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Comparison of Optimised Models for the Investigation of Heating Potential in Abandoned Mines Using Mine Water

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Abstract

After decommissioning and natural flooding, mines become large water reservoirs thermally coupled to the underground. Although the energy storage capacity enables significant heating or cooling potential, high drilling and construction costs require precise plant design. Many stakeholders lack the resources for detailed thermohydraulic modeling approaches. This paper presents a reduced, numerical model using an implicit finite volume method, balancing speed and accuracy. Verified against CFD simulations, it achieves less than 2.5% deviation in laminar flow cases. It can lay the basis of an accessible tool for preliminary geothermal assessments, aiding stakeholders in taking the first step in realising efficient mine water energy systems.

Keywords: Geothermal, Energy, Modelling, Thermodynamics

Introduction

In mining regions, many abandoned mines undergo flooding due to infiltrating surface water [Macklin *et al*. 2023]. The water collects in the mine workings, where it takes on the temperature of the rock and is therefore geothermally coupled to the underground. To gain access and utilize the stored heat in this mine water, drilling into the mine and abstracting the water with pumps is a common method [Ghoreishi-Madiseh *et al*. 2012, Rodríguez & Díaz 2009]. Mine water is then reinjected into the mine at another seam or a distant gallery to create a backflow to the abstraction point, which restores the mine water´s temperature.

Drilling into a mine for mine water access brings its own set of challenges, including regulatory, drilling precision, and safety aspects [Grab *et al*. 2018]. This directly affects how the project is evaluated financially, as dealing with the challenges creates costs, which need to be matched or outperformed by the expected returns. Therein lies a continuous challenge of using geothermal resources, as methods of determining the expected energy gain over the mine water system's lifetime are not easily accessible by many stakeholders. This is especially important since the mine can be thermally exhausted, putting the energy supply at a crucial risk. Cities, energy suppliers, or private firms in small mining regions often lack the necessary personal and financial capacity to carry out pilot studies to investigate the potential yield from the heating and cooling energy [Moulli-Castillo *et al*. 2024]. This is especially driven by a lack of accessible stakeholder tools for conducting initial thermodynamic evaluations for mining.

In order to develop an accessible tool, an underlying thermodynamical model is required that combines accuracy, flexibility and computation speed. Suitable models are found both in the analytical [Pruess & Bodvarsson 1984, Rodríguez & Díaz 2009] and the numerical model domain [Renz *et al*. 2009, Małolepszy 2003, Ghoreishi-Madiseh *et al*. 2012]. Since the researched numerical approaches model the physical system in fine detail, they are not suited for integration into a fast and user-oriented model. Analytical models, however, possess unique advantages. State-of-the-art models like the model from Rodríguez and Díaz (ROD-model) show high computation speed and sufficient accuracy for evaluating heat extraction from mine galleries [Pruess & Bodvarsson, Rodríguez & Díaz 2009]. On the other hand, because of their analytical nature, they lack variability, unable to include varying time-dependent parameters like heat load. The goal of this paper is to introduce a reduced numerical simulation model, tailored for use in preliminary mine water system investigations. This model and the aforementioned analytical model are compared, and their results benchmarked against a 3D computational fluid dynamics (CFD) simulation.

Model Development Approach

The newly developed model (TUBAF-model) needs to approximate the conditions present in a mine water geothermal system. To be comparable to the ROD-model, a cylindrical gallery shape with a finite rock layer surrounding it is used, the gallery being flooded with water. The system therefore integrates conductive heat transfer in the rock mass and diffusive heat transfer to water. This mechanism of coupling solid and fluids enables the simplification that they can be solved independently and subsequently be coupled with the convective heat transfer boundary condition at the gallery wall. The fluid is approximated with an analytical solution for the distribution of the temperature along the gallery. For the solid domain, an implicit Finite Volume Method (FVM) scheme is used. An implicit approach ensures numerical stability when varying the time step and spatial resolution, while the FVM scheme provides flexibility in terms of geometric spacing of the grid. Lastly, the spatial dimensions were investigated for possible reduction in simulation load. The subsequent characteristics of the system were utilized:

- Rotational symmetry
- Quasi-adiabatic conditions in the axial direction within the solid (only heat flow to and from the gallery is considered) [Krause 2024]

The numerical simulation within the solid is therefore simplified to a 1-dimensional (1D) grid. The spatial grid in the whole of the solid domain consists of several 1D layers lined up and coupled through the fluid domain, resulting in a quasi 2D grid. An overview of the modelling approach is given in Fig. 1.

To ensure the accuracy of the results, both spatial and temporal grid independence tests were conducted. The requirement for an applicable grid size was a deviation of 0.15% or less in heat output from a very fine grid after 20 years of continuous heat extraction. Resulting maximal grid sizes were 10 m and 0.2 m in the axial and radial gallery directions, respectively. In the temporal dimension, results yielded the defined accuracy with a timestep of 63,072 s. For simulation efficiency, the model was implemented in the coding language C.

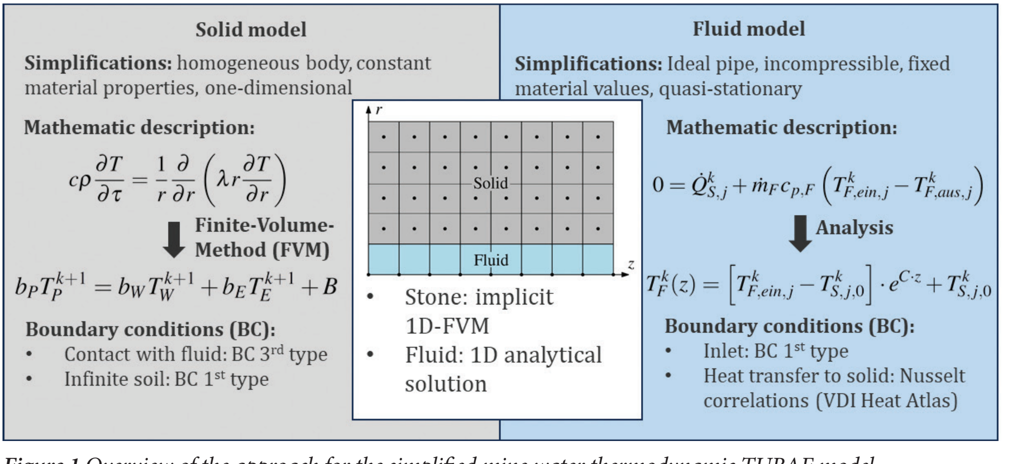


Figure 1 Overview of the approach for the simplified mine water thermodynamic TUBAF model.

CFD-Benchmark Model

In order to evaluate the numerical TUBAF and the analytical ROD-model mine water models, a 3D-CFD model is used. The model was set up using the commercial software STAR-CCM+ [Siemens 2025]. In the fluid, the continuity, momentum and energy equations are solved. For the solid domain, the heat conduction equation for three-dimensional bodies is solved. The model equations are discretized over polyhedral control volumes using the Finite Volume Method (FVM). Prismatic extruder cells, which expand in the axial direction, were used to enlarge the possible simulation geometry. The model consists of a total of 4.2 million cells. The large-scale model mesh with the extruder cells is shown in Fig. 2 a). The fluid-side boundary between the solid and fluid includes additional flat, prismatic cells to better resolve the developing boundary layer and steep parameter gradients, which are shown in Fig. 2 b).

Model evaluation

Using the benchmark model, the TUBAF developed model can be compared to the analytical mine water model. Therefore, the analytical ROD-model is also implemented in C to ensure comparability. Furthermore, the model was modified by flow dependent heat transfer correlations as suggested by [Loredo *et al.* 2017].

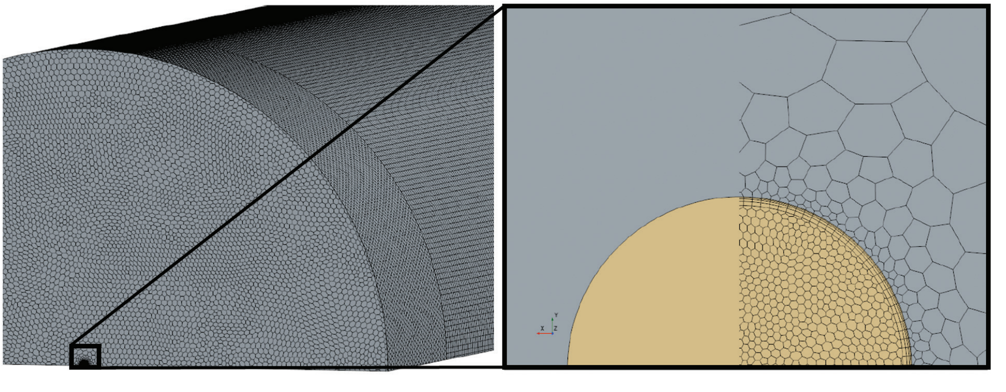
To evaluate the models on performance, a reference case was defined, which included model geometry and material properties, as well as flow characteristics. The parameters chosen are based on values as proposed in the initial ROD-model and conform to realistic rock values for the context of mine water geothermal utilization [Rodríguez & Díaz 2009, Krause 2024]. Case parameters for the following comparisons are described in Table 1.

If not specified, the listed parameters apply in the following investigations. The TUBAF and the literature model are then compared to the 3D-CFD benchmark simulation results.

Laminar Flow

Initially, long-term operation of a mine water geothermal plant with only heat extraction is simulated. In this case, mine water is abstracted and reinjected with a lower temperature at the constant value of 7 °C. In order to simulate heat extraction at a laminar flow regime, the flow rate of Table 1 applies, yielding a Reynolds number of 1438. Model results are shown in Fig. 3 and Table 2.

The analytical approach has the shortest calculation time, being several orders of magnitude lower than the TUBAF model. Simplifications in the calculation of the wall temperatures and the assumptions of a finite radius of thermal influence in the rock lead to a better computational performance. One drawback is the mentioned simplifications do not represent the physical processes as accurately as the TUBAF model. The TUBAF model yields a deviation of −2.5% in comparison to −6.7% of the ROD-model.



a) b)

Figure 2 a) Angled large-scale view of the model with the gallery inlet and solid domain; b) Detailed frontal view of the model with the gallery inlet and solid domain.

Table 1 *Reference case parameters for the model comparison.*

Parameter	Unit	Fluid domain	Solid domain
Radius gallery	m	1	100
Length of gallery	m	1,000	1,000
Start temperature	K	300.15	300.15
Heat conductivity	W/(m·K)	0.58	2.78
Specific heat capacity	J/(kg·K)	4,186	800
Density	kg/m^3	1,000	2,500
Kinematic viscosity	mm^2/second	1.24	–
Volume flow	L/second	2.80	–

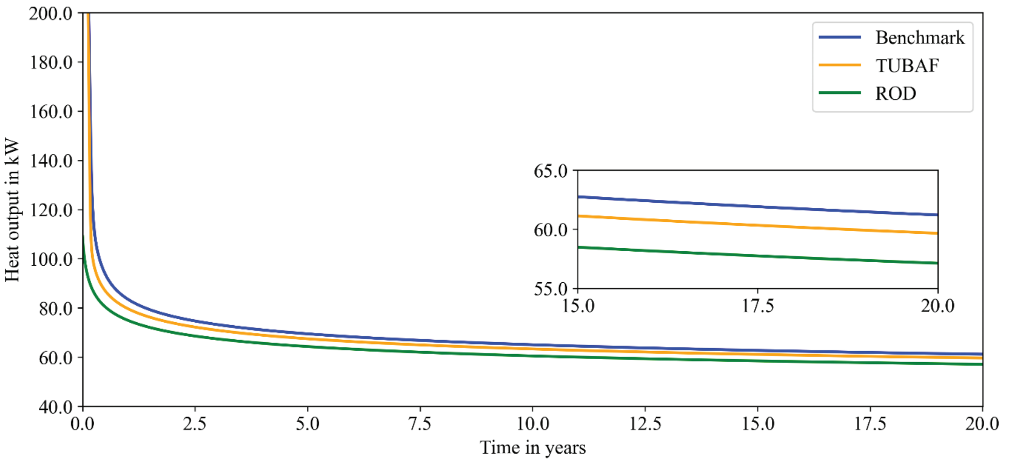


Figure 3 *Development of the heat extraction rate with laminar flow over a period of 20 years according to the models, inlet temperature constant at 7 °C.*

Table 2 *Evaluation parameters of the laminar reference case simulation.*

Evaluation Parameter	Benchmark model	Comparison models	
		TUBAF	ROD
Calculation time in seconds	24,743.3	66.0	< 0.1
Heat output in kW at 20 years	61.2	59.7	57.1
Deviation from benchmark model in %	–	-2.5	-6.7

The TUBAF model is therefore applicable for laminar modelling.

Turbulent Flow

In the practical operation of a mine water system, the geometry and the roughness of the wall surfaces change continuously. Depending on those circumstances and the induced flow rate, the heat transfer changes accordingly. To test the models considering turbulent conditions, the mass flow of the mine water was set to 28 L/s, raising the Reynolds number accordingly to 14380. Results of the simulations are shown in Fig. 4 and Table 3.

Due to the improved heat transfer in turbulent flow, the heat output is continuously higher than for laminar flow. Compared to the laminar case, the computation time remained at the same level, while the deviation from

Table 3 Evaluation parameters of the turbulent reference case simulation.

Evaluation Parameter	Benchmark model	Comparison models	
		TUBAF	ROD
Calculation time in seconds	24,911.7	66.2	< 0.1
Heat output in kW at 20 years	85.4	100.4	76.9
Deviation from benchmark model in %	–	+ 17.7	- 9.9

comparison to benchmark models underwent a change. While the analytical model calculates less heat output, the TUBAF model overestimates the heat output by almost 18%. This deviation shows the limits of the TUBAF mine water calculation code. The higher heat output in the turbulent case is likely a result of the fixed Nusselt correlations that calculates the heat transfer coefficient. Until more specific Nusselt correlations for turbulent flow regimes are tested, only simulations in the laminar flow range can be considered valid. For laminar flow, the code can be used for seasonal heat load investigations, including heat extraction and heat injection.

Conclusions and Outlook

Since there is currently no basis for an inexpensive load-flexible and reduced thermodynamical calculation code for mine water, the goal of this investigation was to establish a reduced numerical calculation code and evaluate its applicable simulation range. It was compared with a state-of-the-art analytical model to a detailed 3D-CFD benchmark model in terms of heat output when applying laminar and turbulent flow regimes. According to the results, the developed model can be used for laminar flow conditions. When this applies, the model can be used for quick investigations of seasonal heat load variations, which can then be compared to a benchmark simulation using detailed physics models. In turbulent flow, the deviation from the benchmark suggests improvement potential in the heat transfer between fluid and solid. After improving the reduced model to fit the results of the benchmarkings, efficiency measures such as the implementation of non-equidistant grids can be considered. The improved model can therefore become the foundation for an easy-to-access tool, which can help to analyze mines in quick pilot studies, thereby creating a better decision basis for use by municipalities and energy suppliers.

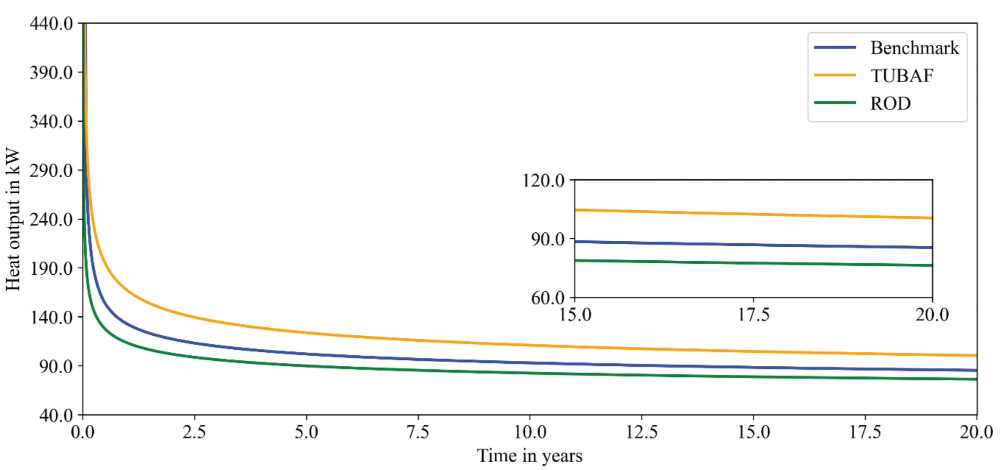


Figure 4 Development of the heat extraction rate with turbulent flow over a period of 20 years according to the models (volume flow at 28 L/s), inlet temperature constant at 7 °C.

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