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New Geotechnical Engineering Design for Underground Heat Storage in Geological Substrates

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Abstract

This paper proposes a new method to store thermal energy for electricity generation in power plants. The system is based on heat exchange between the hot geological substrate and inorganic salt solution to store thermal energy under molten salt form. To this goal, we design an underground pipeline system that transports heat fluid carrier in solid form until reaching the geological substrate at the appropriate temperature for the phase change where heat transfer from the substrate to the fluid melts the salt solution. The proposed design saves space, investment and maintenance costs, and is compatible with modern geotechnical engineering techniques. The system is also compatible with low and high geothermal gradients. Operating temperatures are within the current range for depths between 1.6 km and 2.6 km, which are accessible using conventional drilling techniques. The selected geological substrate maintains molten salt in liquid phase for as long as necessary due to the geological environment, preserving the enthalpy level. A simulation runs for current heat storage system temperature for solar thermal power plants, proving the feasibility of the new design and the capacity of the geological substrate to thermally recharge the heat storage system within time limits. The system reveals as a practical solution to preserve thermal energy long enough to use when heat generation from conventional or renewable energy sources decays or lacks. The proposed methodology is feasible and reliable if we deal with massive energy storage where heat power generation compensates for investment in geological engineering. The system is modular and adaptive to variable working conditions. Besides, it becomes practical for intermittent thermal power generation and fluctuating energy demand.

Keywords: Geological structure, geotechnical engineering, underground thermal energy reservoir, heat storage

INTRODUCTION

Electric generation in power plants is the most widely used form to produce electricity for human needs. Power plants operate under thermodynamic cycles to generate electricity consuming fossil fuel or nuclear energy [1]. In the last decades, the implementation of renewable energies developed alternative solutions to conventional power plants, using solar radiation, biomass, or geothermal energy for electricity generation wherever the natural resource is available [2, 3]. Among them, solar thermal power plants may represent the most widely spread solution because solar radiation covers the entire Earth's surface; however, it suffers from intermittency due to the day and night cycle, which reduces the operational time to the solar day [4, 5]. In past decades, implementing thermal energy reservoirs under molten salt form enlarges the working time, but not enough to cover the night period [6, 7].

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The limitation in thermal energy storage derives from the heat capacity of the molten salt storage unit, which depends on the size; a higher size means higher storage capacity but also higher thermal losses [8]. Therefore, a compromise between heat capacity and thermal losses arises. Geological substrates represent an alternative to surface heat storage systems due to their capacity to retain thermal energy. To this goal, specific geotechnical engineering designs may help to use the geothermal rock enthalpy as the power source to melt inorganic salt solutions and to maintain them in the molten state until required for external surface applications [9–12].

The proposed system bases its geotechnical design on conventional drilling techniques used in geothermal prospection combined with natural or artificial geological cavities where molten salt solution is stored. If there is no natural cavity, geotechnical engineering applies to building an artificial one, providing a space for the heat storage unit.

THEORETICAL FOUNDATIONS

Solar thermal power plants currently operate in the 300ºC to 570ºC range; therefore, if we intend to use a geological substrate as thermal power source for heat storage unit, the substrate should be above this range to compensate for thermal losses in the way from underground storage to solar oven.

Thermal losses depend on the duct length, material and insulation type, according to:

$$\dot{Q}_L = \frac{\kappa_{eq}}{e} S(T_{ms} - T_{env}) \tag{1}$$

κ_{eq} is the equivalent thermal conductivity of the combined duct material and insulation, e is the duct plus insulation thickness, S is the duct side surface, and T is the temperature with *ms* for molten salt and *env* for the geological substrate.

The equivalent thermal conductivity is given by:

$$\kappa_{eq} = \frac{\kappa_d e_d + \kappa_{ins} e_{ins}}{e} \tag{2}$$

Cooper and Rockwool are the current material for geothermal duct and insulation, whose characteristic average thermal conductivity is 432 and 0.028 W/m · K. Applying current thickness for duct and insulation, 2 mm and 5 cm, we obtain:

$$\kappa_{eq} = \frac{(432)(0.008) + (0.028)(0.05)}{0.058} = 59.6\, W/m \cdot K \tag{3}$$

Since geological substrate temperature evolves with depth (Figure 1), considering that the heat carrier fluid maintains temperature in the way back to surface, Equation 1 should be expressed as:

$$\dot{Q}_L = -\frac{\kappa_{eq}}{e} S \int_{z_o}^{0} \frac{dT_{env}}{dz} \tag{4}$$

Looking at Figure 1, it is observed that temperature evolution is linear from 22 m depth; therefore, temperature and depth can be correlated through the equation:

$$T_{env} = T_o + \alpha(z - z_o) \tag{5}$$

z is the geological substrate depth with sub-indexes o and z account for reference and current depth, with reference value equal to 22 m, and α is the temperature gradient coefficient.

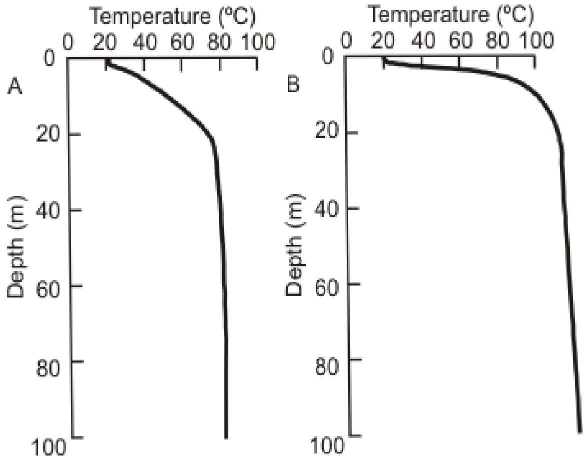

Figure 1. Vertical thermal gradient of geothermal terrain [13].

According to data in Figure 1, the α-coefficient is:

$$\alpha_A = 0.087\ {}^{o}C/m; \quad \alpha_B = 0.139\ {}^{o}C/m \tag{6}$$

Applying Equation 5 to Equation 4 and considering the solar power plant operating temperature:

$$z = z_o + \frac{T_{env} - T_o}{\alpha} \rightarrow \left| \begin{array}{l} z_A = 22 + \dfrac{300 - 76.9}{0.087} = 2586\, m \\ z_B = 22 + \dfrac{300 - 80.5}{0.139} = 1601\, m \end{array} \right. \tag{7}$$

Replacing Equation 4 in Equation 3:

$$\dot{Q}_L = \frac{\kappa_{eq}}{e} \alpha S \left(z - z_o \right) \tag{8}$$

Converting thermal losses in temperature drop:

$$\Delta T = \frac{\dot{Q}_L}{\dot{m} c} = \frac{\kappa_{eq} \alpha S \left(z - z_o \right)}{e \dot{m} c} \tag{9}$$

Therefore, the geological substrate minimum temperature is:

$$T_{\min} = T_{op} + \Delta T = T_{op} + \frac{\kappa_{eq} \alpha S \left(z - z_o \right)}{e \dot{m} c} \tag{10}$$

Retrieving values from literature [14], = 15.28 kg/s and c = 1497.7 J/kg · K

$$T_{\min} = 300 + \frac{(59.6)(0.087)\pi \left(0.508\right)\left(2586\right)}{(0.052)(15.28)(1497.7)} = 318^{o} C \tag{11}$$

Applying the new value to Equation 7:

$$\begin{array}{l} z_A = 22 + \dfrac{318 - 76.9}{0.087} = 2793\, m \\ z_B = 22 + \dfrac{318 - 80.5}{0.139} = 1730\, m \end{array} \tag{12}$$

Depths shown in equation 12 are current in geothermal prospection; therefore, the conventional drilling technique is applicable. Nevertheless, we must perforate until reaching a geological substrate above 300º C to warrant that the inorganic salt melts at the appropriate temperature. To achieve this goal, we should use specific geotechnical engineering.

HEAT STORAGE CHARACTERISTICS

Heat storage units fit in natural or artificial cavities of appropriate volume. Since the mass flow is 15.28 kg/s, we need the compound density and the operational time during no solar hours to determine the cavity volume, which contains the inorganic salt compound.

Daily solar hours depend on latitude and declination according to:

$$DST = \frac{2}{15}\arccos\left(-\tan\delta\tan\phi\right) \tag{13}$$

δ is the declination, and Φ is the latitude.

Since the minimum solar day length determines the heat storage operating time for a given location on Earth, we obtain (Table 1).

Table 1. Minimum solar day length for various latitudes.

Latitude (º)	0	10	20	30	40	50
DST (h)	12.0	11.4	10.8	10.1	9.2	7.8

The maximum considered latitude is 50º since solar power plants are not economically viable above this value.

Using data from Table 1 and mass flow shown above, and considering the inorganic salt solution density, ρ = 1140 kg/m^3, we have a minimum required storage volume of:

$$V = \frac{\left(24 - DST_{\min}\right)\dot{m}}{\rho} = \frac{\left(24-7.8\right)\left(15.28\right)\left(3600\right)}{1140} = 781.7\ m^3 \tag{14}$$

The volume in equation 14 corresponds to a sphere of 11.4 m diameter, representing a small cavity.

GEOTECHNICAL ENGINEERING AND OPERATIONAL MODE

Since natural cavities are scarce or non-existent where a thermal storage unit is required, we should excavate to build an artificial cavity of the mentioned size. Nevertheless, it is more practical to build an individual cavity per operating hour of the heat storage system; therefore, considering 16 hours as the maximum operating time for the heat storage, every cavity has a diameter of:

$$D = \left(\frac{1}{16}\right)^{1/3} D_o = \left(\frac{1}{16}\right)^{1/3}(11.4) = 4.52\ m \tag{15}$$

Because the engineering design intends to heat the inorganic salt solution with the geological substrate geothermal energy, every cavity should be separated from the adjacent ones a distance enough to facilitate heat transfer from rock to inorganic salt to melt it.

If all cavities are placed at the same level and keep a minimum distance between two adjacent cavities equal to the diameter, the cavity distribution covers an area whose diameter is equivalent to 32/π times the diameter of a single cavity. Applying the value obtained in equation 15 results in a 46 m diameter for the heat storage area, corresponding to a perimeter of 144.6 meters.

An engineering smart design saves space and maintains the distance between adjacent cavities, thus preserving heat transfer from the geothermal environment to inorganic salt in the cavity; the new design consists of building the cavities in a two-level distribution, as shown in Figure 2.

The proposed design consists of eight single cavities at each level; the cavity distribution at the lower level is rotated and displaced regarding the upper level to increase the distance between corresponding cavities at the two levels, thus helping to improve heat transfer from the geological substrate to the cavity.

A manifold distributes the fluid flow to every cavity through a horizontal duct at each level. Every duct has an electronic valve commanded from the control unit at the surface operating center. The valve opens and closes depending on the operational mode. If only a cavity supplies molten salt to the surface power plant, the control unit opens the valve at the corresponding duct and closes the other valves. This operational mode maintains molten salt for the non-active cavities at the geological substrate temperature while the active cavity releases its thermal energy through fluid flow. Since every cavity contains working fluid for an hour, the process repeats as many times as working hours for non-sunny periods.

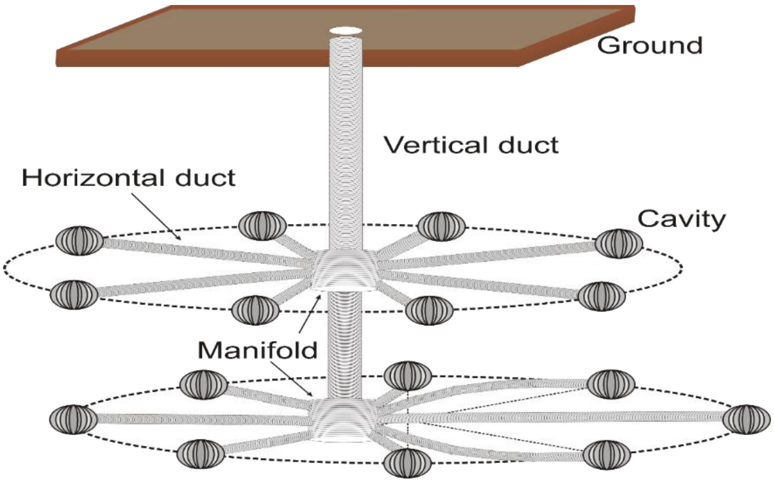

Figure 2. Layout of the cavity system.

The proposed layout reduces the drilling area and volume, lowering investment and maintenance costs. Indeed, the drilled area and volume for the new design is half of the conventional one since the layout diameter is reduced by half.

The heat storage system must fulfill the condition of thermally recharging every cavity during sun hours. The critical condition occurs for the shortest sun day, which in our simulation is 7.8 hours; therefore, the sixteen cavities are thermally depleted and should recharge in such a period.

Heat Transfer

Applying Fourier's law for conduction heat transfer, which is the principal mechanism of cavity thermal recharge:

$$\frac{\partial T_{ms}}{\partial t} = \lambda_{ms} \frac{\partial^2 T_{ms}}{\partial x^2} = \frac{\kappa_{ms}}{\rho_{ms} c_{ms}} \frac{\partial^2 T_{ms}}{\partial x^2} \tag{16}$$

κ, ρ, and c are the thermal conductivity, density, and specific heat of the molten salt (*ms*).

Considering a linear heat transfer across the molten salt, the solution of equation 16 adopts the form:

$$T_{ms} = T_{ms,o} + 2\frac{T_{geo} - T_{ms,o}}{D}x \tag{17}$$

Because heat transfer responds to a transient state:

$$T_{ms}(x,t) = T_{ms,o} + 2\frac{T_{geo} - T_{ms,o}}{D}x + \sum_{n=1}^{\infty} a_n \exp\left(-\lambda\omega_n^2 t\right)\sin\left(\omega_n x + \delta_n\right) \tag{18}$$

The boundary conditions impose:

$$\delta_n = 0; \quad \omega_n D = n\pi \tag{19}$$

Therefore:

$$T_{ms}(x,t) = T_{ms,o} + 2\frac{T_{geo} - T_{ms,o}}{D}x + \sum_{n=1}^{\infty} a_n \exp\left(-4\lambda\frac{n^2\pi^2}{D^2}t\right)\sin\left(\frac{2n\pi}{D}\right) \tag{20}$$

With:

$$a_n = \begin{cases} \frac{2}{n\pi}\left(2T_o - T_{ms} - T_{geo}\right) \rightarrow n: odd\ number \\ \frac{2}{n\pi}\left(T_{geo} - T_{ms}\right) \rightarrow n: even\ number \end{cases} \tag{21}$$

T_{geo} represents the geological substrate temperature while T_{ms} is the organic salt temperature, with sub-indexes *ms* and *ms,o* accounting for molten salt in liquid and solid phase.

At the equilibrium time, $T_{ms} = T_{geo}$; therefore:

$$T_{ms} = T_{ms,o} + \sum_{n=1}^{\infty} a_n \exp\left(-4\lambda\frac{n^2\pi^2}{D^2}t_{eq}\right)\sin\left(\frac{2n\pi}{D}\right) \tag{22}$$

Neglecting summation terms for n=2 and over because of their low impact in the summation, and considering that $T_o = T_{ms,o}$:

$$T_{ms} = T_{ms,o} + \frac{4}{\pi}\left(T_{ms,o} - T_{geo}\right)\exp\left(-4\lambda\frac{\pi^2}{D^2}t_{eq}\right) \tag{23}$$

The time when molten salt converts to liquid phase is:

$$t_{eq} = -\frac{D^2}{4\lambda\pi^2}\ln\left(\frac{\pi}{4}\frac{T_{geo} - T_{ms}}{T_{geo} - T_{ms,o}}\right) \tag{24}$$

Retrieving data from the literature [14–16], establishing the geological substrate temperature as the one shown in Equation 11, considering that molten salt operates between 210º C in the solid phase and 240º C in the liquid phase, and applying a temperature drop of 2º C/km because of thermal losses in the upward duct:

$$t_{eq} = -\frac{D^2}{4\lambda\pi^2}ln\left(\frac{\pi}{4}\frac{T_{geo}-T_{ms}}{T_{geo}-T_{ms,o}}\right) = -\frac{(4.52)^2}{4(6.4\text{ x }10^{-7})\pi^2}ln\left(\frac{\pi}{4}\frac{318-245.4}{318-210}\right) = 28008.3\text{ s} = 7.78\text{ h} \tag{25}$$

Since the minimum available time is 7.8 hours (Table 1), we prove the viability of thermally recharging the cavity.

CONCLUSIONS

A new design for underground heat storage to power solar thermal plants during night or cloudy periods is studied and analyzed, proving the feasibility of the proposed solution.

Specific geotechnical engineering design applies to the heat storage system layout. The new design saves space, investment costs, and maintenance because of the specific layout.

The proposed system is compatible with low and high geological thermal gradients. The required geotechnical engineering is feasible and can be developed using modern techniques.

The simulation proves that the heat storage system thermally recharges in the available time even for the lowest solar daytime.

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