

A heating system using flat plate collectors to control the inside greenhouse microclimate in Tunisia

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(reçu le 01 Juillet 2012 – accepté le 29 Décembre 2012)

Abstract - The continuous increase in the level of greenhouse gas emissions and the rise in fuel prices are the main driving forces behind the efforts for more effectively utilize various sources of renewable energy. In many parts of the world and specifically in Tunisia, the direct solar radiation is considered to be one of the most promising sources of energy. Annual sunshine can reach 3288 kWh/m²/year or 6 kWh/m²/day. A greenhouse using means active conventional heating consumes 1 liter of fuel/m²/year which leads to 10 kWh/m²/year. Tunisia surface of greenhouse crops is about 1000 hectares this corresponds to 107 l of oil and 108 kWh. In order to reduce the cost of heating the agricultural greenhouse we used the vacuum solar collectors. Their efficiency depends at the same time upon the ambient climatic conditions and the thermal performances of vacuum solar collectors. Capillary polypropylene exchangers are used to attenuate the differences between the diurnal and nocturnal air temperatures under the tunnel greenhouses. Water circulates in these exchangers at hydraulic closed circuit. In this work we have realized an experimental study of a solar energy heating system. Two types of studies have been done. During the day the suspended exchangers recover the energy in excess for the plants comfort. This recovered energy is stored into the greenhouse ground through the buried exchangers the first one concern the functioning temperature of the heating system installed near the greenhouse and used to heat the water stocked in a tank of 300 liters. In the second type, the energy stored in the ground will be restored through the underground exchangers during the night; thermal energy already stored in the tanks is brought back by the suspended exchangers to heat the air greenhouse. In order to prove the efficiency of our system, we present thermal results relative to the effect of the heater system on the greenhouse microclimate and the agronomic results of the greenhouse culture of tomato. These results are very interesting compared to an unheated greenhouse and had a high effect on tomato quality.

Résumé – L'augmentation continue du niveau des émissions de gaz à effet de serre et la hausse des prix du carburant sont les principales forces motrices pour une utilisation efficace des diverses sources d'énergie renouvelables. Dans de nombreuses régions du monde et plus particulièrement en Tunisie, l'irradiation solaire directe est considérée comme l'une des sources les plus prometteuses de l'énergie. L'ensoleillement annuel peut atteindre 3288 kWh/m²/an ou 6 kWh/m²/jour. Une serre, en utilisant des moyens actifs de chauffage conventionnel, consomme un litre de fuel/m²/an, qui conduit à 10 kWh/m²/an. En Tunisie, la surface des cultures en serre est d'environ 1000 hectares, cela correspond à 107 l d'aluminium et 108 kWh. Afin de réduire le coût du chauffage de la serre agricole, nous avons utilisé les capteurs sous vide solaires. Leur efficacité dépend à la fois des conditions ambiantes climatiques et des performances thermiques des capteurs solaires sous vide. Les échangeurs capillaires en polypropylène sont utilisés pour atténuer les différences entre les températures diurnes et nocturnes de l'air, dans les serres tunnel.

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L'eau circule dans ces échangeurs à circuit hydraulique fermé. Dans ce travail, nous avons réalisé une étude expérimentale d'un système de chauffage à énergie solaire. Deux types d'études ont été réalisés. Pendant la journée, les échangeurs de suspension récupèrent l'excès d'énergie en excès pour le confort des plantes. Cette énergie récupérée est stockée dans le sol dans des échangeurs de serre enterrés; le premier type concerne la température de fonctionnement du système de chauffage de l'installation, et à proximité de la serre pour le chauffage de l'eau stockée dans un réservoir de 300 litres. Dans le second type, l'énergie emmagasinée dans le sol sera restituée à travers les échangeurs enterrés pendant la nuit. L'énergie stockée dans ces réservoirs est ensuite ramenée par les échangeurs suspendus pour le chauffage de l'air de la serre. Afin de connaître l'efficacité de notre système, nous présentons les résultats relatifs sur l'effet du système de chauffage par rapport au microclimat de la serre et les résultats relatifs à la culture de tomate en serre. Ces résultats sont intéressants par rapport à une serre non chauffée, qui peuvent avoir un effet significatif sur la qualité de la tomate.

Keywords: Solar energy - Greenhouse - Energy storage - Capillary heat exchanger - Vacuum solar collector.

1. INTRODUCTION

A greenhouse heating system is used to increase the thermal energy storage inside the greenhouse during the day or to transfer excess heat from inside the greenhouse to the heat storage area. This heat is recovered at night to satisfy the heating needs of the greenhouse. In Mediterranean areas, the greenhouses face overheating problems during the day and excessive cold at night. These problems affect the product quality and the production. Consequently, it is necessary to improve the air-conditioning of these greenhouses. Heating of greenhouse is one of the most important and essential requirements for better growth in summer even better in winter [1]. Greenhouse heating can be carried out either by passive or an active method [2]. The study of greenhouse heating by the passive method has also been made by many scientists [3-6]. The passive heating may be realized through water storage, rock bed storage, presence of north wall, mulching, phase changing material, movable insulation and thermal curtain.

Among passive heating modes, a thermal curtain or thermal screen is one of the most practical and appropriate means for reducing the energy consumption in greenhouse [7, 8] allowed active heating methods we have; ground collector, the ground geothermal water, an earth-air heat exchanger and phase change material storage. Thermal heating of greenhouse using the active method has been investigated by many researchers namely, Lazaar *et al.* [9], Santamouris *et al.* [10], Jain *et al.* [11] and Kurklu [12]. In composite system, the same system is used for heating the greenhouse in winter and cooling it in summer.

Currently, earth-air heating exchanger system (EAHES) is the most successfully used composite system for agricultural greenhouses. EAHES use the underground constant temperature of earth mass to transfer/dissipate heat to/from the greenhouse. In addition to EAHES, aquifer coupled cavity flow heating exchanger system (ACCFHES) has also been developed. It utilizes the constant temperature of deep aquifer water at the ground surface through an irrigation tube well for heating as well as cooling of the greenhouse [13].

Photovoltaic panels are integrated with greenhouse for generating the required electrical power. This system proves an energy efficiency level of approximately 4 % [14].

In this work, we present only the experimental results concerning the climatic variables. We have considered two tunnel greenhouses of the same size. The experimental one is heated and the reference one is unheated. Results show the agronomic efficiency gain on growing tomato, obtained with the heated greenhouse compared to the reference one.

2. DESCRIPTION OF THE EXPERIMENTAL INSTALLATION

2.1 The site of installation

In Laboratory of Energetic and the Thermal Processes (L.E.P.T) of the Center of Technology and Research Energy from Tunisia located at Borj Cedria (latitude $36^{\circ}48'$ N, longitude $10^{\circ}10'$ and altitude 3 m above mean sea level) which is Mediterranean type climate with a high rate of relative humidity, a good rate of sunshine in the summer and high frequency of bad weather days in the winter.

According to the results of several years of continuous measurements carried out in the Solar Energy Laboratory of Logical weather of Tunis, the yearly average temperature is close to 18.4°C . The seasonal ones are close to 26.6°C in the summer, 21.2°C in the autumn, 12°C in the winter and 16.7°C in the spring. The yearly global solar radiation is about 1805 kWh/m^2 and the yearly mean sunshine duration is about 2632 h.

2.2 The agricultural greenhouse

In Laboratory of Energetic and the Thermal Processes (L.E.P.T) of the Center of Energy Technologies and Researches from Tunisia, we installed two agricultural greenhouses hemi cylindrical structure (Fig 1) and its dimensions are 12.5 m length, 8 m width and 3 m height.



Fig. 1: The tow experimental greenhouses

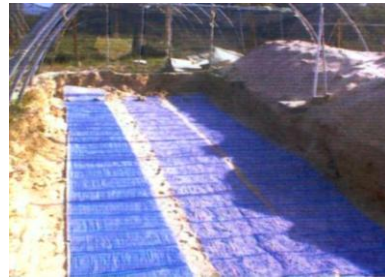


Fig. 2: Capillary heat exchanger burred in the soil of the greenhouse



Fig. 3: Agrotherm suspended in the greenhouse

Each greenhouse is covered with a plastic cover (polyethylene with low density and with thickness of 180 μm) and a tomato cultivating was used. Both greenhouses are placed in a semi-urban medium far from the buildings, so it is an “insulated greenhouse”.

2.3 The heating system

The figure 4 shows that the heating system is composed of three distinct parts:

- One tank of 300 liters composed of: - A corrosion resistant material which is also resistant to the limestone deposit at the temperature close to 100°C; - An insulator to store the heat with a polyurethane cover of flexible foam; - An exchanger of heat which transfers heat from the solar circuit to the interior circuit.

- A vacuum solar collector: it is a WEL-CH-15 heat pipe sensor which consists of fifteen vacuum tubes (each one optical surface is 2 m^2).

- A heating system: composed of two exchangers coupled between them to manage thermal energy in a greenhouse. The first exchanger is a battery of plaits with capillary tubes at 120 m^2 of surface buried under ground with a depth of 70 cm. The second one is an air exchanger based on black plastic tubes (agrotherms) and suspended with 2.5 m height and posed on the ground.

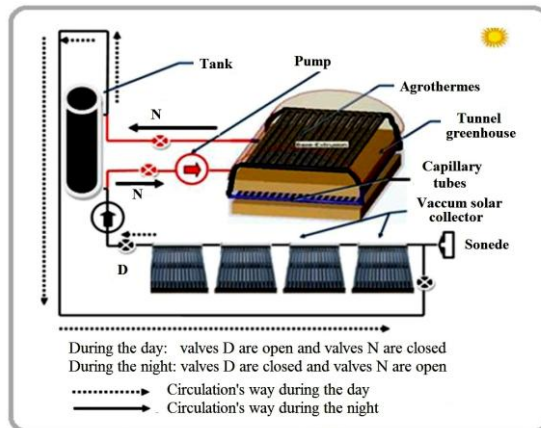


Fig. 4: Experiment tunnel greenhouse with the heating system

3. MEASURED VARIABLES

Using a computer based data acquisition system HP 3470A, analogical data are collected during time intervals appropriate well to the test concerned. A particular attention has been given to the calibration of different thermocouples and measurement instruments. Systematic controls and permanent verifications of measurements have been executed. Measurements concern the climatic variables, which characterize the microclimate inside the greenhouse, and the thermal variables, which characterize the considered system. Functioning temperatures of the heating system: In addition to the climatic variables measured inside and outside the greenhouse, the measurements of the functioning temperatures of the heating system (vacuums solar collector inlet and outlet water temperature, storage tank temperature, inlet and outlet capillary tubes temperature), permit to determine the functioning performances and the thermal efficiency of the installation.

4. MATHEMATICAL MODELING

4.1 For the greenhouse

The considered model is a greenhouse divided into four coats: the internal air, the cover, the plant and the ground. The Figure 5 illustrates all the flows of energy considered in the model.

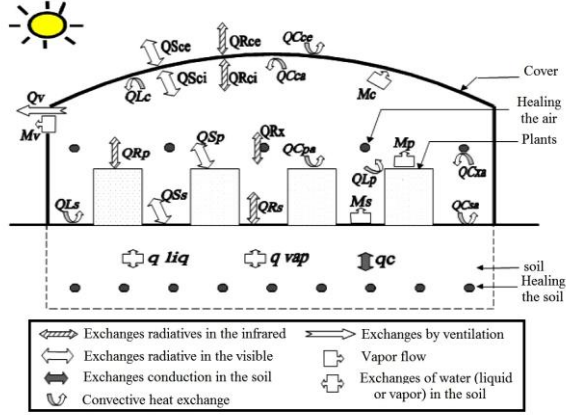


Fig. 5: Different exchanges in the studied model

with: Q_R , the infrared radiative assessment; Q_S , the absorbed solar flow; Q_C , the convective exchanges of sensitive heat, Q_L , the convective exchanges of latent heat; Q_V , the exchange of sensitive heat by the air renewal; M , the vapour flow; q_c , the conductive exchanges in the ground; q_{vap} and q_{liq} , the vapor / liquid water exchanges of mass in the ground.

Two equations of balance sheet are written for the internal air to predict its temperature T_i and its specific humidity W_a .

•For the air temperature-

$$\rho_a \times C_{pa} \times V_a \times \frac{dT_a}{dt} = -Q_{C_{ac}} - Q_{C_{ap}} - Q_{C_{as}} - Q_{C_{ax}} - Q_V$$

•For the specific humidity of the air-

$$\rho_a \times V_a \times \frac{dW_a}{dt} = -M_C + M_P + M_S - M_V$$

The storage capacity of the cover and the plant emplacement are unimportant compared to the daily energy put in game. In fact, the internal air and the ground are more interesting to study. So two equations of balance sheet are then written to predict the cover temperature T_c and that of the plant placement T_p .

•For the temperature of the cover-

$$Q_{R_{co}} + Q_{R_{ci}} + Q_{S_{co}} + Q_{S_{ci}} + Q_{C_{ca}} + Q_{C_{co}} + LM_{ci} = 0$$

•For the temperature of the plant-

$$Q_{R_p} + Q_{S_p} + Q_{C_{ap}} - LM_p = 0$$

4.2 For the tank

The thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification, can be modeled by assuming that the tank consists of N ($N \leq 15$) fully mixed equal volume segments, as shown in figure 4. The degree of stratification is determined by the value of N . If N is equal to 1, the storage tank is modeled as a fully mixed tank and no stratification effects are possible.

Options of fixed or variable inlets, unequal size nodes, temperature dead band on heater thermostats, incremental loss coefficients, and losses to gas flue of auxiliary heater are all available. Flow streams enter the tank at fixed positions. If it reaches the top of the tank or the auxiliary is not specified.

The load flow enters at the tank bottom and the hot source stream enters just below the auxiliary. At the end of each time interval, any existing inversion temperature is eliminated by total mixing of the appropriate adjacent nodes.

An assumption, employed in this model, is to assume that the fluid streams, flowing up and down from each node, are fully mixed before they enter each segment. This implies that $\dot{m}_1$ is added to $\dot{m}_4$, $\dot{m}_2$ is added to $\dot{m}_3$, and a resultant flow, either up or down, is determined: (Fig. 6).

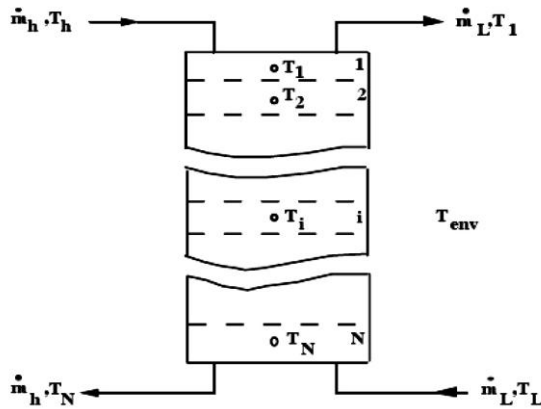


Fig. 6: Stratified fluid storage tank

- An energy balance on the i_{th} segment (neglecting losses) is then written:

$$M_i \times C_{pf} \times \frac{dT}{dt} = \{(\dot{m}_1 - \dot{m}_3) \times C_{pf} \times (T_{i-1} - T_i) \quad \dot{m}_1 > \dot{m}_3$$

$$M_i \times C_{pf} \times \frac{dT_t}{dt} = \{(\dot{m}_3 - \dot{m}_1) \times C_{pf} \times (T_{i+1} - T_i) \quad \dot{m}_1 < \dot{m}_3$$

- An energy balance written about the i_{th} tank segment is expressed:

$$\begin{aligned} M_i C_{pf} \times \frac{dT_t}{dt} = & \alpha_i \times \dot{m}_h \times C_{pf} \times (T_h - T_i) + \beta_i \times \dot{m}_L \times C_{pf} (T_L - T_i) + U \times A_i (T_{env} - T_i) \\ & + \gamma_i \times (T_{i-1} - T_i) C_{pf} \quad \text{si} \quad g_i > 0) \\ & + \gamma_i \times (T_i - T_{i+1}) C_{pf} \quad \text{si} \quad g_i < 0) \end{aligned}$$

$$\dot{Q}_i \quad \text{for} \quad i = 1, \dots, N$$

The temperatures of each of the N tank segments are determined by the integration of their time derivatives expressed in the above equation. At the end of each time step, temperature inversions are eliminated by mixing appropriate adjacent nodes.

Energy flows and change in internal energy are calculated as follows:

$$\dot{Q}_{\text{env}} = \sum_{i=1}^1 U \times A_i \times (T_i - T_{\text{env}}) + \gamma_f \times \sum_{i=1}^1 (U \times A_i)_{f,i} \times (T_i - T_f)$$

$$\dot{Q}_S = \dot{m}_L \times C_{p_f} \times (T_1 - T_L)$$

$$\dot{Q}_{\text{int}} = \dot{m}_h \times C_{p_f} \times (T_h - T_N)$$

$$\Delta E = \frac{V \times \rho_f \times C_{p_f} \times \left(\sum_{i=1}^N T_i - \sum_{i=1}^N T_i \right) \Big|_{t = \text{Time}0}}{N}$$

4.3 For heat exchangers

▪ Air heat exchanger water-air-

The useful power exchanged with the heat exchanger water-air spells:

$$\dot{Q}_u = \dot{m} \times C_{p_w} \times (T_{f_s} - T_{f_e})$$

▪ Underground heat exchanger water-ground-

The two-dimensional equation of distribution of the heat spells:

$$\frac{\partial T_s}{\partial t} = K_s(\theta) \times \left(\frac{\partial^2 T_s}{\partial y^2} + \frac{\partial^2 T_s}{\partial z^2} \right) + S(y, z)$$

The term $S(y, z)$ spells:

$$S(y, z) = \frac{\dot{m} \times C_{p_w} \times d T_f(y)}{C_S \times d}$$

C_S is the calorific capacity of the ground.

5. MICROCLIMATE INSIDE THE UNHEATED AND HEATED GREENHOUSES:

The evolution of the interior and exterior greenhouse climate allows studying the answers of the greenhouse according to the weather conditions.

Fig 7 and 8 represents the variation curve of the internal temperature ($T_{\text{in-air-wh}}$, $T_{\text{in-air-h}}$) with and without heating and external ($T_{\text{ex-air}}$) in April as well as the period of sunshine G .

We can subdivide one day in two time intervals:

- The period situated between 7 am and 5 pm, the sunshine reaches its maximal values entraining an increase of the ambient temperature outside and inside the greenhouse.

- The period situated between 5 pm and 6 am in the morning which is characterized by low sunlight. We notice that the outside and internal temperature of the greenhouse decreases strongly.

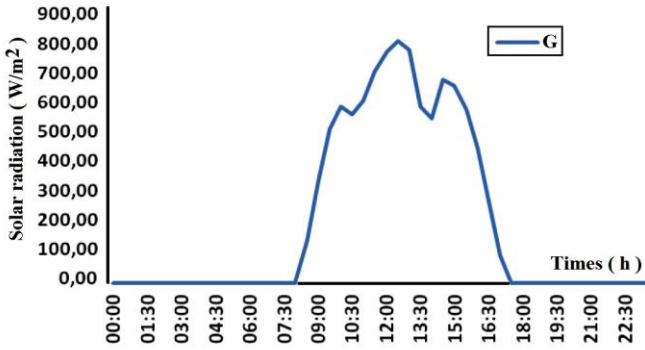


Fig. 7: Variation in the sunshine with time

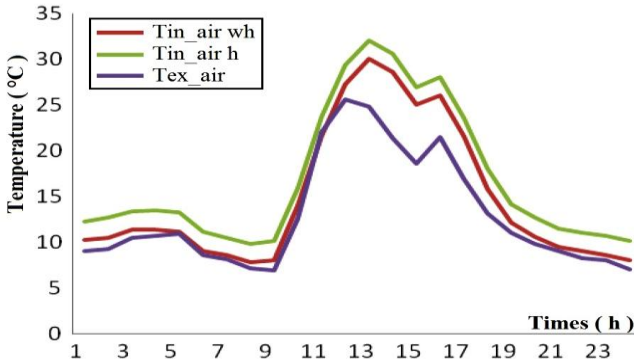


Fig. 8: Evolution of the interior and exterior air temperature under greenhouse with and without heating system at the date (05/04/2010)

The results shows that the internal ambient (T_{in-air}) under the greenhouse during the day is bigger than the outside temperature (T_{ex-air}). While, these values are relatively close at night.

The temperature in the greenhouse falls quickly between 3 pm and 7 pm and brings no comfort for the plant which requires a less stressful and relatively stable climate for its normal growth, where from the necessity of a heating system to improve the climate under greenhouse.

The heating of the greenhouse internal air during the night is realized by the experimental device represented in the figure 4 (Circulation's way during the night).

The figure 8 represents the variation of the outside and internal ambient temperature of the greenhouse with time. We notice that the internal temperature of the air inside the greenhouse increase of 2 °C compared to the outside temperature during the night due to the contribution of energy stored during the day in the tank and in the ground. [15]

6. EFFECTIVENESS OF THE VACUUM SOLAR COLLECTOR

The figure 9 represent the variation of the entered and exits temperatures of four vacuum solar collectors and the ambient temperature.

During this test, we noticed that the temperature of the water at the exit of the first vacuum solar collector does not overtake 38 °C and it increases in passing by a vacuum solar collector to another to reach finally 74 °C at the exit of the fourth vacuum solar collector. This last value will be used to warm the greenhouse air at night.

In the figure 9 we represent the effect of every vacuum solar collector with the evolution of temperature.

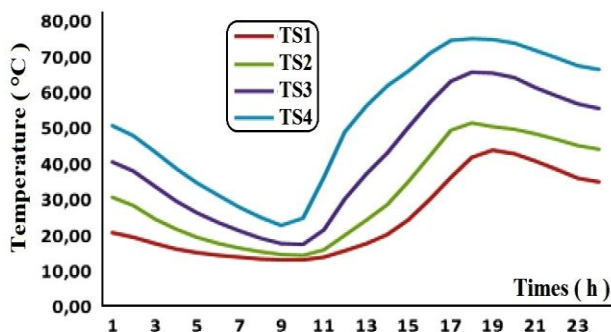


Fig. 9: Evolution of temperature according to time (Flow = 25 kg/h)

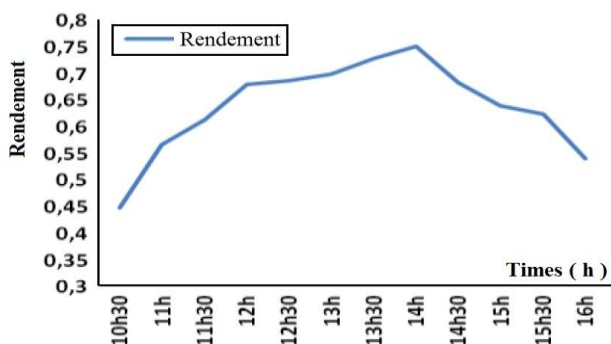


Fig. 10: The effectiveness evolution of the vacuum solar collector according to time

We note that the effectiveness of vacuum solar collector depends on several factors like flow of the water, wind speed, period of sunshine... We choose a typical day to test our vacuum solar collector. We notice that its effectiveness attends its maximum at 2 pm and reaches 75 %. (Fig. 10) [16]

7. VARIATION OF ENTRY AND EXIT TEMPERATURE OF THE TANK

To warm the greenhouse during the night we need a storage tank which allows the storing of solar heat energy supplied by the vacuum solar collector.

Figure 11 represents the temperature entrance and exit variation of the tank according to time.

We notice that the exit temperature of the tank is always higher than the entrance one. Actually, for a typical day and using four vacuum solar collectors, the outlet temperature of the tank can reach 80 °C at 1 pm. It is at this moment when we have to store the surplus of energy in the ground of the greenhouse by using the capillary tubes. This energy will be useful at night when the temperature falls.

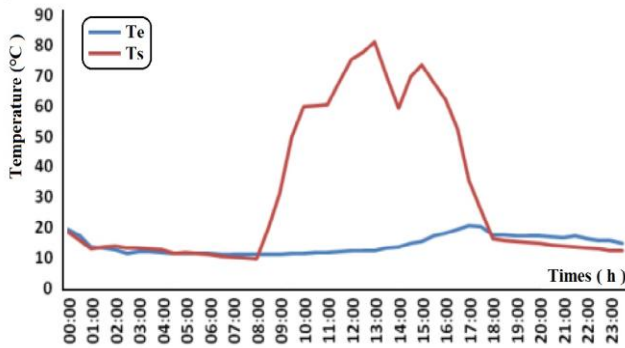


Fig. 11: The entrance and exit temperature variation of the tank (26/04/2010)

The heat storage in the tank is realized by an experimental device represented in Figure 4 (Circulation's way during the day).

The energy stored in the tank during the sunny period of the day added to the energy stored in the soil can improve the climate in the greenhouse at night.

The temperature of water inside the tank rises with increasing the water level (Fig. 12). For this reason, we have to use a circulation pump to homogenize the temperature of water in the tank. [17]

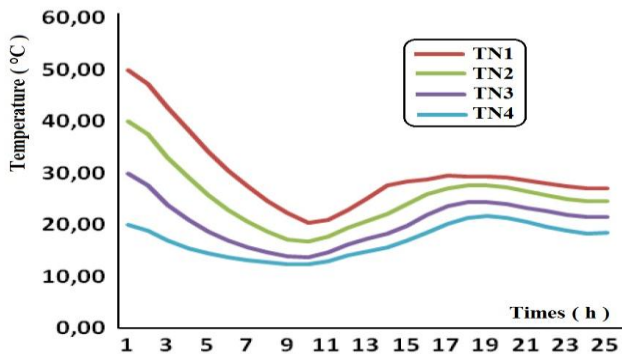


Fig. 12: Water temperature variation in the tank at different nodes

8. VARIATION OF THE TEMPERATURE IN ENTRY AND EXIT IN THE CAPILLARY TUBES

We notice that the temperature in the entry of the capillary tubes is bigger than it at the exit during the night (Fig. 13).

From 6 am in the morning, both temperatures become almost equal. What implies that the energy stored in the sunny period of day in the tank is totally used.

In fact, the temperature inside the greenhouse begins to decrease at 5 pm which obliges us to begin a new cycle of heating.

The energy stored in the tank is going to be used according to the greenhouse internal temperature until its end.

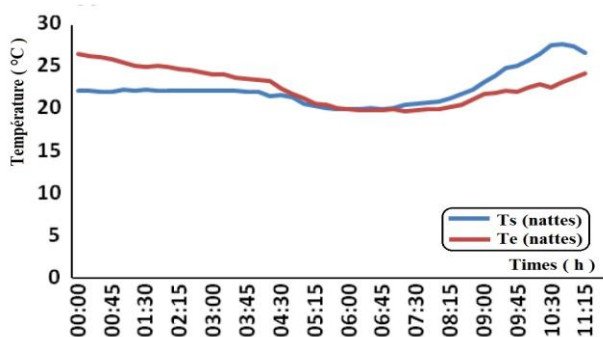


Fig. 13: The entrance and exit temperature variation in the capillary tubes at the date 29/04/2010

9. EVOLUTION OF THE SOIL TEMPERATURE AT DIFFERENT DEPTH

In order to found the best position to put the capillary tubes, we have to studies the variation of the ground temperature at different depth. Figure 14 shows that for depths from 10 cm to 30 cm, the soil temperature evolution is random due to the direct radiations and influenced by the agrotherm exchangers.

This zone can't be used as an energy storage section, it is a transition zone. Consequently, the zone which can be useful as a thermal energy storage is of depth beyond 30 cm (we not that our studies reaches 70 cm depth). [18]

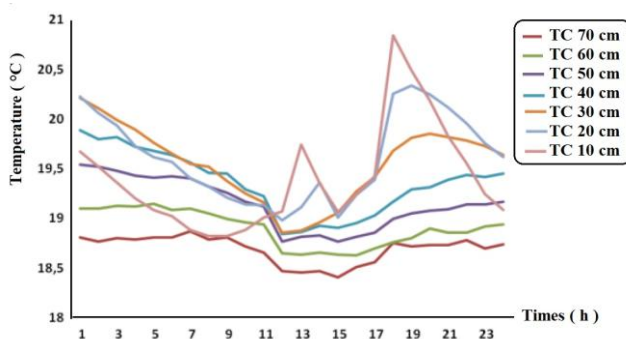


Fig. 14: Evolution of the soil temperature at different depth (from 10 to 70 cm)

10. CONCLUSION

The temperature is an important parameter to control under greenhouse climate and to improve the quality of productions.

In this work, we have showed that the solar heating system that we have conceived and experimented permits to demonstrate that:

- To a depth between 10 and 30 cm, the evolution of the soil temperature is random. That's why, it is better to store thermal energy to deeper than 30 cm.
- When the water maximum temperature in the tank reach 80 °C, the excess energy in the greenhouse floor is stored through the capillary mats.
- Due to the stratification phenomenon, the temperature in the tank is not homogeneous.
- By increasing the air temperature inside the greenhouse during the night by 2 °C, this study shows the effectiveness of a solar system and its ability to provide an amount of heat to reduce the cost of heating greenhouses.

NOMENCLATURE

QR : Infrared radiative assessment, W/m^2	QC : Convective exchanges of sensitive heat, W/m^2
QS : Absorbed solar flow, W/m^2	
QL : Convective exchanges of latent heat, W/m^2	Qv : Exchanges of sensitive heat by the air renewal, W/m^2
qc : Conductive exchanges in the ground, W/m^2	qvap & qliq : Vapor/liquid water exchanges of mass in the ground, W/m^2
$\dot{M}$: Mass flow, kg/s	M : Vapour flow, W/m^2
QC : Sensible heat flux exchanged by convection, W	QV : Sensible heat flux exchanged by ventilation, W
C _p : Specific heat of a component of the greenhouse, J/kg.K	K _s (z) : Thermal diffusivity of the soil depth z, m^2/s
T : Temperature of a component of the greenhouse, °C	V : Volume of a component of the greenhouse, m^3
W : Specific humidity, kg of W./kg of dry a.	Z : Depth ground, m
$\dot{m}$: Water flow, l/h	S : Source term, K/s
C _S : Specific heat of the soil, J/kg.K	M _i : Mass of fluid in the i_{th} section, kg
C _{pf} : Specific heat of the tank fluid, J/kg.K	A _i : Surface area of the i_{th} tank segment, m^2
T _{env} : Temperature of the environment surrounding the tank, K	Q _{in} : Rate of energy input to tank from hot fluid stream, W
T _h : Temperature of the fluid entering the storage tank from the heat source, K	T _L : Temperature of the fluid replacing that extracted to supply the load, K
ΔE : Internal energy change of the tank, J	ρ_a : Air density, kg/m^3
θ : Volumetric water content of the soil, m^3 of water / m^3 of soil	A : indoor air, - C : coverage, - ce : outer face (cover), - ci : internal face (cover)
e : outdoor air, - i : indice i tank segment with the top (hottest) segment having $i=1$	p : plant or vegetation, - s : ground, - x : heating, - w : water
f _e : fluid at the inlet, - f _s : fluid at the outlet,	
α_i : a control function defined by $\alpha_i = 1$ if $i = Sh$; 0 otherwise	
β_i : a control function defined by $\beta_i = 1$ if $i = SL$; 0 otherwise	
N : Number of fully mixed (uniform temperature) tank segments ($N \leq 15$)	

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