ECONOMIC DESIGN OF A ROCK BED STORAGE DEVICE FOR STORING SOLAR THERMAL ENERGY

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Abstract—This study deals with the optimization of design and operational parameters of a rock bed thermal energy storage device coupled to a two pass single cover solar air heater, i.e., charging time (Θ), rock bed size (flow length, H), and cross-sectional area for square cross section (A_R), rock size (D_R), air mass velocity per unit bed cross-sectional area (G), and void fraction (ϵ). The optimization has been accomplished by investigating the effects of the above parameters on the total energy stored and the cost per unit energy stored in the rock bed for the winter climatic conditions of Delhi.

INTRODUCTION

Whenever a gap exists between availability and requirement of energy, temporary storage of energy is needed to maintain the continuity of the thermal process. Rock bed energy storage is generally preferred for the air-based thermal energy storage system. The performance of the rock bed storage system is influenced by various design and operational parameters such as size of rock, size of bed, air mass flow rate, void fraction within the rock bed, thermal and physical properties of rock, and inlet temperature of air. For efficient applications, many scientists have studied the performance and approximate designing methods of rock bed energy storage device. Clark and Beasley (1982) have developed one and two dimensional numerical models for the dynamic response of both fluid and solid temperatures in a packed bed and have studied the effects of void fraction, flow distribution, wall heat capacity, and wall energy losses on the dynamic response of the packed bed subjected to an arbitrary time dependent inlet and initial temperatures. Clark and Nabozny (1977) have developed a computer program, ROCKBED, for formulating the dynamic response and thermal storage capacity of a rock bed storage unit for both charging and recovery modes. Saez and McCoy (1982) have developed a mathematical model for simulating the dynamic temperature response of a packed column to an arbitrary, time dependent inlet temperature. The Saez and McCoy model includes axial thermal dispersion as well as intra particle conduction. Rao and Suri (1969) have investigated both analytically and theoretically unsteady state heat transfer through a packed bed storage of homogeneous spheres. Chandra and Willits (1981) have conducted an experimental study and concluded that pressure drop is influenced by rock size, bed porosity, and air flow rate. Chandra and Willits also found that volumetric heat transfer coefficient is dependent only upon rock size and air flow rate.

Cost of solar equipment plays a significant role in their marketing, hence the cost–benefit ratio must be an aspect of all studies. Unfortunately, rich literature is not available on design optimization of the rock bed thermal energy storage that keeps the cost-effectiveness aspect in view. In the present study, a detailed theoretical analysis of the rock bed storage coupled to a double pass, single cover air heater (Fig. 1) has been carried out. Operational and design parameters such as charging time (Θ), rock bed size (in particular flow length, H, and cross-sectional area, A_R for a square air flow passage), rock size (D_R), air mass velocity (G), and void fraction (ϵ) are optimized and their effects on the dynamic response of both air and solid's temperatures in charging mode have been studied. The optimization criterion is based on selecting those combinations for which the energy gain is the maximum at lower cost.

THEORETICAL ANALYSIS

The rock bed storage-cum-air heater unit under investigation is shown schematically in Fig. 1. The selection of the air heater (source of heat for the rock bed storage) design and its parameters are based on the design optimization studies on air heaters made by Choudhury *et al.* (in press). As per this study, the cost effective design of the air heater corresponds to a length of 3 m, width of 1 m and air duct depths of 3 cm

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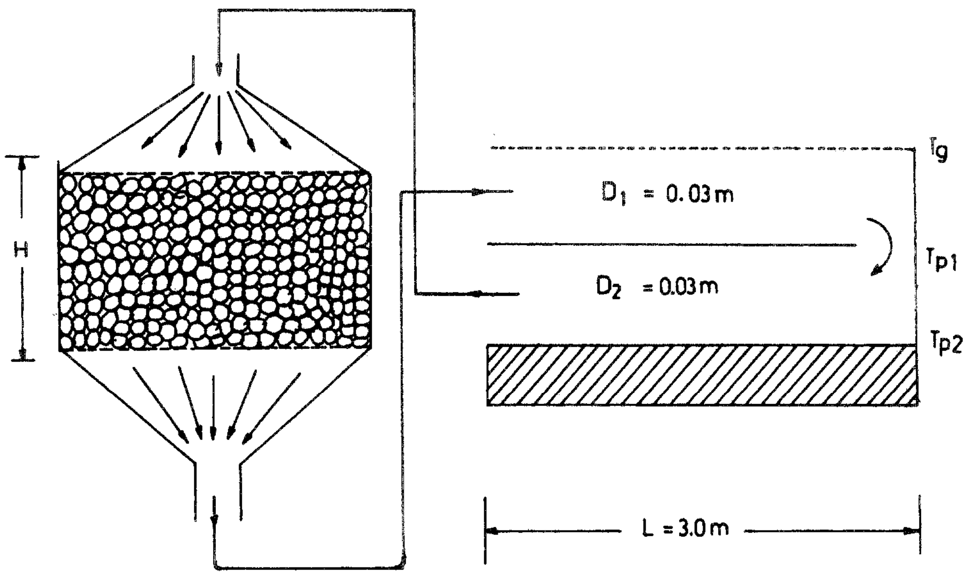

Fig. 1. Schematic view of the rock bed energy storage device coupled to a two-pass, single cover solar air heater.

Table 1. Ambient temperature and solar flux data for a winter day in Delhi

Time, Θ(h)	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0
Ambient temperature, t_a(°C)	8.7	11.0	13.8	16.3	17.0	17.8	19.6	19.7	19.6	19.1
Solar flux, G_s(W/m^2)	186.1	426.6	628.0	719.7	853.5	847.4	771.8	625.4	423.9	195.5

Table 2. Design and operational variables of rock bed of square cross section

Breadth of bed (B)	1.0–4.0 m
Width of bed (Z)	1.0–4.0 m
Height of bed (H)	1.0–5.0 m
Rock diameter (D_R)	0.01–0.05 m
Void faction (ϵ)	0.35–0.50
Air mass flow velocity (G)	25–100 kg/hm^2

above and below the absorber. The optimum air flow rates up to which the air heater was most cost-effective were observed as <500 kg/h m^2 or <1500 kg/h. With air flow rates above these, the single cover, single pass air heater was observed to be more cost-effective than the single cover, double pass solar air heater. Therefore, the design optimization of the rock bed in the present study has been made for the above design and operational parameters of the single cover, two pass solar air heater which is coupled to the storage unit as a source of hot air.

The weather input data for a winter day in Delhi and design and operational data of the rock bed storage are presented in Tables 1 and 2, respectively.

Daily energy stored in the rock bed (DES)

The energy balance equations for different components of the air heater and the rock bed energy storage system and their initial and boundary conditions are given below.

Air heater:

$$M_g c_g \, dt_g/d\Theta = \alpha_g G_s + h_{rp1g}(t_{p1} - t_g) - h_{cgf1}(t_g - t_{f1}) - h_{ga}(t_g - t_a) \quad (1)$$

$$M_{f1} c_{f1} \, dt_{f1}/d\Theta + (\dot{M}/W) c_{f1} \, dt_{f1}/dx = h_{cp1f1}(t_{p1} - t_{f1}) + h_{cgf1}(t_g - t_{f1}) \quad (2)$$

$$M_{p1} c_{p1} \, dt_{p1}/d\Theta = \tau_g \alpha_{p1} G_s - h_{rgp1}(t_{p1} - t_g) - h_{cp1f1} \times (t_{p1} - t_{f1}) - h_{rp1p2}(t_{p1} - t_{p2}) - h_{cp1f2}(t_{p1} - t_{f2}) \quad (3)$$

$$M_{f2} c_{f2} \, dt_{f2}/d\Theta + (\dot{M}/W) c_{f2} \, dt_{f2}/dx = h_{cp1f2}(t_{p1} - t_{f2}) - h_{cp2f2}(t_{f2} - t_{p2}) \quad (4)$$

$$M_{p2} c_{p2} \, dt_{p2}/d\Theta = h_{rp1p2}(t_{p1} - t_{p2}). + h_{cp2f2}(t_{f2} - t_{p2}) - U_r(t_{p2} - t_a). \quad (5)$$

Rock bed:

$$\rho_f c_f \epsilon \, dt_f/d\Theta + G c_f \, dt_f/dx = h_{vfR}(t_R - t_f) \quad (6)$$

$$\rho_R c_R (1 - \epsilon) \, dt_R/d\Theta = h_{vfR}(t_f - t_R). \quad (7)$$

Initial and boundary conditions:

$$t_f(x,0)=t_{fi}=t_a(1) \quad \text{and} \quad t_R(x,0)=t_{Ri}=t_a(1) \tag{8}$$

$$t_{f1}(x,0)=t_{f2}(x,0)=t_a(1) \quad \text{and} \quad t_{p1}(x,0)=t_{p2}(x,0)t_g(x,0)=t_a(1) \tag{9}$$

$$t_{fi}(0,\Theta)=t_a=\text{inlet temperature for air heater} \quad (\text{if } t_R(H,\Theta)<t_a) \tag{10}$$

$$t_{f1}(L,\Theta)=t_{f2}(0,\Theta)$$

$$t_{f2}(L,\Theta)=t_{fo}=\text{outlet (inlet) air temperature for air heater (rock bed).} \tag{11}$$

The temperatures of the air (t_f) and solids (t_R) within the rock bed at different locations and times are calculated by solving the above equations which use the finite difference method. The daily energy stored (DES, kWh) is calculated as given below.

$$\text{DES}=\frac{\sum_{i=0}^{n_z-1}[((t_R(i)+t_R(i+1))/2)-t_a(1)]}{nz*(3.6*10^6)}M_Rc_RA_R \tag{12}$$

where, $t_R(i)$ is the rock temperature at the ith zone and nz is the number of zones.

The radiative (h_{rp1g} and h_{rp1p2}) wind related convective (h_{ga}) and conductive (U_r) heat transfer coefficients are calculated by using the standard heat transfer relations summarized in Duffie and Beckman (1980). The forced convective heat transfer coefficients for the air heater h_{cgf1}, h_{cp1f1}, h_{cp1f2}, and h_{cp2f2}, are calculated by using the relation derived by Tan and Charters (1969). The heat transfer coefficient between air and rock in the rock bed, h_{vfR}, is computed by using the Coutier and Farber (1982) relation

$$h_{vfR}=700(G/D_R)^{0.76}. \tag{13}$$

Daily cost (DC)

In order to calculate the daily cost (DC) of the rock bed solar thermal energy storage/air heater device, the different cost factors are calculated as given below.

$$\text{Daily pumping cost (DPC)}=(\dot{M}\Delta p/\rho_f)\Theta_{op}CE \tag{14}$$

where the pressure drop (Δp) across the two-pass flow channel of the air heater is obtained by using the relations from Hollands and Shewen (1981) and that across the rock bed is (Ergun, 1952):

$$\Delta p=f(H/D_R)(G^2/\rho_f)(1-\epsilon)/\epsilon^3 \tag{15}$$

with

$$f=150(1-\epsilon)/\text{Rep}+1.75 \tag{16}$$

$$\text{Rep}=GD_R/\mu. \tag{17}$$

$$\text{Daily capital cost of storage cum air heater device (DCC)}=\text{CRF*CI}/300 \tag{18}$$

where

Capital investment (CI) = materials cost + blower cost + paint cost + fabrication cost

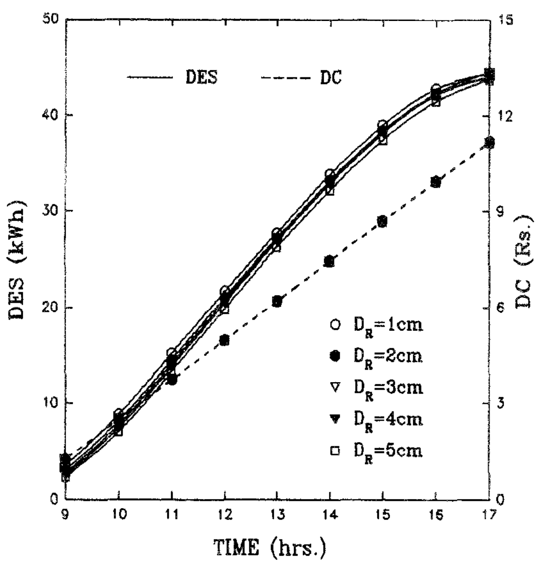

Fig. 2. Cumulative daily energy stored (DES) and daily cost (DC) as function of charging time for different rock sizes ($\epsilon=0.35$; $G=100$ kg/hm^2; $H=1$ m; $A_R=16$ m^2).

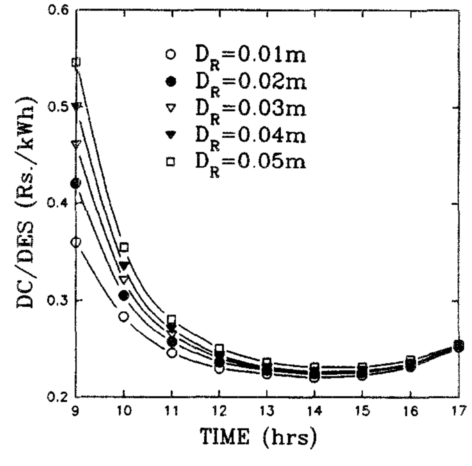

Fig. 3. Cost–benefit ratio as function of charging time for different rock sizes ($\epsilon=0.35$; $G=100$ kg/hm^2; $H=1$ m; $A_R=16$ m^2).

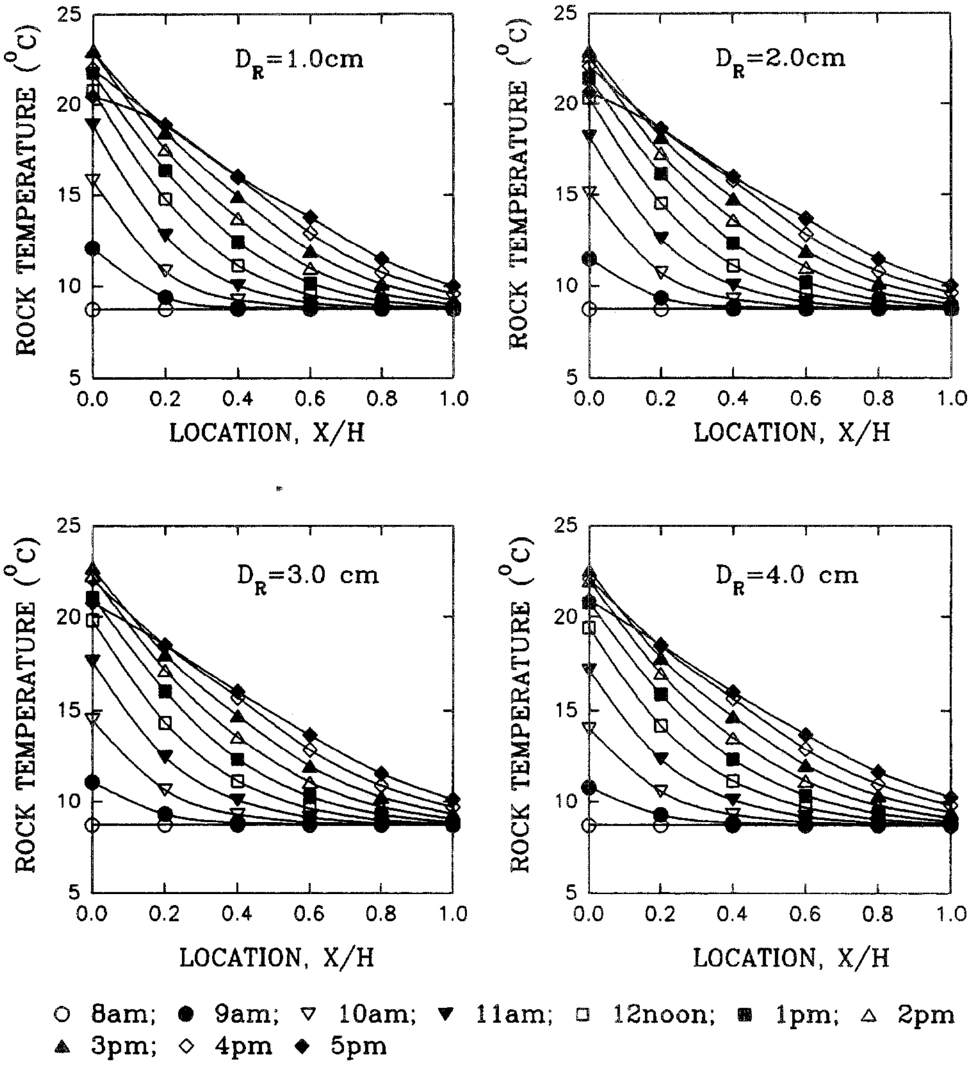

Fig. 4. Effect of rock size on transient response of rock temperature at different locations in rock bed ($H=1$ m; $A_R=16$ m^2; $G=100$ kg/hm^2; $\epsilon=0.35$).

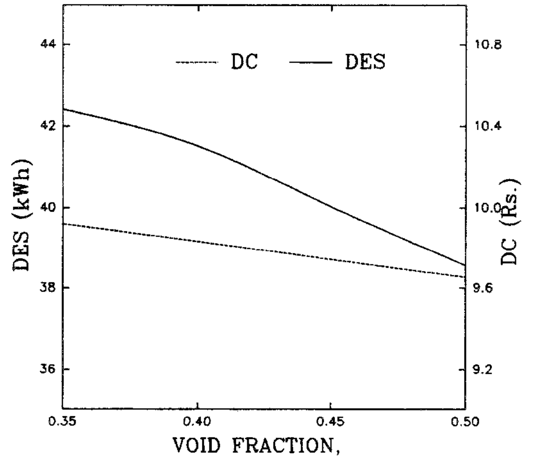

Fig. 5. Cumulative daily energy stored (DES) and daily cost (DC) as function of void fraction in rock bed ($G=100$ kg/hm^2; $H=1$ m; $A_R=16$ m^2; $D_R=4$ cm).

and

Capital recovery factor (CRF)

$$=i(i+1)^n/[(i+1)^n-1]. \quad (19)$$

The Daily Maintenance Cost (DMC) of the storage cum air heater device is considered to be 10% of the daily capital cost (DCC) of the system.

Daily salvage value (DSV)

$$=(\text{SFF}*\text{SV})/300 \quad (20)$$

where

Salvage fund factor (SFF)

$$=i/[(i+1)^n-1] \quad (21)$$

and

$$\text{Salvage value (SV)}=0.1(\text{CI}). \quad (22)$$

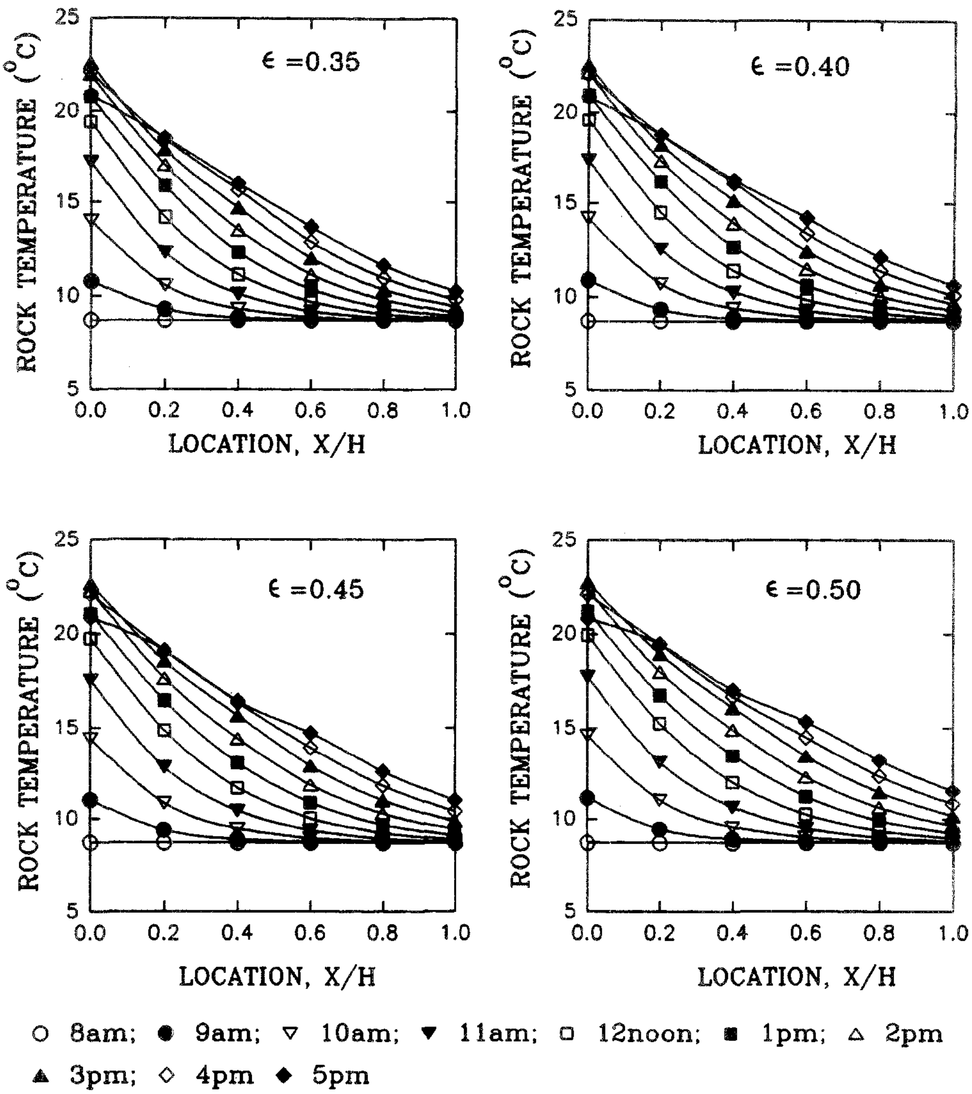

Fig. 6. Effect of porosity on transient response of rock temperature at different locations in rock bed ($H=1$ m; $A_R=16$ m^2; $G=100$ kg/hm^2; $D_R=4$ cm).

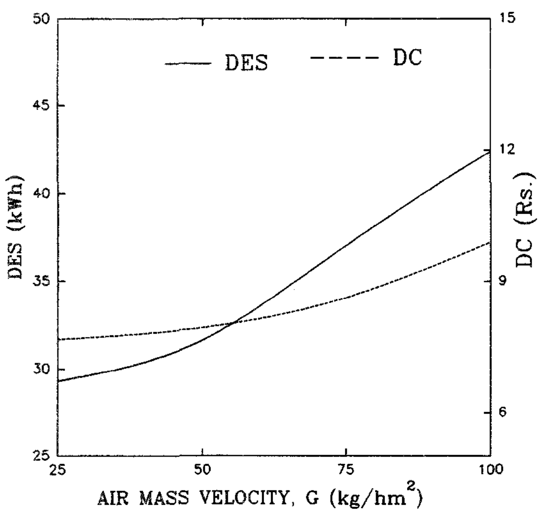

Fig. 7. Effect of air mass velocity on cumulative daily energy stored (DES) and daily cost (DC) ($H=1$ m; $A_R=16$ m^2; $D_R=4$ cm; $\epsilon=0.35$).

The daily cost (DC) is then calculated as

$$\text{DC}=\text{DCC}=\text{DMC}=\text{DPC}-\text{DSV}. \quad (23)$$

For the numerical calculation the cost of absorbing paint is assumed as Rs. 50/m^2, cover as Rs. 125/m^2, air duct material as Rs. 160/m^2, side plates as Rs. 130/m^2, insulation as Rs. 80/m^2, rock (CR) as Rs. 300/m^3, and wood sheet as Rs. 100/m^2. The cost of the blower is taken as Rs. 4500 and cost of electricity (CE) as Rs. 1.5/kWh. The rate of interest (i) is assumed as 10% and life of device (n) as 10 years. The fabrication cost is considered to be 25% of the capital investment. The operational time is considered as 300 days/year and 9 hours/day.

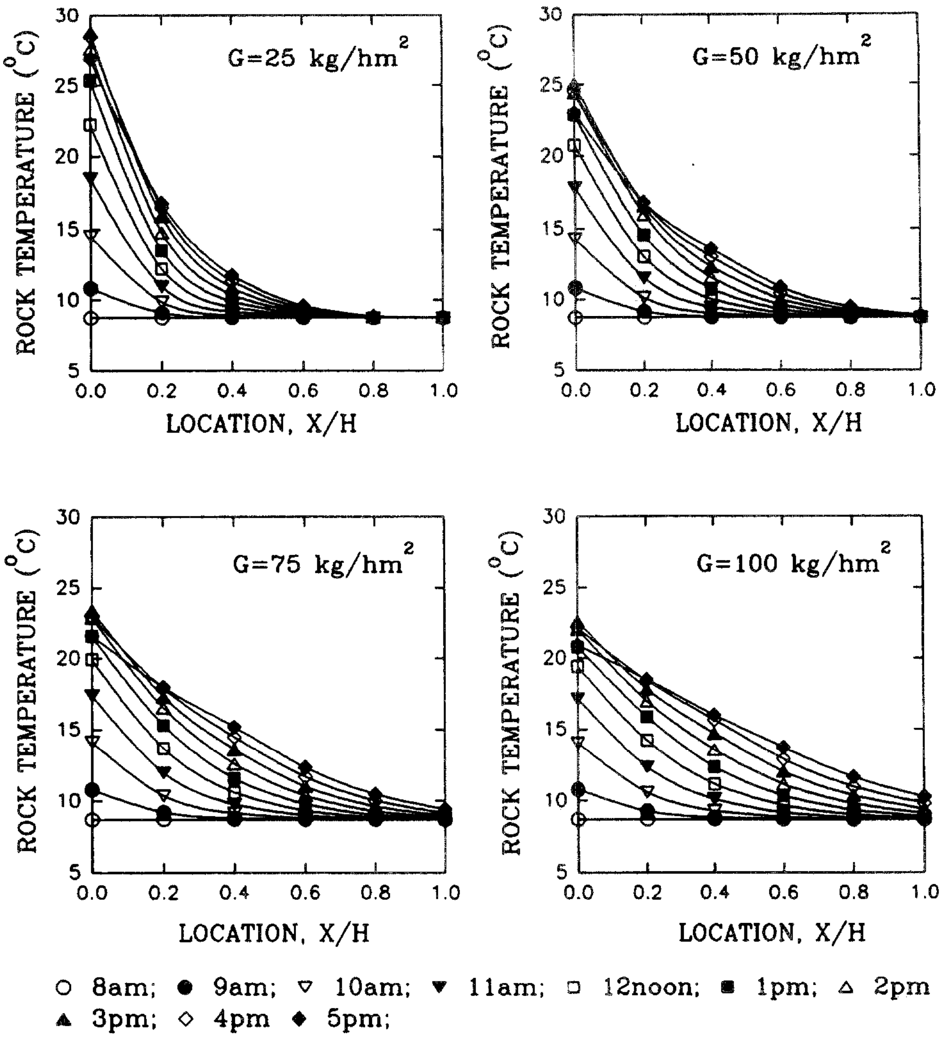

Fig. 8. Effect of air mass velocity on transient response of rock temperature at different locations in rock bed ($H = 1$ m; $A_R = 16$ m^2; $D_R = 4$ cm; $\epsilon = 0.35$).

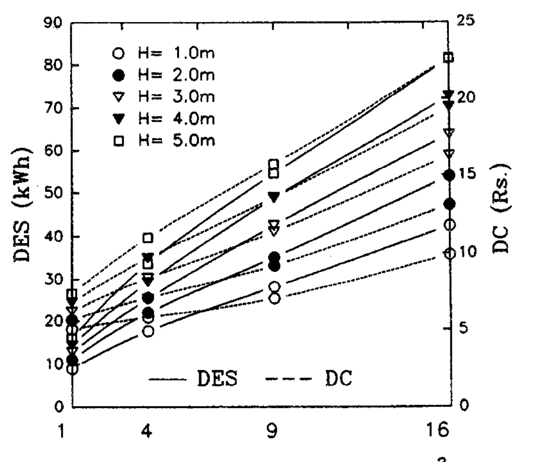

Fig. 9. Variation in cumulative daily energy stored (DES) and daily cost (DC) with respect to cross sectional area of rock bed (A_R) for different air flow depths H ($G = 100$ kg/hm^2; $\epsilon = 0.35$ cm; $D_R = 4$ cm).

RESULTS AND DISCUSSION

The charging cycle of the rock bed storage unit coupled to the two pass solar air heater was assumed to be initiated at 8 A.M. in the morning. As shown in Fig. 2, variation in the cumulative energy stored in the rock bed with respect to the charging time for different rock sizes resulted in an increase in the energy stored in the bed with increase in time up to 4 P.M. after which it increased only slightly. The corresponding values of the cost per unit energy stored shows (Fig. 3) a minimum DC/DES at around 2 P.M. With an increase in charging time, although the DC/DES increases for the period 2–4 P.M., the increase in DC/DES is only 0.05 Rs./kWh where as the increase in DES is ≈ 10 kWh. This factor is substantially lower than the cost of electrical energy, which in the present study is considered as 1.5 Rs./kWh.

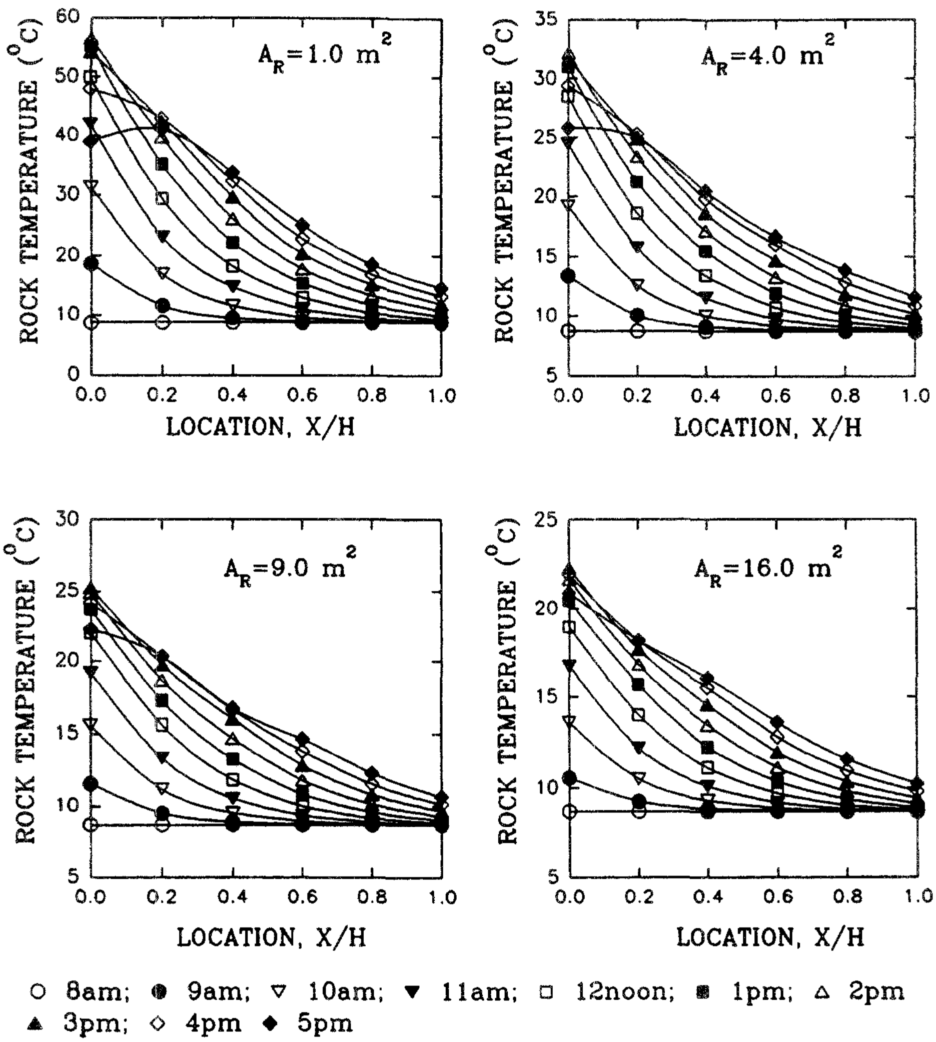

Fig. 10. Effect of cross-sectional area (square channel) of rock bed (A_R) on transient response of rock temperature at different locations in rock bed ($H=1$ m; $G=100$ kg/hm^2; $D_R=4$ cm; $\epsilon=0.35$).

Based on this result, the ideal charging time can be considered to be 8 hours, i.e., from 8 A.M. in the morning to 4 P.M. in the afternoon. From the above figures, it can also be seen that the effect of rock size in the range of 1.0–5.0 cm on the cost per unit energy storage is quite insignificant. The corresponding values of bed temperatures at different locations for different charging times are presented in Fig. 4.

As depicted in Fig. 5 variation in bed porosity in the range 0.35–0.50 was observed to have only slight affect on the cost–benefit ratio of the storage unit. With increase in porosity, the decrease in DES was observed to be more significant than the decrease in cost DC. For $H=1$ m, $B=4$ m, $D_R=4$ cm, and $G=$ 100 kg/hm^2, the porosity (ϵ) for which the ratio DC/DES is minimum is observed to be 0.35. The corresponding values of bed temperature at different locations during charging (Fig. 6) also show insignificant effect of porosity on the temperature of the rock. Figure 7 reveals that the air mass velocity (G) affects significantly the energy stored in the rocks and its corresponding cost. With increase in G, both DES and DC increase and a very high DES with a relatively lower DC/DES is obtained for $G=100$ kg/hm^2. Transient response of rock temperature for different values of G (illustrated in Fig. 8) shows that, although the rock temperature of the top surface at the air inlet side is higher, for lower air mass flow velocity, the temperature of the bottom layer of the bed (1 m length) is observed not to increase at all. With increase in air mass velocity, however, due to the lower outlet temperature of the air heater, the temperature of

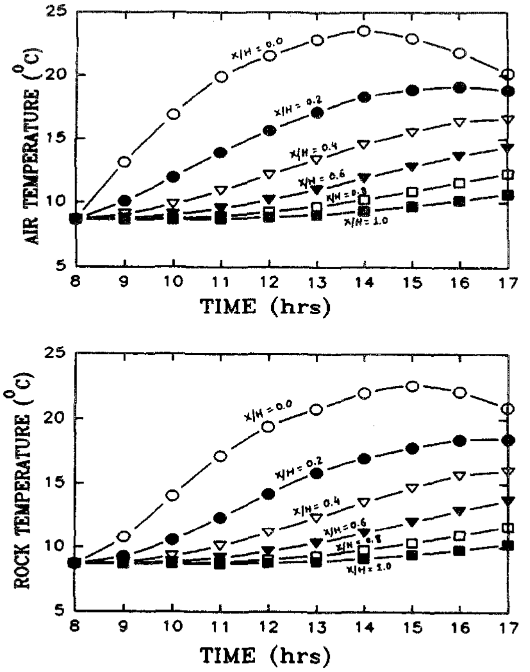

Fig. 11. Dynamic response of air and rock temperatures with respect to charging time for the optimized design of rock bed ($\epsilon = 0.35$; $D_R = 4$ cm; $A_R = 16$ m^2; $G = 100$ kg/hm^2).

the top surface was lower, but due to the larger air velocity, the bottom layer of the bed was also observed to be charged to a certain extent.

Effect of bed size (of square cross section) on energy stored per day (DES) in rocks and the corresponding daily cost (DC) for $G = 100$ kg/hm^2; $\epsilon = 0.35$, and $D_R = 4$ cm is shown in Fig. 9. The curves show that both DES and DC increase with increase in rock bed size, i.e., cross sectional area, A_R (of square flow channel) and air flow length, H. However, a minimum DC/DES was obtained for the bed cross-sectional area $A_R = 16$ m^2 and bed length $H = 1$ m. However, with an increase in the bed cross-sectional area for a fixed G value, the total flow rate of air, $\dot{M}$, through the bed and, hence, through the air heater increases. This causes a decrease in outlet temperature of the air heater and, hence, a decrease in the temperature of the rock bed with increase in A_R (Fig. 10).

The dynamic response of the air and the rock at different axial locations and operating times (Fig. 11) for the optimized design and operational parameters for which the cost–benefit ratio is the lowest, shows the difference between the air and the rock temperatures to be only marginal during the whole charging period of the rock bed.

CONCLUSIONS

From the above discussion one may conclude that the optimum charging time of the rock bed storage unit coupled to a two pass solar air heater of optimum design is 8 hours, i.e., from 8 A.M. in the morning to 4 P.M. in the evening. The bed porosity and the rock size were observed to have an insignificant influence on cost and performance during charging mode. Although minimum DC/DES was observed for air mass flow velocity, $G = 100$ kg/hm^2, bed length, $H = 1$ m and bed cross-sectional area, $A_R = 16$ m^2, higher bed temperature was achieved for $G < 100$ kg/hm^2 and $A_R < 16$ m^2. These higher operating temperatures can be achieved for only a slight increase in the DC/DES of the system. Therefore, when designing and operating of rock bed, the value of G and A_R should be selected depending on the requirement of temperature for any particular application.

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NOMENCLATURE

- A rock bed cross-section area (m^2)
- c specific heat capacity of air (Wh/kg °C)
- D duct depth in air heater/rock diameter (m)
- f friction factor
- G air mass flow velocity through rock bed (kg/h m^2)
- h heat transfer coefficient [W/m^2 °C (W/m^3 °C for rock bed)]
- i interest rate (%)
- $\dot{m}$ specific mass flow rate of air (kg/h m^2)
- $\dot{M}$ mass flow rate (kg/h)
- M mass (kg/m^2)
- n life of the device (yr)
- t temperature (°C)
- W width of the air heater (m)

Greek

- α solar absorptance
- τ solar transmittance
- ρ density (kg/m^3)
- Θ time (h)
- Δp pressure drop experienced by air (Pa)

Subscripts

- a ambient
- c convective
- f fluid in rock bed
- f1 fluid above the absorber
- f2 fluid below the absorber
- g glazing
- o outlet
- op operational
- p1 absorber
- p2 rear plate
- r radiative/rear
- R rock
- s solar

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