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Thermal Performance of a Solar Heat Storage Accumulator Used For Greenhouses Conditioning

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Abstract: The use of solar energy for greenhouse heating has gained an increasing acceptance during the last years. Active solar systems applied to greenhouses can supply a significant part of the heating requirements. However, there are some problems related to the cost of the heat collection unit and the heat storage methods. In this context several techniques were born. The most famous of these techniques is the seasonal storage of thermal heat in soil. The objective of our work is to study a system of thermal energy storage conceived in our Laboratory (LEPT, Tunisia). The system is composed of a vat having a large dimension (6 m^3) filled with fin sand. Inside the vat three batteries of capillary exchangers are buried at three different levels. To heat the accumulator soil, we use a solar collector with a surface equal to 6 m^2. In order to size the heat accumulating system, a numerical study is started. It allows evaluating the soil temperature as well as the energy cumulated inside the accumulator during the charging and the discharging period.

Keywords: Renewable energy sources, capillary heat exchanger, solar collector.

INTRODUCTION

The primary objective of greenhouses is to produce agricultural products, outside the cultivation season. So it is necessary to heat the greenhouses, particularly during the cold seasons. However even for the countries in the process of development heating cost exceeds 30% of the overall greenhouse cost (M. Santamouris et al [1]). In this context several techniques were born. The most important technique consists in seasonal thermal heat storage in the soil characterized by a very significant heat-storage capacity. Kurata. K et al [2] assumed a system composed of solar collectors connected to a tubular heat exchanger, buried in the greenhouse soil. Another set of heat exchanger were suspended inside greenhouse. A numerical study showed that the efficiency of the seasonal storage, as well as the daily storage, depends on the system configurations, the climate conditions and soil thermal characteristics (Bejan. A et al [3]). During the day, the excess of the solar heat is collected for short- or long-term storage and it is recovered at night in order to satisfy the greenhouses heating needs (Oztûrk. H et al. [4]). In their approaches, Oztûrk. H et al. contemplate a daily solar energy store inside greenhouse soil by the use of a solar collector. Numerical results permit to evaluate the effect of thermal conductivity, the capacity of heat and the water content on soil temperature and on thermal energy storage. Several tests, for the evaluation of the soil thermal conductivity effect on the thermal heat were carried out. The improvements of the method for such study consist in the evaluation of the temperature, moisture profiles and the cumulated energy in the deep soil (between 20, 40 cm) (Reuss. M et al. [5] Lamard. E et al. [6]). The influences of the input climatic parameters on the ground surface tempertaure were investigated using a neural network approach. Starting with the calculated surface temperature, the ground temperature can be estimated (Ogée. J et al. [7]). They used the energy balance equation to predict ground surface temperatures. A number of investigations which aimed at improving the greenhouse thermal performance have been done by some researchers in the design, modelling and testing of solar collector adopted for greenhouses heating. Arinze. E et al. [8] developed a dynamic model for predicting temperatures and moisture levels in greenhouse soil. Willits.D .H et al. [9] investigated factors affecting the performance of rock storage as solar energy collection/storage systems for the greenhouses. They took the data from two similar rock-storage systems of slightly different design attached to two different greenhouses. Other researchers studied the phenomenon of water evaporation from the ground (Sifaoui. M.S. [10]). In his work Sifaoui. M.S has studied the surface and the deep soil evaporation by analysing the assessment of energy such as the sensible heat flow, the heat flow absorbed by the soil and the latent heat flow. He noticed that if the soil surface is exposed to an intense flow of heat solar radiation, a superficial dry layer will be formed. He also noticed that wet soil temperature is lower than the dry soil for only 20 cm of depth. For the other depths the temperatures are almost the same.

As an alternative to the analytical approach, several numerical simulation models based on finite differences have also contributed to characterize diffusive heat exchangers. Some of them are limited to the description of the soil behaviours if we use an only tubular heat exchanger buried in the

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soil at the depth of 20 cm (Balducci. M et al. [11], Krane. R. J et al. [12] and Hollumer. P. B et al. [13] and Moran.M. J et al. [14]). Other numerical simulation allow's to describe the effects of the coupling of many tubular heat exchangers on the cumulated thermal energy evolution which depends on thermal and physical properties of the heat storage soil, heat storage temperature and the heat exchanger design (Bowman. G. E et al. [15], Boulard. T et al. [16], Sanner. B et al. [17] and Bakema. G et al. [18], Nakajima.Y et al. [19] and Tanaka. T et al. [20]). In our work we have studied an accumulator of sensible heat used for greenhouse air-conditioning. Three batteries of capillary heat exchanger are buried inside the accumulator. The capillary baids, used as water/soil heat exchanger have a very significant heat-transferring surface. They are not clogged by earthy waters contrary to the metal tubular exchangers and they have a not a very expensive price. This investigation is supplemented by a numerical simulation to predict the influence of the operation parameters on the accumulator performances.

MATERIALS AND METHODS

Materials: The schematic arrangement of the system is given in Fig. 1. The accumulator of thermal energy mainly consists of two elements: (i) The parallelepipedic vat with a volume of 6 m^3 is filled with fin sand. Inside the vat we buried a network of capillary polypropylene heat exchanger at three different depths (20 cm, 40 cm and 50 cm). With an aim of reducing the environment influence on the stock, we have covred the vat surface with a double poly-mouss layer. (ii) The solar collector having a surface equal to 6m² is formed by a concrete matrix used as solar layer absorber. Inside the concrete we imbricated a capillary heat exchanger. To increase the greenhouse effect we covered the solar collector by PVC (Akyver) with a thickness equal to 10 mm and a transmission coefficient equal to 0.85.

Soil measurements: Soil temperature was measured at ten different depths using 20 home-made thermocouples, i.e. copper-constantan soldered joints coated with water proof paint. Thermocouples and probes were connected to a multiplexer and the data was collected on a *HP* data-logger related through an external modem to a data processing (PC). The measurements were made and recorded every 10 mn. Temperature measurements were accurate within 0.1 °C.

Operation modes: To heat the accumulator soil we ensure the coupling between the buried capillaries exchangers and the solar collector. The heated water is pumped from the solar collector to the buried heat exchanger through a tubular system. The experiment consists in heating the accumulator soil until thermal balance (*charging period*), then we follows the soil temperature evolution (*discharging period*). The two modes of operation were investigated in this system. The first mode occurs when solar radiation is available for collection. During this mode the hot water, that receives its energy from the solar collector, is sent to the capillary heat exchanger by the water circulating pump. The second mode occurs when soil temperature is at its maximum

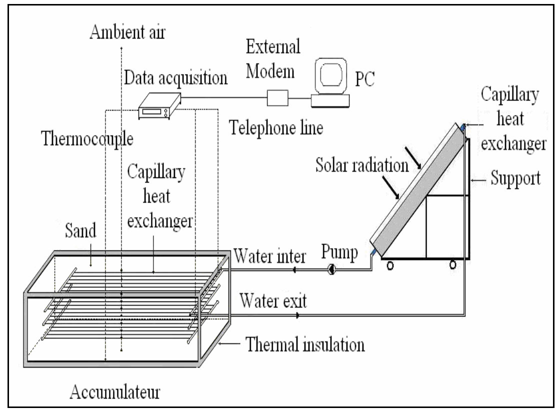


Fig.1: Accumulator of thermal solar energy

NUMERICAL MODELING

For the modeling of the thermal heat exchange inside soil, we evaluated the overall heat coefficient and the heat exchanger effectiveness of the capillary exchanger which we used. Therefore we wrote the energy balance relative to the heat exchanger buried in soil. The numerical simulation allows evaluating the soil temperature as well as the energy cumulated inside the accumulator during the charging and the discharging period.

Evaluation of the heat exchanger performances: The capillary exchanger, used in this study, consists of 90 capillaries connected at their ends, by two collecting tubes. The temperature of each section is taken as being a constant average which depends only on the exit temperature of the preceding section and which linearly varies along the capillary tube (Fig. 2). The mean water temperature could be a linear combination of supply and exaust water temperature shown as:

$$Ti[I] = Ti[0] + (\frac{Tso - Ti[0]}{N}).I \qquad (1)$$

Where Ti[0] is the supplied water temperature.

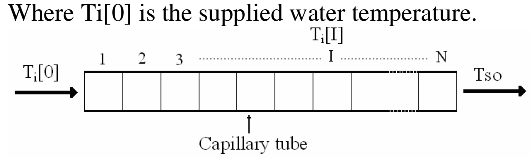


Fig. 2 : Scheme of a capillary tube

The overall heat transfer coefficient U is represented by:

$$U = \frac{1}{N}\sum_{i}^{N} U_i \qquad (2)$$

The heat flow rate exchanged is derived from a thermal balance on the water side:

$$Q = \dot{m}_w .\rho.c_{pw}.(T_0 - T_i) \qquad (3)$$

Where:

c_{pw} is the water specific heat (J $kg^{-1}K^{-1}$)

$\dot{m}_w$ is the flow rate of the charging water (m^3 s^{-1}).

N is number of sections.

Q is the rate of heat by the capillary heat exchanger (W).

T_o is the water outlet temperature (K).

T_i is the water inlet temperature (K).

U is the overall heat transfer coefficient ($Wm^{-2}K^{-1}$).

U_i is the local heat transfer coefficient ($Wm^{-2}K^{-1}$).

ρ is the water density ($kg.m^{-3}$).

Evaluation of the temperature fields inside soil heat accumulator: The ground is regarded as being homogeneous. The convective coefficient is supposed to be constant throughout the tube. Taking into account the simplifying assumptions, the equation of the heat conduction in the soil is given by the relation:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_s \frac{\partial T}{\partial y}\right) \qquad (4)$$

The discretization of the equation is carried out by the integration of the equation (4) on the control volume and the interval (between T at t+Δt).

$$a_p T_p = a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_p{}^0 T_p{}^0$$

Where

$$a_E = \frac{(\lambda_s)_e \Delta y}{\partial x_e},\ a_W = \frac{(\lambda_s)_w \Delta y}{\partial x_w},\ a_N = \frac{(\lambda_s)_n \Delta x}{\partial y_n},$$

$$a_S = \frac{(\lambda_s)_s \Delta y}{\partial y_s},\ a_p^0 = \frac{\rho C \Delta x \Delta y}{\Delta t} \text{ and}$$

$$a_P = a_E + a_W + a_E + a_S + a_p{}^0$$

For the resolution of the equation we use the method of specific relieving (S.O.R) which is effective and relatively easy to program. We use Chebyshev convergence algorithm which consists in seeking, during iterations, the relaxation optimal factor (Patanckar [21]). The resolution of the energy equation allows evaluating the temperature fields at various soil levels.

Treatment of boundary conditions: The corresponding boundary conditions are:

$$-\lambda s \frac{\partial T}{\partial x}_{/x=0} = 0 \quad -\lambda s \frac{\partial T}{\partial x}_{/x=L} = 0$$

$$-\lambda s \frac{\partial T}{\partial y}_{/y=0} = 0 \quad -\lambda s \frac{\partial T}{\partial y}_{/y=l} = 0$$

$$-\lambda s \frac{\partial T}{\partial x}_{/x=\frac{L}{4}} = h(T_{water} - T_m)$$

at $x = \frac{L}{4}$, the capillary heat exchanger is buried in soil accumulator.

Energy analysis for the charging and discharging periods: The rate of heat transfer $Q_{Charging}(t)$ from the solar collector into the heat storage accumulator was calculated during the charging period by using the following equation:

$$Q_{Charging}(t) = \dot{m}_{w1}\, \rho cp [T_i(t) - T_e(t)] \quad (5)$$

The rate of heat stored in the accumulator heat storage $Q_{Storage}(t)$ was determined with respect to the heat transfer rate into the accumulator and heat losses for the charging period:

$$Q_{Storage}(t) = Q_{Charging}(t) - Q_{Losses}(t) \qquad (6)$$

$Q_{Losses}(t) = S_s \lambda_s [T_m(t) - T_s(t)]$, is rate of heat loss from the whole surface area of the accumulator. The energy efficiency for the charging period was defined as the ratio of the heat stored in the heat storage unit to the heat transfer from the sollar heat collector. Then, the total energy efficiency during the charging period $\eta_{Charging}$ (t) in % can be formulated as follows:

$$\eta_{Charging}(t) = \frac{Q_{Storage}(t)}{Q_{Charging}(t)}.100 \qquad (7)$$

The rate of heat recovered from the heat accumulator during the discharging period $Q_{Discharging}(t)$ was calculated by:

$$Q_{Discharging}(t) = \dot{m}_{w2}.\rho.c_{pw}.[T_e(t) - T_i(t)] \quad (8)$$

Where:

$\dot{m}_{w,1}$ is the flow rate of the charging water ($m^3 .s^{-1}$)

$\dot{m}_{w,2}$ is the flow rate of the discharging water ($m^3 .s^{-1}$)

$Q_{Charging}$ is the rate of heat supplied from the collector (W)

$Q_{Discharging}$ is the rate of heat supplied from the accumulator (W)

Q_d is the rate of heat recovery from the heat accumulator (W)

Q_{Loss} is the rate of heat loss from the accumulator (W)

$Q_{Storage}$ is the rate of heat stored into the accumulator (W)

S_s is the accumulator surface area of the accumulator (m²)

t is the time (s)

T_m is the soil temperature inside the accumulator (K)
T_s is the soil temperature inside the greenhouse (K)
$\eta_{Charging}$ is the net energy efficiency for charging period (%)
τ is the transmittance for solar radiation.
λ_s is the equivalent heat conduction coefficient ($W.m^{-1}K^{-1}$).

Heat requirement of the tunnel greenhouse: The heat requirement of the tunnel greenhouse was calculated from the following equation (Bailey et al. 1988 [22]).

$$Q_{Greenhouse}(t) = \frac{S_c}{S_g} u[T_g - T_d(t)] - \dot{I} \tau \gamma \quad (9)$$

The overall heat loss coefficient u represents the total energy loss of external area of the greenhouse for a difference of 1K between the inside and outside temperatures. The value of the overall heat loss coefficient depends on especially external climatic conditions (principally on the wind speed but also on rain and snow), it is always given in relation to the wind speed. A number of relationships have been developed to predict the overall heat loss coefficient of different type of greenhouses (Damrath et al. (1982) [23]).

Where:

$\dot{I}_t$ is the total solar radiation ($W.m^{-2}$).
$Q_{Greenhouse}$ is the greenhouse heat requirement ($W.m^{-2}$).
S_c is the surface area of the greenhouse covers (m²).
S_g is the ground area of the greenhouse (m²)
T_d is the outside air temperature (K).
Tg is the air temperature in the greenhouse (K).
u is the overall heat loss coefficient ($Wm^{-2}K^{-1}$).
γ is the conversion factor of global radiation energy to thermal energy.

RESULTS AND DISCUSSION

Performances of the capillary heat exchanger: The tests are carried out under the experimental conditions represented in Table 1. For the first test; the accumulator soil is dry, we represented the evolution of the exchanged thermal power according to the logarithmic average temperature difference (Fig. 3.a).

We noted that this evolution is linear and the curve passes by the origin although the stationary mode is not reached. The slope of this curve, reported to the unit of area, represent a coefficient (in variable mode) which can be compared to the overall heat exchange coefficient. This coefficient is about 15 W/m².°C.

Table 1: Experimental conditions

Soil nature	Water flow, $l.h^{-1}$	Water temperature, °C	Soil temperature, °C
Dry soil	180	[12 - 35]	[16 - 23]
Wet soil	180	[14 - 33]	[16 – 23]

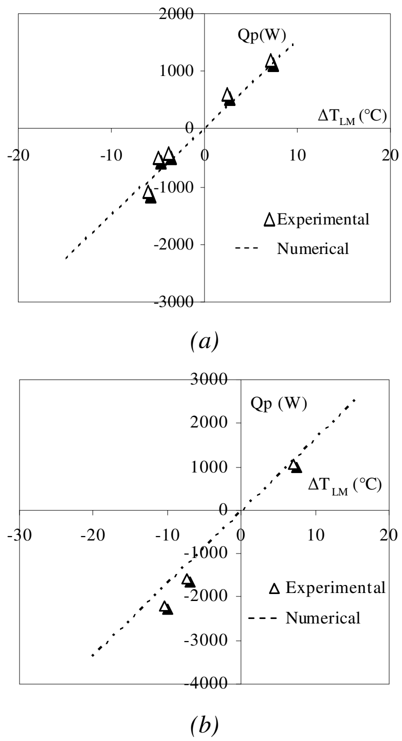


Fig.3: Thermal power exchanged according to the temperature average logarithmic variation soil and for a heat-transferring surface equal to 15 m² ;
(a) Dry soil; (b) Wet soil

For the second test, the accumulator soil is wet. The heat exchange coefficient is about 20 W/m².°C (Fig. 3.b). This coefficient is higher than that found when the capillary heat exchanger is buried in a dry soil. We can allot this variation to the increase of the soil thermal conductivity and heat capacity according to the soil water content. In fact the thermal conducticity of the soil is greatly affected by its constituents. In particular, air is a poor conductor and in soil it reduces the effectivness of the solid and liquid phases.

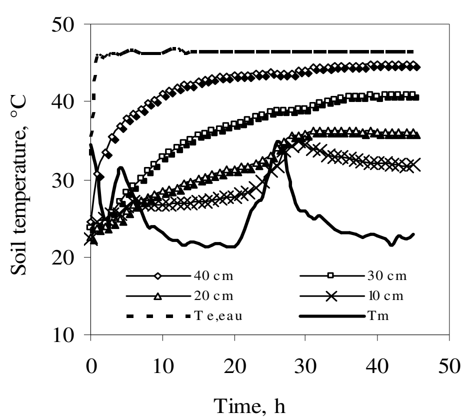
The conductivity is increased as bulk density increases. An increase in bulk density reduces the air content and brings the solid particules more closely into contact. Water content has a marked effect because in the wet soil, water replaces air so it provides bridges between particles and it greatly increase the soil conductivity.

Soil thermal behaviour during the charging periods: The tests are carried out under the experimental conditions represented in Table 2. The experimental results of soil heating were evaluated for the diurnal charging periods.

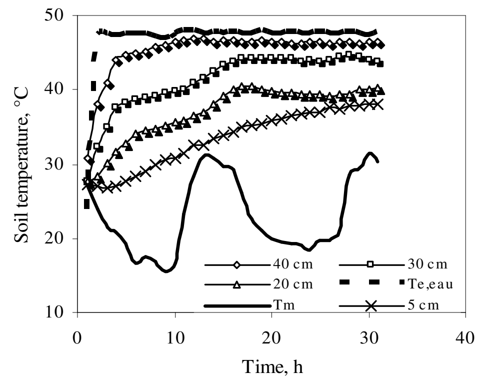
Table.2: Experimental conditions

Soil nature	Water flow, $l.h^{-1}$	Water temperature, °C	Soil temperature, °C
Dry soil	180	[40 - 45]	[16 – 37]
Wet soil	180	[40 - 45]	[18 – 41]

By analyzing soil temperature variation we noticed that the superior layers of soil accumulator undergoes easily with the external climatic variation. Beyond a certain depth, the soil temperature does not vary between the day and the night (Figs. 4.a, b). We note that the effect of the soil heating is felt more when the soil accumulator is wet. Because of its higher thermal conductivity, the wet soil store more heat than the dry soil. Thus soil accumulator can be divided into two zones (upper and lower). The thickness of the upper zone depends on the temperature of the heating water. It is about 20 cm when soil accumulator is heated by water at the temperature of 45°C.



(a)



(b)

Fig.4: In both cases the capillary heat exchanger is placed at a depth of 40 cm. It is crossed by a water at the value of about 48 °C ;(a) Temperature fields for dry soil; (b) Temperature fields for wet soil

The lower zone stores heat provided by the solar collector and heat which is not restored at night by the upper zone. The temperature fluctuations are reduced in this zone. Thus, this layer is considered to be a long-term storage section. By using the numerical model we evaluated the thermal energy stored in the heat storage accumulator during the charging periods.

The thermal stored energy was calculated by Equation. 6. The results of this analysis are shown in Fig. 5.

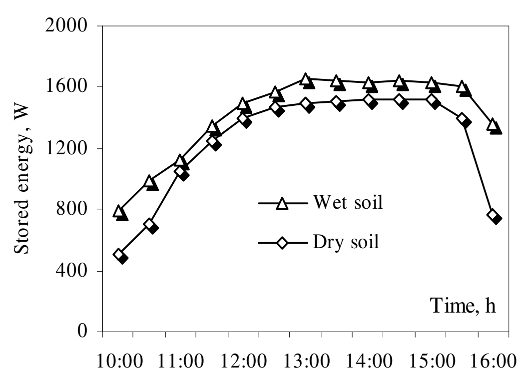


Fig.5: The rates of thermal heat stored in the accumulator during the charging periods for a dry and wet soil

The thermal energy stored in the accumulator increased with increasing inlet temperature of the heat transfer water circulating between solar collector and accumulator during the charging periods. Fig. 5 shows that the average hourly rate of thermal energy changed with time during the charging periods. During these periods, the rate of the heat stored in the accumulator, when the soil is dry, ranged from 500 W to 1.4 kW. When the soil is wet the maxim of solar energy stored is higher. It varies between 800 W to 1.65 kW. The net energy efficiencies of the heat storage accumulator during the charging periods were calculated by using equation. 5. The changes of the average hourly energy efficiencies during the charging periods are shown as a function of time in Fig. 6. Result shows that the net energy efficiencies increased with the increasing of the water inlet temperature coming from the solar collector. Fig. 6 show that for a dry soil the net energy efficiency ranged from 22.6 to 45.3%, during the charging period it reached the maximum value at 13:00 h.

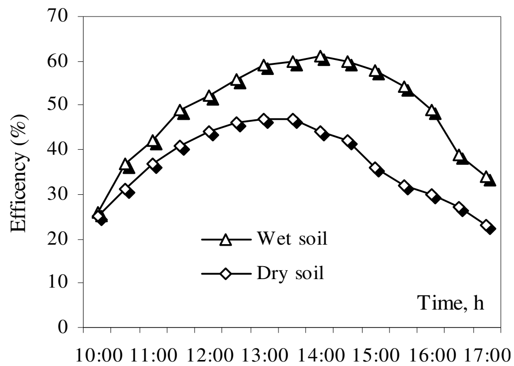


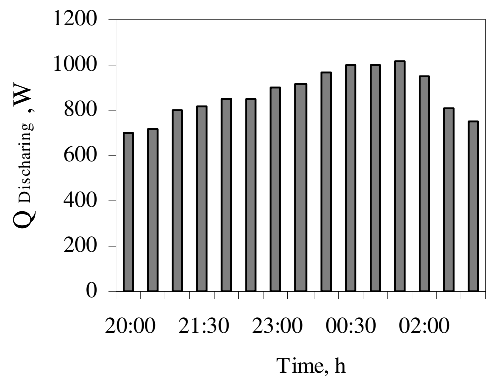
Fig.6: The change of the net energy efficiencies during the charging periods for a wet and dry soil

The average daily net energy efficiency of the heat storage accumulator remained nearly constant (approximately 34 %) during the charging periods.

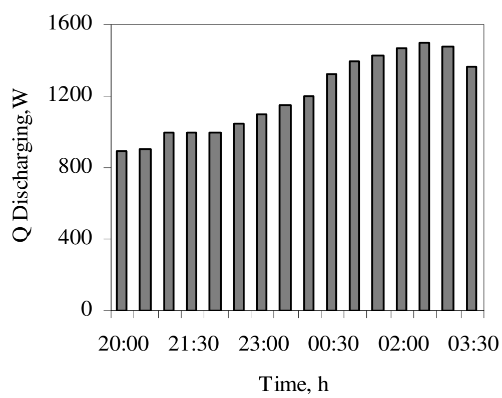
For a wet soil the net energy efficiency ranged from 33.8 to 63.5 %. The maximum value of the efficiency is obtained at 14:00 h. During the charging periods and for a wet soil the average daily net efficiency of the accumulator is approximately 49 %.

The thermal ground behaviour during the discharging periods: At the depth of 40 cm soil temperature remains much heigher than air temperature. The excess of heat is collected from the soil accumulator by the use of the buried heat exchanger system. During the daytime, water coming from solar collector is heated at the temperatures of 40-50°C. The hot water gives up its thermal energy to the heat exchanger and then dissipates to the soil by conduction. When the soil temperatures inside the accumulator increased over a set-value, cold water (20°C) was circulated through the heat storage accumulator during the night. In other words, the heat stored in the accumulator during the charging periods was recovered during the nights (22:00–02:00 h). During the energy discharging, the soil temperature in the accumulator decrease quickly in the first two hours. However the temperature variation for a wet soil is weaker. The thermal energy of the sensible heat storage accumulator is evaluated for the discharging periods. The amounts of thermal heat recovered from the heat storage accumulator discharging periods were calculated by using Equation.8.

The changes of the average hourly rates of thermal heat recovered from the accumulator during the discharging periods are shown as a function of time in Fig. 7a, 7b. The amount of heat recovered from the accumulator, when the soil is dry, was in the range of 1kW. The results show that for the wet soil the thermal heat recovered from the accumulator during the discharging periods is definitely higher than in dry soil. It is about 1.4 kW.



(a)



(b)

Fig.7: The rates of thermal heat and recovered heat from the accumulator during the discharging periods; (a) Dry soil; (b) Wet soil

Greenhouse energy needs: The overall heat requirements of the tunnel greenhouse during the discharging periods were calculated from Equation. 9.

The changes of the total heat requirement of the tunnel greenhouse and the amount of heat recovered from the heat storage unit during the discharging periods are represented in Fig. 8.

The possible amount of thermal energy stored in the accumulator decreased with the decreasing of difference between the water inlet and outlet temperatures during the charging periods. It also depends on the outside temperature. The amount of thermal energy required by the greenhouse was higher compared with the thermal stored energy in the accumulator. In fact during the discharging period, the total heat requirement of the tunnel greenhouse ranged from 7.63 to 8.20 kW, while the rate of heat recovered from the heat storage unit to the tunnel greenhouse was in the range of 300 W. In this case, 40 % of the total heat requirement of the tunnel greenhouse was obtained from the accumulator.

The differences between the required and stored energy are attributed to the inlet and outlet water temperatures, the outside air temperature and the accumulator design. In addition the microclimate inside the greenhouse, using only solar thermal energy, depends on the stored thermal energy collected during the day and the predicted energy needs at night (Fig. 8).

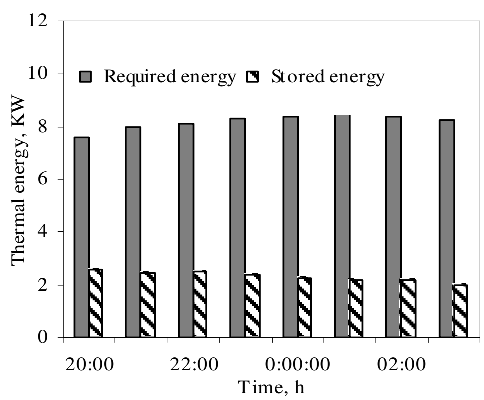


Fig.8: The maximum contribution of the accumulator heating necessary to maintain the nocturnal temperature at 18 °C

In Fig. 9 we represent the stored solar energy heat necessary to maintain the nocturnal temperature under greenhouse equal to 18°C, according to months. Whereas, the yielded heat during the night is more significant than that received during the day. The accumulator used for greenhouse heating, during the night and for the cold months of the year represent 20% of the annual energy needs for greenhouse heating.

Overall, the accumulator performance in greenhouse heating strongly depends on the prevailing outdoor weather conditions.

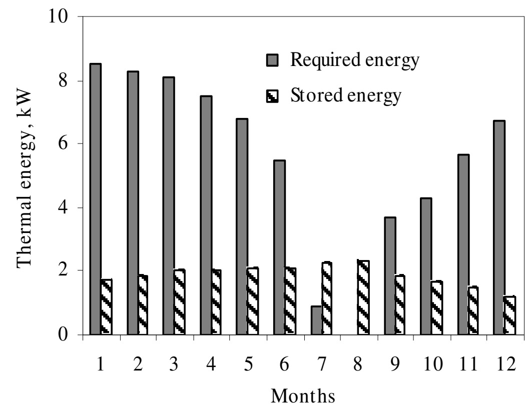


Fig.9: The changes of the total heat requirement of the tunnel greenhouse and the rate of heat recovered from the heat storage unit during the discharging periods according to months

CONCLUSION

The use of solar energy accumulator applied for the heating of greenhouses, can supply a significant part of the heating requirements. Therefore, thermal energy analysis must be used to design the accumulator with the highest possible efficiencies by receiving energy at the maximum rate without excessive losses.

During the charging and discharging process, soil moisture increases the heat storage capacity in the long-term storage zone and facilitates the heat extraction from court-term storage zone to the greenhouse inside air at night.

However at daytime soil moisture in the court-term storage zone increases the evaporation which is harmful to plants and greenhouse microclimate. Therefore, when designing the accumulator system, the nature of soil and soil humidity should be selected properly to raise the temperature of thermal storage accumulator. The position of capillary heat exchanger inside accumulator appears to be an important factor to optimize the design of the heat exchanger and the accumulator capacity to obtain a good performance.

Results show, also, that the amount of the stored thermal energy in the accumulator decreased with the decreasing of difference between the inlet and outlet temperatures during the charging periods. It also depends on the outside temperature. So a good thermal insulation of accumulator area has great effects on temperature distribution in the soil and on the thermal energy losses.

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