Effect of operational parameters on the performance of heat storage in a rock bed used in a tunnel greenhouse

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Abstract— **In this paper a mathematical model of sensible heat storage in a rock bed used in a tunnel greenhouse is presented. A computer program based on MATLAB software has been used to predict the time evolution of the temperature. The numerical results show that the heat storage system is mainly affected by the diameter of the rocks (rocks size), convective heat transfer coefficient and the type of the rocks. The heat storage performance can be improved by a good choice of these parameters. The simulation results show great agreement with the experimental data.**

***Keywords*— Greenhouses, Solar Energy, Rock-bed, Thermal modelling.**

I. INTRODUCTION

Use of solar agricultural greenhouses in agricultural production has increased manifold over the last two decades (Sethi and Charma 2008). The primary objective of a greenhouse is to produce a higher yield outside the cultivation season, which can be achieved by maintaining optimal temperature at every stage crop. Greenhouse production systems were originally implemented in cold regions at northern latitudes in order to extend the production season of plants, where usually they will not grow optimally (Alkilani et al. 2011).

However, heating of greenhouse is one of the most energy consuming activities during winter periods. Greenhouses can be considered as a large solar collector having no air inlet and outlet. As the solar energy is intermittent, it needs to be stored in clear days to use the energy stored for heating at night (Bouhdjar et al 1996). Several systems for greenhouse heating have been proposed by many researchers, the important existing greenhouse heating systems are: water storage, rock bed storage and phase change material storage classified as shown in Figure 1.

Various researches showed that the rock-bed system could achieve an inside air temperature 4–20 °C higher than the outside air, in combination with a variety of energy conservation methods (Bouhdjar et Boulbina 1990), and such systems could supply 20–70% of the annual heat requirement (Bredenbeck 1987). Solar energy storage efficiencies of rock-bed systems varied from 8% to 19% (Willits et Peet 1987, Bouhdjar et al. 1996, Ahmet et al. 2003).

Although the rock bed represents a sensible heat storage material, used widely due to the economical property is used generally as an air-based thermal energy storage material. The performance of heat storage in a rock bed is affected by various design and operational parameters such as rock size and bed, air mass flow rate, void fraction,…etc.

A popular and economical heat storage material is rock-bed (pebble, gravel and bricks).

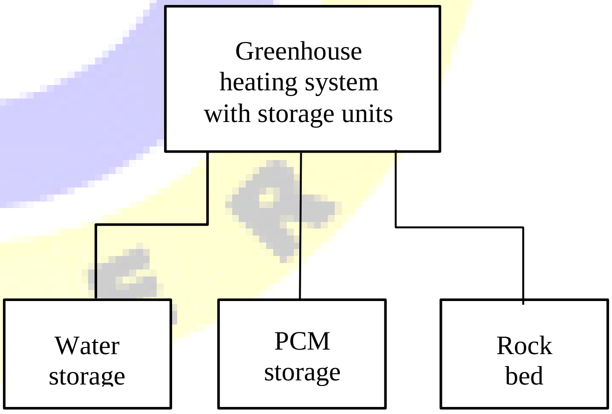

Fig. 1 Classification of various thermal storage methods in the greenhouse heating system.

Bouhdjar et al 1996, A 240 m^2 (30m x 8m) single PE greenhouse situated at the INRA station in Algiers suburban area (36° 7'N), Algeria, was performed for more than sixteen weeks the greenhouse was coupled to a 4.9 m3 rock bed having 20 tons of 50–100 mm gravel.

The greenhouse air (warm or cold) is blown in the same direction by two blowers disposed on each side (at the U's "bottoms "), at a total rate of 1000 m3/h. The air was transferred from inside the greenhouse when inside air temperature exceeded 27 °C. When the temperature inside the greenhouse dropped below 13 °C, the system reversed direction and retrieved the stored heat.

The system could achieve an increase of 4–6 °C inside temperature as compared to outside (figure 2).

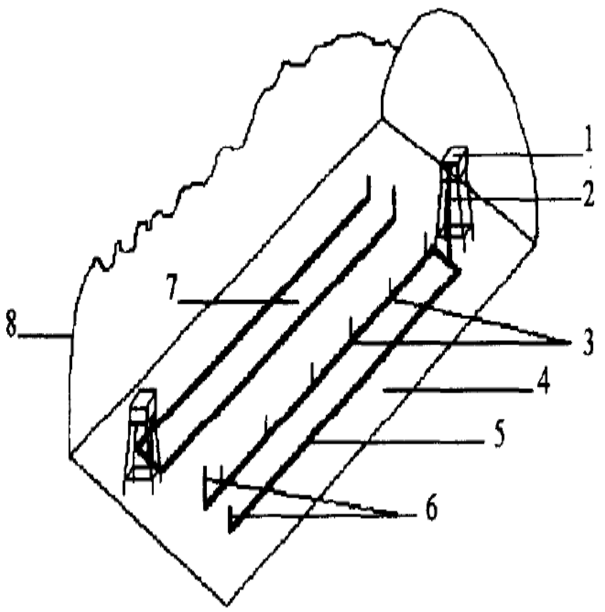

Fig. 2. Storage disposal scheme : l- Blowers, 2-Pipe inlet, 3-Temperature measurement in pipe, 4- Temperature measurements in soil ,5- pipes filled with gravels, 6- Pipe outlet, 7- Ambiant temperature measurements, 8- Greenhouse. . (Bouhdjar et al 1996)

S. Bezari and A. Bouhdjer, 2015 erected an experiment at the Applied Research Unit for Renewable Energy-URAER in Ghardaia (23° N 03°E), South-Algeria.

An experimental 200 m^2 (25m x 8m) PE greenhouse, coupled to rock-bed of 50-100 mm gravel and an identical greenhouse with no rock bed was also erected for control purposes. The storage system composed (04) rock-bed canal in PVC (warm or cold at the H's "bottoms").

The system could achieve a gain from 3–5 °C between the inside and outside air (figure 3).

Figure. 3. External view of the two greenhouses, experimental and witness, (Bezari et al. 2015).

A rock bed system by Kruklu et al., 2003 created an air temperature difference of about 10 °C at night.

Table1. Summary of the performance of various greenhouses using rock bed as heat storage material.

Reference	Type and mass of rock (kg)	Cover	Total heat capacity a of rock (kJ/ ◦ C)	Heat capacity of rock per unit m 2 area	Performance
Fotiades	Gravel, 74,000	PE	53,280	177.6	76% heating needs using 1.7kW fan
Jelinkova	Gravel, 43,000	Glass	30,960	71.67	4–6 ◦C higher, 400 m^3h^{-1} flow rate
Brendenbeck	Gravel, not known	Polycarbonate	-	-	30% heating needs, 60,000 m^3h^{-1} using 12 fans
Bricault	Gravel.202,000	PE	145,440	51.03	40% heating cover
Kavin and Kurtan	Bricks, 48,000	PE	48,960	489.6	5500 m^3h^{-1} flow rate, with 53.4% heat recovery
Santamouris et al.	Pebble, not known	Glass	-	-	3600 m^3h^{-1} flow rate
Santamouris et al.	Gravel, 13,000	Glass	9360	492.63	10–20 ◦C higher
Bouhdjar and Boulbing	Gravel, 20,000	PE	14,440	60.17	4–6 ◦C higher
Arizov and Niyazov	Gravel, 5700	Double PE	4104	102.6	13 ◦C higher
Santamouris et al. Huang et al.	Gravel, 14,000 Gravel, 15,700	Double glass Glass	10,080 11,304	62.16 64.22	20% heating needs 5 ◦C higher
Ozturk and Bascetincelik	Volcanic. 6480	-	-	-	18.9% heating cover
Bouhdjar et al.	Gravel, 20, 000	PE	-	-	an increase of 4–6 °C inside temperature as compared to outside
Bezari et al.	Gravel,	PE	-	-	a gain from 3–5 °C between the inside and outside air

II. Modelisation

Extensive work by Lof and Hawlay (1948), Close (1965), Dunkel and Ellul (1972), Kulakowski and Smidt (1982) has led to a good understanding of the thermal behavior of rock-piles. The following assumptions were made: 1) Properties of both solid and fluid are constant, 2) No heat loss and mass transfer to the surroundings, and 3) Conduction from the fluid to the rocks were negligible.

Consider a bed rock of uniform cross section A, divided into N equal horizontal sections of thickness Δz. The rate of heat gain by the rocks can be expressed as [3]:

$$\rho_r C_{p,r}\, A\, \Delta z \frac{dT_{r,n}}{dt} = h_V\, A\, \Delta z\big(T_{a,n-1} - T_{r,n}\big) - Q_{loss} \qquad (1)$$

Where ρ_r is the density of the rocks, including voids, $C_{p,r}$ is the specific heat of the rocks, h_V is the volumetric heat

transfer coefficient, $T_{a,n-1}$ is the temperature of the nth section and Q_{loss} is the loss of heat from the nth section of the rock pile to the surroundings through the wall of the container.

The heat loss by the air can be expressed as :

$$\dot{m}C_{p,a}\left(T_{a,n-1} - T_{a,n}\right) = h_V\ A\ \Delta z\left(T_{a,n-1} - T_{r,n}\right) \quad (2)$$

Where $\dot{m}$ is the mass flow rate, $C_{p,a}$ is the specific heat of air and h_V is the volumetric heat transfer coefficient. Numerical stability in the equation (2) requires:

$$h_V\ A\ \Delta z/\dot{m}C_{p,a} < 1$$

$$\rho_r C_{p,r}\ A\ \Delta z\left(T_{r,n,f} - T_{r,n,i}\right) = h_V\ A\ \Delta z\left(T_{a,n-1} - T_{r,n,f}\right) t \quad (3)$$

$$C_{p,a}\ \left(T_{a,n-1} - T_{a,n}\right) = h_V\ A\ \Delta z\left(T_{a,n-1} - T_{r,n,f}\right) t \quad (4)$$

Where $T_{r,n,i}$ and $T_{r,n,f}$ are the initial and final rock temperatures.

Equations (3) and (4) can be re-written thus:

$$C\ \left(T_{r,n,f} - T_{r,n,i}\right) = D\ \left(T_{a,n-1} - T_{a,n}\right) \quad (5)$$

$$C\ \left(T_{r,n,f} - T_{r,n,i}\right) = E\ \left(T_{a,n-1} - T_{r,n,f}\right) \quad (6)$$

Where $C = \rho_r C_{p,r}\ A\ \Delta z$
$D = \dot{m}C_{p,a}\ t$
$E = h_V\ A\ \Delta z$

C, D end E are constants for a given rock pile and mass flow rate.

From equation (5)

$$T_{r,f,n} = \frac{D\ (T_{a,n-1} - T_{a,n})}{C} + T_{r,n,i} \quad (7)$$

Substituting in equation (6)

$$C\ \frac{D\ \left(T_{a,n-1} - T_{a,n}\right)}{C} + T_{r,n,i} - T_{r,n,i} = E\ \ T_{a,n-1} - \frac{D\ \left(T_{a,n-1} - T_{a,n}\right)}{C} - \ T_{r,n,i} \quad (8)$$

From which

$$T_{a,n} = \frac{\left[D\ T_{a,n-1}(1+E/C) + E\left(T_{r,n,i} - T_{a,n-1}\right)\right]}{\left[D\left(1+\frac{E}{C}\right)\right]}$$

$T_{r,n,f}$ is then found by substitution in equation (7).

Thus it is possible to calculate, for each section of the rock pile the final temperature of the rocks and the temperature of the air leaving the section.

Equivalent diameter of the rocks was calculated by using the equation below [10];

$$D_e = \sqrt[3]{\frac{6V_r(1-\varepsilon)}{\pi n_r}} \quad (9)$$

Volumetric convective heat transfer was calculated as follows [10]

$$h_v = 652\ \left(\frac{m}{A_r D_e}\right)^{0.7} \quad (10)$$

Table 2 Properties of the rock-bed and the air used in this simulation.

Equivalent diameter	32 mm [3]
Density	1430 kg/m^3
Porosity	0.5
Specific heat	800 J/kgK [4]
Thermal conductivity	2.9 W/mK [4]
Air mass flow rate	1000 m^3/h [1]
Air specific heat	1000.5 J/kgK
Volumetric heat transfer coefficient	2304.8 W/ m^{3}K [Eq (9)]
Gravel volume	4.9 m^3
Mass of rocks	20 000 kg [1]

III. RESUTLS AND DISCUSSION

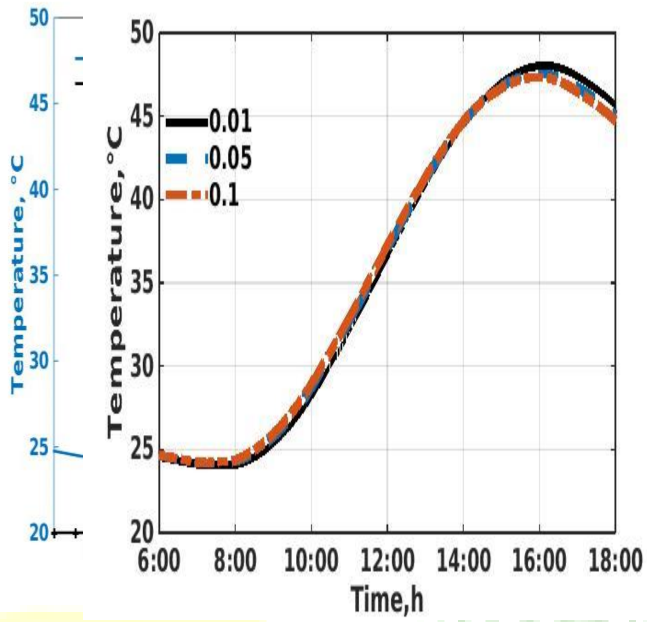

Figure 4. Hourly distribution of the average daily global solar radiation and temperature in the greenhouse for a typical winter day in Ghardaia-URAER.

III.1. Effect of rock size

In Figure 5 the effect of equivalent diameter of the rock on the thermal performance in the rock-bed is presented. It is found from the figure that, lowering the effective diameter of the rocks increases the temperature of the air. Smaller rocks allow for more efficient storage of energy than large rocks. The rock particle size should be small enough to provide sufficient surface area for adequate heat transfer between the rock and air, (Garzoli, 1989).

Figure 5. Effect equivalent diameter of the rock.

III.2. Effect of convective heat transfer coefficient

Figure 6 present the effect of different values of the convective heat transfer coefficient on the thermal performance of the rock-bed. The results show that this parameter has significant influence on the thermal performance of the rock-bed. The greater convective heat transfer coefficients, the greater air temperature.

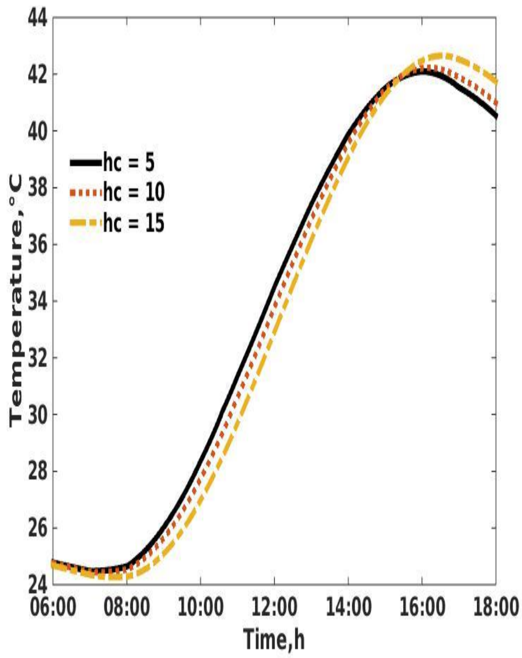

Figure 6. Effect of varying convective heat transfer coefficient.

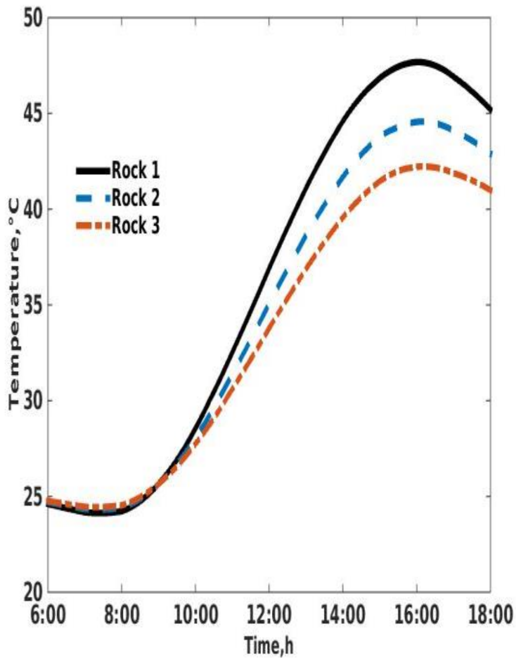

Figure 7. Effect of heat capacity of rocks.

III.3. Effect of heat capacity

Fig. 7 present the effect of heat capacity on the thermal performance of the thermal storage. This shows that the higher heat capacity lowers the temperatures during the day time.

IV. Conclusions

In this study, the effect of different operating parameters on the performance of thermal storage is simulated. The numerical results show that heat storage system is mainly affected by the diameter of the rocks (rocks size), convective heat transfer coefficient and the type of the rocks. The results of this study are as follow:

- The higher convective heat transfer coefficients produce the higher gain in the air temperature.
- The higher heat capacity lowers the temperatures during the day time.
- Smaller rocks allow more efficient storage of energy than large rocks.

The results show great agreement with the experimental data.

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