Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25001

179 (2020) 28–37
March

Solar pond driven seawater greenhouse – simulations on different Moroccan locations

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Received 10 February 2019; Accepted 7 October 2019

ABSTRACT

To cope with the large energy consumption in the most commercial desalination processes, along with the growing concern about climatic change resulting in CO_2 emission, much effort has been made since almost four decades to use renewable energies to run desalination units. Among the numerous desalination processes driven by renewable energies, the seawater greenhouse received much attention for decentralized production of fresh water. The paper deals with an innovative hybrid approach of seawater desalination that has been explored. It combines a seawater greenhouse (SWGH) with a solar pond to produce more fresh water. Furthermore, it enables a better management of brine, which represents a major issue for all desalination processes. Indeed, the rejected brine of the SWGH will be recycled, by using it in a solar pond as a heat storage plant and a heat source to warm the air to more or less than 70°C at the inlet of the second evaporator of the SWGH. The process scheme and the mathematical and software models of both the classical SWGH and of its hybridization with a solar pond are presented. The calculations show that the fresh water production rate of the new SWGH concept is more than five times higher than of the classical SWGH one. Simulations on different Moroccan sites were realized as a case study, to estimate the added value of the new SWGH model and, at the same time, to compare its profitability in these implantation locations.

Keywords: SWGH; Solar pond; Brine; Storage; Evaporator

1. Introduction

Morocco is the only North African country with no natural oil resources. It covers over 95% of its energy needs through imports. Furthermore, this country came 19th in the projected Country Water Stressed Ranking for 2040 [1].

Indeed, without additional resources, water will become increasingly scarce and, whatever the size of the large dams constructed, they alone cannot meet the demands of economic and social development. The battle of Morocco in the field of mobilization of water resources has to be made differently, by the desalination of seawater.

As thermal desalination processes such as multi-stage flash and multiple-effect distillation are energy intensive technologies, Morocco has used, since more than 30 years, seawater reverse osmosis which is less energy-intensive (3–4 kWh/m^3) [2].

However, given that Morocco is invested in sustainable development technologies, the use of all these technologies is considered as incompatible with this concept, because of their direct and indirect use of fossil fuels that contributes to CO_2 emission [3].

As an alternative, renewable energy powered desalination systems have been extensively studied in both developed and developing countries to provide additional water to communities experiencing shortages in remote and arid regions [4–14]. Among these technologies, SWGH seems promising for Morocco where water becomes scarcer even

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for agriculture. The SWGH combines the greenhouse with the humidification–dehumidification (HD) technology. The process boasts low building and maintenance costs due to fewer mechanical parts carried out in it and requires a low level of technical support.

The review of the literature studies on the SWGH process shows that most of the studies have focused on the evaluation of its fresh water production rates.

Until now, five SWGH systems have been installed in different regions, namely in the Tenerife, Canary Islands site, which was chosen to host the first pilot project of such system in 1994. The SWGH was assembled in the United Kingdom, and then set up on site [15]. This greenhouse covered an area of 360 m^2 where agricultural products were successfully grown [16]. The amount of fresh water produced by this greenhouse was close to 1.5 m^3/d. It exceeded the irrigation water needs. It has been reported that the maximum amount of water produced was up to 20 times the water requirements of the greenhouse [17,18].

The second SWGH was built in Al-Aryam Island, Abu Dhabi, United Arab Emirates in 2000. It was the first SWGH built in the Middle East [19,20]. The total area of this greenhouse was 864 m^2. After several modifications, the daily production of water from this greenhouse has approached 1 m^3 with excellent water quality and this volume has almost reached the irrigation needs of crops [18,21].

In 2004, the third SWGH was built in Oman, covering an area of 720 m^2 [22–25]. However, it was not able to cover the water demand of cultivated cucumber, as the quantity of fresh water production was only 0.3 to 0.6 m^3/d [23,26].

The fourth SWGH was built in Port Augusta, South Australia in 2010. This greenhouse initially covered an area of 2,000 m^2 to expand to 20 ha. It represents the first project with commercial focus [15].

The last one was installed in October 2017, near Berbera, Somaliland [15].

Sablani et al. [27] used a software program developed by Light Works Limited (England) to model thermodynamic analysis of the HD seawater greenhouse system. They found that the dimensions of the greenhouse (i.e., width to length ratio) had the greatest overall effect on water production and energy consumption. The water production was not significantly affected by the roof transparency and evaporator height [27].

Dawoud et al. [28] presented a theoretical study on possibilities to cool the condenser of a SWGH by applying evaporative cooling for surface seawater, by making use of a cooling machine, or by using deep seawater as a condenser coolant.

Mahmoudi et al. [26] analyzed hourly wind speed and solar radiation measurements, to examine the feasibility of using hybrid (wind + solar) energy conversion systems to run a seawater greenhouse in the Arabian Gulf country of Oman. Based on the overall results, the seawater greenhouse can be powered only with wind and solar energies without any back-up support of fossil fuel energy sources [26].

Yetilmezsoy and Abdul-Wahab [29] developed an empirical model based on the composite desirability function methodology for predicting mass condensate flux of a condenser in a seawater greenhouse located at Al-Hail, Muscat, Oman. The performance of the proposed empirical model was estimated by means of various descriptive statistical indicators. The simulation results obtained from the proposed empirical model were also compared with the outputs of some real theoretical models. The results showed that the proposed empirical model presented a satisfactory performance concerning the estimation of the mass condensate flux in the seawater greenhouse [29].

Given the relative low water production recorded in the above-mentioned studies, a novel process scheme consisting of coupling a SWGH with a solar pond is analyzed in this paper. The main objective of the present study was the increase of the fresh water production rate with the focus on optimizing the rejected brine and the energy consumption.

2. Process description

The classical seawater greenhouse (SWGH) system consists of a conventional greenhouse with two evaporators (humidifiers), a condenser (dehumidifier), fans and of course a roof with a suitable transmission coefficient [30].

Indeed, the SWGH is a water desalination method based on HD process, which is an unconventional water desalination technique.

As it is presented in Fig. 1 that illustrates the basic concept of SWGH, the air sucked from outside into the greenhouse crosses the first evaporator where the salt water trickles down. By exchanging heat and humidity with the salt water, the outside air cools down and gets humidified. The sunlight passing through the transparent cover of the greenhouse heats up the air and consequently reduces its relative humidity. This air passes through a second evaporator similar to the first one where it is once again humidified till its saturation point.

In the last stage, the hot and relatively saturated air passes through a condenser cooled by the incoming salt water stream. Along the condenser, the saturated air condenses and preheats the salt water stream. The condensed water constitutes the fresh water production of the installation.

The incoming salt water is preheated in the condenser before flowing through the two evaporators.

The innovative proposed system aims to increase the fresh water production rate via the use of a solar pond. This element is coupled to the greenhouse to play the role of both a thermal storage system and a heat source. It allows the air to warm up further before it passes through the second evaporator by adding a water/air heat exchanger before this evaporator. Once heated, the air achieves better capacity to get more humidified when it passes through the second evaporator. Consequently the fresh water production rate will be greater at the condenser.

During the night, when the greenhouse does not work in desalination mode, the heat stored in the solar pond can also be used for heating the greenhouse when it is necessary.

The diagram of the new system is illustrated in Fig. 2 during the daily operation and as shown in Fig. 3 during night operation.

The water is used as a heat transfer fluid (HTF) flowing in a closed loop between two heat exchangers placed, respectively, in the solar pond and in the greenhouse.

During the day, the HTF coming from the solar pond passes through a heat exchanger set before the second

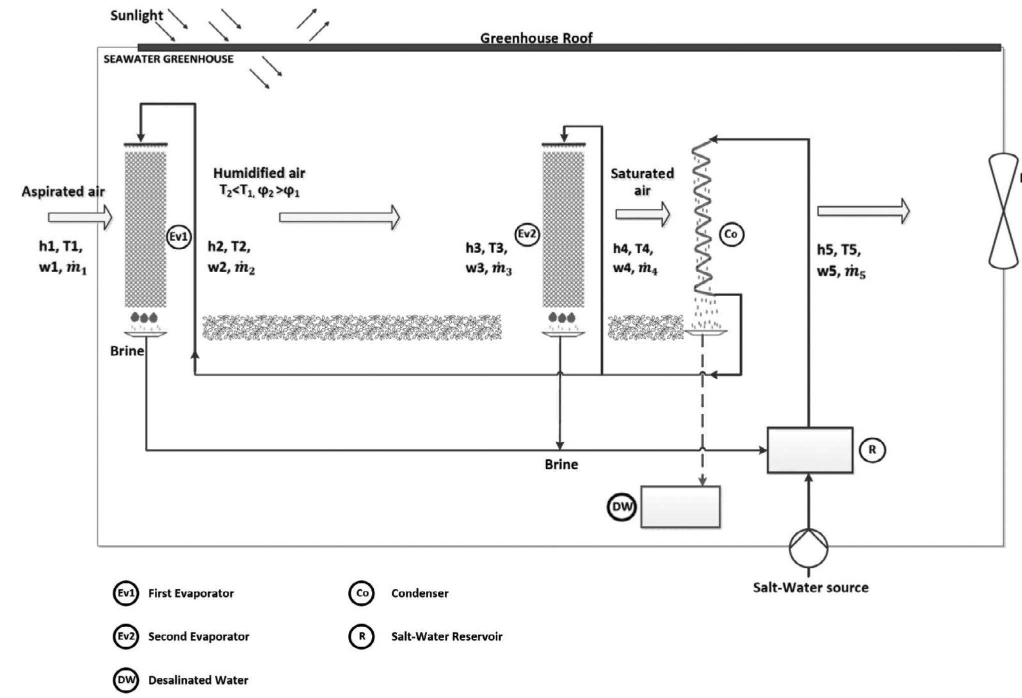

Fig. 1. Diagram of a basic seawater greenhouse.

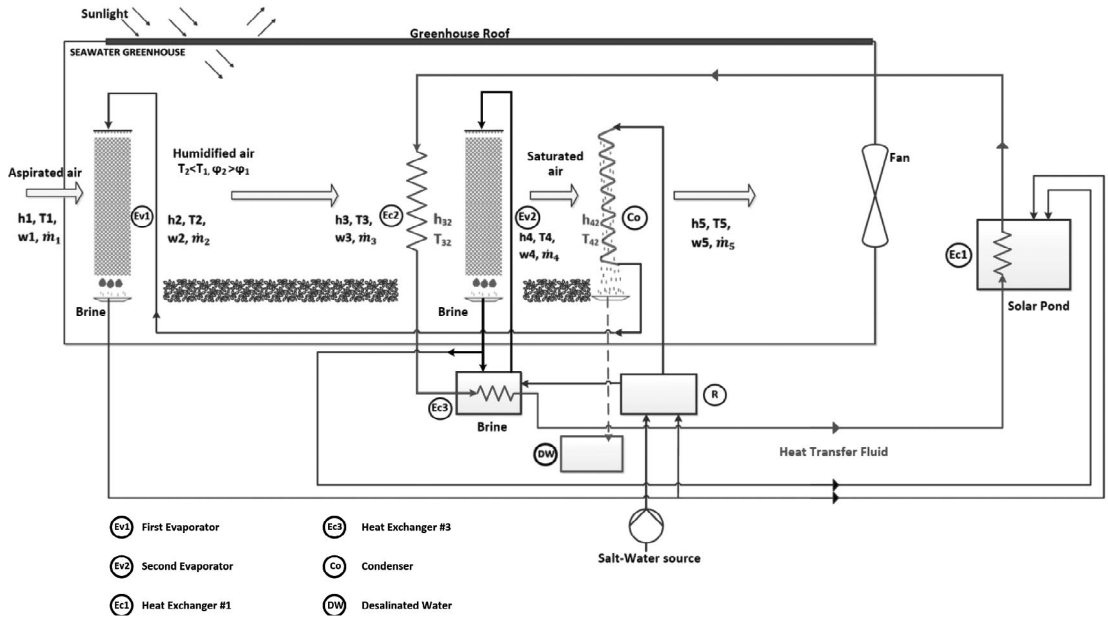

Fig. 2. Diagram of the innovative system – day operating mode.

evaporator and perpendicularly to the direction of the air flow to warm it up.

During the night, the HTF coming from the solar pond passes through a tubular heat exchanger set in the soil of the greenhouse to keep the greenhouse warm.

Basically, the salt gradient solar pond (SGSP) is made up of three zones: lower convective zone (LCZ) or the storage zone: containing brine of uniform concentration.

Non-convective zone or the gradient zone: containing brine of variable concentration. It represents a transparent insulator.

Upper convective zone: thin top layer, frequently created [31].

Solar radiation is absorbed by the salty solution and it is converted to thermal energy in the LCZ. This stored energy can be extracted by using a heat exchanger system.

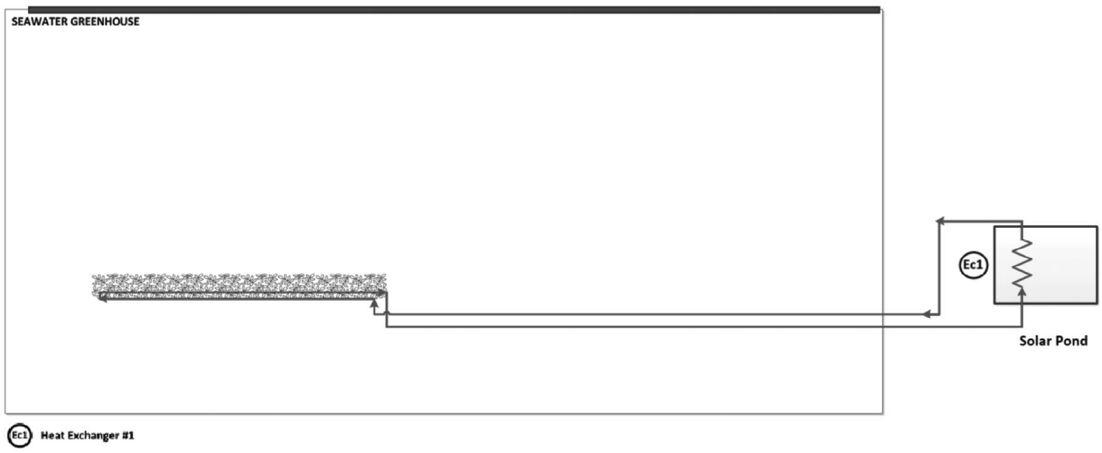

Fig. 3. Diagram of the innovative system – night operating mode.

The position of exchanger tubes has to minimize the vertical mixing of the pond [32].

Economically and operationally, the SGSP is the best option for heat storage for daily and seasonal cycles [31].

The addition of this pond and its combination to the basic greenhouse system will contribute to the increase of the fresh water production.

3. Process modeling

As shown on diagrams above, the seawater greenhouse has key components, two evaporators (humidifiers), a condenser (dehumidifier) and a transparent cover. To model the HD desalination process in the seawater greenhouse, the energy and mass balances are considered.

3.1. Evaporator #1 Formulas

The mass balance of the evaporator 1 is:

$$\begin{cases} \dot{m}_1 = \dot{m}_{\text{as}} + \dot{m}_{e1} \\ \dot{m}_2 = \dot{m}_{\text{as}} + \dot{m}_{e2} \end{cases} \tag{1}$$

where $\dot{m}_1$ is the mass flow of the air at the inlet of the first evaporator, and $\dot{m}_2$ is the one at its outlet.

Knowing that $\dot{m}_{\text{as}}$ is the mass flow of the dry air and $\dot{m}_e$ the mass flow of the water, the amount of evaporated water through evaporator 1 ($\dot{m}_{\text{evap1}}$) is:

$$\dot{m}_{\text{evap1}} = \dot{m}_{e2} - \dot{m}_{e1} = \dot{m}_2 - \dot{m}_1 \tag{2}$$

With:

$$\begin{cases} \dot{m}_{e1} = w_1 \dot{m}_{\text{as}} \\ \dot{m}_{e2} = w_2 \dot{m}_{\text{as}} \end{cases} \tag{3}$$

Thus,

$$\dot{m}_{\text{evap1}} = \dot{m}_2 - \dot{m}_1 = \dot{m}_{\text{as}} \left(w_2 - w_1 \right) \tag{4}$$

where

$$w_1 = \frac{18}{29} \frac{p_{v1}}{P_{\text{atm}} - p_{v1}} \tag{5}$$

where p_{v1} is the partial pressure of water vapor at the inlet of the evaporator 1.

With:

$$p_{v1} = \varphi_1 p_{\text{vs1}} \tag{6}$$

where p_{vs1} is the vapor saturation pressure at the inlet of evaporator 1.

$$p_{\text{vs1}} = 10^{27,877 + (7,625 T_1)/(2,416 + T_1)} \tag{7}$$

Valid for $T_1 > 0$ (°C) with the presence of liquid water.

φ_1 measurable via psychrometer.

In the Mollier humid air diagram, the evolution of air follows an isenthalpic $h_1 = h_2$, with:

$$h_1\left(T_1, P_1, w_1\right) = C_{p,\text{as}} T_1 + w_1 \left(\Delta h_{g0} + C_{p,e(v)} T_1 \right) \tag{8}$$

$$h_2\left(T_2, P_2, w_2\right) = C_{p,\text{as}} T_2 + w_2 \left(\Delta h_{g0} + C_{p,e(v)} T_2 \right) \tag{9}$$

Δh_{g0} = 2,501.6 (kJ/kg)
$C_{p,\text{as}}$ = 1.007 (kJ/kg K) [35]
$C_{p,e(v)}$ = 1.881 (kJ/kg K) [35]
Furthermore,

$$\dot{m}_{\text{as}} = d v_1 S_1 \tag{10}$$

With:

$$d = \frac{\text{PM}}{RT} = 1,292 \frac{27,315}{T_1} \tag{11}$$

T_1 expressed in Kelvin; v_1 measurable via anemometer.

Table 1
Estimated daily mean values of meteorological parameters - Nador – Morocco [37,38]

Month	Relative humidity (%)	Temperature (°C)	Wind speed (m/s)	Solar irradiation (kWh/m²)
January	80	12.2	3.33	2.97
February	80	12.8	5.83	3.89
March	80	13.9	4.58	5.08
April	75	15.6	3.61	6.58
May	75	17.8	3.61	7.22
June	75	22.8	3.61	7.86
July	75	25	3.19	7.72
August	75	25.6	4.17	6.92
September	75	22.8	3.47	5.69
October	80	18.9	2.78	4.25
November	80	15.6	4.17	3.11
December	80	12.8	3.61	2.61
Average	77.5	17.98	3.83	5.33

Coordinates: Elevation: 19 m latitude: 35 10N longitude: 003 56W.

3.2. Greenhouse roof formula

$$\dot{m}_2\left(h_3 - h_2\right) = \beta\varepsilon RT \tag{12}$$

where β is the percentage of radiation transmitted to the greenhouse air, R is the total irradiance, T is the roof area and ε is the transmission factor of the surface.

We put β ε = 0.5.

3.3. Evaporator #2 formulas

The same approach as for evaporator 1.

With:

$$w_3 = w_2 \tag{13}$$

$$h_3 = h_4 \tag{14}$$

$$\dot{m}_{\text{evap2}} = \dot{m}_4 - \dot{m}_3 = \dot{m}_{\text{as}}\left(w_4 - w_3\right) \tag{15}$$

where $\dot{m}_3$ is the mass flow of the air at the inlet of the second evaporator, and $\dot{m}_4$ is the one at its outlet.

3.4. Condenser formulas

Condensed water amount $\dot{m}_{\text{cond}}$:

$$\dot{m}_{\text{cond}} = \dot{m}_4 - \dot{m}_5 = \dot{m}_{\text{as}}\left(w_4 - w_5\right) \tag{16}$$

where $\dot{m}_4$ is the mass flow of the air at the inlet of the condenser, and $\dot{m}_5$ is the one at its outlet.

With:

$$w_5 = \frac{18}{29}\frac{p_{v5}}{P_{\text{atm}} - p_{v5}} \tag{17}$$

where

$$p_{v5} = \varphi_5 p_{\text{vs5}} \tag{18}$$

$$p_{\text{vs5}} = 10^{2,7877+\left(7,625T_5\right)/\left(241,6+T_5\right)} \tag{19}$$

Valid for $T_5 > 0$ (°C) with the presence of liquid water.

φ_5 measurable via psychrometer.

3.5. Solar pond heater formulas (if added)

$$w_3 = \frac{18}{29}\frac{p_{v3}}{P_{\text{atm}} - p_{v3}} \tag{20}$$

where,

$$\varphi_{32} = \frac{p_{v3}}{\left(10^{27,877+\frac{7,625T_{32}}{2,416+T_{32}}}\right)} \tag{21}$$

φ_{32}: The relative humidity of the air after being heated by the pond (%); T_{32}: The temperature of the air after being heated by the solar pond (°C).

This mathematical modeling has been translated into computer models, represented, respectively, in Figs. 4 and 5.

4. Simulations and results

The research conducted aims to investigate the possibilities enabling a better fresh water production rate of the SWGH system, by recovering and reusing the rejected brine.

In order to validate the added value of the novel system, a comparison between both the seawater greenhouses is necessary.

Table 2
Estimated daily mean values of meteorological parameters - Kenitra – Morocco [37,38]

Month	Relative humidity (%)	Temperature (°C)	Wind speed (m/s)	Solar irradiation (kWh/m²)
January	81.2	12	3.06	2.94
February	79.8	13	4.17	3.89
March	77.1	14	3.33	5.22
April	75.6	16	3.75	6.44
May	74.6	18	4.31	7.31
June	74.7	21	4.17	7.64
July	74.6	23	3.89	7.58
August	76	23	3.89	6.97
September	76.2	22	3.89	5.78
October	75.9	19	3.33	4.25
November	78.2	16	3.89	3.11
December	80.5	13	3.19	2.53
Average	77.03	17.50	3.74	5.31

Coordinates: Elevation: 14 m latitude: 34 18 N longitude: 006 36 W.

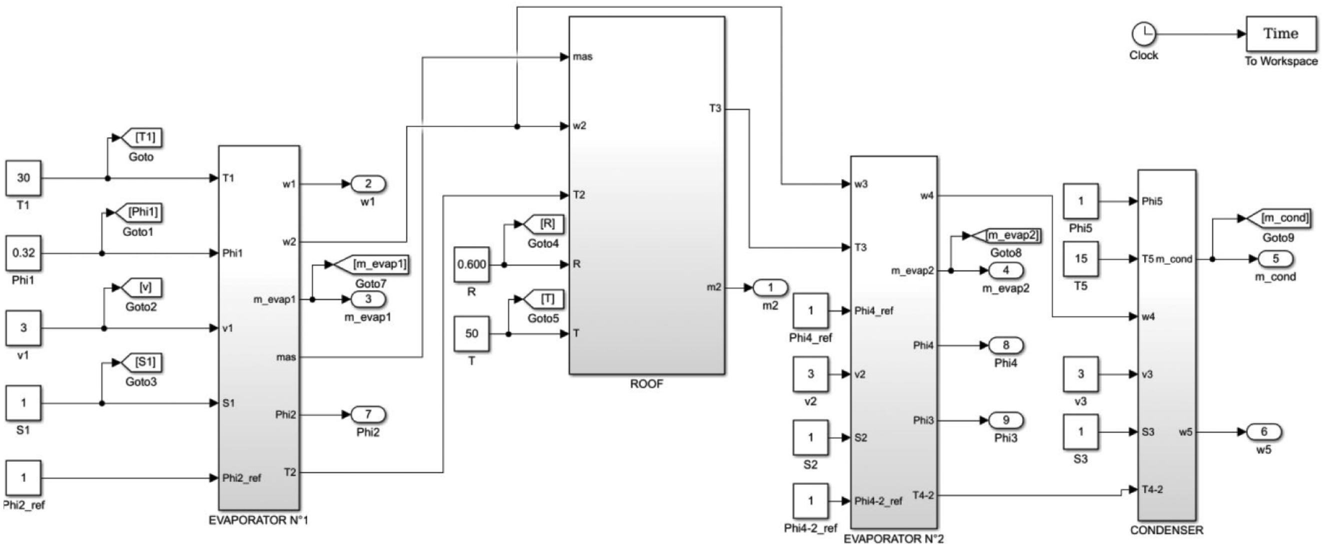

Fig. 4. Blocks model of a basic SWGH.

As a case study, meteorological data of Kenitra town have been chosen for October 1st 2018. A computer program based on above energy and mass balance equations was developed. The model assumptions include the following conditions:

- *Evaporator 1, area S_1 = 1 m²
- *Evaporator 2, area S_2 = 1 m²
- *Wind velocity = 3 m/s
- *Roof area T = 50 m²
- *Air humidity after crossing the two evaporators: 100%
- *Temperature at the inlet of the evaporator 2 after by solar pond T_{32} = 70°C.

Figs. 6–8 show the daily evolution of the irradiance, temperature and air humidity of Kenitra. As it is illustration in Fig. 8, the air humidity decreases as the air temperature increases.

The results of the simulations were as follows in the figure below.

Fig. 9 represents the fresh water production rate during the day of October 1st 2018 for both the seawater greenhouses. The production of the new SWGH is 5.35 times higher than the classical one. The additional supply of heat to the air before it passes through the second evaporator in the innovative SWGH greatly improves the fresh water production.

4.1. Simulations for different Moroccan locations

Different potential sites in Morocco have been chosen for the simulation of the innovative SWGH and its comparison with the basic one.

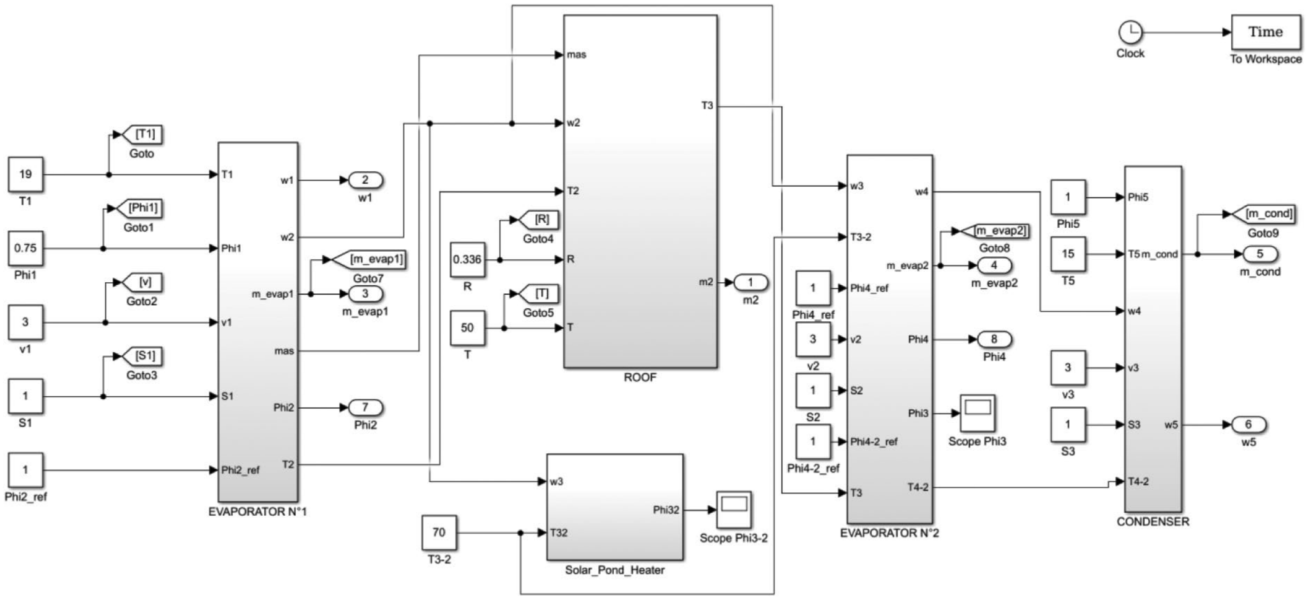

Fig. 5. Blocks model of the innovative system.

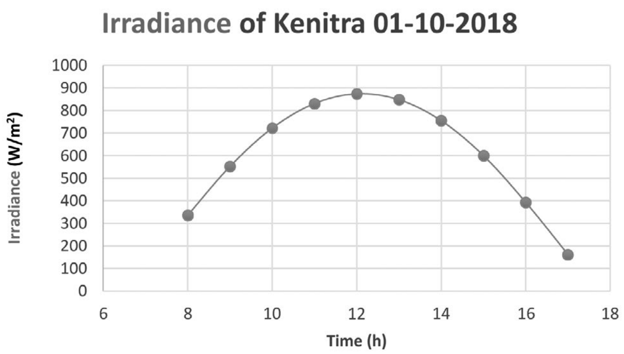

Fig. 6. Daily irradiance evolution of Kenitra town, October 1st 2018–PVGIS.

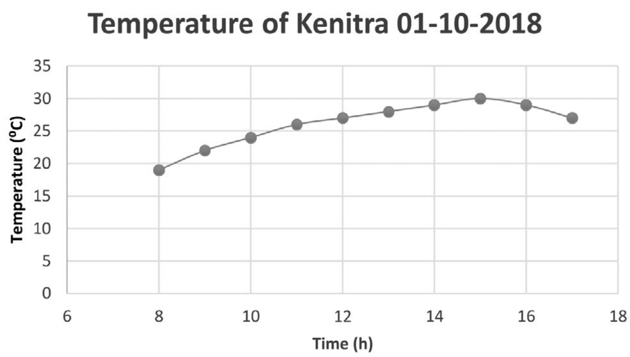

Fig. 7. Daily temperature evolution of Kenitra town, October 1st 2018 [36].

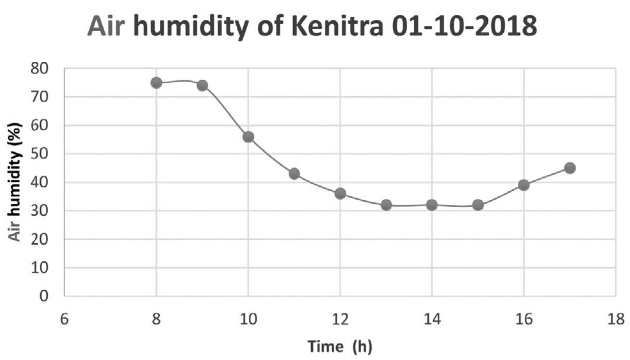

Fig. 8. Daily humidity evolution of Kenitra town, October 1st 2018 [36].

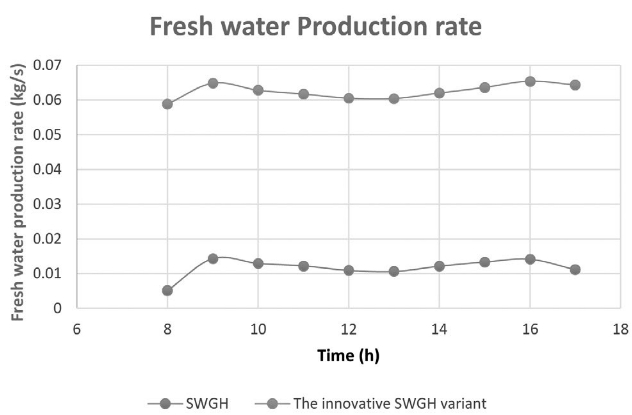

Fig. 9. Fresh water amounts produced by the basic SWGH and by the innovative one.

Table 3
Estimated daily mean values of meteorological parameters - El Jadida – Morocco [37,38]

Month	Relative humidity (%)	Temperature (°C)	Wind speed (m/s)	Solar irradiation (kWh/m²)
January	80.1	13	3.00	3.14
February	79.2	13.8	3.39	4.08
March	76.5	14.7	3.61	5.42
April	76.3	15.9	3.89	6.64
May	75	17.9	3.89	7.39
June	76.1	20.3	3.69	7.44
July	74.7	23.1	3.89	7.39
August	75	23.5	3.69	6.92
September	76.1	22.6	3.31	5.94
October	76.3	19.9	3.11	4.44
November	78.1	16.6	3.00	3.33
December	80.4	13.9	3.00	2.75
Average	76.98	17.93	3.46	5.41

Coordinates: Elevation: 8 m latitude: 33 15 N longitude: 008 30 W.

Table 4
Estimated daily mean values of meteorological parameters - Agadir – Morocco [37,38]

Month	Relative humidity (%)	Temperature (°C)	Wind speed (m/s)	Solar irradiation (kWh/m²)
January	82	14	2.50	3.78
February	83	15	3.33	4.67
March	83	17	4.44	5.89
April	86	17	4.72	6.94
May	88	18	4.72	7.53
June	89	20	4.72	7.61
July	90	22	3.33	7.03
August	89	22	3.33	6.61
September	86	22	3.89	5.97
October	85	20	3.89	4.86
November	81	18	3.33	3.94
December	81	15	3.33	3.36
Average	85.25	18.33	3.80	5.68

Coordinates: Elevation: 22 m latitude: 30 23 N longitude: 009 34 W.

Five cities have been chosen for their agricultural and sunny characters: Nador, Kenitra, El Jadida, Agadir and Dakhla.

The simulations used the meteorological database represented in Tables 1–5 [37,38].

Fig. 10 shows the results of the simulations carried out on the two SWGH models for five cities:

From Fig. 10 it can be noted that the difference in the fresh water production obtained for each town is much related to the difference in air humidity. The greater the humidity, the better the production is for the fresh water. The wind speed moving through the greenhouse is assumed to be the same for the five towns.

Agadir can be considered as the best implantation site for the SWGH technology among the five Moroccan cities.

By coupling the SWGH to the solar pond, the production rate in Agadir has been increased by 0.0527 kg/s, so for 8 h per day, the new SWGH can produce 1,731 L/d.

5. Conclusion

Mathematical modeling and computer simulation of HD in both the Seawater Greenhouses were investigated. The results included the effect of different parameters on fresh water production rate. These results show that the amount of fresh water produced by the SWGH is directly related to solar radiation, dimensions of the evaporator, wind velocity, area of the roof and air relative humidity and temperature.

The evolution of the second evaporator inlet temperature, for example, goes in the same way of the SWGH efficiency

Table 5
Estimated daily mean values of meteorological parameters - Dakhla – Morocco [37,38]

Month	Relative humidity (%)	Temperature (°C)	Wind speed (m/s)	Solar irradiation (kWh/m²)
January	69.6	13.7	2.81	3.78
February	68.4	14.7	3.31	4.67
March	66.9	16.2	3.69	5.89
April	67.3	16.5	4.00	6.94
May	66.5	18.2	4.11	7.53
June	67.4	19.8	4.11	7.61
July	67.3	21.7	4.50	7.03
August	68.7	21.9	4.31	6.61
September	69.9	21.5	3.39	5.97
October	69.1	19.8	3.11	4.86
November	69.8	17.4	2.81	3.94
December	70.3	14.2	2.81	3.36
Average	68.4	18	3.58	5.69

Coordinates: Elevation: 80 m latitude: 30 25 N longitude: 009 33 W.

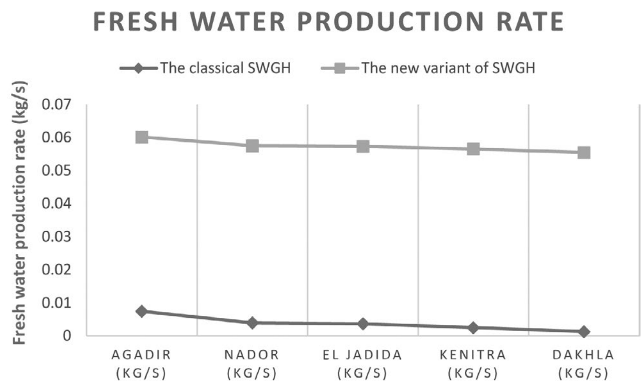

Fig. 10. Simulations results – estimated mean values of fresh water production rate for the basic SWGH and for the new one in different Moroccan locations.

evolution. In this context, our system raises this temperature, while managing the brine release of our greenhouse via a solar pond.

Indeed, the system optimizes the produced fresh water amount and the quality of crop growth, by heating the air entering to the second evaporator the day, and heating all greenhouse the night.

Furthermore, the case study simulations show that the implantation of this desalination process in Morocco can, technically, be very beneficial, given its perfectly adapted climate.

Symbols

$\dot{m}_{as}$ — Mass flow of dry air, kg/s
$\dot{m}_e$ — Mass flow of water, kg/s
Ti — Temperature in the space *i*, °C
w — Absolute humidity
p_v — Partial pressure of vapor, Pa
P_{atm} — Atmospheric pressure, Pa
P_{vs} — Vapor saturation pressure, Pa
ϕ — Relative humidity, %
h — Specific enthalpy, kJ/kg
Δh_{g0} — Vaporization heat of water at 0°C, kJ/kg
$C_{p,e(v)}$ — Specific heat (vapor), kJ/kg K
$C_{p,as}$ — Specific heat (dry air) at 100 kPa between 0°C and 50°C, kJ/kg K
d or ρ — Density of dry air, kg/m³
v_1 — Velocity or speed of the air entering to the greenhouse, m/s
S_1 — Evaporator N°1 area, m²
β — Percentage of radiation transmitted to the greenhouse air, %
R — Irradiance, kW/m²
T — Roof area, m²
ε — Transmission factor of the surface, %
SGSP — Salt gradient solar pond
LCZ — Lower convective zone

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