The Optimization of Rock Bed Storage Configurations for Effective Thermal Space Conditioning in Cold Climatic Regions

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Abstract: The energy consumption for heating the buildings in cold regions is much higher than the cooling energy in “Hot and Dry/Humid” regions. Various studies have been conducted to reduce the conventional energy to heat the building in cold regions. The four categories of rock-bed storage configurations have been explored to draw potential heat through solar radiation and integrated the non steady state heat flow to the solar thermal model and simulated the indoor temperature swings. It is observed from the study, that all four configurations can provide adequate heat for space conditioning where the average indoor temperature is ranging from 20°C to 25°C, but the cylindrical configuration has achieved nearly 5°C rise in the indoor air temperature. The cylindrical-shaped thermal storage system is more efficient configuration compared to the other configurations such as cube, cuboids, and triangular prism to achieve heating requirement in cold regions.

Keywords: Rock bed configurations, solar thermal model, stratification, heat flux and indoor temperature swings

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1 INTRODUCTION

Global Warming is a specific example of the broader term “Climate Change” and refers to the observed increase in the average temperature of the air near Earth’s surface and oceans in the recent decades. According to the United Nations, cities consume two thirds of global energy use. It was emphasized that 76% of the world’s energy-related carbon dioxide (CO₂) are also emitted by cities through transport, industry, and building and construction related activities. Recent studies have shown that buildings and construction activities use 40% energy, 30% mineral resources and 20% water of the world’s resources. It also accounts for 40% CO₂ emissions, 30% solid wastes and 20% water pollution in the world. Givoni (1991) studied and presented several advantages of underground thermal storage options for passive heating of the buildings in cold regions. Kaushik et al. (2011) investigated widespread experimental study to analyze the effect of shape of large sized material elements and void fraction of the bed under set of the operating conditions. Mawire and McPherson (2009) simulated the performance of storage materials for pebble bed thermal energy storage (TES) systems. Maithani et al. (2013) investigated a computational analysis of temperature distribution of the bed elements of the storage system as a function of time and location that had been determined. There are various possible configurations of solar heat storage exchangers that could provide a wide range of performance for thermal comforts. It is possible to stratify the rock bed medium using ground as insulation at base and storage. The air can be recycled (room to rock bed and rock bed to room) in to a building to meet the heating requirement in winter as solar energy is not sufficient in certain cold regions. The attached rock bed serves the purpose of storing heat energy owing to a higher temperature. This paper aims to analyze the efficiency of rock bed storage configurations, partly attaching to the ground surface and to the building from plinth level to window. The exposed side has been oriented to southern side to get the maximum solar radiation with respect to the sun path of Simla, Himachal Pradesh, India, located at northern hemisphere.

A study has been conducted to underground stor-
age geometries/configurations (cube, cuboid, cylindrical and triangular prism as shown in the Figure 1) of the air heat exchanger to provide thermal comfort in cold regions have been undertaken. The three most common ways of thermal storage are the sensible heat, latent heat and the heat of chemical reaction. Many of the materials available for sensible solar energy storage, the most commonly used are water, sand, concrete and ground. Shelton (1975) proposed the possibility of storage of water in insulated ground. Further, Givoni (1991) reviewed options for long-term storage of thermal energy and discussed advantages of soil storage facilities. Nicholls (1980) provided an analytical study of a few proposed ground heat storage models. Thermal storage system due to its relevance to passive solar heating and cooling has been addressed in a number of experimental and numerical studies in the literature (Hughes et al. 1976; Riaz 2014; Gross et al. 1980; Clark and Arpaci 1984). But, only a few pertain to subject matter of underground thermal storage options (Bansal et al. 1983) which help to conserve conventional energy, particularly in tropical climatic conditions. Riaz (2014) and Givoni (1991) studied various advantages of underground thermal storage options for passive solar heating and cooling of a building but the configurations of the storage have not been analyzed adequately. The effect of variations in the principal parameters such as cross-sectional area, length and depth has been considered to study the storage capacity of a typical rock bed. Phueakphum and Fuenkajorn (2010) investigated the efficiency of a solar thermal energy storage system using basaltic rock fills through a scaled-down model and the results indicate that throughout the night the system can increase the room temperature to 4-6 °C more than the surroundings, depending on the packing density, tube size, and surrounding temperature and it has been analyzed that the efficiency of this storage system is about 35%. An important phase of modeling is achieved by temperature de-stratification calculations, which allows estimating the thermal response expected from the bed during the heat recovery period. The quantity of energy made available and the temperature levels across spatial length of the rock-bed has been analyzed for various configurations of thermal storage options. The objective lies in improving the thermal performance of a building by selecting effective configuration in the underground thermal storage. The inlet area of different configurations was calculated based on minimum surface to volume criterion while keeping the heat losses constantly.

2 ENERGY BALANCE EQUATION OF ROCK BED STORAGE

An important part of the study is to determine the energy \(Q_R\) available from rock-bed thermal storage. The stratified state of rock bed is useful as it minimizes the inlet temperature and energy balance across the rock bed is governed by these two partial differential equations: For air:

\[
(\rho C_p)_f \frac{\partial T_f}{\partial t} = - \frac{(m C_p)_f \frac{\partial T_f}{\partial x}}{A} + h_v(T_b - T_f) + U_L \pi D(T_f - T_a) \tag{1}
\]
Similarly, for rock bed (b) energy balance equation is given by:

\[(\rho C_p)_b(1 - \epsilon)\frac{\partial T_b}{\partial t} = h_v(T_f - T_b) + K_f \frac{\partial^2 T_b}{\partial x^2}\]  

(2)

Neglecting conduction and heat losses, the primary equations of energy balance for the fluid (f) and bed are given separately as:

\[(\rho C_p)_f \frac{\partial T_f}{\partial t} + \frac{(m C_p)_f}{A} \frac{\partial T_f}{\partial x} + h_v(T_f - T_b) = 0\]  

(3)

\[(\rho C_p)_b(1 - \epsilon_R)\frac{\partial T_b}{\partial t} = h_v(T_f - T_b)\]  

(4)

On further simplification, one can obtain,

\[\frac{\partial T_f}{\partial t} + u \frac{\partial T_f}{\partial x} + r_1(T_f - T_b) = 0\]  

(5)

\[\frac{\partial T_b}{\partial t} - r_2(T_f - T_b) = 0\]  

(6)

where, \(r_1 = \frac{h_v}{c_p \rho T_f}\) and \(r_2 = \frac{h_v}{c_v \rho_v T_b}\) and \(u\) is the fluid velocity inside the configuration as given by \((G/\rho)_f\), \(G\) is mass flow rate per unit area of air and \(h_v\) is the volumetric heat transfer coefficient between the bed and the air. It is possible to estimate the fluid and rock temperatures at various spatial locations with changing time. Hence the available heat flux can be estimated at different times as

\[Q_R = (m C_p)_f \Delta T_f\]  

(7)

Now, the heat obtained from rock bed configuration is coupled with building simulation of solar thermal model with the same input parameters. The pumping power for the rock bed is written as

\[P = 0.0226 \frac{\partial Q_R}{\partial t} \Delta P\]  

(8)

In order to avoid excessive flow, it is recommended that the bed pressure drop to be in the range of 37 to 75. The actual power input to fan shall be greater by the efficiency of the unit. Ideally, the pumping power should be small in comparison with the amount of power collected. The simulation has been performed for two sets of pressure drop determined as described. From a convenient set of design curves, the pressure gradient in the bed \(\Delta P/L\) is obtained, and it is given as a function of face velocity and various effective rock diameters. In order to appreciate the effect of pressure drop, the simulation has been performed for two typical values of face velocity viz. 0.06 m/s and 0.03 m/s. correspondingly for an average rock size; the pressure drop per length is nearly varying from 15 Pa/m to 40 Pa/m. Thus for a bed length of 3.2 m, the total pressure drop is 48 Pa and 128 Pa respectively. Hence the pumping power estimated from above mentioned correlation is nearly 3.5 W - 10 W accounting the efficiency of the unit, this is very small in comparison with the actual power output from the rock bed and is thus neglected in the discussion. Rock-beds will involve random packing of non-uniform size particles; usually a void fraction of 0.4 is suggested for spheres. Another important factor is the flow velocity of air across rock-bed. For the usual bed sizes the flow condition \((G)\) would fall from the range of 146 kg/h.m\(^2\). In order to establish this flow rate from room to rock bed a small fan may be used. The calculations have been performed for a typical rock bed with a 1.44 m\(^2\) cross-section area and 3.2 m length. Optimum length and area is selected as per energy requirement of the external conditions.

3 ROCK BED THERMAL STORAGE SYSTEM

Different shapes of configurations have been shown for rock bed thermal storage in Figure 1. Four types of storage system have been critically analyzed by comparing the efficiency in terms of volume for equal amount of heat loss through their surfaces i.e. they have equal amount of surface area. The storage system has been integrated to a residential unit for bed rooms facing towards south side to get the maximum solar radiation to the heating system. The floor plan of a residence, the location of rock bed to heat the bed room and the stratification length of the rock bed shown is in Figure 3. The cross section of the configuration is shown in the Figure 4. The analysis has been confined to only one room with attached rock bed to the length of 3.2 m with different configuration.

The heating storage and flow of heated air from rock bed to the room and room to bed has also been shown in the cross section with due consideration to thermal buoyancy. Now on equating the volume of different configurations, the following relation among the above can be given as:

\[4a l = 6 b l = 3 c l = 2 \pi r l\]  

(9)

Now suppose the side of a square configuration, \(a = 1.2\) m and length, \(l = 3.2\) m then it is possible to evaluate other parameters from Eq. (1). \(b = 0.8\) m, \(c = 1.6\) m, \(r = 0.7639\) m

The space efficiency volume can be compared by the equivalent surface area of different configurations as shown in the Table 2. It is seen from the Table 2 that the equivalent surface area for heat loss/gain of cylindrical configuration can generate comparatively more cross sectional area.

Now on equating the surface area we get the following relation

\[a^2 = 2 b^2 = \frac{\sqrt{3}}{4} c^2 = \pi r^2\]  

(10)

Now if \(a = 1.2\) m and length, \(l = 3.2\) m then we can evaluate other parameters i.e. \(b = 0.8485\) m, \(c = 1.82360\) m and \(r = 0.6770\) m, so we can compare heat loss through surface (surface area) for a given volume (space efficiency)

Table 3 cross section and surface area calculation for
different configuration and $t$ is evident from the Table 3, that equivalent cross sectional area of different configuration may give varying surface areas. The cross sectional area of cylindrical configuration is found to give less surface area.

### 4 INTEGRATION OF ROCK BED HEAT FLOW IN THERMAL MODEL

In the present analysis, the analytical solution is explicit and simple, but significant errors may result in dealing with complex situations, hence to provide more flexibility and competence for complex environmental conditions, MATLAB based simulation is employed for calculating the Fourier coefficients with more accuracy. The advantage of this technique is that the heat fluxes are obtained simultaneously. The results are incorporated in the overall heat balance of the solar thermal model. The results are shown for changing geometry, infiltration losses, and sizing of rock-bed, which includes inlet area, stratified length. Thus, the optimal configuration is ascertained for feature. Further the simulated model also helps to determine the optimum size of the rock-bed. A very important aspect of this study is shown with the effect of area on heat rate. For an inlet area of 1.83 m$^2$ with cylindrical configuration, the outlet temperature of fluid remained almost constant, being equal to initial rock bed temperature of 25°C, thus heat could be restored for 24 hours by using the fully charged rock bed. Similarly, the rock bed is analyzed for 3.2 m and used in further analysis of different configurations. The thermal storage configurations have been analyzed using the above thermal models and the brief observations such as power, temperature variations and heat supply hours shown in Table 4. It is assumed that the ideal conditions restricting the infiltration losses may not be available. Thus the model can be simulated for high infiltration losses. It is also assumed that the ideal conditions restricting the infiltration losses may not be available. Thus the model can be simulated for high infiltration losses. The heating load tends to increase, but optimal sizing of rock-bed accounts for the losses incurred. It can be determined the optimal selection of the rock-bed configuration for high infiltration losses. Here the analysis has been carried for stratified length of 3.2 m. The cylindrical configuration may again surpass the other storage options. These conclusions are further consolidated by the following explanations of the simulation results. The thermal stratification of a rock bed during heating from a constant air temperature (Maximum 30°C and 10°C) is shown in Figure 2. for a bed length of 3.2 m with reference to the room size. The mass velocity has been considered as 0.076 kg/m$^2$-s for a 3.2 m length of rock bed and for a rock of size 1.28 cm. The hot air enters at a temperature of about 30°C where as the bed temperature is considered as 10°C. Because of the high heat transfer coefficient the air gives its heat quickly to the rock bed. In the initial stage the rocks near the inlet are heated but the temperature of the rocks near the exit remains unchanged and the exit air temperature remains very close to the initial bed temperature. It is observed that as time progresses, the rock bed temperature increases throughout the bed. After 6 hours of the time the bed gets almost charged and the exit air temperature begins to rise.

#### 4.1 Integration Heat from Rock-Bed Heat Exchanger to Heat Balance Equation for Inside Air Temperature

Numerical results are obtained using the finite difference technique, which exists for a step change in inlet conditions as well as for a cyclic operation, which is similar to Clark’s model. Finite Difference method is used to transform the governing nodal equation into algebraic form. Eq. (5) is expressed with forward finite difference in time and central finite difference in $x$, but $n^2h$ position is expressed in terms of backward differ-
Table 3. Cross section and surface area calculation for different configuration

<table>
<thead>
<tr>
<th>Name of Configuration</th>
<th>Cross-section area</th>
<th>Surface area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube</td>
<td>$a^2 = 1.44 \text{ m}^2$</td>
<td>$4a = 15.36 \text{ m}^2$</td>
</tr>
<tr>
<td>Cuboid</td>
<td>$2b^2 = 1.44 \text{ m}^2$</td>
<td>$6b = 16.2917376 \text{ m}^2$</td>
</tr>
<tr>
<td>Triangular Prism</td>
<td>$(\sqrt{3}/4)c^2 = 1.44 \text{ m}^2$</td>
<td>$3c = 17.5066142 \text{ m}^2$</td>
</tr>
<tr>
<td>Cylinder</td>
<td>$\pi r^2 = 1.44 \text{ m}^2$</td>
<td>$2\pi r = 13.61244557 \text{ m}^2$</td>
</tr>
</tbody>
</table>

Table 4. Comparative analysis of different configuration of rock bed

<table>
<thead>
<tr>
<th>Description</th>
<th>Square</th>
<th>Rectangular</th>
<th>Triangular</th>
<th>Circular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area</td>
<td>$4a$</td>
<td>$6b$</td>
<td>$3c$</td>
<td>$2\pi l$</td>
</tr>
<tr>
<td>Sectional area</td>
<td>$a^2$</td>
<td>$2b^2$</td>
<td>$(\sqrt{3}/4)c^2$</td>
<td>$\pi r^2$</td>
</tr>
<tr>
<td>Geometry</td>
<td>Cube</td>
<td>Cuboid</td>
<td>Triangular Prism</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Stratified Length</td>
<td>3.2 m</td>
<td>3.2 m</td>
<td>3.2 m</td>
<td>3.2 m</td>
</tr>
<tr>
<td>Void Fraction</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Supplied power (kW)</td>
<td>1.46</td>
<td>1.46</td>
<td>1.46</td>
<td>1.42</td>
</tr>
<tr>
<td>Height Temperature</td>
<td>29.9°C</td>
<td>26.9°C</td>
<td>28°C</td>
<td>30°C</td>
</tr>
<tr>
<td>Lowest Temperature</td>
<td>18.9°C</td>
<td>16.9°C</td>
<td>20°C</td>
<td>22°C</td>
</tr>
<tr>
<td>Heat supply hours</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Inlet Area</td>
<td>1.83 m²</td>
<td>1.83 m²</td>
<td>1.83 m²</td>
<td>1.11 m²</td>
</tr>
</tbody>
</table>

Figure 2. Stratified rock bed configuration for a length 3.2 m

ence. However, Eq. (6) is expressed in forward finite difference, with $t + \Delta t$ as a reference.

The boundary conditions are given as follows:

$T_f(x, 0) = T_i(x)$ \hspace{1cm} (11)

$T_b(x, 0) = T_{bi}(x)$ \hspace{1cm} (12)

$T_f(0, t) = T_f(1, t)$ \hspace{1cm} (13)

The undistributed bed and air initially have an assumed temperature distribution at time $t = 0$. This is given by Eq.(11) and (12) where $i$ refers the initial conditions. The fluid temperature at inlet will vary according to the changes in ambient conditions. Hence the variation of fluid temperature at $x = 0$ or at the inlet air temperature of the segmental node ‘1’ is expressed in Eq. (13). Using boundary conditions Eq. (11)-(13) and finite difference method, the above equations are solved to obtain the solution. One can express the second Eq. (6) in forward finite difference method as

$T_b(x, t + 1) - T_b(x, t) = \Delta t \frac{r^2}{2} (T_f(x, t + 1) - T_b(x, t + 1))$ \hspace{1cm} (14)

$T_b(x, t + 1) = \frac{T_b(x, t)}{1 + \frac{r^2}{2} \Delta t} + \frac{r^2}{2} \Delta t T_f(r, t + 1)$ \hspace{1cm} (15)

The Eq. (5) can be expressed with forward finite difference in time and central finite difference in $x$ for all
Figure 3. Residential unit with rock bed heating system for bed rooms facing towards south spatial locations, but \( n^{th} \) position is expressed in terms of backward difference.

\[
\frac{T_f(x, t + 1) - T_f(x, t)}{\Delta t} + u \frac{T_f(x + 1, t) - T_f(x - 1, t)}{2\Delta x} + r_1(T_f(x, t) - T_i(x, t)) + \frac{r_2\Delta t(T_f(r, t + 1))}{r_2\Delta t} = 0
\]

Hence, it is to obtain a system of \((n-1)\) linear homogeneous algebraic equations in \((n-1)\) unknowns namely \( T_f(i, t + 1) \) where \( i \) varies from 2 to \( n \). This way it is possible to estimate the fluid and rock temperatures at various spatial locations with changing time. Hence the available heat flux can be estimated at a different times as shown in the Eq. (7). The heat balance for inside air is the integration of various components such as heat flux entering in to a room through walls and roof, isothermal mass, heat conduction in the ground, air infiltration and ventilation and the direct solar radiation through openings etc. A building module of rectangular shape and having an ordinary glass window on the south wall of a room is considered to analyze the thermal behavior of a building. The equation of the temperature of the inside air is given by the mass balance equation, where \( M_a \) is the total mass, \( C_a \) is specific heat capacity of dry air at constant pressure; the heat transfer rate of inside walls/roof is \( Q_T \), for windows is \( Q_W \), the outside air through ventilation and infiltration is \( Q_V \), the isothermal mass i.e. furnishings is \( Q_S \), and the ground conduction is \( Q_G \) respectively.

\[
M_a C_{air} \frac{dT_{air}}{dt} = Q_T + Q_W - Q_V - Q_S - Q_G + Q_R
\]

The \( Q_R \) indicates the auxiliary heating requirements obtained from rock bed heat exchanger. The net heat balance for the internal air of the room is:

\[
M_a C_{air} \frac{\partial T_{air}}{\partial t} = \sum_{q=1}^{5} h_2(T_q(x = l_q, t) - T_{air})A_{Wq} - h_4(T_{air(t)} - T_A(t))A_{w} + A_{g}g \frac{\partial \theta(y, t)}{\partial y} + Q_R
\]

where \( Q_R \) is shown in the Eq. (7).

4.2 Results and Discussion

The thermal storage configurations are analyzed using the above thermal models and the results shown in Figure 5 with respect to the architectural design of a building and its sections shown in Figure 4.
4.2.1 Cylindrical rock bed storage configuration

Figure 5A shows the variation of hourly room air temperature for cylindrical configuration. It is seen that the heat flux available for an inlet area of \((1.83 \text{ m}^2)\) equals 1.4 kW and available for a continuous 14 hours from fully charged rock-bed, establishes the indoor air temperature successfully in the comfort zone. The peak temperature is in the order of 30°C at 6 PM and gradually reaches to the 22°C by 6 AM. However, the indoor air temperature has similar swing as compared the Cube type configuration. The Cylindrical configuration can contribute to a desirable extent of the indoor air temperature for heating period.

4.2.2 Cube type storage configuration

Figure 5B shows the effect of Cube type configuration with a square shaped cross-sectional area of \((1.44 \text{ m}^2)\) \((1.2 \text{ m} \times 1.2 \text{ m})\) with the proposed geometry for packing of rocks size 1.28 cm. Stratified length of 3.2 m is taken. This storage configuration has a cube type arrangement of rocks with a void fraction of 0.28, supplied power 1.464 kW for nearly 10 hours from 19.00 h - 05.00 h. The result shows that height and lowest indoor air temperature values are 9.9°C and 18.9°C respectively. This happened when a rock bed supplied heat at the rate of 1.464 kW for a period of continuous 10 hours. Further it was found that temperature suddenly dropped to 20°C very sharply right after the time when the rock-bed got uncharged fully. It is found that the Cube type configuration of underground storage is providing 25°C hourly average room air temperature in heating period.

4.2.3 Cuboid type rock bed storage configuration

The results cover two more of the typical rock bed thermal storage configuration viz. triangular and rectangular. From Figure 5C, a fairly wide variation in the indoor air temperature is seen for rectangular configuration. The maximum and minimum difference between room air temperature and ambient air temperature is in the order of 4°C and 12°C. This is largely in agreement with inadequate storage capacity for Cuboid type configuration of rock bed. It is seen from the above figure that the minimum indoor temperature of the room occurred at 8 PM and maximum at 7 PM. It is also noted that the room air temperature is gradual gradient after 7 PM to 8 Am.

4.2.4 Triangular prism rock bed storage configuration

Finally in Figure 5D, shows the effect of the triangular Prism configuration of rock-bed with similar arrangement of rocks in bed length of 3.2 m for inlet area of \((1.11 \text{ m}^2)\) on hourly room air temperature. The simulation is performed for an area of 1.11 m². It is seen that a reduction in the level of temperature stratification as
The hourly room air temperature is decreased to $13^\circ C$ by 7 AM and increased to $22^\circ C$ by 7 PM. The power output at a slightly lesser rate of 1.4 kW is available for only 8 hours.

5 CONCLUSION

It is evident that the rock bed storage may be an effective solution to heat the space in cold regions for all the configurations. The application of rock bed heating is an effective solution to save the energy. In the present study, the length of rock-bed storage system is increased to give a larger level of stratification as concluded from simulated curves. The analysis of different configurations, coupling with building is considered in this study to predict the solar thermal performance of the building. The study shows that cylindrical-shaped rock-bed thermal storage system is appropriate for exposing the minimum surface area and ensuring a uniform flow with regular and tight packing of rock-beds. In particular, this conclusion is likely to be useful while designing of buildings, where the building has to pass through an unnecessary phase of excessive heating and cooling. The present study also lends confidence in the efficient use of storage capacity by keeping rocks tightly packed with the configuration being close to cylindrical type. This will not only serve the purpose of energy saving by loss minimization but also allows better packing. With this configuration, a nearly $5^\circ C$ rise in the indoor air temperature is achieved over other type of configuration. Conclusively, the amount of savings shown by using cylindrical configuration clearly justifies that this option is one of the efficient options to be integrated to the buildings for heating the buildings in the Cold Regions. The study shows that cylindrical-shaped rock-bed thermal storage system is appropriate for exposing the minimum surface area and ensuring a uniform flow with regular and tight packing of rock-beds. With this configuration, a nearly $5^\circ C$ rise in the indoor air temperature is achieved over other type of configuration.

REFERENCES


