Underground heat mine – potential for large scale production and storage of thermal energy

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Abstract. We have studied possibilities to utilize the 1.4 km deep Pyhäsalmi mine as a source of geothermal energy. Measured thermal conductivities of the Precambrian (1.9 Ga) crystalline bedrock hosting the massive Cu-Zn sulphide deposit vary between 2.5 and 3.5 W/m·K, depending on the rock type, and the bedrock temperature increases with depth by 12–14 K/km. The design concept for heat utilization studied in this project is based on an underground borehole field exchanging heat between the bedrock and the water circulation loop, which then transfers thermal energy to the heat pumps. In the borehole heat exchanger (BHE) performance evaluations, we focused on a coaxial configuration, in which formation water circulates down in contact with borehole wall and returns inside a pipe. The borehole field modelled has a hemispherical geometry, so that all boreholes start from a central hall at the bottom of the mine (where the temperature is 21 °C) and would be directed radially outwards. Our reference case consists of 136 boreholes having length of 300 m, thus covering a rock volume of 57 million cubic meters. Simulations indicate that this BHE fields can sustain heating power of 1 MW for at least 44 years, but the average temperature of the borehole field would decrease by about 10 degrees. Thermal power can be increased substantially by increasing the borehole density, but the lifetime of the BHE field decreases.

1. Introduction
The Pyhäsalmi Cu-Zn-S mine in Finland is an underground facility that has gradually reached the depth of 1.4 km during its 60 years of operation. Extraction of metals from the mine will end in the near future and different re-use options of the underground space have been studied and planned. These include pumped hydroelectric energy storage (PHES), underground research laboratory, as well as various underground cultivation and storage applications.

Today, many cities consider low-temperature geothermal energy as one of the options to replace the use of fossil fuels for heating. However, in densely built environments, the lack of unbuilt ground space leads to requiring a high geothermal energy supply from a limited ground area. This motivates the current efforts to drill ever deeper boreholes (to depths of kilometres) to obtain more ground-source energy to heat pumps or even to direct supply of heat to district heating networks. Utilization of mine water thermal energy from old flooded mines is a well-known concept [1]. However, we studied the utilization of a deep drained mine for the extraction of thermal energy stored in the bedrock.
2. Geological and thermal characteristics of the site

The Pyhäsalmi volcanogenic massive sulfide (VMS) ore deposit of volcano-sedimentary origin is situated in Precambrian metamorphosed crystalline bedrock (~1900 Ma old). The lithostratigraphy of the deposit is comprised of felsic and mafic metavolcanic rocks, of which the felsic volcanic rocks and related altered rocks dominate the lower part surrounding the deposit. Mafic volcanic rocks occur mostly in the upper part of the stratigraphy overlying the deposit [2]. The mafic volcanic rocks originate from basalts, and the felsic volcanic rocks originate from rhyolitic and andesitic tuffs and lavas. The mafic rocks are dense and have low silica content compared to the felsic rocks. Pegmatite veins occur within the metavolcanic sequences, and larger intrusives are located in the eastern part of the site. The term granitoid refers here to igneous intrusive rock types (granite, quartz diorite, granodiorite, pegmatite). The metavolcanics have preserved much of the primary depositional variation, even though they were folded and deformed in later tectonic events. The deformed ore body extends from the surface down to a depth of 1,400 metres. The rocks around the orebody have been strongly altered by hydrothermal processes and deformed by later tectonic events.

The ore was initially excavated as an open pit mine and subsequently as an underground operation. Access to the underground working levels is by a decline (spiral tunnel) or by the main shaft elevator, which is predominantly used to lift the ore. Detailed 3D geological structure and the extent of the ore body has been ascertained by numerous drill holes during the progress of the mining operation (figure 1). We selected 57 representative drill core samples from the main rock types, for which the thermal conductivity, specific heat capacity and density were measured in the GTK laboratory. Thermal conductivities were measured with two methods, the Divided Bar and Hot Disk TPS and heat capacities were measured calorimetrically [3] [4] [5].

Figure 1. Geology of Pyhäsalmi mine site in 3D. The upper and lower ends of the generalized bedrock cylinder around the orebody (magenta) are at depths of 500 and 2000 metres below the sea level, respectively. The decline spiral is shown by blue. Exploration drill holes show the actual lithological variation: Yellowish colours indicate formations predominated by felsic volcanic rocks; green colour indicates mafic volcanites; red colour indicates granitic (pegmatites) rocks and granodiorites. Thermal-petrophysical properties of the rock categories are summarized in the included table.
Petrophysical measurements indicate that mafic and felsic volcanic rocks are clearly different with respect to their thermal properties. High thermal conductivity of the felsic volcanites, even in comparison with granitic intrusives, is evidently related to the high silica content (up to 70-80 %) of the primary volcanic rocks (e.g. rhyolite) [6]. Variability of heat capacities between rock types is small, and mainly due to the density differences.

Bedrock temperatures were measured as a function of depth from several deep boreholes down to a depth of 2100 m (figure 2b) using the distributed temperature sensing (DTS) method. DTS method is based on detecting back scattering of light in a fibre optic cable. The method utilizes the intensity of Raman scattering to measure temperature distribution along the entire length of the cable with a spatial resolution of one metre between consecutive measurement points. Typically, the thermal resolution is around 0.01 K and the detection accuracy is in the range of ±1°C. Measurements are calibrated by a temperature gauge at the surface (Pt100) or by connecting an accurate temperature logger to the lower end of the cable during measurement.

Only few of the underground drill holes enabled temperature measurement. In addition to blockage or disappearance of the borehole mouth, low – near horizontal – inclination and lack of borehole water precluded measurements. On the other hand, many holes drilled in steep angle from the deepest part of the mine had to be plugged because of a strong overflow. There are, however, many very deep (≈1500 m, diameter 76 mm) exploration drill holes available for measurements from the ground surface on the eastern side of mine site. By combining all measurements and calculating the values to the vertical depth scale, we obtain the geothermal gradient (i.e. depth vs. temperature relation) for the bedrock near the Pyhäälmi mine (figure 2a). Thermal disturbance caused by the mine tunnels can be clearly seen in the measurement starting from the depth level 660 m, where temperature gradient of the uppermost 20 m is disturbed. Deeper down this effect vanishes, and the bedrock wall temperature exceeds the ventilation temperature.

Figure 2. Temperature vs. depth graph constructed from all temperature measurements made in 8 drill holes and spatial distribution of the drill holes.
Geothermal gradient measured from the uppermost two kilometres in Pyhäselmi mine is about 12–14 K/km. Figure 2 also indicates that the gradient is close to 12 K/km in the upper part but increases to about 14 K/km in the deepest measurements. The apparent gradient change can be attributed to the last glaciation, because similar effect has been observed in other deep measurements in Finland, as well [7]. No overall change in thermal conductivity was observed that could explain the gradient change. Geothermal heat flow density \(q\) can be estimated from the average thermal conductivity \(\lambda\) of the bedrock and the average geothermal gradient \(\Gamma\) by Fourier’s law in 1D:
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q = \lambda \cdot \Gamma = 2.92 \text{ W/m/K} \cdot 0.013 \text{ K/m} = 0.038 \text{ W/m}^2 = 38 \text{ mW/m}^2
\]

3. **Performance of the borehole heat exchanger**

A crucial question is how to extract thermal energy from the deep and warm bedrock, which – in this case – would be accessible without expensive deep drilling. Based on a structural geological model, we identified some planar structures that might be water conducting zones between injection and abstraction wells. However, these structures seemed to be few and uncertain. Thus, instead of the geothermal doublet system, we chose to investigate borehole heat exchangers (BHEs), in which fluid flow takes place in a single well and which are thus more predictable and multiplicative.

Underground conditions enable and require BHEs different from those used in surface-based solutions such as closed loop U-tube and coaxial tube as well as heat extraction from open-well water (figure 3). Open systems extract heat from formation water, which is then returned to an injection well. Standing column concept utilizes both heat conduction and convection through the borehole wall [8]. Boreholes drilled downwards in an underground space are often overflowing and become pressurized when plugged—or they may remain practically dry in the absence of water-bearing fractures. We conclude that an underground BHE needs to be made hydraulically closed by means of a collar construction shown in figures 3e and 3f.

![Figure 3. Borehole heat exchanger types. Closed systems usually circulate an antifreeze solution either in a U-tube (a) or in a closed coaxial tube (b). Open systems circulate or use the borehole water directly. The open system presented in (c) was used in the Luleå borehole thermal storage [9] while (d) is a simplified presentation of the standing column well, in which the borehole is kept at lowered hydraulic head to facilitate convective heat supply. Our underground BHE concept is presented in (e) and (f) in which the downflow occurs in the annulus and coaxial pipe respectively.](image-url)
The proposed underground BHE has the following properties: (1) there is no lifting of fluid against the gravitation, but the pumping force is only needed to compensate the flow friction of the fluid circulation; (2) the borehole thermal resistance is considerably diminished because the heat transferring fluid is in direct contact with the rock wall; (3) the collector dimensions as well as the flow rate are optimized for convective heat transfer; (4) the collector pipe wall is insulated which increases the BHE efficiency as the short circuiting effect between the cold and warm flows is minimized. Currently, testing of the BHE concept is underway. However, here we present only the results of our theoretical modelling study.

We studied the performance of a coaxial BHE by varying operational parameters and simulating the performance. The operation of a single U-tube BHE was also simulated for comparison. Modelling and simulation were based on the finite element method and solved using COMSOL Multiphysics®. We constructed the model for the coaxial BHE as a 2D axisymmetric model with the symmetry axis going through the centre of the coaxial pipe and the U-tube model as a 3D model with one symmetry plane. The heat collector was modelled as a tube with flowing water inside. Heat was transferred by conduction from the bedrock to the water circulating in the borehole or inside a closed collector loop immersed in the borehole water. Fluid flow was modelled using forced convection with a constant velocity profile and turbulence was approximated using a very large thermal conductivity on the horizontal plane, i.e., the plug flow approximation was used in both models.

The effect of collector pipe properties on the thermal output of the BHE was investigated by varying the pipe radius, pipe wall thickness and thermal conductivity of the pipe. The effect of insulation on the thermal output was investigated by assuming a composite pipe with air between its walls (figure 4). Furthermore, the flow rate of the heat carrier fluid and the operation mode of the BHE (i.e., downflow in annulus, which is normal mode, or downflow in the pipe which is reverse mode) were also varied to investigate their effect on the thermal output of the BHE. The results from the coaxial BHE simulations using different operation modes and pipe insulation levels were compared with the results from corresponding U-tube BHE simulations (figure 5). The effect of insulation was also simulated by increasing the length of the insulated section along the pipe wall. Parametric simulations indicate that a coaxial collector insulated throughout its length with fluid injection through the annulus attains the best performance. In case of the coaxial BHE performance, the insulation of collector wall is the key factor, and the operation mode is the subsequent factor. U-tube BHE attains lower performance than any of the simulated coaxial BHEs.

Figure 4. 3D model of the composite pipe with hollow spaces between its inner and outer walls. Heat flow modelling shows that the narrow walls separating the inner and outer walls from each other conduct most of the heat in the system. The entire tube wall (12 mm) in this construction has an equivalent (apparent) thermal conductivity ($\lambda$) of 0.1 W/(m•K), if made of PE $\lambda = 0.42$ W/(m•K)
Figure 5. Vertical temperature profiles of down and up flowing fluids in the 300-meter-deep coaxial borehole heat exchanger with different operation modes compared with the U-tube borehole heat exchanger. The borehole radii were 140 mm and flow rates were 0.6 litres per second. The results are from the end of the 25th year of simulation.

The effects of the borehole and pipe radii as well as the flow rate on the performance of BHEs were examined. The highest thermal performance was attained in a large-diameter borehole, but the difference between larger and smaller diameter boreholes is minimal. A larger inner radius of the coaxial pipe in a BHE allows a larger volume flow which leads to better BHE performance than in the case of coaxial pipes with smaller radii. The dimensions of a borehole diameter versus a pipe diameter are parameters to be optimised. Controlling the flow rate allows to attain either a higher outlet temperature or a higher heat rate from BHE as there is an inverse relationship between the outlet temperature of circulation water and the borehole thermal power.

4. Performance of the underground borehole heat exchanger field
To extract large amounts of geothermal energy from the deep bedrock, a borehole heat exchanger field would need to be constructed in the deepest levels of the mine. Such a field could be constructed by drilling boreholes from a central space, fanning them out into the surrounding bedrock. As only BHEs that incline downward would be considered, the BHE field would occupy a hemispherical volume below the space from which it would be constructed.

To investigate the performance of such a BHE field, we constructed a three-dimensional finite element model of a hemispherical BHE field that is comprised of 136 boreholes. The directions of the boreholes were determined using a geodesic sphere with 252 vertices of which 136 lower hemisphere vertices were used as the endpoints of the boreholes. This ensured that all the BHEs extracted heat from approximately equal volumes of rock (the endpoints were approximately equidistantly distributed on a hemispherical surface) which is the optimal way to construct a hemispherical BHE field.
The deepest mine tunnel at a depth of 1,440 m was chosen as the depth level from which the BHE field would to be constructed. According to measurements, the temperature at this depth is 21 °C so that the 57 million m$^3$ volume of deep bedrock spanned by the 300-metre-long boreholes of the field (Figure 6) would host 1100 GWh of thermal energy (lowering the temperature of the bedrock volume to 2 °C).

The BHE type chosen for modelling was the coaxial normal mode BHE with insulated pipe walls which was found to be the most efficient underground BHE type in the heat collector investigation. The BHEs were modelled fully in three-dimensions, including the collector pipes and heat carrier fluid flows in the annuli and pipes. As in the collector investigation, the fluid flow was modelled using the plug flow approximation. The evolution of the temperature field in the BHE field and in the surrounding bedrock was simulated for one million years so that the heat transfer in the model reached steady state conditions. The lengths of the BHEs were varied between 300 and 600 meters between simulations.

Figure 6. Deep hemispherical borehole heat exchanger field. The field has 136 boreholes which are 300-m long (yellow tubes). The field was constructed below the ore body (magenta volume) from the end of the deepest mine tunnel (blue tube) at a depth of 1,440 m.
The results indicate (Figure 7a) that a field of 136 BHEs could produce a constant heat rate of 1 MW (or 9 GWh/a) for a minimum of 44 years with 300-meter-long BHEs. If the BHE length is increased, the 1 MW heat rate could be sustained for a longer period. A field with 600-m long BHEs could sustain the 1 MW heat rate even 709 years. The heat rate of 2 MW (or 18 GWh/a) could be sustained for a much shorter time period (Figure 7b). With 300-metre-long BHEs, this level of heat extraction could be sustained only for 3 years. Increasing the BHE length to 600 metres gives 103 years more of sustained heat extraction with 2 MW.

We observed that once the deep hemispherical BHE field has consumed all accessible thermal energy in its vicinity and a new steady state has been reached (Figure 8a), it gets replenished only by the geothermal heat flux coming from below the field (Figure 8b). The field with 300-meter-long BHEs could access 86% (942 GWh) of the stored heat of 1100 GWh and had a replenishing rate of 162 kW that could be sustained infinitely.

Figure 7. Results of finite element simulations. The figures show how long a constant heat extraction of 1 MW (a) and 2 MW (b) can be sustained from a field of 136 BHEs having lengths (300–600 m).

Figure 8. Thermal energy extracted by the deep hemispherical borehole heat exchanger field, operating at maximal power, and the temperature disturbance caused by it. (a) The field extracts 942 GWh of thermal energy from within the field volume during the first 100 years of operation after which all replenishing energy comes from the geothermal heat flux at the rate of 162 kW. (b) The heat extraction causes a temperature drop in the vicinity of the field which is replenished only by the geothermal heat flux. The black arrows indicate the direction of heat flow.
5. Discussion and conclusions

In the present drained conditions, the Pyhäsalmi mine has a substantial head start regarding the possibilities of exploiting geothermal energy from depths below 1.4 kilometres. However, the underground space, which was excavated during the mining operations, and which is essential to access the deep bedrock, cannot be easily recreated for geothermal energy production in densely populated urban environments. Consequently, in addition to studying the feasibility of this exceptional geothermal exploitation concept in a mine setting, we also put a major effort to study the possibility to use underground space, in general, in the utilization of geothermal resources. Obvious benefits can be seen in terms of land use as the underground BHE field would not take up ground space and management of the heat transfer fluid. In underground conditions, i.e., below the (undisturbed) groundwater table, formation water can be used as the heat transfer medium without considerable environmental effects, especially if seated deep enough below the near-surface fresh groundwater domain subjected to the hydrological circulation.

The use of a BHE was concluded to be the straightforward choice to extract heat from the bedrock. The preferred collector configuration was proposed to be the semi-open coaxial collector with a single central tube in the borehole, because in this configuration the heat-collecting water is in direct contact with the bedrock and, thus, heat transfer is more effective than in other configurations. Due to the simple geometry, pressure loss of this collector configuration is low, making it suitable for use in deep and/or slim boreholes, thus, possibly reducing drilling costs. The numerical simulations indicated that borehole diameter has only a very small effect on the effectiveness of a BHE. Interestingly, neither the thermal insulation of the collector pipe nor the direction of the circulation had a significant effect on the efficiency of a 300-metre-long BHE.

As a rule, the total yield of thermal energy from boreholes depend on the active metres available, as well as on the temperature and thermal conductivity of the bedrock surrounding the boreholes. Because the cost of drilling increases strongly with increasing borehole length, our strategy was to study a borehole field consisting of relatively short boreholes, i.e., 300-metre-long boreholes as the reference case. Having a thermal power of 1 MW as the base case, we generated a hemispherical borehole field for the modelling purposes. Simulations show clearly that geothermal energy in our bedrock has two components: the huge amount of thermal energy stored in the bedrock during the geological history (heat in place) and the smaller continuous renewable geothermal heat flux.

Large-scale extraction of heat from the bedrock creates a cold region with relatively sharp boundaries, which is mainly replenished by the slow geothermal heat flux, unless heat injection is included in the operational scheme of the BHE field. On the other hand, persistence of a sharp thermal boundary indicates that the bedrock has a good ability to store thermal energy, if well isolated from the cold ground surface.

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