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Desalination unit coupled with solar collectors and a storage tank: modelling and simulation

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Abstract

The behaviour of a distillation module of a desalination unit coupled with hot water storage tank heated by a solar collector field is investigated by a series of simulation, in order to increase productivity of the desalination unit. Mathematical models are developed to give the ability to estimate the expected performance of the system under given climatic conditions, allowing the choice of the proper design solutions in relation to the desired usage. The whole investigation is based mainly on experimental data under real usage conditions.

Keywords: Water desalination; Storage tank; Solar collector; Modeling; Numerical simulation

1. Introduction

For solar desalination process, thermal energy storage has an important function to ensure the availability of energy at night or the next day. It has always been one of the most critical components in solar applications. Solar radiation is a time-dependent energy source with an intermittent and dynamic character. Thermal energy storage provides a reservoir of energy to adjust the energy needs at all times. It is used as a bridge to cross the gap between the energy source, the sun and the desalination unit. For storing heat in solar desalination systems to be efficient, the next points should be considered:

- It should not greatly reduce the temperature of the water in the evaporation compartment,

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and thereby decrease the evaporation rate during the day.
- The storing technique must be simple and cheap in order to keep the capital cost of the system as low as possible.

This paper deals with the modeling and simulation aspects of the main components of a solar hot water system of the desalination unit using the solar multiple condensation evaporation cycle (SMCEC) principle. Mathematical models and simulation allow predicting the behavior and energy balance of a solar collector, testing configurations of the distillation module together with different sizes and types of hot water storage tanks and the effect of the storage device on the production of the unit.

2. Description of the desalination process

The desalination plant consists of a solar unit, which provides the thermal energy, and a desalination module that uses multi-effect humidification to treat the brackish water. The corresponding system scheme presented in Fig. 1 is an illustration of the unit components along with the description of the different modes (daytime and night time/storage mode). The solar unit consists of a:
- flat plate collector field,
- conventional insulated heat storage tank,
- heat exchanger,
- control unit, circulation pump and an electrically temperature controlled mixing valves (three-way valve).

The desalination module is constituted with two chambers: one for evaporation and one for condensation. The evaporation chamber is filled with a packed bed, where the hot brackish water is uniformly distributed. The brackish water evaporates under ambient pressure, and the saturated air is transported by free or forced convection to the condenser chamber, where it condenses on the surface of the plastic heat exchanger. The air circulates in the opposite direction of the water, which is thereby preheated in the condenser plates

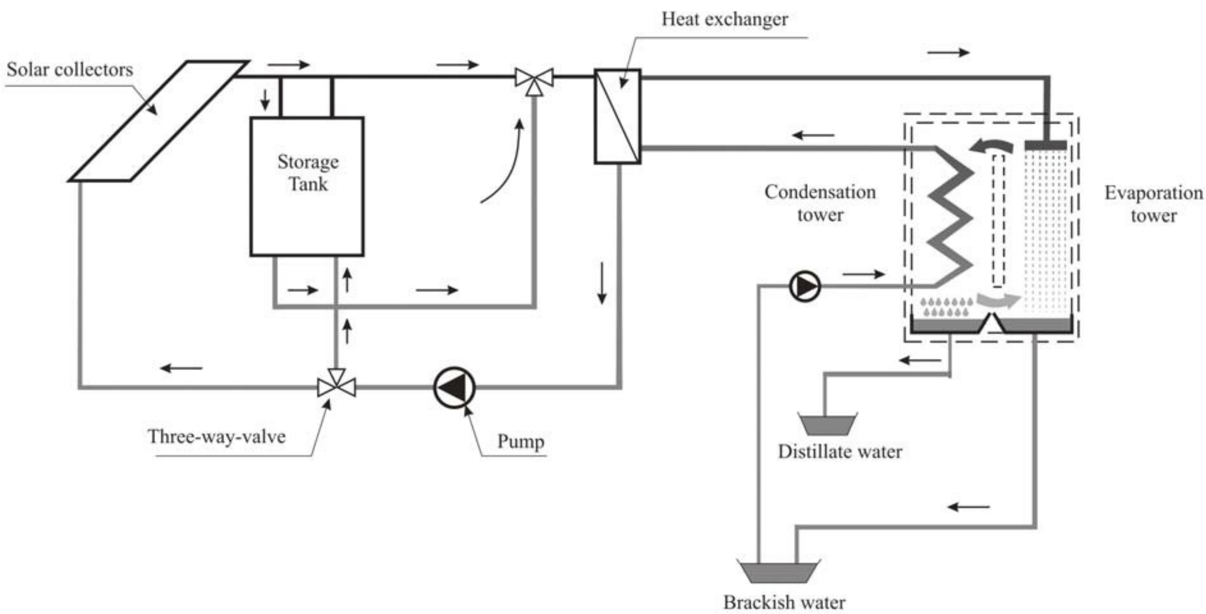

Fig. 1. Principle scheme of the desalination unit coupled with solar collectors and storage tank.

by the heat of condensation. The condenser is made of polypropylene bridged double plates, through which the cold brackish water flows upwards. With the installation of the three-way valve, quasi steady-state conditions for the evaporation are guaranteed even during the daytime mode. If the temperature of the collector outlet exceeds the temperature adjusted for the mixing valve, cold water from the bottom of the storage tank is added. At the same time, the storage tank is automatically filled from the top with the surplus of hot water. The control device of the solar unit regulates the whole desalination system. When one of the following conditions is satisfied, the three-way valve switches the system into the storage mode automatically (night-time), discharging the tank from above:

- the temperature level of the collector outlet is lower than the minimum temperature for the evaporation,
- the security criterion of the storage tank, for example the maximum temperature at the bottom of the tank, is reached.

The pump of the solar unit works in the storage mode until the minimum temperature for evaporation is reached. More details concerning the description and operation principle of the desalination plant are presented in [1–4].

3. Process optimisation

The brackish water debit (L) and the air debit (G) represent the controllable input signals for the desalination module. The water temperature at the evaporation tower entrance (T_1) is a very influential factor in the unit production. The insolation $I(t)$ represents the important non controllable input signal to the system and, therefore, can be considered as perturbations. The condensed water amount (W_c) is an output signal for the entire system. Based on the optimisation conditions of the three different modules of the desalination unit (solar collectors, evaporation tower, condensation tower), several compromising actions need to be made among the command signals. The optimum mode of functioning depends on both economic and technical factors. It is a compromise between the highest possible water temperature at the evaporation tower entrance in favour of optimum mass-transfer and heat inside the distillation module, the limitations of this temperature in favour of gaining acceptable collector efficiency and to minimize overall thermal losses. The supplementation of the system by a high temperature thermal storage tank makes it possible to keep the temperature range and the volume flow at the evaporation chamber entrance over 24 h at a certain level. The fluctuations of the daily temperature are determined by the heat capacity of the storage tank, and the average volume flow depends on the size of the solar collector field. The ratio of the collector area to the size of the desalination module is defined by the consideration of the economic efficiency of the total system. In order to minimize the specific distillate costs, one will operate the desalination module at an operating state (volume flow rate and inlet evaporation temperature) above the energetic optimum because it is the most expensive component of the system [5,6].

The integration of the thermal storage device can be adopted in different possibilities: the storage tank can contain either brackish or distilled water, the collector field can be loaded by fresh or brine water and the desalination module can be connected directly to the storage tank or using a heat exchanger. One preferred configuration is to use a thermal storage tank and a solar collector field being loaded by brackish water. This permits more efficiency due to elimination of heat exchangers, but higher demands are to be made on the materials used.

4. Modelling approaches

4.1. Flat plate solar collector model

The model of the flat plate solar collector, called two temperatures model, was developed in a previous work [7]. It can be written as:

$$\begin{cases} \dfrac{T_f}{t} = -v\dfrac{T_f}{x} + c_1\left(T_c - T_f\right) \\ \dfrac{\mathrm{d}T_c}{\mathrm{d}t} = a_1\left(f(t) - T_c\right) + b_1\left(T_f - T_c\right) \end{cases} \quad (1)$$

with:

$$v = L\frac{m_f}{M_f},\ a_1 = \frac{SU'}{M_c C_c},\ b_1 = \frac{Sh}{M_c C_c},$$

$c_1 = \dfrac{Sh}{M_f C_f}$, $f(t) = \dfrac{BI(t)}{U'} + T_a(t)$ — the ambient condition function.

The obtained mathematical model for the solar collector allows the determination, for variable solar intensity levels and ambient temperature, of the fluid instantaneous temperature at any point of the collector as a function of the command, geometrical, and physical parameters (flow rate, collector area, material, and inclination angle of the collector). It should be noted that the fluid temperature and flow rate at the collector outlet are the two parameters with the most significant impact on the unit production as they are the input parameters of the distillation module.

4.2. Hot water storage tanks models

Three different kinds of storage tank models are developed.

4.2.1. Storage tank with heat exchangers

Mode 1

Fig. 2 represents the model adopted for the hot water storage tank with two internal coils heat exchangers. T_{f1} and T_{f2} are respectively the inlet and the outlet solar collector temperatures. m_f is the flow rate of the collector. T_s is the temperature of the water storage tank. A completely mixed storage tank is assumed. T_{l2} corresponds to the inlet temperature at the top of the evaporation tower. T_{l1} is the outlet water temperature at the bottom of the evaporation tower. L is the water debit injected at the top of the evaporation tower.

To establish the model of the energy balance in the storage tank, the following assumptions are taken into account:

- there is no change in heat storage in the coil,
- the coil is in steady state,
- the heat storage tank is entirely insulated.

Eqs. (2), (3) and (4) present the corresponding model:

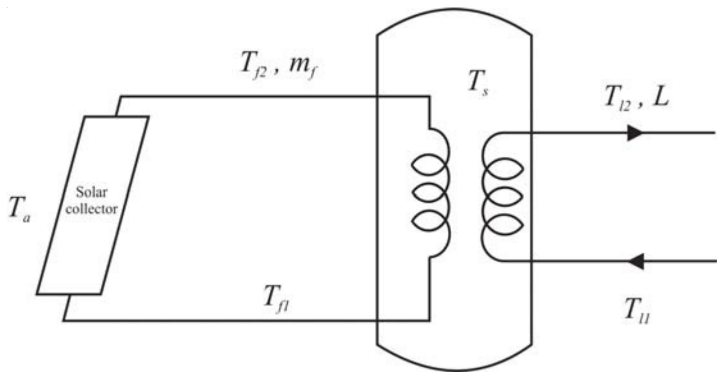

Fig. 2. Hot water storage tank with internal heat exchangers — mode 1.

$$MC_f \frac{dT_s}{dt} = m_f C_f \left(T_{f2} - T_{f1}\right) - LC_f \left(T_{l2} - T_{l1}\right) \tag{2}$$

$$m_f C_f \left(T_{f2} - T_{f1}\right) = U_1 A_1 \frac{\Delta T_{f2} - \Delta T_{f1}}{\ln\left(\Delta T_{f2} / \Delta T_{f1}\right)} \tag{3}$$

$$LC_f \left(T_{l2} - T_{l1}\right) = U_2 A_2 \cdot \frac{\Delta T_{l2} - \Delta T_{l1}}{\ln\left(\Delta T_{l2} / \Delta T_{l1}\right)} \tag{4}$$

with $\Delta T_{f2} = T_{f2} - T_s$ and $\Delta T_{f1} = T_{f1} - T_s$;
$\Delta T_{l2} = T_{l2} - T_s$ and $\Delta T_{l1} = T_{l1} - T_s$

From Eqs. (3) and (4), T_{f1} and T_{l2} can be developed respectively as follows:

$$T_{f1} = \left(T_{f2} - T_s\right) e^{-\left(\frac{u_1 A_1}{m_f C_f}\right)} + T_s \tag{5}$$

$$T_{l2} = \left(T_{l1} - T_s\right) \frac{1}{e^{-\left(\frac{U_2 A_2}{LC_f}\right)}} + T_s \tag{6}$$

Mode 2 (Fig. 3)

For the same assumptions used in mode 1, the following equations present the corresponding model:

$$MC_f \frac{dT_s}{dt} = m_f C_f \left(T_{f2} - T_s\right) - LC_f \left(T_{l2} - T_{l1}\right) \tag{7}$$

$$LC_f \left(T_{l2} - T_{l1}\right) = U_2 A_2 \frac{\Delta T_{l2} - \Delta T_{l1}}{\ln\left(\Delta T_{l2} / \Delta T_{l1}\right)} \tag{8}$$

with $\Delta T_{l2} = T_{l2} - T_s$,

$\Delta T_{l1} = T_{l1} - T_s$

and

$$T_{l2} = \left(T_{l1} - T_s\right) \frac{1}{e^{-\left(\frac{U_2 A_2}{LC_f}\right)}} + T_s \tag{9}$$

4.2.2. Divided hot water storage tank

In the following case, the model is built up as a divided hot storage tank with internal heat

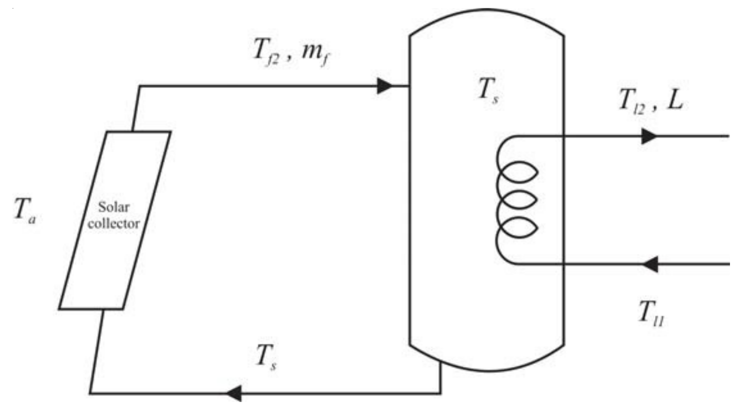

Fig. 3. Hot water storage tank with internal heat exchanger — mode 2.

exchanger (Fig. 4). This configuration performs the heat transfer through a wall surface. Both sides are supposed to be fully mixed. V_1 and V_2 are the volume of storage tank sections and A_3 is the surface of the heat transfer between the storage tank sections.

The next equations describe the behaviour of the divided hot water storage tank:

$$M_1 C_f \frac{\mathrm{d}T_{s1}}{\mathrm{d}t} = m_f C_f \left(T_{f2} - T_{s1}\right) - U_3 A_3 \left(T_{s1} - T_{s2}\right) \tag{10}$$

$$M_2 C_f \frac{\mathrm{d}T_{s2}}{\mathrm{d}t} = L C_f \left(T_{l2} - T_{l1}\right) + U_3 A_3 \left(T_{s1} - T_{s2}\right) \tag{11}$$

$$L C_f \left(T_{l2} - T_{l1}\right) = U_2 A_2 \frac{\Delta T_{l2} - \Delta T_{l1}}{\ln\left(\Delta T_{l2} / \Delta T_{l1}\right)} \tag{12}$$

with $\Delta T_{l2} = T_{l2} - T_s$, $\Delta T_{l1} = T_{l1} - T_s$

and

$$T_{l2} = \left(T_{l1} - T_S\right) \frac{1}{e^{-\left(\frac{U_2 A_2}{L C_f}\right)}} + T_s \tag{13}$$

4.3. Model of the desalination module

The model of the distillation module consists of the coupling of the individual models of both evaporation and condensation towers. The global mathematical model based on thermal and mass balances allows the determination of coupling equations between the water and the humid air temperatures and the water content inside each tower. The obtained model is a set of equations with partial derivatives with respect to space and time, ordinary differential equations as well as algebraic equations. The model is based on some previous assumptions [8–12]. More details concerning the established model were presented earlier [13]. The following equations present the corresponding model:

$$\varepsilon_l \rho_l C_l \frac{\partial T_l}{\partial t} = L C_l \frac{\partial T_l}{\partial z} - h_l a \left(T_l - T_i\right) \tag{14}$$

$$\varepsilon_g \rho_g C_g \frac{\partial T_g}{\partial t} = -G C_g \frac{\partial T_g}{\partial z} + h_g a \left(T_i - T_g\right) \tag{15}$$

$$h_l \left(T_l - T_i\right) + h_g \left(T_g - T_i\right) = L_v k_g \left(X_i - X_g\right) \tag{16}$$

$$\varepsilon_g \rho_g \frac{\partial X_g}{\partial t} = -G \frac{\partial X_g}{\partial z} + k_g a \left(X_i - X_g\right) \tag{17}$$

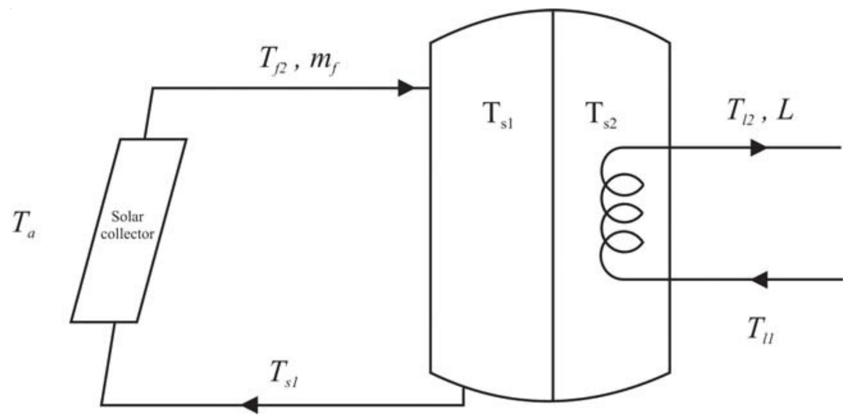

Fig. 4. Divided hot water storage tank with internal heat exchanger.

$$X_i = 0.62198 \frac{P_{ws}}{1 - P_{ws}} \tag{18}$$

$$\varepsilon_c \rho_c C_c \frac{\partial T_c}{\partial t} = -D_c C_c \frac{\partial T_c}{\partial z} + UA(T_{ic} - T_c) \tag{19}$$

$$\varepsilon_G \rho_G C_G \frac{\partial T_G}{\partial t} = G C_G \frac{\partial T_G}{\partial z} - h_G A(T_G - T_{ic}) - L_v k_G A(X_G - X_{ic}) \tag{20}$$

$$h_G(T_G - T_{ic}) + U(T_c - T_{ic}) = L_v k_G (X_{ic} - X_G) \tag{21}$$

$$\varepsilon_G \rho_G \frac{\partial X_G}{\partial t} = G \frac{\partial X_G}{\partial z} + k_G A(X_G - X_{ic}) \tag{22}$$

$$X_{ic} = 0.62198 \frac{P_i}{1 - P_i} \tag{23}$$

$$\mathrm{d}W_c = k_G A(X_{ic} - X_G)\mathrm{d}z \tag{24}$$

In this study, the process of condensation is slow enough to assume that $\mathrm{d}W_c$ can be that at the steady-state condition. P_{ws} and P_i represent the saturation pressure given by:

$$\ln(P_{ws}) = -6096.938 \frac{1}{T_i} + 21.240964 - 2.71119 \times 10^{-2} T_i + 1.67395 \times 10^{-5} T_i^2 + 2.43350 \ln(T_i)$$

The relationships giving the mass exchange coefficients (k_g, k_G), the heat transfer coefficients (h_l, h_g, h_G) and the overall heat transfer coefficients (U) were presented earlier [8].

5. Simulation results

With high solar insulation, the solar collectors output feed partly the storage tank and the distillation module. Before starting the operation of the desalination unit, water circulates in closed loop between the storage tank and the solar collector field. The storage temperature is held above the desirable desalination input temperature level in order to keep the storage size small. This action can take more than one day (it depends on the meteorological conditions). The storage tank is perfectly insulated to reduce the heat losses to ambient air.

At daytime solar collectors feed the desalination unit. During the evening or the cloudy periods, the storage tank feeds partly the desalination unit. In order to maintain a minimum quantity of hot water in the tank, the feeding from it will be interrupted once the water temperature reaches a fixed threshold.

Three tank models utilizing different configurations are considered to test their effect on the desalination unit production. Many simulations were conducted. The simulations are carried out on a solar 1 m^3 and 2 m^3 tank. Real climatic and operating conditions presented in previous work [7], is used for simulation. Table 1 presents the system technical specifications and operation data used for the simulation.

The temperature profiles of the storage tank show the charging (daytime mode) and discharging (storage mode or night time mode) of the storage tank. All measurements started at 8:00 a.m. At 16.00 h the system switched into the storage mode. The discharging temperature is limited to 40°C. The temperature profiles inside the tank are obtained shown in Figs. 5–7.

Curves presented with thin line and bold line correspond respectively to temperature profile of the storage tank of 1 m^3 and 2 m^3. The similar shape of the curves, monitored for different storage tank configurations, indicates that the use of the storage tank of 1 m^3 allow high temperature and large discharging duration than using a storage tank of 2 m^3.

Fig. 8 presents the temperature profiles for different storage tank configurations of 1 m^3: the

Table 1
System technical specifications and operation data used for the simulation

Technical specifications and operation data	Value
Solar collector	
Total aperture area, m^2	37
Effective transmission absorption	0.8
Loss coefficient, W/(m^2 K)	4
Glass type	4 mm low iron glass
Collector insulation	Fibreglass 30 mm sides
	Fibreglass 50 mm back
Evaporation tower	
Size, m	1.20×0.50×2.55
Solid packing: thorn trees (volume fraction)	$\varepsilon_p = 0.02$
Air mass velocity (G), kg m^{-2} s^{-1}	0.15
Volume fraction	$\varepsilon_g = 1 - \varepsilon_l - \varepsilon_p$
Water mass velocity (L), kg m^{-2} s^{-1}	0.15
Water volume fraction	$\varepsilon_l = 0.01$
Mass transfer coefficient	$k_g = (2.09\ G^{0.11515}\ L^{0.45})/a$
Heat transfer coefficient	$h_l = (5900\ G^{0.5894}\ L^{0.169})/a$
	$h_g = C_g\ k_g$
Condensation tower	
Size, m	1.20×0.36×3.00
Plates type	Polypropylene
Plates volume fraction	$\varepsilon_{Pc} = 0.048$
Air mass velocity (G), kg m^{-2} s^{-1}	0.15
Volume fraction	$\varepsilon_G = 1 - \varepsilon_c - \varepsilon_{Pc}$
Cooling water mass velocity (D_c), kg m^{-2} s^{-1}	0.28
Cooling water volume fraction	$\varepsilon_c = 0.018$
Heat exchanger	
Overall heat transfer coefficient (U), W/(m^2 K)	250
Exchange surface, m^2	1
	2
Storage tank	
Volume, m^3	1
	2

temperature profile for configuration 1 — mode 1 (bold line), the temperature profile for configuration 1 — mode 2 (thin line) and the temperature profile for configuration 2 (dashed). Fig. 8 shows that storage tank with configuration 2 has large discharging duration than configuration 1 with mode 1 and 2.

The model of the solar collector and the hot water storage tank models were coupled to the models of evaporation and condensation towers. The simulation of the global resulting model allows the prediction of the desalination unit production (Fig. 9). Fig. 9 shows the amount of distilled water estimated with the different storage tank configurations: the amount of distilled water estimated with configuration 1 — mode 1 (thin line), the amount of distilled water estimated with configuration 1 — mode 2 (bold line) and the amount of distilled water estimated with configuration 2 (dashed). Such as storage tank configura-

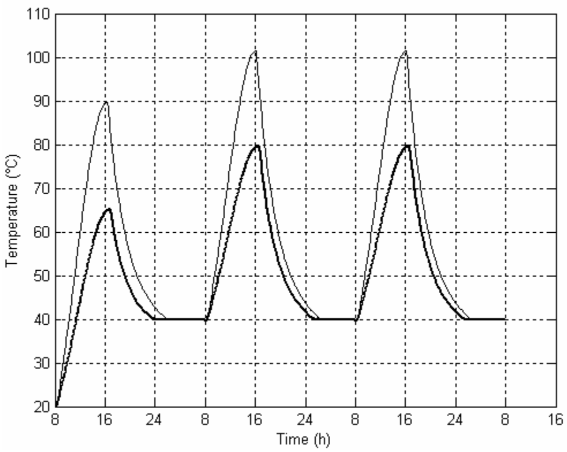

Fig. 5. Temperature distribution inside the tank with internal heat exchangers — mode 1.

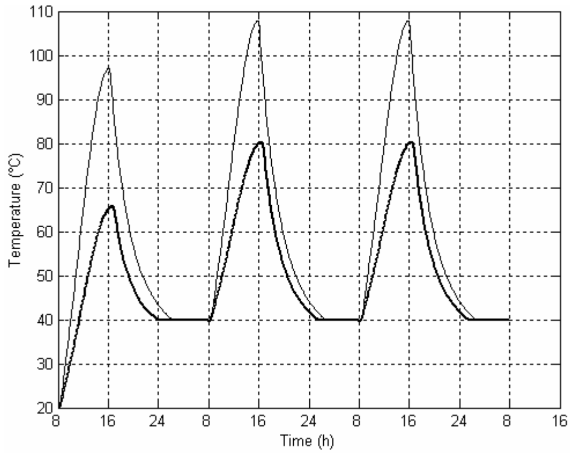

Fig. 6. Temperature distribution inside the tank with internal heat exchanger — mode 2.

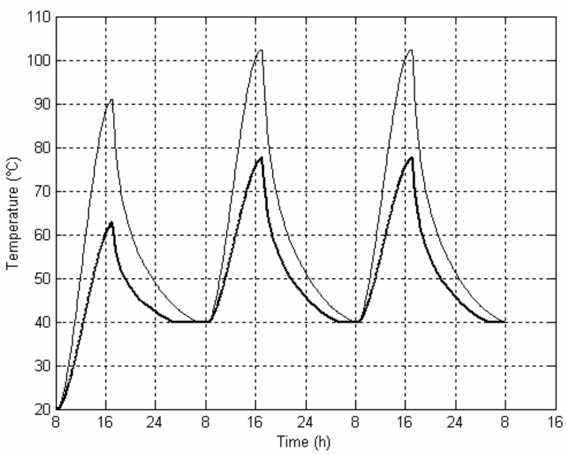

Fig. 7. Temperature distribution inside the divided hot water storage tank with internal heat exchanger.

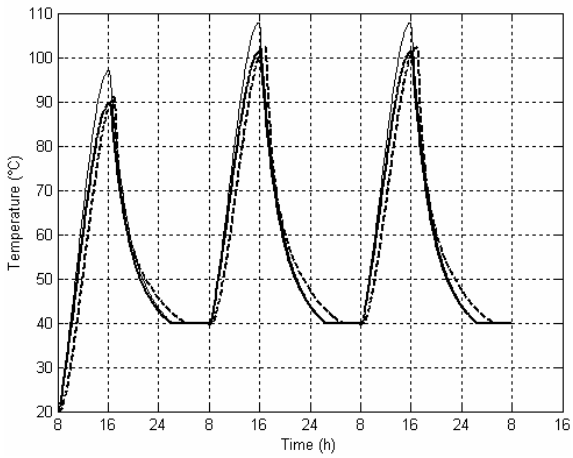

Fig. 8. Temperature distribution inside the hot water storage tank: comparison of the three functioning modes ($V = 1\ m^3$).

tion 2 has large discharging duration than configuration 1 with mode 1 and 2, so configuration 2 allows production of distilled water for a long period than the others configurations.

6. Conclusion

The main improvement in the solar desalination unit efficiency can be reached by continuous operation. This measure prevents thermal losses during standstill periods and low efficiency periods restarting the system. Twenty-four hour operation can be realized by an extended collector field combined with a hot water storage tank.

In this paper, mathematical models were carried out and used for simulation of three different configurations solar hot water systems: a hot water storage tank with two internal heat

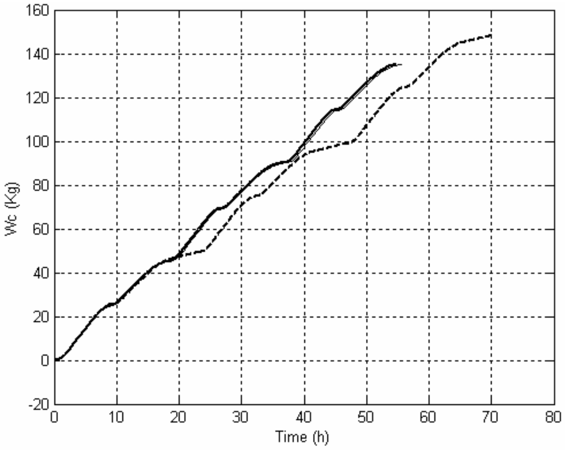

Fig. 9. Simulated distilled water production with different storage tank configurations ($V = 1$ m^3).

exchangers (mode 1), a hot water storage tank with one internal heat exchangers (mode 2) and a divided hot water tank with internal heat exchanger. The purpose of this work was to study the effect of three different configurations on the unit production. The modelling and simulation results achieved showed that a divided hot water tank with internal heat exchanger increasing considerably the production of distilled water than those obtained with the others configurations.

Symbols

A — Air–water exchange area in the condensation tower per unit volume, m^2/m^3
$A_{1,2}$ — Surfaces of the coils in the storage tank, m^2
a — Air–water exchange area in the evaporation tower per unit volume, m^2/m^3
B — Effective transmission absorption product, $B = \alpha.\tau$
C_f — Water specific heat, J/(kg.K)
C_c — Absorber mass thermal capacity, J/(kg.K)
C_l — Water specific heat in the evaporation tower, J/(kg.K)
C_c — Water specific heat in the condensation tower, J/(kg.K)
C_g — Humid air specific heat in the evaporation tower, J/(kg.K)
C_G — Humid air specific heat in the condensation tower, J/(kg.K)
D_c — Cooling water mass velocity in the condensation tower, kg/(m^2.s)
G — Mass velocity of humid air, kg/(m^2.s)
h — Exchange coefficient absorber-fluid in the solar collector, W/m^2 °C
h_l — Water heat transfer coefficient at the air–water interface in the evaporation tower, W/(m^2.K)
h_g — Air heat transfer coefficient at the air–water interface in the evaporation tower, W/(m^2.K)
h_G — Air film heat transfer coefficient in the condensation tower, W/(m^2.K)
I — Flux of incident radiation, W/m^2
k_g — Water vapour mass transfer coefficient at the air–water interface in the evaporation tower, kg/(m^2.s)
k_G — Water vapour mass transfer coefficient at the vapour–condensate interface in the condensation tower, kg/(m^2.s)
L — Water mass velocity in the evaporation tower, kg/(m^2.s)
L_v — Latent heat of water vaporization, J/kg
M — Mass, kg
m_f — Fluid flow rate in the absorber, kg/s
S — Absorber surface, m^2
T_g — Humid air temperature in the evaporation tower, K
T_G — Humid air temperature in the condensation tower, K
T_l — Water temperature in the evaporation tower, K
T_i — Temperature at the air–water interface in the evaporation tower, K
T_c — Cooling water temperature in the condensation tower, K
T_{ic} — Temperature at the air–water interface in the condensation tower, K
T_a — Ambient temperature, K
T_c — Absorber temperature, K

T_f — Fluid temperature, K
T_s — Temperature of the extracted water from the storage tank, K
$U¢$ — Overall heat loss coefficient from the absorber to the surroundings, W/(m^{2}K)
U — Overall heat transfer coefficient in the condenser, W/(m^2.K)
$U_{1,2}$ — Overall heat transfer coefficient of the coil in the storage tank, W/(m^2.K)
X_g — Air humidity in the evaporation tower, kg$_{water}$/kg$_{dry\ air}$
X_G — Air humidity in the condensation tower, kg$_{water}$/kg$_{dry\ air}$
X_i — Saturation humidity in the evaporation tower, kg$_{water}$/kg$_{dry\ air}$
X_{ic} — Saturation humidity in the condensation tower, kg$_{water}$/kg$_{dry\ air}$

Greek

α — Absorbance of the collector absorber surface
ε_l — Water volume fraction in the evaporation tower
ε_g — Air volume fraction in the evaporation tower
ε_c — Cooling water volume fraction in the condensation tower
ε_G — Air volume fraction in the condensation tower
ε_p — Volume fraction of the packed bed in the evaporation tower
ε_{pc} — Volume fraction of the condensation plates in the condensation tower
ρ_l — Water density in the evaporation tower, kg/m^3
ρ_g — Air density in the evaporation tower, kg/m^3
ρ_c — Cooling water density in the condensation tower, kg/m^3
ρ_G — Air density in the condensation tower, kg/m^3
τ — Transmittance

Subscripts

c — Condensation tower
G — Condensation tower
g — Evaporation tower
l — Evaporation tower

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