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BASIMO – Borehole heat exchanger Array SIMulation and Optimization Tool

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ABSTRACT

Arrays of borehole heat exchangers (BHE) are an increasingly popular source of renewable energy. Furthermore, they can serve as borehole thermal energy storage (BTES) systems for seasonally fluctuating heat sources in district heating grids like solar thermal energy or industrial waste heat. Projects generally tend to grow in size and capital cost with more and deeper BHEs. Thus, a priori simulations become an essential part of the planning process.

1. INTRODUCTION

In contrast to single borehole ground source heat pump systems, many mathematical simplifications are not exploitable for modeling and simulation of BHE arrays as they result in too large errors. Thus, current simulation tools cannot – or only to some extent – describe BHE arrays in sufficient detail. Key features like stratigraphy dependent thermo-physical and hydrogeological properties can only be captured in more complex and more sophisticated simulations. Arbitrary bore paths for each individual BHE or partly insulated boreholes can even require fully discretized models of the borehole heat exchangers. However, fully discretized models often come at a high computational cost, especially for large arrays of BHEs.

We give an update on the development of BASIMO (Schulte et al., 2016): A **B**orehole heat exchanger **A**rray **SIM**ulation and **O**ptimization tool, which uses one-dimensional thermal resistance and capacity models for the BHEs coupled with a numerical finite element model for the conductive and convective subsurface heat transport in a dual-continuum approach. An unstructured tetrahedral mesh bypasses the limitations of structured grids for bore path geometries, while the thermal resistance and capacity model is improved to account for BHE properties changing with depth. Thereby, partly insulated boreholes can be considered in the model. Furthermore, BASIMO can be used to improve the design of BTES systems: the tool allows for automated parameter variations and is readily coupled to other code like mathematical optimization algorithms. Optimization can be used to determine the required minimum system size or to increase the system performance.

2. NUMERICAL SIMULATION

The operation of BHEs is simulated with a set of MATLAB functions, which dynamically calculate the conductive and convective heat transport within the subsurface using a finite element method (FEM) algorithm (Galerkin method of weighted residuals, Alberty et al., 1999) and also the heat transfer within the BHE. The tetrahedral elements constitute fully unstructured grids, which allow for arbitrary geometries with local refinements around the BHEs. For the meshing TetGen (Si, 2010) is used (Figure 1).

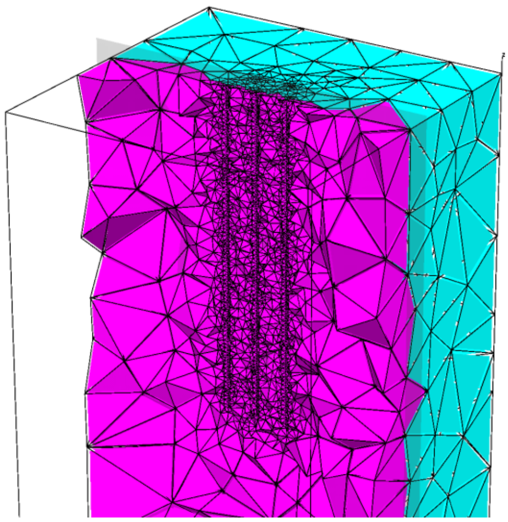

Figure 1: Unstructured tetrahedron mesh generated in TetGen. The mesh has a finer discretization around the BHE nodes.

The thermal interaction of the BHEs is determined by a local steady-state thermal resistance and capacity model (Diersch et al., 2011) based on the approach of Eskilson and Claesson (1988). Fed with an inlet temperature and a flow rate, it calculates the temperature distribution in the inlet- and outlet-pipes and provides nodal heat sources for the FEM model considering the thermophysical parameters of the BHE materials as well as the borehole wall temperature. This analytical solution is coupled to a 1-D discretization of the BHEs in the FEM subsurface model to account for the transient behavior of the BHE array. A predictor-corrector time integration scheme and an iterative solution of the non-linear equation system of the corrector via Picard‘s method ensure robust and automated time stepping.

Due to their slow thermal response, arrays of borehole heat exchangers (BHE) represent suitable storage systems for seasonally fluctuating sources like solar energy or district heating grids (Bär et al, 2015). Excess heat is fed in during summer and extracted in winter (Figure 2). Since drilling is the most critical cost factor, an a priori simulation of the storage operation is imperative. Furthermore, the design of a borehole thermal energy storage (BTES) needs to be optimized for the heat demand of a specific application scenario. This represents a textbook example for an application of BASIMO.

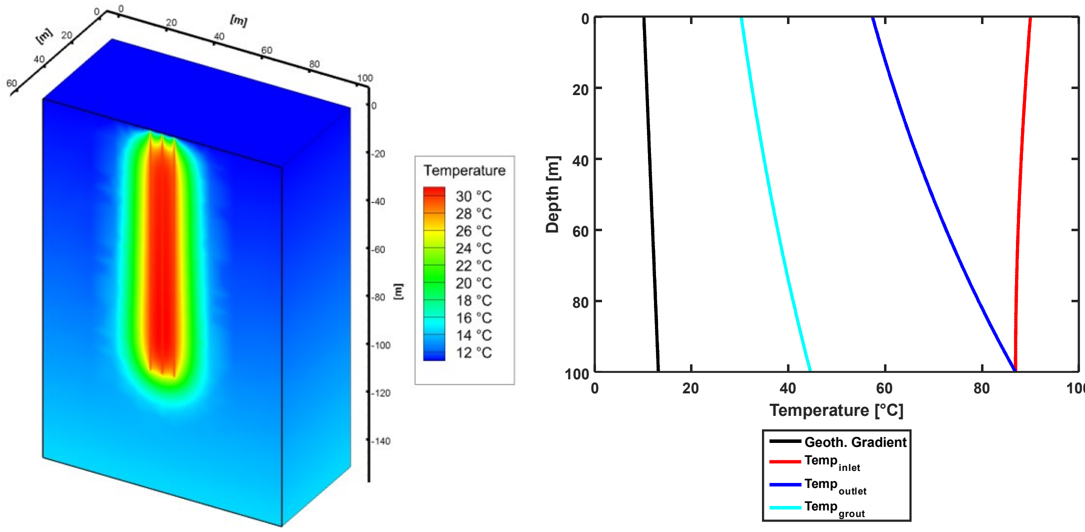

Figure 2: Subsurface heat plume of a 100 m BTES with 7 BHEs after a 6 months charging cycle (left); corresponding output of the analytical solution - temperature distribution of the coaxial BHE in grout, inlet- and outlet pipe with central tube inlet temperature of 90 °C and a flow rate of 2.5 l/s (right).

3. MATHEMATICAL OPTIMIZATION

BHE arrays are characterized by several discrete parameters like the number of BHEs or industrial standard sizes for pipes. To capture the model's dependence on all parameters we project the physical model described in the previous section onto a mathematically optimal proxy model via arbitrary polynomial chaos expansion (Oladyshkin and Nowak, 2012). The resulting polynomial allows for rapid and manifold evaluation by an optimization algorithm. Hence, a Genetic Algorithm (Goldberg, 1989) is applied to the proxy model for the optimization of the BTES as it can deal with mixed integer problems and factor in discrete or even categorical variables.

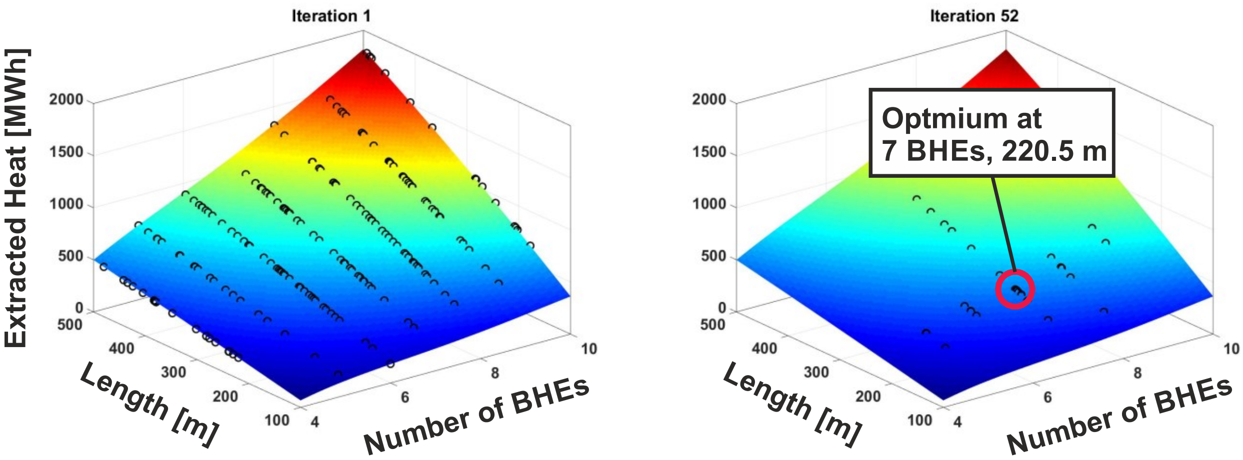

Figure 3: Exemplary optimization (minimization) of the size of a BTES. The objective function is the total borehole length with the length being exponentially penalized over the number of BHEs. The algorithm is constrained to solutions with at least 500 MWh annual heat extraction (i.e. heat demand to be covered) and more than 200 m borehole length to factor in a hypothetical legal regulation.

In every iteration, the score of a user-defined objective function is evaluated for a set of parameter tuples. The algorithm tries to minimize the score (i.e. converge on an optimal solution) partly by combining variable values of tuples with a low score and partly by choosing random values for the next iteration's set. The solution is validated by an additional numerical simulation run, which is used for refinement of the proxy model if it fails to pass a quality criterium (Figure 4).

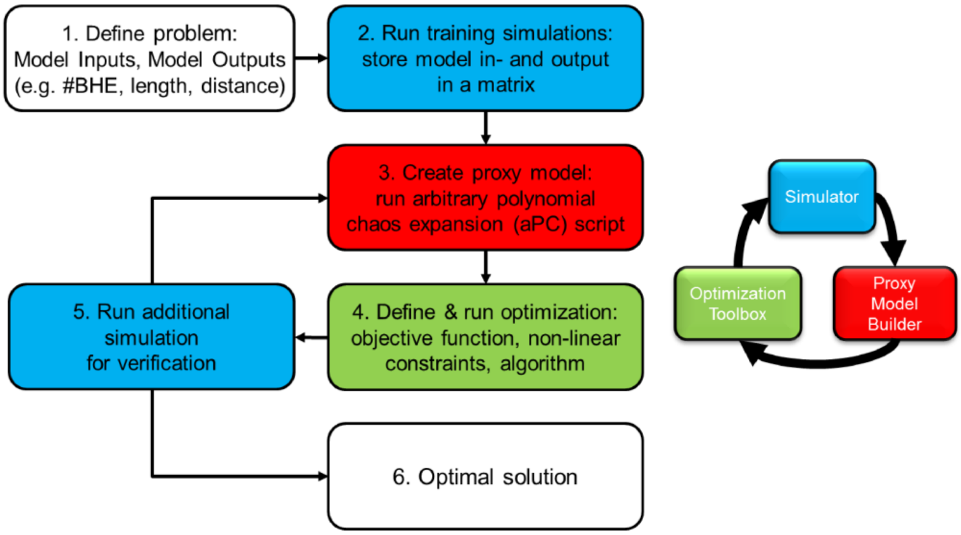

Figure 4: Workflow of the optimization scheme.

4. CONCLUSION

The presented software tool can simulate the operation of a BHE arrays and optimize its design efficiently. A careful definition of the problem and selection of the variable parameters and their boundaries is imperative in order to obtain significant results. The application of a proxy model generated by arbitrary polynomial chaos expansion greatly accelerates the optimization algorithm. The possibility to rerun optimizations considering different boundary conditions with little additional computational cost gives this approach an advantage over simulation codes tailored for a specific optimization problem. Our generic and modular approach allows for an easy adaptation to other optimization problems with different objectives.

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