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**Numerical thermal back-calculation of the Kerava Solar Village underground thermal energy storage**

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Abstract

With increasing pressure to reduce the fraction of energy coming from fossil fuels, there is an increased need for research into feasible and sustainable energy sources, such as solar energy. The problem with solar energy is the mismatch between supply and demand, and so the energy needs to be stored. This research paper is a part of the project titled “Tackling the Challenges of a Solar-Community Concept in High Latitudes”, and aims in helping to design a thermal energy storage system for southern Finland that is economically feasible and has a high performance. For this purpose, a back-calculation of the underground thermal energy storage (UTES) of the Kerava Solar Village was performed. The primary objective was to calibrate the numerical models to be used in an optimisation by quantifying the thermal properties of the surrounding granite and soil. The UTES of the Kerava Solar Village consisted of a rock pit filled with water and two surrounding rings of boreholes. COMSOL Multiphysics 5.2® was used to create a model in which the temperature of the rock pit was used as the heat source and the heat propagation through the surrounding rock as the output to which the measured data was compared. The best replication of the temperature inside the rock near the surface was achieved with a conductivity of 2.8 and 1.0 W/(m·K) for granite and soil respectively. When looking at the deeper sections, the best fit was obtained for a conductivity of 5.5 and 1.0 W/(m·K) for granite and soil respectively. These results are conflicting, and outside the realistic range for granite. The strange behaviour of the measured isotherms could be explained by a presence of an additional heat source in the ground originating from a leakage of hot water from the tank into surrounding rocks. The critical issue identified in this study was the lack of data. All the parameters of the system, such as the geology, hydrology, and detailed technical drawings, but also the temperature distribution inside the heat source, and heat storage medium need to be known for back-calculation study to be successful.

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1. Introduction

With increasing pressure to reduce the fraction of energy coming from fossil fuels, there is an increased need for research into available and sustainable energy sources. One of those sources is solar energy. The problem with solar energy is that the supply and demand are negatively correlated. In the summer period there is an abundant supply of solar radiation but a low heat demand, and in the winter months, this is reversed. A solution to this mismatch would be to store the energy into a system that gives the user the ability to take energy from the system when needed. This research paper is a part of the project titled “Tackling the Challenges of a Solar-Community Concept in High Latitudes”.

The Kerava solar project was the first Finnish solar district heating system using seasonal heat storage that was operating from 1983 till 1986 [1-8]. It was located in the town Kerava, about 35 km North of Helsinki (Fig. 1b).

The Kerava solar village harnessed the solar energy during the summer using solar collectors mounted on the roofs of single-family houses. The solar heat was then stored seasonally in a rock pit water heat store of 1500 m³ volume (Fig. 1a) by increasing the temperature of the water in the tank. The stored thermal energy was used to heat-up the buildings during the winter time with the help of a heat pump. Borehole heat exchangers were installed in the boreholes around the water store to increase the overall efficiency of the storage systems by recovering the heat loss from the water tank. The boreholes were drilled in two circles around the water store. The inner circle consisted of 18 boreholes to a depth of 22 m and at an angle of 12°. The outer circle had 36 boreholes to a depth of 24 m at an angle of 24°. The boreholes formed a rock store of 11 000 m³ which had the same effective storage capacity of 300 m³ of water. The heat loss was recovered by circulating cold water coming from the heat pump evaporator through the holes before returning the water to the bottom of the water store [4].

In this paper, the heat storage at Kerava Solar Village project is back-calculated using COMSOL Multiphysics 5.2® to calibrate the models for use in an optimization. Measured data is used as input, and the simulation output is compared to measured data. When the output correlates to the measurements, the confidence level of the simulated results increases.

2. Methodology

2.1. Available data

The Kerava Solar Village was monitored using 141 measuring points, which monitored temperatures in the piping system, the water store and inside the surrounding rock mass as well as energy flows. The heating plant contained 108 sensors, the homes and collector groups 30, and for the weather three sensors were employed.
For this paper, only the 18 sensors inside the water store, the 63 inside the rock, and the three weather sensors are relevant. The graphs depicting the temperatures inside the rock [6] and the temperatures inside the water store [8] use isotherms to visualize the temperature changes over time at a given depth. An example of such isotherm is given in Fig. 4.

Historical data containing technical drawings of the topography, soil layer and bedrock [9] was used to create a 3D-model.

2.2. Input data

The period from the 1st June until the 31st August 1984 was chosen for the simulation, as the energy flow through the boreholes in those months was zero to non-existent [6].

The temperature of the water store at the water level, as well as below 16 m, was unknown and was assumed. At the water level, the temperature was assumed to be 65°C because the boiler, which was used to create additional heat, had a set point of 65°C [4] and according to the graph it was above 60°C but below 70°C. At the bottom, the temperature was set to 15°C because according to [4] this was the maximum temperature at the bottom and the water store was being charged during this period. The isotherms were digitized and including the assumed values for the top and bottom were imported into COMSOL and were used as the heat source during the simulation. The initial temperature of the surrounding rock was taken from the graphs given by [6]. The depths of the isotherms on the 1st June were used with some assumed temperatures in between and a temperature of 5.3°C at a depth of 30 m, as this was the average air temperature of the region in the ten years before 1984 [10]. The outside air temperature graph [8] was digitized and the mean temperature was used for the simulation. The complete temperature distribution of the surrounding rock, as well as the water store, can be found in [11].

2.3. Output data

With the initial temperature state and the temperature changes of the water store, the temperature of the surrounding rock alternates during the simulation. The temperature changes measured at a 2 m distance from the water storage in the northern direction [6] were used for comparison with the simulations. The temperatures along a vertical line starting at the surface and going to a depth of 30 m, located 2 m away from the water store are extracted from the model for each day during the simulation. The depths of the relevant isotherms were calculated and consequently compared to the measured data from [6].

2.4. Model setup

The heat transfer in solids physics module was chosen for the simulation. It requires three thermal properties assigned to all domains, i.e. the thermal conductivity (\(k\)), heat capacity (\(C_p\)) and density (\(\rho\)) to solve the heat equation:

\[ \rho C_p \frac{dT}{dt} + \nabla \cdot q = Q \quad (1) \]

\[ q = -k \nabla T \quad (2) \]

2.4.1. Geometry

The geometry (Fig. 2) was created according to the cross-sections found in [9]. The cross-sections contain some identified material domains in each drillhole. The soil types present are silt and a sandy moraine which does not show continuity between boreholes. Hence, the soil was modelled as a single layer. Similarly, the bedrock consists of multiple, alternating rock domains without continuity. The rock types are light granite, dark grey quartz diorite, quartz, light quartz feldspar schist and dark amphibolite. For simplicity, the bedrock was modelled as a single layer
of granite. The complete model was build up out of 5 concentric domains to create boundaries on which the initial temperature can be set (Fig. 2). The radii of all domains correspond to the rock sensor distances from the water store. The water store of radius 5 m and height 20 m was cut into the middle of the model. The water level (zero elevation) was set just under the soil-granite boundary.

![Fig. 2. 3D-Models from AutoCAD according to [9], with (a) soil layer; (b) bedrock and (c) assembly of soil and bedrock. Blue is an inner cylinder of radius 7 m, magenta is 7 m until 11 m, green is 11 m until 15 m, yellow is 15 m until 19 m, and red is 19 m until border.](image)

2.4.2. Material thermo-physical properties

The average conductivity for granitic rocks in the world is 2.68 W/(m·K) [12] with a most typical range between 2 and 4 W/(m·K) [13]. The average heat capacity is 790 J/kg·K [12]. The typical range of thermal conductivities for Finnish granite is between 1.6 and 5 W/(m·K) with 3.5 W/(m·K) mean value [14]. Kukkonen [15] shows an average thermal conductivity, heat capacity, and density of 3.0 W/(m·K), 714 J/kg·K and 2635 kg/m³, respectively. The complete list of input parameters for rock and soil domains used in the model is given in Table 1.

The heat capacity of soil at constant pressure was calculated using:

\[
C_{vs} = \frac{\rho_s}{\rho_w} \left(0.18 + 1.0 \frac{W}{100}\right) * C_{vw} = 2412.3 \text{kJ/m}^3\text{K}
\]

\[
C_{ps} = \frac{C_{vs}}{\rho_s} = 1419 \text{J/kgK}.
\]

Where \(\rho_s\) and \(\rho_w\) are the density of soil (1700 kg/m³) and water (1000 kg/m³) respectively, \(w\) is the water content (15 %), and \(C_{vw}\) is the heat capacity at constant volume for water (4300 kJ/m³·K) [16]. The thermal conductivity was first assumed to be 1.5 W/(m·K), but it was varied during the parameter sweeps.

<table>
<thead>
<tr>
<th>Thermal property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock thermal conductivity</td>
<td>3.5</td>
<td>W/(m·K)</td>
</tr>
<tr>
<td>Rock heat capacity</td>
<td>714</td>
<td>J/(kg·K)</td>
</tr>
<tr>
<td>Rock density</td>
<td>2635</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Soil thermal conductivity (first assumption)</td>
<td>1.5</td>
<td>J/(kg·K)</td>
</tr>
<tr>
<td>Soil heat capacity at constant pressure</td>
<td>1419</td>
<td>J/(kg·K)</td>
</tr>
<tr>
<td>Soil density</td>
<td>1700</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>
2.4.3. Study steps
For the initial temperatures inside the domains, an interpolation function was used. It interpolates linear and extrapolates constant. Because the zero elevation level (water level) was set just underneath the soil, there was much material above this level, and because of the constant extrapolation, this material attained the same temperatures as at the zero level. This was too hot and not representing reality, but there was no data on this domain, so to get a temperature distribution that resembles reality better, a stationary study step was introduced that precedes the main simulation step to approach the real values outside the known values. The main simulation, which was the second study step, used the results of the first study step as its initial values.

2.4.4. Boundary selection
During the stationary study step the initial rock temperature from [6] were imported separately at 2, 6, and 10 m away from the water store. Cylindrical temperature boundaries were created at each of those distances, and the temperature was set to its corresponding interpolation function. Two other temperature boundaries were created, one that sets the water store boundary temperature to the value of the first day used for the simulation and the second that introduces a constant temperature at a depth of 30 m of 5.3°C. The heat flux boundary describing the outside air was given an external temperature averaging the 30 days previous to the period of interest which was 10°C. The part of the water store that was cut into the model but was above the zero level was set to an adiabatic boundary just as the sides and bottom of the model. The boundaries are visualised in Fig. 2.

During the second time-dependent study step, the water store was modelled using two temperature boundaries, one for the side of the store and one for the bottom. The temperature on those boundaries was described by an interpolation function dependent on time and depth as outlined by the data from [8]. The outside air temperature was modelled by an external, natural convection, heat flux boundary on the surface using the air temperature found in [8]. The same adiabatic boundaries were used.

![Fig. 3. North-South Cross-section of the 3D-model. Red lines show the location of temperature boundaries with 1 for the water store, 2-4 for the concentric cylinders (radii of 7, 11 and 15 m) with known temperatures, and 5 for the low temperature at depth. The green line shows the heat flux boundary at the top surface, and blue show the insulated boundaries on the outside of the model and in the water store above the water line.](image)

2.4.5. Meshing
The required precision level of the simulated results is decreasing with increasing distance from the water store, and thus the mesh can get coarser with increasing radius and depth. The domain that was directly surrounding the water store used the predefined extremely fine element size and the concentric domains going outward were assigned with the predefined extra fine, finer, and the fine element size. The last one was slightly customised to use a minimum element size of 1.06 m to avoid problems with narrow regions. The domains below a depth of 30 m and the domain surrounding the last cylindrical domain were assigned the predefined normal element size.
There were still some problematic regions such as the overall minimum element quality, which is $7.327 \times 10^{-12}$ but because they were all in an area that was of low interest this should not interfere with the results. The average element quality (quantifies the regularity of the shapes of the mesh elements from 0 to 1, with 1 being the highest) of all 230,905 elements was 0.71.

### 2.5. Results comparison

To be able to evaluate which simulation produces better results, a quantifiable parameter needed to be created that represents the quality of measured data reproduction. An obvious parameter would be the coefficient of determination ($R^2$). The measured 35°C isotherm, however, appeared for the first time around the 9th June and so the simulated isotherm might appear early or late and the $R^2$ could only be calculated when the simulated, and measured isotherm both had value. The model could also lose heat near the surface to the surrounding air, and it might be 35°C in two locations. This meant that the $R^2$ value needed to be adjusted. The standard $R^2$ value was calculated for the deepest part of the simulated isotherm that shared the time range with the measured one. It is defined as:

$$ R^2 = 1 - \frac{SS_{res}}{SS_{tot}} $$

(5)

$$ SS_{res} = \sum_t (h_t - s_t)^2 $$

(6)

$$ SS_{tot} = \sum_t (h_t - \bar{h})^2 $$

(7)

$$ \bar{h} = \frac{1}{n} \sum_{t=1}^{n} h_t $$

(8)

Where $h_t$ is the depth of the measured isotherm at time $t$, and $s_t$ the depth of the lower part of the simulated isotherm at time $t$.

Then, to adjust for the upper part of the isotherm and the part of the measured or simulated isotherm that is outside the simulated time range, a surface calculation was done to serve as a penalty to the standard $R^2$ (Fig. 4).

The surface penalty was calculated as a ratio of the mismatch surface to the total green surface above the measured isotherm (Fig. 4). The mismatch surface is the surface above the measured isotherm until the dividing line (Fig. 4a) plus the surface above the simulated isotherm from the dividing line (Fig. 4b). This ratio was subtracted from the regular $R^2$ to give the adjusted $R^2$ value.
3. Results and discussion

The soil thermal conductivity was varied in a parameter sweep between 1 and 2 W/(m·K) and for the granite between 3 and 4 W/(m·K) with increments of 0.2 W/(m·K). Because the soil only had an effect on the upper layer, the 35°C isotherm was evaluated separately. The final results are displayed in Fig. 5 and Fig. 6.

When looking at the 35°C isotherm only, an optimal fit was found with a conductivity of 2.8 and 1.0 W/(m·K) for granite and soil respectively (Fig. 5).

To find the optimum for all isotherms, the conductivity of granite was increased with a constant soil conductivity of 1 W/(m·K).

When looking at all isotherms, an optimum was reached with a conductivity of 6.5 and 1.0 W/(m·K) for granite and soil respectively (Fig. 6). When looking at all isotherms except the 35°C, an optimum was reached with a conductivity of 5.5 and 1.0 W/(m·K) for granite and soil respectively (Fig. 6).
The values for the conductivity of granite over 4.0 W/(m·K) were unrealistic and produced the 40°C isotherm near the surface which should not show up according to the data. The observed behaviour of the isotherms suggests a presence of an unidentified heat source in the subsurface that can be an outcome of a leakage of hot water from the water tank through fracture zones.

The main issue with the simulation is the scarcity of input data. There is not enough data to build a comprehensive model. As a result, the current model was limited by the fact that the rock in the subsurface was modelled as homogeneous and isotropic granite domain. A more realistic representation of the geology would include several rock domains, with the anisotropy of the thermo-physical properties taken into account. The discrepancies between the measured and simulated data could also be reduced by modelling the water store as a body of water to account for temperature difference at the water to rock interface compared to the centre of the tank. Such configuration would produce more realistic temperature distribution in the tank and allow for the introduction of turbulence created by the varying height of the water inlet.

4. Conclusion

The purpose of this paper was to aid in the design of a thermal energy storage system for southern Finland that is economically feasible and has a high performance. To help achieve this goal a back-calculation of the underground thermal energy storage of the Kerava solar village has been performed to calibrate future models and to increase the confidence level of simulated results.

The R-square method with the surface penalty calculation was successfully used for the comparison of the measured and simulated data to find the thermal properties that lead to the best fit. However, the results showed an inconsistency between the simulated and historical isotherms. When looking at different isotherms, the resulting best fitting thermal properties were conflicting and unrealistic. This could be linked to the presence of a potential heat source that originated from seepage of hot water from the water store into the surrounding rock through fractures. Such addition of heat in the ground could explain the abnormal behaviour of the isotherms observed from the data.

This study revealed the importance of several site-specific parameters that are essential for reliable predictions. For example, a good description of the local geology (such as rock domains, fracture zones and hydrogeology) and more detailed description of the time-dependent temperature data (such as rock temperatures at different locations) could help to build a more comprehensive model. For future studies, a well-documented project with measured data of high quality and a good description of relevant parameters is recommended.

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