of ambient temperature and still output which demonstrates the effect of ambient temperature on still output. These results are in agreement with those reported by El-Sebaii [22], Garg and Mann [23], and Cooper [24].

Fig. 6 shows the effect of wind speed on the daily yield. It appears that daily yield increases as wind speed increases

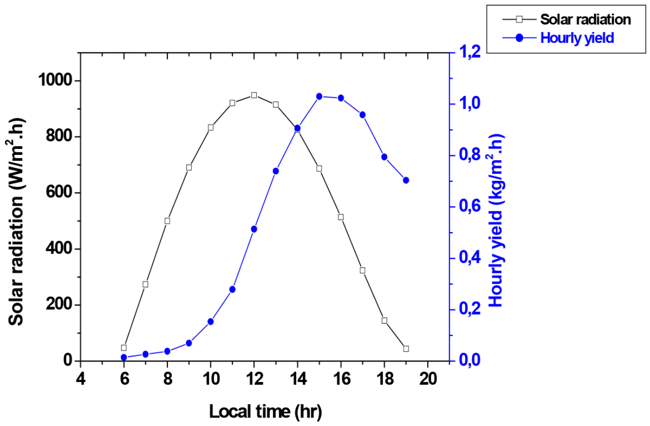

Fig. 4. The variation of solar intensity and hourly yield of the solar still output on typical summer day.

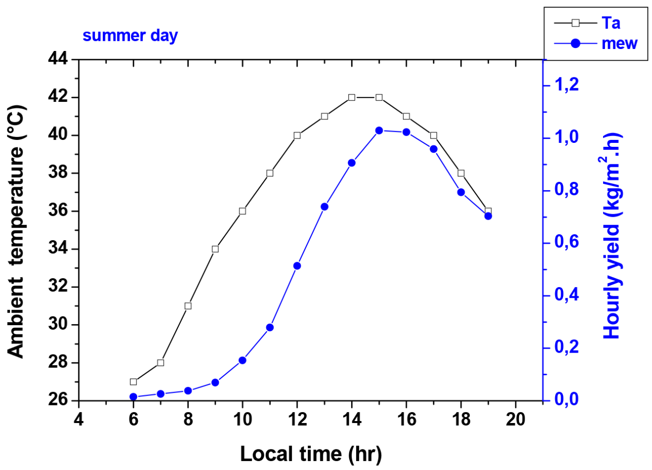

Fig. 5. Variation of Ambient temperature and the yield with time of a passive solar still.

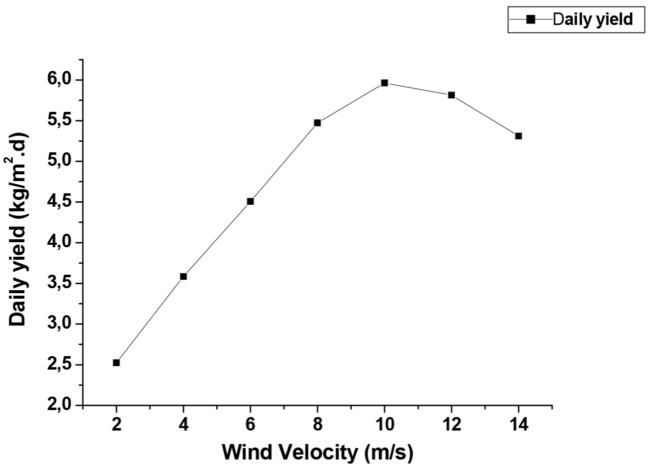

Fig. 6. Effect of wind speed V on daily yield of a solar still on a typical summer day.

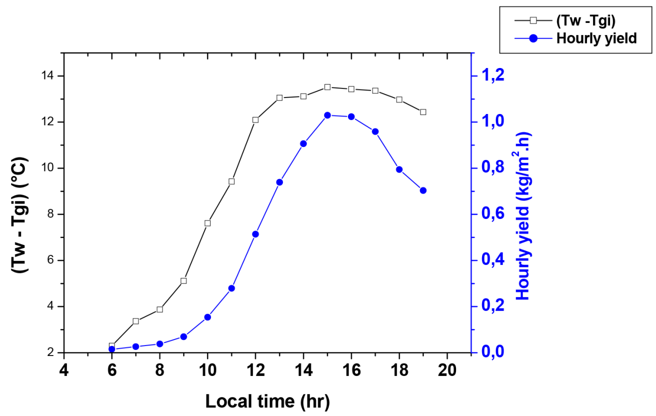

Fig. 7. Variation of temperature difference of the inner cover and the water with time and with the hourly yield for a solar still.

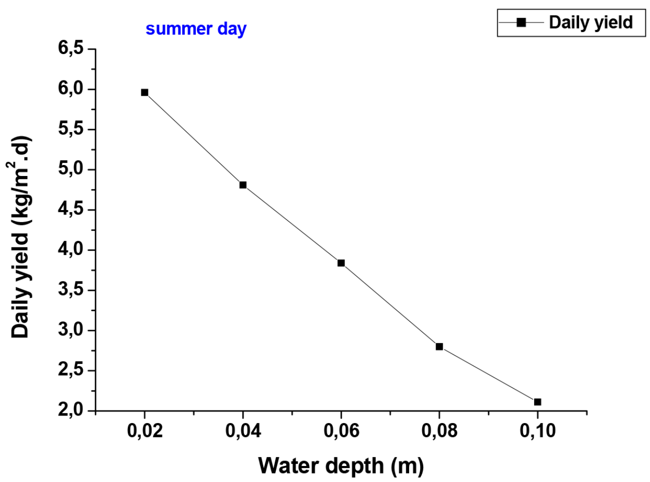

Fig. 8. Effect of water depth on the daily yield of solar still.

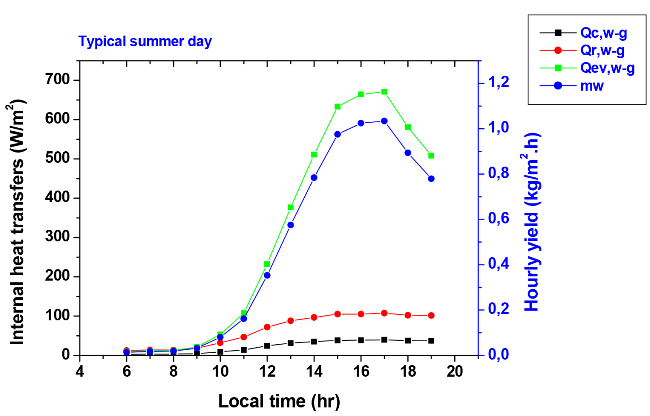

Fig. 9. Variation of internal heat transfers with time and hourly yield of a solar still.

up to critical value at 10 m/s where production reaches its maximum and then it starts to decrease to insignificant levels. The still productivity has increased by 57, 71% when the wind velocity increases from 2 to 10 m/s. These results are in agreement with those reported by Garg and Mann [22], Rajvanshi [25], and El-Sebaii [9]. Moreover Cooper [14] points out that increasing wind velocity cause an increase in output. The wind velocity is also affecting the cover temperature. At higher wind velocity the convective heat transfer from the cover to atmosphere increases due to increase in convective heat transfer coefficient between cover and atmosphere. This effect increases the condensing and evaporation rate and productivity of the still [26].

Fig. 7 illustrates the variation of temperature difference (delta T) of the inner cover and the water with time and with the hourly yield for a solar still. In the same manner, the progress of the curves of delta T and the hourly yield with time show a similar pattern. The effect of delta T on the productivity of still is due to the increase of the process of evaporation-condensation of the still. However the evaporation of water depends on the natural convection circulation of air mass inside the still which is the function of temperature difference between the water and the glass. This temperature difference is the driving force for the circulation of air and the water temperature [24]. Lowering the cover temperature helps in increasing the productivity. Increasing the temperature difference between the glass and the basin water increases the natural circulation of air mass inside the still. It increases both convective and evaporative heat transfer between basin water to cover [7]. We concluded that the temperature differences play an important role on the still productivity.

The effect of various depth of water in the basin of solar still is shown in Fig. 8. We notice that shallow water at 0.02 m gives higher productivity and the daily yield increases by 64, 59% when a water depth decreases from 0.10 m to 0.02. This is due to the increase of the heat capacity of the water in the basin. It is well known that the water depth is inversely proportional to the productivity of the still [5,27] and a water depth of 0.02 m was found to be the optimum [28]. Aboul-Enein et al. [29] concluded from their mathematical model that the productivity of the still decreases with an increase of heat capacity of basin water during the daylight and reverse in case of overnight.

Fig. 9. represents the variation of internal heat transfers and the hourly yield of a solar still. From the above figure, the comparison of the effect of different curves of

heat transfers on still hourly yield indicates that heat transfer of evaporation has a major positive significant effect on yield still where it increases as the heat transfer of evaporation increases and attains the maximum value at around 4.00 p.m. Contrary, the heat transfers of radiation and convection are minimized and insignificant in their tendency. This can be explained by the received solar intensity by a water depth and causes the act of evaporation. The evaporative fraction from the evaporator decreases with increasing temperature difference while that from the solar still increases.

6. Conclusion

Through the obtained results, it noticed that the performance of a single basin passive type solar still planted in area of Constantine (east of Algeria), is affected by some internal and external parameters. The following conclusions may be given:

- The greatest value of solar radiation reception is obtained for solar still at the south–north orientation because of the maximum concentration of solar radiation in this orientation.
- 10° is the optimum angle of the cover of the still that received a maximum solar radiation.
- The productivity of the still is directly related to the intensity of the solar radiation received and the maximum value of the solar intensity is received earlier than obtained the maximum daily yield, this difference is due to the time lag of the system.
- The still output increases with increase the ambient temperature during the period of the summer day.
- Daily yield increases as wind speed increases up to critical value at 10 m/s where production reaches its maximum. The still productivity has increased by 57, 71% when the wind velocity increases from 2 to 10 m/s.
- The yield of a solar still mainly depends on the difference between water and glass cover temperatures in relation with the increases in the process of evaporation-condensation and the temperature difference is the driving force for the circulation of air and the water temperature.
- A shallow water at 0.02 m gives higher productivity and a water depth decreases from 0.10 m to 0.02 results in increase of the daily yield by 64, 59%. this is due to the increase of the heat capacity of the water in the basin.
- The heat transfer of evaporation has a major positive significant effect on yield still where it increases as the heat transfer of evaporation increases. Contrary, the heat transfers of radiation and convection are minimized and insignificant in their effect on yield still.

Nomenclature

A — Area, m^2
C — Specific heat, J/kg K
Gr — Grashof number, dimensionless
I — Fraction of an absorbed solar radiation, W/m^2
h_1 — Total internal heat transfer coefficient, $W/m^2 K$
h_2 — Total external heat transfer, $W/m^2 K$
K — Thermal conductivity, W/m K
L — Thickness, m
m — Mass, kg
mew — Production rate, $kg/m^2 \cdot h$
P — Partial pressure, N/m^2
Pr — Prandtl number, dimensionless
Q — Heat flux, W/m^2
t — Time, s
dt — Small time interval, s
T — Temperature,°C
U — Overall heat transfer coefficient, $W/m^2 K$
V — Wind velocity, m/s

Greek

α' — Absorptivity
β — Inclination angle (°)
σ — Constant of Stefan–Boltzmann, $W/m^2 K^4$
ε — Emissivity, dimensionless
δ — Declination angle (°)

Subscripts

a — Ambient
b — Basin liner
c — Convection
cd — Conduction
eff — Effective
ev — Evaporation
g — Glass
i — Internal
in — Insulation
r — Radiation
w — Water

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