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EVALUATION OF UNDERGROUND SEASONAL SOLAR THERMAL ENERGY STORAGE

BY

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Abstract. This paper presents an approximative analytical solution used to determine the heat seasonally stored underground. This model was applied for a period of 180 days, considering third kind of boundary conditions. The soil as an energy storage system, has always been considered to be a homogeneous environment with properties evaluated experimentally. The domain of thermal conductivity of soil, was approximately evaluated function of thermal conductivity of soil components. There were assumed two models in calculating the apparent thermal conductivity of the soil, serial and parallel. These models use the analogy between the thermal conductivity and electrical conductivity. The volume of each component depend on its concentration in soil. This approximate analytical solution can be adapted to actual soil composition, according to data collected through geological survey. Heat underground stored along the "warm" season, from spring to autumn, was calculated depending on the size of the underground heated volume function of the temperature field and apparent thermal conductivity.

Key words: thermal energy; energy storage; soil composition.

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1. Introduction

Storing underground solar thermal energy during "warm" season, might be a way to extend the operation of geothermal heat pump based systems during the winter.

It is very difficult to evaluate accurately the underground apparent thermal conductivity and thus the seasonal stored heat function on the evolution of temperature field in time and finally the energy efficiency of corresponding geothermal heat pump based systems during the winter. Therefore the evaluation of the costs/savings ratio is nearly impossible. Some studies proved that thermal conductivity of soil, is related to water content and bulk density (Evett *et al.,* 2012; Schibuola *et al.,* 2013). A higher water content in soil, causes an increase in thermal conductivity.

Other underground thermal energy storage systems, are using aquifer for storing heat (or cold) (Diersch and Bauer, 2015). In this case, an open loop heat pump is necessary, to extract water form a place in the ground and then inject it or evacuate it in another location. Usually, this type of heat pumps, are used for cooling buildings, like large university buildings in Turin, Italy (Lo Russo *et al.*, 2011), or for an IKEA store from Collegno, Italy (Lo Russo and Civita, 2009).

To improve underground thermal energy storage systems, R. Yumrutas and M. Unsal developed a model with an underground storage tank, that uses water to store thermal energy (Yumrutas and Unsal, 2012). This paper also presents soil as a homogeneous medium, made out of limestone, coarse or granite.

Also, as presented in the paper wrote by Zhang *et al*. (2007), one of the soil characteristics that causes errors between developed model and experimental data about thermal conductivity of soils, is quarts quantity in it, because quartz has a high thermal conductivity. In this paper is also presented a similar model developed by us, since they also consider soil to be formed by air, water and soil, but they used porosity, degree of saturation and effective thermal properties of the soil, dependent of type of soil.

Evaluating the amount of energy that can be stored in ground during a season, that is known also as a storage phase, could provide data for storage volume and land surface needed in order to store a certain amount of thermal energy and depth required in order to avoid influence of weather over the stored heat. Also an important role in storing thermal energy, is attributed to heat exchanger, borehole diameter, depth and grouting thermal conductivity, as proved by Luo *et al.* (2013).

In this paper we try to adapt an analytical solution for semi-infinite walls in order to approximately evaluate solar thermal energy that can be stored in ground during the warm season. Apparent thermal conductivity was calculated using electrical models of series and parallel. The real thermal conductivity is considered to be limited by those two apparent thermal conductivities evaluated by those two models.

2. Mathematical Model

2.1. Initial Data and Boundary Conditions

In this paper, ground is considered to be a semi-infinite plane wall, with a thermal conductivity calculated from all thermal conductivities of main substances that composes soil. For calculating average thermal conductivity of ground, we assume, from electrical theory, that particles are arranged in series and parallel, as seen in Fig. 1.

The small particles that compose soil, are noted in Table 1 with their dimensions (Ward Chesworth, 2008). We can assume that a bigger particle (with series and parallel arrangement) will contain all substances that are part of ground and for this particle is calculated the minimum and maximum thermal conductivity and heat capacity.

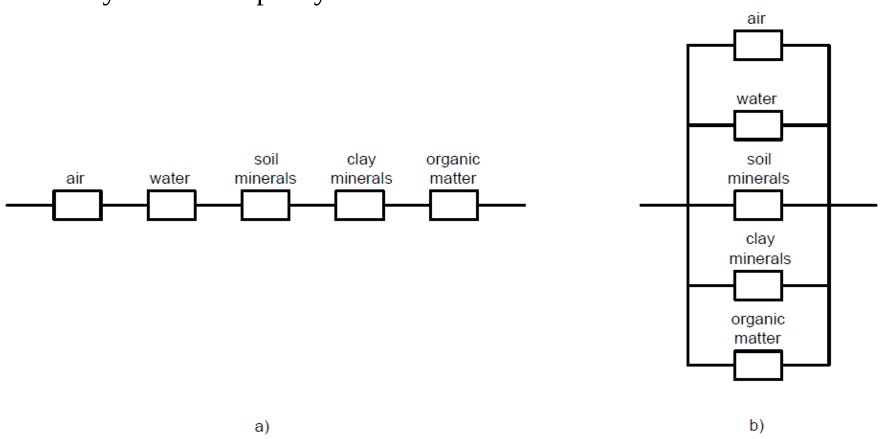

Fig. 1 – Soil particles arrangement for estimating average soil thermal conductivity: *a*) series arrangement; *b*) parallel arrangement.

Table 1

The Relative Sizes of Sand, Silt and Clay Particles (Taylor and Fancis, 2006)

Name	Size, diameter [mm]
Very coarse sand	1 – 2
Coarse sand	0.5 – 1
Medium sand	0.25 – 0.5
Fine sand	0.1 – 0.25
Very fine sand	0.05 – 0.1
Silt	0.002 – 0.05
Clay	Smaller than 0.002

Thermal properties of substances that form the ground are listed in the Table 2 (Blasch, 2003; Ward Chesworth, 2008).

Table 2
Thermal Properties of Substances that form Ground
(Blasch, 2003; Ward Chesworth, 2008)

Name	Density $10^6 gm^{-3}$	Volumetric thermal capacity $10^6 Jm^{-3}°C^{-1}$	Thermal conductivity $Wm^{-1}°C^{-1}$	Thermal diffusivity $10^{-6} m^2 s^{-1}$
Air	0.001	0.001	0.024	19
Liquid water	1.0	4.2	0.60	0.14
Ice	0.9	1.9	2.2	1.2
Quartz (Sand)	2.7	1.9	8.4	4.3
Sand minerals	2.7	1.9	2.9	1.5
Clay minerals	2.7	2.0	2.9	1.5
Organic matter	1.3	2.5	0.25	0.10

Particles considered in this model are air, liquid water, sand minerals, clay minerals and organic matter, with ratio of 25%, 25% 25%, 20% and respectively 5%.

The model used for developing this thermal storage evaluation is a beam, Fig. 2, that is 20 m in length and has a section area of 1x1 m.

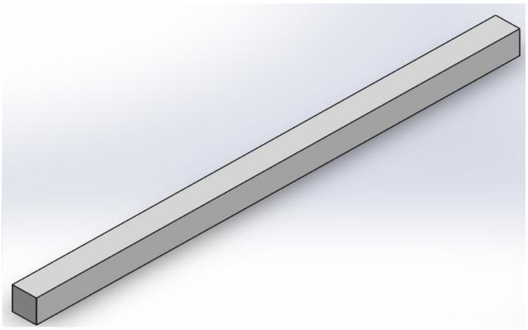

Fig. 2 – Design of soil for evaluating underground thermal storage.

2.2. Apparent Thermal Conductivity Evaluation

We consider soil to be a semi infinite wall, with a constant heat flux, and an equivalent thermal conductivity, calculated from thermal conductivities of particles that compose ground.

From electricity we know that average resistance for series mounting is:

$$R_s = \sum_{i=1}^{n} R_i \tag{1}$$

And for parallel mounting is:

$$R_p = \sum_{i=1}^{n} \frac{1}{R_i} \tag{2}$$

Thermal resistance is:

$$R_t = \frac{\delta_i}{k_i} \tag{3}$$

To evaluate proportions of each substance in soil, we will use an equivalent volumic concentration:

$$x_i = \frac{\delta_i}{\delta} \cdot \frac{A_i}{A} \tag{4}$$

where:

$$\delta = \delta_a + \delta_w + \delta_{sm} + \delta_{cm} + \delta_{om} \tag{5}$$

From Eqs. (1)-(4) we assume that equivalent thermal conductivity is:

− for series particles:

$$k_s = \frac{1}{\frac{x_a}{k_a} + \frac{x_w}{k_w} + \frac{x_{sm}}{k_{sm}} + \frac{x_{cm}}{k_{cm}} + \frac{x_{om}}{k_{om}}} \tag{6}$$

− for parallel particles:

$$k_p = k_a \cdot x_a + k_w \cdot x_w + k_{sm} \cdot x_{sm} + k_{cm} \cdot x_{cm} + k_{om} \cdot x_{om} \tag{7}$$

We assumed the third kind boundary conditions, respectively, constant mean temperature of heat transfer fluid and constant convective heat transfer coefficient.

During charge phase, we assume heat transfer from heat exchanger to be convective:

$$q(t) = h \cdot [T_0 - T(0,t)] \tag{8}$$

2.3. Mathematical Equation

Analytical equations of temperature field, from heat flux will be (Cengel and Gajar, 2015):

$$\frac{T(x,t)-T_0}{T_f-T_0}=erfc\left(\frac{x}{2\sqrt{\alpha\cdot t}}\right)-exp\left(\frac{h\cdot x}{k}+\frac{x^2\cdot\alpha\cdot t}{k^2}\right)\cdot erfc\left(\frac{x}{2\sqrt{\alpha\cdot t}}+\frac{h\sqrt{\alpha\cdot t}}{k}\right) \quad (9)$$

Heat accumulated underground during time *t*, is:

$$\delta Q_{ac}=A\cdot C_v\cdot\left[T\left(x,t_e\right)-T_0\right]dx \quad (10)$$

where

$$Q_{ac}=\int_0^x A\cdot C_v\cdot\left[T\left(x,t_e\right)-T_0\right]dx \quad (11)$$

2.4. Numerical Results

According to data from Tables 1 and 2, we can calculate next dimensions:
− gross dimension soil particle, containing all soil components, δ

$$\delta=\left(0.025+0.025+0.1+0.002+0.005\right)\cdot10^{-3}=0.157\cdot10^{-3}\text{m} \quad (12)$$

− equivalent thermal conductivity for particles arranged in series:

$$k_s=\frac{1}{\left(\frac{0.15926}{0.024}+\frac{0.15926}{0.6}+\frac{0.63694}{2.9}+\frac{0.01273}{2.9}+\frac{0.03184}{0.25}\right)\cdot10^{-3}}= \\ =0.1379\text{W}/\left(\text{K}\cdot\text{m}\right) \quad (13)$$

− equivalent thermal conductivity for particles arranged in parallel:

$$k_p=(0.024\cdot0.15926+0.6\cdot0.15926+2.9\cdot0.63694+2.9\cdot0.01273+ \\ +0.25\cdot0.03184)\cdot10^{-3}=1.99\text{W}/(\text{K}\cdot\text{m}) \quad (14)$$

Assuming that underground temperature is constant, at 10°C, so, T_0 = 10°C and considering heat pump to have an auxiliary heat storage system in order to keep the temperature of heat transfer fluid constant, at 30°C or higher, T_f = 30°C, during day and night and during cloudy days, we need to evaluate heat flux from heat exchanger to underground, using Eq. (9) and (15).

$$q=-k\cdot\left.\frac{\partial T}{\partial x}\right|_{x=0} \quad (15)$$

Heat flux according to time, was determined for a period of 1 h, 1 day, 10 days and 180 days. As we can see from Fig. 3, heat flux decreases quickly in 1st hour of charging and during 1 day is decreasing under 100 W/m^2. In this evaluation we used red line for series arrangement and blue line for parralel arrangement of soil composition.

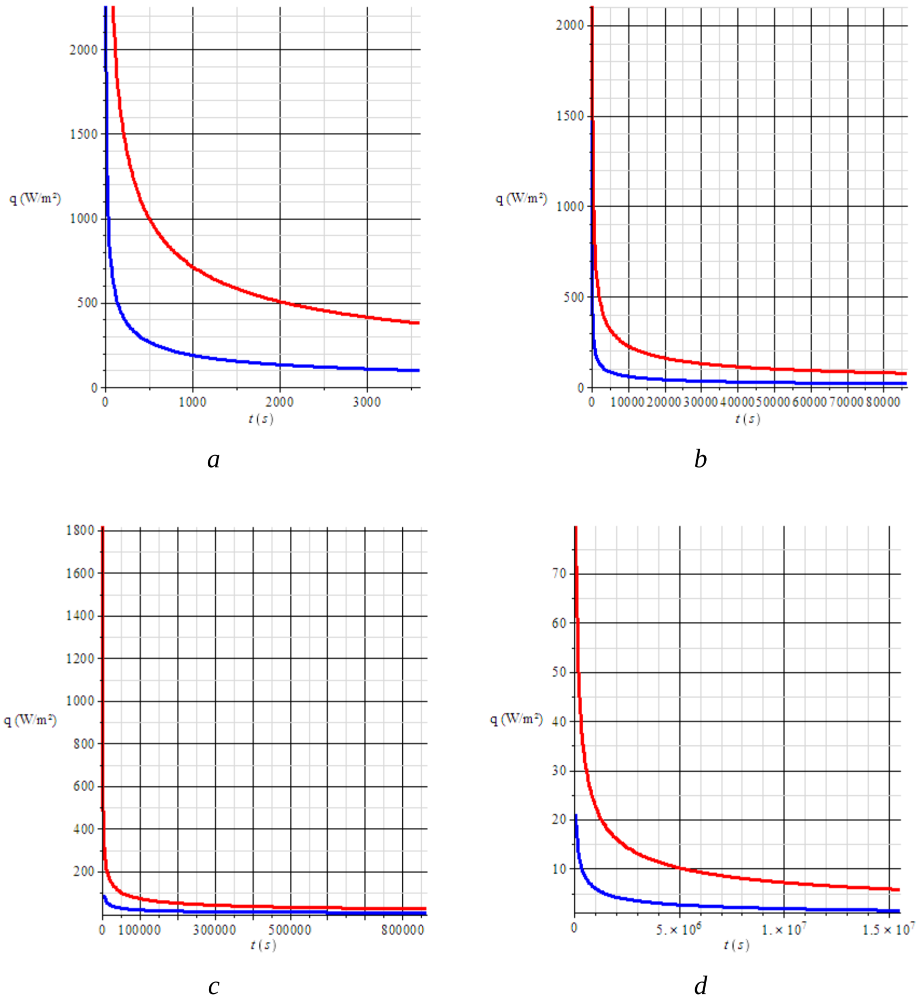

Fig. 3 – Heat flux during different time periods:
a) t = (0 .. 3600) s (1h); *b*) t = (0 .. 86400) s (1 day);
c) t = (0 .. 864000) s (10 days); *d*) t = (0 .. 15552000) s (180 days).

In Table 3 is presented heat flux for certain periods of time.

Table 3
Heat Flux Variation in Time

Heat flux q, [W/m^2]		Time of charging thermal energy undergound, [s]
series	parallel	
4444.5	7721.2	1 s
767.4	2644.3	60 s (1 min)
141.3	534.6	1800 s (30 min)
99.9	378.9	3600 s (1 h)
28.8	109.6	43200 s (12 h)
20.4	77.5	86400 s (1 day)
6.45	24.5	864000 s (10 days)
3.72	14.15	(30 days)
2.63	10	(60 days)
1.86	7.08	(120 days)
1.53	5.78	(180 days)

From Fig. 3, it can be observed that heat flux to charging face, is rapidly decreasing, due to the fact that temperature of heated face, increases by heat gained. A low thermal conductivity, causes heat to dissipate slow inside an semi-infinite soild, so while accumulated heat increases, heat flux decreases.

Assuming that, heat will be charged in ground for 180 days, 24 h each day.

$$t = 180\text{days} \cdot 24\text{h} \cdot 3600\text{s} = 1.5552 \cdot 10^7\text{s} \tag{16}$$

Density for gross particle that contains all ground compositions, will be calculated as a proportion of each one of the substances:

$$\rho = \rho_a \cdot 25\% + \rho_w \cdot 25\% + \rho_{sm} \cdot 25\% + \rho_{cm} \cdot 20\% + \rho_{om} \cdot 5\% \tag{17}$$

$$\begin{aligned}\rho &= \left(0.001 \cdot 25\% + 1 \cdot 25\% + 2.7 \cdot 25\% + 2.7 \cdot 20\% + 1.3 \cdot 5\%\right) \cdot 10^3 \\ &= 1.53 \cdot 10^3 \text{kg} / \text{m}^3\end{aligned} \tag{18}$$

Similar conditions are used to calculate volumetric thermal capacity for gross particle:

$$c_v = c_{va} \cdot 25\% + c_{vw} \cdot 25\% + c_{vsm} \cdot 25\% + c_{vcm} \cdot 20\% + c_{vom} \cdot 5\% \tag{19}$$

$$\begin{aligned}c_v &= (0.001 \cdot 25\% + 4.2 \cdot 25\% + 1.9 \cdot 25\% + 2 \cdot 20\% + 2.5 \cdot 5\%) \cdot 10^6 \\ &= 2.05 \cdot 10^6 \text{J} / (\text{m}^3 \cdot \text{K})\end{aligned} \tag{20}$$

Thermal diffusivity can now be calculated, for gross soil particle, for series and parallel arrangement with equation:

$$\alpha_{s,p} = \frac{k_{s,p}}{c_v} \tag{21}$$

− for series arrangement:

$$\alpha_s = \frac{0.1379}{2.05 \cdot 10^6} = 6.726 \cdot 10^{-8} \mathrm{m}^2/\mathrm{s} \tag{22}$$

− for parallel arrangement:

$$\alpha_p = \frac{1.99}{2.05 \cdot 10^6} = 9.713 \cdot 10^{-7} \mathrm{m}^2/\mathrm{s} \tag{23}$$

To find the interval of heat accumulated in ground, during time t, we solve Eq. (11) using (9) and get:

$$Q_{ac_{s,p}} = -\int_0^x \left[A \cdot c_v \cdot \left(T_0 - T_f\right) \left(erfc\left(\frac{x}{2\sqrt{t \cdot \alpha_{s,p}}}\right) - erfc\left(\frac{x}{2\sqrt{t \cdot \alpha_{s,p}}} + \frac{h\sqrt{t \cdot \alpha_{s,p}}}{k_{s,p}}\right) \cdot e^{\frac{h \cdot x}{k_{s,p}} + \frac{h^2 \cdot t \cdot \alpha_{s,p}}{k^2_{s,p}}} \right) \right] dx \tag{24}$$

Amount of heat that can be stored underground in one cubic meter of soil (A = 1 m^2, x = 1 m), considering temperature of fluid at 30°C, heat convection coefficient at 10 W(m^{2}K) and initial temperature in soil of 10°C, will be:

− for series arrangement:

$$Q_{ac_s} = 2.9837 \cdot 10^7 \mathrm{J} = 29.8371 \mathrm{MJ} \tag{25}$$

− for parallel arrangement:

$$Q_{ac_p} = 3.686 \cdot 10^7 \mathrm{J} = 36.8635 \mathrm{MJ} \tag{26}$$

Heat accumulated underground in 180 day, with heat transfer fluid at a temperature of 30°C, should vary between 29.8371 MJ and 36.8635 MJ. We calculated the amount of heat that will accumulate for both arrangements, so that we can have an interval to verify upcoming results.

For accurate results, we calculate different mean values, arithmetic (am), geometric (gm), harmonic (hm) and logarithmic (lg), of thermal conductivities between series and parallel arrangements of soil particles.

$$k_{am} = \frac{k_s + k_p}{2} = \frac{0.1379 + 1.99}{2} = 1.065\,\mathrm{W/(m \cdot K)} \tag{27}$$

And thermal diffusivity for arithmetic mean of thermal conductivity:

$$\alpha_{am} = \frac{k_{am}}{c_v} = \frac{1.065}{2.05 \cdot 10^6} = 5.193 \cdot 10^{-7}\,\mathrm{m/s^2} \tag{28}$$

In this scenario, considering initial data the same, accumulated heat, is:

$$Q_{am} = 36.1\,\mathrm{MJ} \tag{29}$$

For geometric mean:

$$k_{gm} = \sqrt{k_s \cdot k_p} = \sqrt{0.1379 \cdot 1.99} = 0.524\,\mathrm{W/(m \cdot K)} \tag{30}$$

$$\alpha_{gm} = \frac{k_{gm}}{c_v} = \frac{0.524}{2.05 \cdot 10^6} = 2.556 \cdot 10^{-7}\,\mathrm{m^2/s} \tag{31}$$

$$Q_{ac_{gm}} = 34.66\,\mathrm{MJ} \tag{32}$$

For harmonic mean:

$$k_{hm} = \frac{2}{\frac{1}{k_s} + \frac{1}{k_p}} = \frac{2}{\frac{1}{0.1379} + \frac{1}{1.99}} = 0.2579\,\mathrm{W/(m \cdot K)} \tag{33}$$

$$\alpha_{hm} = \frac{k_{hm}}{c_v} = \frac{0.2579}{2.05 \cdot 10^6} = 1.258 \cdot 10^{-7}\,\mathrm{m^2/s} \tag{34}$$

$$Q_{ac_{hm}} = 32.50\,\mathrm{MJ} \tag{35}$$

For logarithmic mean:

$$k_{\lg} = \frac{k_s - k_p}{\ln k_s - \ln k_p} = \frac{0.1379 - 1.99}{\ln(0.1379) - \ln(1.99)} = 0.6942\,\mathrm{W/(m \cdot K)} \tag{36}$$

$$\alpha_{\lg} = \frac{k_{\lg}}{c_v} = \frac{0.6942}{2.05 \cdot 10^6} = 3.386 \cdot 10^{-7}\,\mathrm{m^2/s} \tag{37}$$

$$Q_{ac_{\lg}} = 35.32\,\mathrm{MJ} \tag{38}$$

where: Qacs – heat accumulated using series arrangement of soil particles for calculating thermal conductivity; Qacp – heat accumulated using parallel arrangement of soil particles for calculating thermal conductivity; Qacam – heat accumulated using arithmetic mean between thermal conductivities of series and parallel arrangement; Qacgm – heat accumulated using geometric mean between thermal conductivities; Qachm – heat accumulated using harmonic mean between thermal conductivities; Qaclg – heat accumulated using logarithmic mean between thermal conductivities.

Ranging the distance *x*, from 0.01 m, to 20 m, we can observe how heat is accumulating underground in 180 days, from graph presented in Fig. 4. It can be observed that if heat transfer fluid has a steady temperature of 30°C, heat will only be stored in 10 m^3 of soil and after 10 m, soil will no longer store heat.

We used ANSYS to verify the results obtained and it proved that our results are confirmed, as seen in Fig. 5.

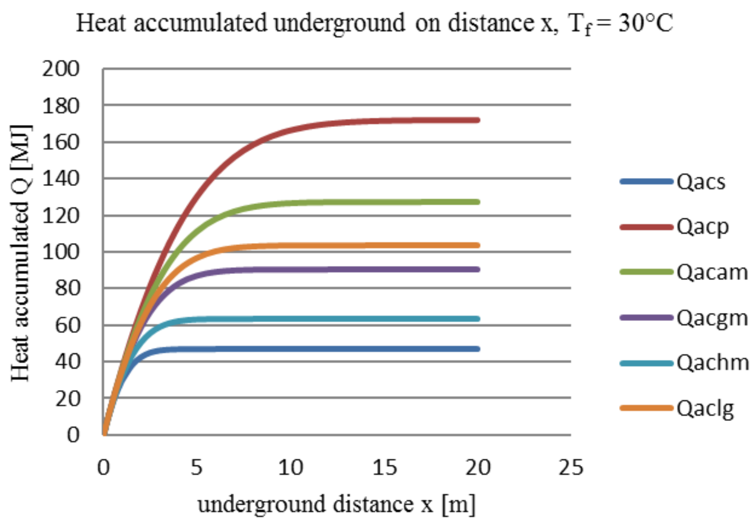

Fig. 4 – Heat accumulated underground using various methods to achieve a mean thermal conductivity for soil, using a constant temperature for heat transfer fluid of 30°C.

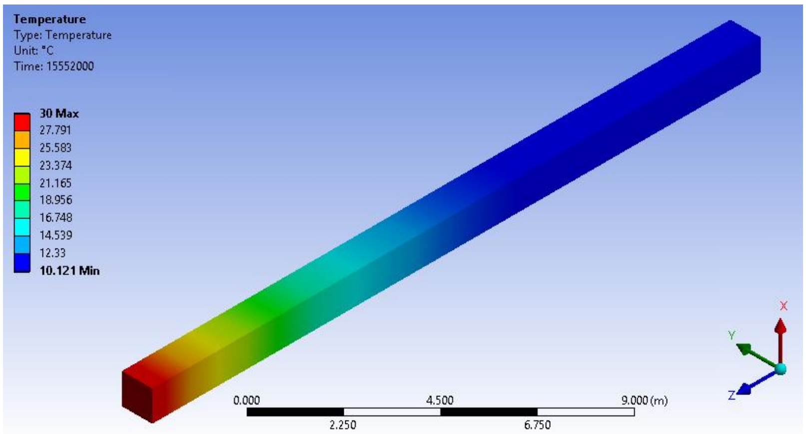

Fig. 5 – Heat accumulated underground using various methods to achieve a mean thermal conductivity for soil, using a constant temperature of heat transfer fluid of 30°C.

Another analisys was made with constant temperature of heat transfer fluid of 120°C. The graph presented in Fig. 6, was developed using equations above and it showed that the difference between temperature of heat transfer fluid from 30°C to 120°C is only in quantity of stored heat, in the same volume of soil. Again, results were verified with ANSYS and presented in Fig. 7.

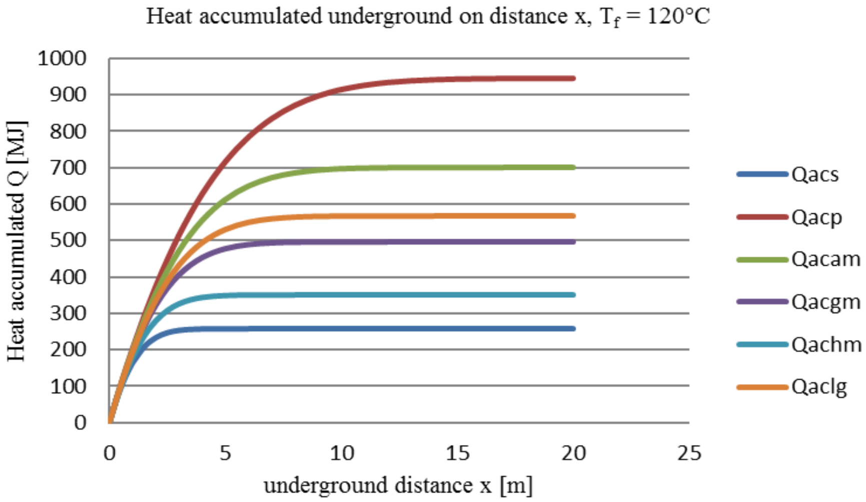

Fig. 6 – Heat accumulated underground using various methods to achieve a mean thermal conductivity for soil, using a constant temperature for heat transfer fluid of 120°C.

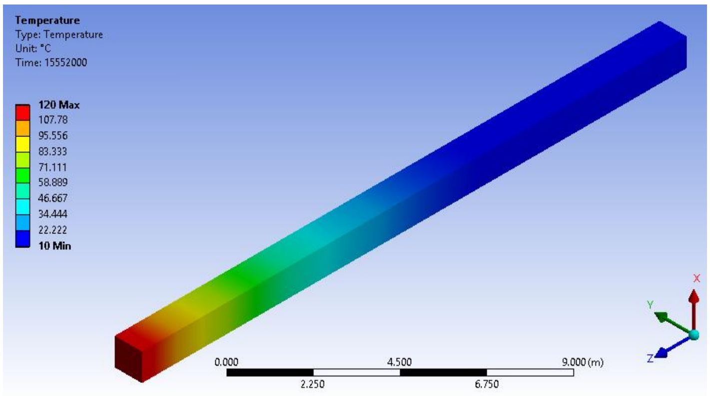

Fig. 7 – Heat accumulated underground using various methods to achieve a mean thermal conductivity for soil, using a constant temperature for heat transfer fluid of 120°C.

From graph in Figs. 4-7, we can see that Q_{ac}, accumulated heat, will increase slower after 10 m, because temperature inside soil increseas and storage volume remains almost constant. So we can consider a volume of 10 m^3 to 13 m^3 of soil to be enough for our underground energy storage, using this configuration.

In order to prove that by using a constant volume of soil, accumulated heat underground is increasing by increasing temperature of heat transfer fluid and also observe how thermal conductivity affects heat storage, in point x = 1 m, if we increase temperature of heat transfer fluid, from 30°C, to 120°C, we can see that accumulated heat will also increase, Fig. 8. We did the same, for x = 10 m, in this case, 10 m^3 of soil and presented results in Fig. 9.

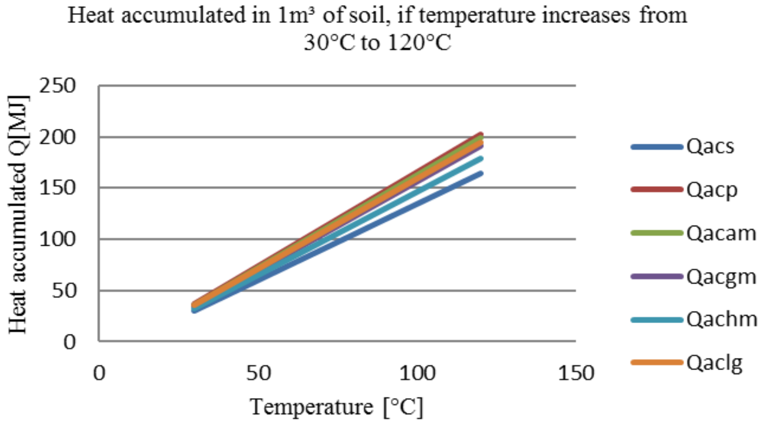

Fig. 8 – Heat accumulated underground if temperature of heat transfer fluid would increase from 30°C to 120°C.

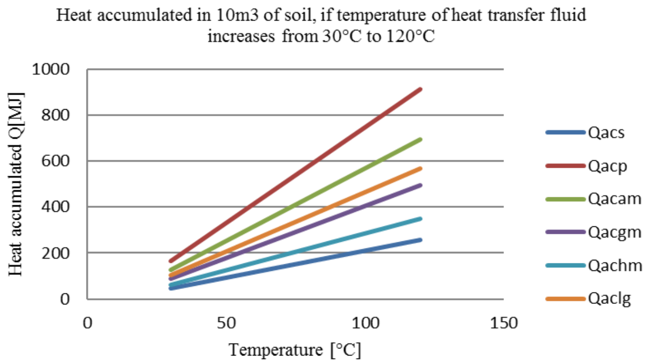

Fig. 9 – Heat accumulated underground if temperature of heat transfer fluid would increase from 30°C to 120°C.

From all graphs, we can see that a higher thermal conductivity of soil, will increase accumultated heat underground, but also, will increase the volume soil needed for heat storage.

It can be observed from Fig. 9, that in 180 days of charing thermal energy underground, in 10 m^3 of soil, thermal conductivity of soil has a serious impact over accumulated heat. For a temperature of heat transfer fluid of 120°C and a thermal conductivity of 0.1379 W/(m·K), in case of series arrangement of soil particles, accumulated heat in 180 days, is 257.18 MJ. In same conditions, accumultated heat for a thermal conductivity of 1.99 W/(m·K), is 914.60 MJ. So a soil rich in clay minerals and sand minerals is preffered in order to store thermal energy.

In Fig. 10, is presented heat accumulated varying time, using temperature of heat transfer fluid of 30°C.

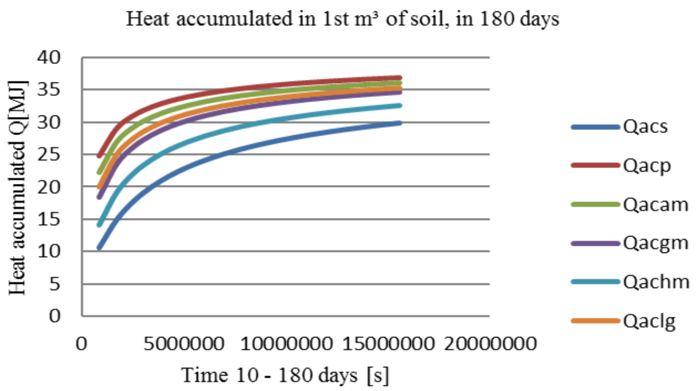

Fig. 10 – Heat accumulated underground for $x = 1$, (1 m^3), in time, from day 10 to day 180, for a temperature of heat transfer fluid of 30°C.

From Fig. 10, we can see that after 100 – 110 days, heat accumulates slower.

3. Conclusions

The paper presents an approximative analytical solution used to determine the heat seasonally stored underground. We used different solutions to evaluate the numerical results, in order to develop a model for underground heat storage. This mathematical model can now be used to determine the optimal temperature of the heat transfer fluid and charging time for different types of soil and also to evaluate the volume of soil that is necessary for storing heat undergound. Further researches will be on applications of determining discharge rate of undergound heat.

Nomenclature

R – thermal resistance, [(K·m)/W]
k – thermal conductivity, [W/(K·m)]
q – heat flux, [W/m^2]
T – temperature, [K]
x – distance from heat flux to measured temperature, [m]
h – heat convection coefficient, [W/(m^2K)]
t – time, [s]
Q – heat, [J]
A – wall surface, [m^2]
C_v – volumetric heat capacity, [J/(m^3·K)]
C_p – specific heat capacity, [J/(kg·K)]
ρ – density, [g/m^3]

Greek
δ – soil particle dimension, [m]
α – thermal diffusivity, [m^2/s]

Subscripts
s – series
p – parallel
t – thermal
i – index number
a – air
w – water
sm – sand minerals
cm – clay minerals
om – organic matter
f – heat transfer fluid
0 – initial
pw – plane wall
e - end
ac – acumulated

am – arithmetic mean
gm – geometric mean
hm – harmonic mean
lg – logarithmic mean

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EVALUAREA ENERGIEI TERMICE SOLARE STOCATĂ SUBTERAN

(Rezumat)

Această lucrare prezintă o soluţie analitică aproximativă utilizată pentru a determina căldura stocată sezonier în subteran. Acest model a fost aplicat pentru o perioadă de 180 de zile, având în vedere condiţii de contur de speţa a treia. Solul ca sistem de stocare a energiei, a fost întotdeauna considerat a fi un mediu omogen cu proprietăţi evaluate experimental. Domeniul conductivităţii termice a solului, a fost evaluat aproximativ, în funcţie de conductibilitatea termică a compuşilor solului. S-au presupus două modele în calculul conductivităţii termice aparente a solului, serial şi paralel. Aceste modele folosesc analogia dintre conductivitatea termică şi conductivitatea electrică. Volumul fiecărui compus depinde de concentraţia acestuia în sol. Această soluţie a analitică aproximativă poate fi adaptată la compoziţia reală a solului, potrivit datelor colectate prin studii geologice. Căldura stocată subteran în timpul sezonului ,,cald", din primăvară până în toamnă, a fost calculată ţinând cont de mărimea volumului de pământ subteran de încălzit, funcţia câmpului de temperatură şi conductivitatea termică aparentă.