Efficient modelling of flow and heat in abandoned flooded mines coupled to parameters estimation: case study Heerlen, the Netherlands

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ABSTRACT

Water from abandoned flooded mines can be used for heating and cooling purposes. This study explores how such mines can be modelled to assess the sustainable energy output and hence to determine the evolution of the geothermal fluid flowrate and temperature. The proposed modelling approach provides insight into the heat storage capacity, heat transfer, water movement, sustainable exploitation and depletion of the underground system. To come up with a fast-computing, flexible and accurate model that can handle the typical geometry of a mine, a custom-made model based on the EPANET code from EPA is proposed. The original model is extended so that thermal interactions between the fluid and the surrounding rocks are taken into account. This is done by adding a heat exchange calculations model to account for this thermal water/rock interaction. This model is a parametrized first order heat exchange model. To estimate the parameters of the model a Markov-Chain Monte-Carlo method has been implemented. The calibrated model can be used to explore some applications, like the potential of high temperature storage, efficiency of heat storage and equilibrium exploitation and depletion of flooded mines. The abandoned and flooded mines of Heerlen (The Netherlands) are chosen as a use case.

1. INTRODUCTION

The use of low temperature geothermal energy from abandoned mines ted some interest, leading to some research worldwide and potential assessment (such as in Poland: Malolepszy (1998), in Belgium: Van Tongeren and Dreesen (2004), in Canada: Ghomshei et al., (2003); Lund, (2003); Raymond and Therrien, (2007)). Few examples of the successful use of mine water in geothermal heat pumps systems installations are known from Canada (Springhill, Nova Scotia (Jessop, 1995)), the Netherlands (Heerlen), Spain (Hunosa), USA (Park Hills, Missouri), Germany (Rottluff 1998) and the UK (Lumphinnans and Shettleston, Scotland (Burke, 2002)). The Mine water system in Heerlen (the Netherlands) is a unique example of a mine water system being used to deliver heat and cold and to serve as a storage reservoir.

Reliable reservoir modelling is crucial to predict how geothermal mine water systems will react to predefined exploitation schemes and to define the energy potential and development strategies of large-scale geothermal – cold/hot storage mine water systems.

Generally, the heat capacity of the mine systems is limited especially when the mine is foreseen to be used for heat/cold production mainly. It is thus mandatory to assess the total rate of sustainable heat/cold extraction before exploitation of the resource (Ghoreishi et al., 2012) as well as storage capacity of the system (Ferket et al., 2011).

To assess the capacity of the system for extraction of heat or cold, analytical and semi-analytical solutions have been proposed for simple geometries and homogeneous reservoirs (Loredo et al., 2017; Rodriguez and Diaz, 2009). A few studies have also been conducted using numerical approaches to assess the capacity of realistic minewater reservoirs accounting for the complexity of the network of galleries (Ghoreishi et al., 2012; Ferket et al., 2011). In this paper we propose improved numerical modelling of heat and flow in mine systems that can be coupled to control applications and to parameters estimation.

Most numerical reservoir modelling software is developed for typical environments, such as porous media (i.e. many codes developed for petroleum reservoirs or groundwater formations, like TOUGH2 [Pruess et al., 1999] or COMSOL (Reference Guide, 2007) and cannot be applied to mine systems. Indeed, mines are atypical environments that encompass different types of flow, namely porous media flow, fracture flow and open pipe flow usually described with different modelling codes. Efficient modelling tools are needed to understand, predict, control and follow-up mine water reservoirs.

2. METHODOLOGY

In this work we propose a fast-computing, flexible and accurate model that can handle the typical geometry of a mine. The basis of this work is a custom-made model based on the EPANET code from EPA (Rossman 2000)

proposed by Ferket et al. (2011). The existing hydraulic module of EPANET allows to integrate the complex geometry and advective flows in the mine but EPANET is not originally designed to account for heat transfer. Ferket et al. (2011) modified the code to include heat transfer from the surrounding host rock to the fluid that circulates into the galleries. Their model assumes unilateral fluid/rock heat interaction (the rock temperature was kept at a fixed value). As a consequence, the model cannot take into account the depletion of the surrounding rocks and the long term impact of the exploitation on the host rock cannot be assessed. Nevertheless, the model proved to be well suited for short term modelling. It was validated by comparing its results with historical data available from the Heerlen mine. Up to now, the numerical model was used as a tool to follow up the resource and to detect any unexpected behaviour of the reservoir.

In the current paper we propose an update of the 2011 model to achieve reliable long term modelling of minewater systems. In this updated model, the rock temperature is no longer fixed on the wall of the galleries but at a given distance from them (radius of influence). This distance can be fixed by the user or determined by means of parameter estimation method. Hence, in the updated EPANET version, bilateral heat transfers between the rock and the fluid are taken into account. Using this new numerical model, development strategies of the system on the long term can be adapted and optimized. Recommendations can be formulated for the future reservoir exploitation if it appears that they are not optimal and jeopardize the sustainability of the reservoir use.

Compared to the 2011 model, additional equations for describing heat flow from the rock massif to the fluid circulating into the mine galleries have been implemented. The advantage is that the full complexity of the subsurface mine structure is described by a network of pipes and that computing is still fast enough (less than one hour for a network of hundreds of pipes) to allow implementing and testing several scenarios in an efficient way.

Numerical Implementation

EPANET improvement

EPANET can calculate fluid transport in complex piping systems, which is the type of flow we assume to happen in flooded mines. It has a module to evaluate 'chemical' reaction in the fluid. We have modified this module to follow water temperatures. The novelty here is that a rock compartment is added around the galleries and discretized so that additional properties are added to every pipe segment of EPANET. These additional states describe the rock temperature at variable distances from the pipes.

Similar to Ghoreishi-Madiseh et al. (2012), in our model, we make the assumptions that water will move chiefly through the mine galleries and that the advection of water from the host rock into the galleries is negligible as well as natural convection inside the rock mass. In the case of Heerlen, it has been observed that most of the flow effectively flows through the galleries. However, it appears that water infiltration is also playing a role. Our model can take this additional heat exchange into account indirectly by using an "equivalent thermal conductivity for the rock" rather than the exact value. This equivalent value can be estimated by means of parameter estimation method.

Figure 1 shows the schematics of a pipe in the updated EPANET model. Water flows in the inner pipe and exchanges heat with the surrounding rock gallery. For the heat exchange the geometry is assumed to be axisymmetric.

First the hydraulics is solved with the original hydraulic module of EPANET. In a second step, the heat transfer between the flowing water and the rock are solved at each time steps. The transient energy equation is solved.

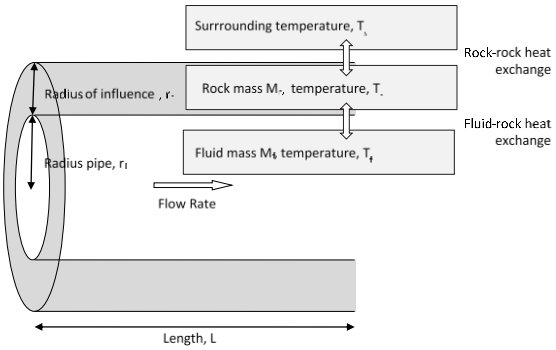

Figure 1: Simplified scheme of the heat exchange mechanisms.

For the discretization of the rock compartment we used the same approach as the one described by Verhelst (2012). A 1D, radial approximation of the heat diffusion process in the host rock is modeled as a series of concentric volumes, each representing a thermal capacity Ci, separated by thermal resistances Ri (Figure 2). The 1-dimensional finite-difference model (1D-FDM) of the radial heat transfer process around the galleries is implemented in the EPANET code. The inner node (left-hand side in Figure 3) represents the mean fluid temperature (Tf) at which the fluid is flowing. The outer node represents the undisturbed ground temperature (Ts). This representation is based on two assumptions that define the time frame for which this representation is accurate.

First, it is assumed that the heat transfer rate from the fluid to the ground is directly proportional to the difference between the mean fluid temperature Tf and the mean pipe wall temperature Tp and inversely proportional to the effective pipe wall resistance Rp (K/W). This assumption is valid for time t such as:

$$t > \frac{5r_p^2}{\alpha} \quad (1)$$

Where r_p is the pipe radius in m and α is the thermal diffusivity if the ground in m²/s (Verhelst , 2012).

The second assumption is that heat conduction in the ground occurs only radially. For time scales shorter than 5% of the steady-state time ts (equation (2)), the axial heat transfer can be neglected [Eskilson (1987); Lamarche L. and B. Beauchamp, (2007)].

$$t_s \approx \frac{l^2}{9\alpha} \quad (2)$$

Where l is the length of the pipe in m.

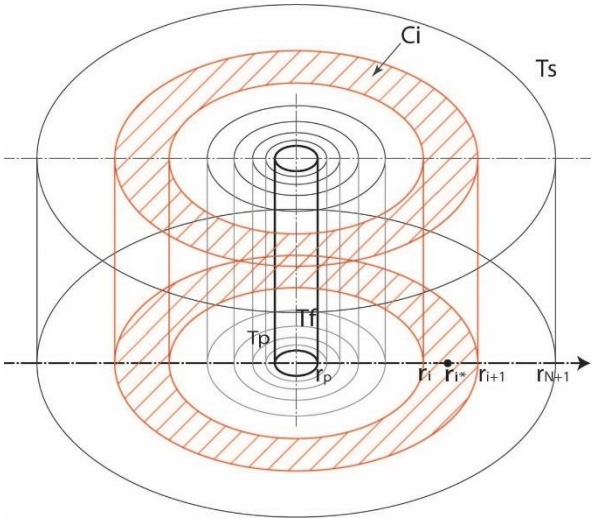

Figure 2: Discretization of the ground surrounding a single pipe into a finite number of cylindrically shaped volumes. Ci the capacity of the ith concentric cylindrical, r*$_i$ the center of the ith cylindrical volume; T_p the temperature of the pipe wall, T_f the fluid temperature, T_s the ground temperature considered as undisturbed.

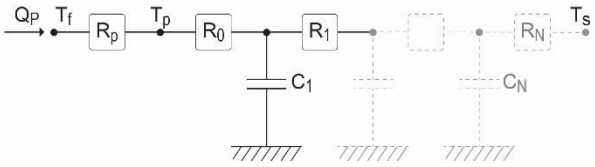

Figure 3: Representation of the one-dimensional radial approximation of heat diffusion in the surrounding rock, modified from Verhelst (2012).

For such a model, the values of the thermal resistances Ri and capacities Ci can be determined as follows (Eksilon, 1987):

$$R_0 = \frac{1}{2\pi k_r l}\ln\left(\frac{r_1^*}{r_b}\right)$$

$$R_i = \frac{1}{2\pi k_r l}\ln\left(\frac{r_{i+1}^*}{r_i^*}\right) for\ i = 1 \dots N-1$$

$$R_N = \frac{1}{2\pi k_r l}\ln\left(\frac{r_{N+1}^*}{r_N^*}\right)$$

$$C_i = \rho c_r \pi (r_{i+1}^2 - r_i^2) l\ for\ i = 1 \dots N$$

All these equations have been implemented into the EPANET code to account for the heat exchange between the fluid and the rock surrounding the galleries.

3. PARAMETERS ESTIMATION METHOD

In most case, data from the literature can be used for fluid and rock thermal conductivities to run the models in the feasibility phase of a project. The radius of influence is set based on the maximum duration of the modeled period (Eskilson, 1987).

Once historical data are available the model can be refined by estimating the values of the parameters. To estimate the parameters (kf, kr and r_{N+1}) a Markov-Chain Monte-Carlo method has been implemented [http://www.mcmchandbook.net/HandbookChapter1.pdf].

In the present study, a 1-norm cost function has been used, where every modelled value is simply weighted by the absolute value of its deviation.

Markov-Chain Monte-Carlo methods use random perturbations of the parameters, and the selection of parameters is pushed slightly towards regions with higher probability to contain good parameter values and this without becoming too greedy and ending up in a local minimum. Many alternative methods exist, like genetic algorithms (Rechenberg, 1973), and probably all these methods will work well and result in identical conclusions. System identification techniques, like the Levenberg-Marquardt method [(Levenberg, 1944); (Marquardt, 1963)] need to invert the model by means of its Jacobian. Here, we need to estimate the parameters used for the EPANET model heat transfers calculations. Markov-Chain Monte-Carlo methods have been chosen because they present several advantages compared to the pre-cited methods. They only need a forward integration of the model. The main disadvantage is that the parameter estimation itself takes more time. In the examples used in this paper, the parameters where found in less than 2 hours for the single pipe and in less than one day for the real field data. This is a reasonable time; especially compared to the manual tuning of the parameters.

The Markov-Chain Monte-Carlo algorithm consists of the following steps

1. The model parameters are initialized and are stored in a vector =[fluid thermal conductivity (W/m²/K), rock equivalent thermal conductivity (W/m²/K), radius of influence (m)].
2. The initial cost function is set equal to infinite.
3. The parameters are perturbed with a normally distributed random number and are temporarily

stored in θ. The mean of this distribution is evidently zero, the standard deviation was set equal to 5% of the initial parameter values.

4. Constraints on the parameters were checked to exclude negative values. If a perturbed parameter set would lead to negative value, step (3) is repeated until the constraints are met.
5. The model is integrated.
6. The new cost function is calculated. We have used the one-norm as cost function

$$K = \sum_{t=1}^{N} \left| T_{\text{measured}}(t) - T_{\text{model}}(t) \right| \qquad (1)$$

With K the cost function, t the sample number, N the number of samples, T_{measured} the measured temperatures and T_{model} the modelled temperatures.

7. Accept or reject the new parameter values. If a random number r ,sampled from a uniform distribution between zero and one is below the ratio K / K_0 ,
    a. The parameter vector θ_0 is overwritten with θ ;
    b. The initial cost function K_0 is overwritten with K ;

    Otherwise the algorithm continues from the values θ_0 and K_0 .

The acceptance rate is an important tuning parameter. If it is too small, too many parameter values are rejected and the step size is probably too large. If the acceptance rate is too high, too many parameter values are accepted and the risk exists that the algorithm will spend too much time in remote areas in the parameter space. A good acceptance rate varies between 30 and 60 %.

8. The procedure, starting at (3) is repeated *M* times.

VALIDATION OF THE CODE AND PARAMETER ESTIMATION

Single pipe

Parameter estimation and comparison with TOUGH2 results

As a test, we simulate simple heat and flow transfers in a single pipe using the commercially available code TOUGH2 (Pruess, 1991). In the experiment, we simulate a water flow within a 500 m long pipe. Axial symmetry is used and the lateral boundary on which the temperature is fixed is set at 100 m from the pipe center. Initially water and rock temperatures are set to 25 °C. Water of 10 °C flows into this pipe at a flow rate of 20 m³/h. Detailed parameters can be found in Table 2. The duration of the experiment is 365 days.

The temperature results of the TOUGH2 model are then used as calibration data to estimate the input parameters (values of the thermal conductivities of the rock and water and of the radius of influence) to be used in the updated EPANET model to replicate the results.

Some key fixed parameters used in the EPANET model are listed in Table 1. In addition, we have initialized the parameters with conductivities values close to the ones used in TOUGH2 i.e. θ_0=[0.6,2.78,100].

Table 1: EPANET parameter values

Symbol	Value used
c_f	4200 J/kg/K
c_r	900 J/kg/K
ρ_f	1000 kg/m³
ρ_r	2500 kg/m³
Time step	24 h

Table 2: Parameters used in the TOUGH 2 model.

Parameter	Value
Rock heat capacity (J/kg/°C)	800
Water heat capacity (J/kg/°C)	4200
Water density (kg/m³)	998.5
Flow (m³/h)	20.19
Area of the section of the pipe (m²)	27.52
Length (m)	500
Input T (°C)	10
Initial T(°C)	25
Time to reach output (days)	28.4
Thermal conductivity of the rock, kr (W/m/°C)	2.78
Thermal conductivity of water, kf (W/m/K)	0.6
Infinite temperature (°C)	25
Distance of "infinite boundary" (m)	100

In the estimation process, 1200 model runs are performed. Figure 4 shows the distribution of the cost function as a function of the parameter values. No local minima seem to be present. If the water thermal conductivity gets closer to zero, the cost function increases rapidly. If the parameter value is too big, the match with the observations does not seem to change that dramatically. The same holds for the radius of influence, while the rock thermal conductivity is more symmetrical. Because it is impractical to use parameter distribution in EPANET, to estimate the best parameters we select the values with the lowest cost function.

The best parameter values are:

- water thermal conductivity is 0.66 W/m²/K,

- rock thermal conductivity is 2.84 W/m²/K

- rock radius factor is 49.1m

The fit between the measurements and the model when using these values as input parameters into the updated EPANET model, is shown in Figure 5. Except in the transition phase, the results of the updated EPANET model fit very well with the ones of the TOUGH2 model. The reason why the transition phase is not well modelled is because the cold water front is mixing with the hot water. At the end of the pipe, this causes a smoother transition from warm to cold water. This mixing is a process that is not incorporated in the EPANET model. Therefore, the EPANET model has a much sharper transition. If we ignore this transition, the average absolute deviation is 0.01 °C (with a maximum deviation of 0.023 °C), which is very precise. However, both still differ in the mixing details.

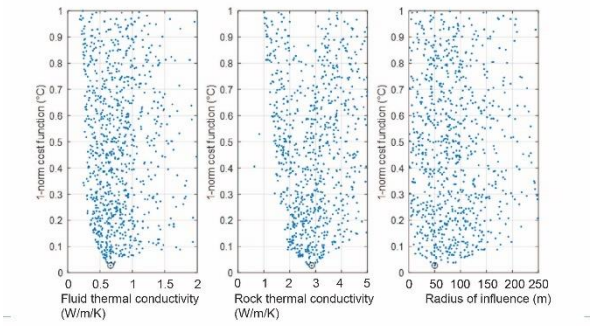

Figure 4: parameter distributions for the three parameters, estimated on the TOUGH2 model. The circle indicates the parameter value with the lowest cost function.

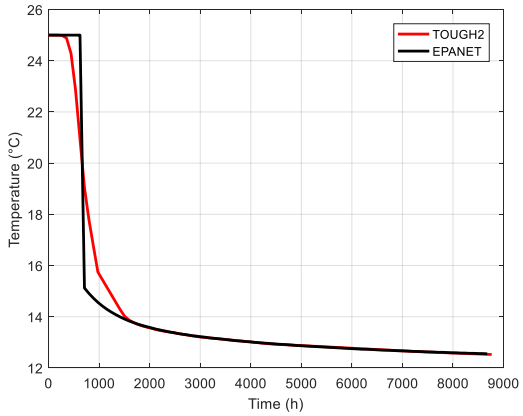

Figure 5: Match between observations (TOUGH2 model) and the model (EPANET model).

Parameter estimation, based on a field test

In a second step to confirm the applicability of our model on real mines networks to correctly model heat transfers and to estimate the right parameters, we have matched the refined EPANET model on data from a field test in Heerlen, The Netherlands (Figure 6). In the example given here, cold water is periodically extracted from one of the 5 operational wells. It is worth noting that we have used the water temperatures measurements to calibrate the EPANET model only when the flow rate is above 15 m³/h (see Figure 7(b)). This threshold of 15 m³/h is somewhat arbitrary, but it allows us on the one hand to estimate the parameters and on the other hand to validate the estimated parameters on the remaining data. In fact, because the divers measuring the temperature are located at the pump levels (shallower than the depth from which the water is extracted) when the flow rate is close to zero, the temperature may not reflect the temperature in the mine, but rather the temperature influenced variations at the surface.

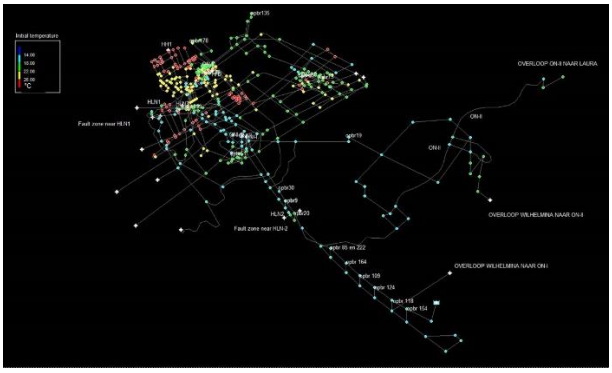

Figure 6: EPANET-model of the complex mine geometry with main connections used for the modelling of flow and heat.

Figure 7 (a) shows the measured and modelled well temperatures. Only the full line is used in the parameter estimation. During three periods cold water has been extracted from the well. The parameter estimation method fits the rock equivalent thermal conductivity and the radius of influence on the three periods simultaneously. The thermal conductivity of the fluid was assumed to be fixed at 0.6 W/m/K in this example which is a realistic assumption as the thermal of the fluid is not expected to vary much. The mismatch between the measurements and model are less than 0.5 °C, which is pretty good. The trends in the measurements are reflected well in the model, like the periods of increasing water temperatures.

When the flow rate is between 5 and 15 m³/h, the predicted temperatures still closely overlap with the measured temperatures. This is an indication that the model is well able to predict variations in outlet temperatures.

However, a closer look at the distribution of the parameter values reveal a complex situation, as is

shown in Figure 6. The fluid thermal conductivity is fixed to 0.6 W/m²/K in this experiment. The cost function for the rock equivalent thermal conductance increases rapidly once the value drops below 3 W/M²/K, while any value between 3 and 4 to 5 W/m²/K have similar mismatches. The optimal value is 3.72 W/m³/K.

The cost function for the radius of influence is scanned between 5 and 25 m. The optimal value is 5.64 m, which is close the minimum value. This minimum is well defined. Higher values have significant higher mismatches with the measurements.

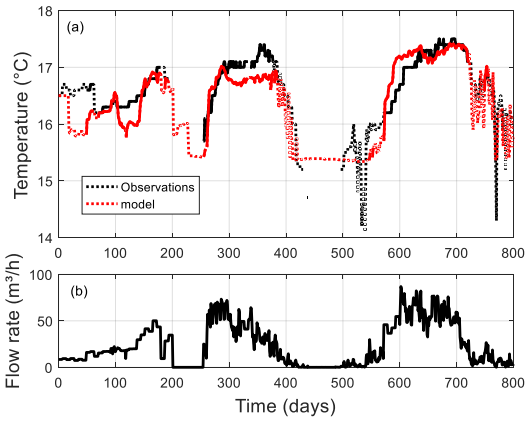

Figure 7: (a) measured (black) and modelled (red) temperatures at the well. The full line corresponds to flow rates above 15 m³/h, the dotted line to flow rates below 15 m³/h. (b) the flow rate.

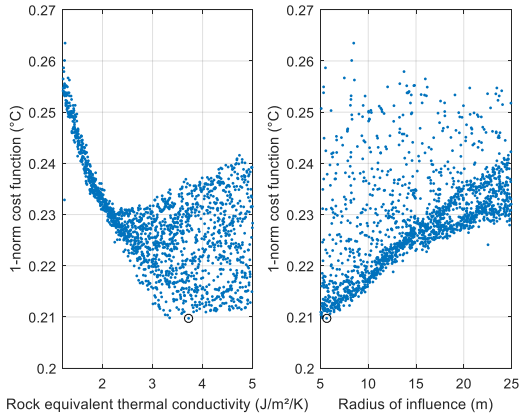

Figure 8: parameter distributions, estimated on the field data from the Heerlen mine. The circle indicates the parameter value with the lowest cost function.

The value of 3.72 W/m/K for the equivalent rock conductivity is slightly higher than the rock thermal conductivity that we expect for the rock lithology surrounding the galleries. This is probably reflecting the fact that some advection of heat is taking place in addition to the purely conductive heat transfers. We are currently investigating this result.

CONCLUSIONS

This paper proposes an updated model to simulate heat and flow processes in flooded mines used for geothermal purposes. The model is based on the EPANET code that is used originally to simulate flow and chemistry in pipe networks. Assuming that mine galleries can be modelled as interconnected pipes, the original EPANET can be used to model the flow in the network of galleries. However, EPANET does not allow to include realistic thermal interactions between the fluid flowing in the pipes and a possible surrounding medium. Ferket et al. (2011) already proposed a modified version of EPANET which included unilateral heat transfers between the fluid and the surrounding medium. In their model, the surrounding medium was assumed to remain at a fixed temperature and the fluid was exchanging heat/cold with it. Here, we propose a second update of the EPANET model. The update consists in including a special compartment around the pipes to simulate the conductive/convective heat exchange between the rock surrounding the different pipes and the fluid that flows into the galleries. In this model the temperature is assumed constant not on the wall of the pipes but at a distance (so-called radius of influence) where the thermal influence of the fluid flowing in the galleries is assumed to be negligible.

Additionally, based on real or artificial production data, we propose to estimate this radius of influence, together with the fluid and rock thermal conductivities using Markov-Chain Monte-Carlo methods.

In this paper we showed that if the model is matched on a simple single pipe model, all parameters can uniquely be defined. On the other hand, if complex field test data is used, the thermal conductivity of the rock surrounding the galleries is more difficult to uniquely identify. This indicates that further complexity may result in unidentifiable parameters or that non-unique parameters have to be used for the rock properties depending on the location in the mine. This can reflects two different phenomena, either that the rock thermal properties can vary depending on the location or that the heat exchanges locally can be influenced by advection in addition to conduction and resulting in locally high equivalent thermal rock conductivity.

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