BASIMO
Borehole Heat Exchanger Array Simulation and Optimization

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Introduction

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. 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. A MATLAB-based tool for **B**orehole heat exchanger **A**rray **SIM**ulation and **O**ptimization (BASIMO) was developed (Schulte et al., 2016a).

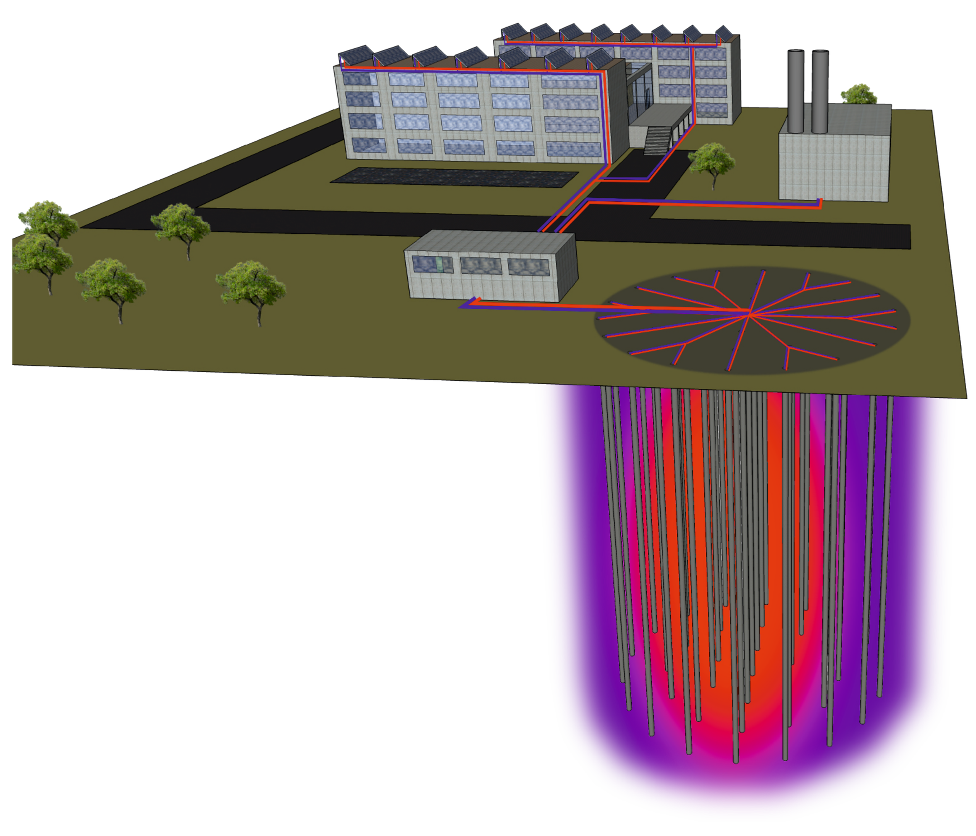

Figure 1: *Storage of solar thermal heat and industrial waste heat in a BTES.*

Features

BASIMO was initially developed for the design and optimization of BTES systems, but it can also be applied to conventional BHE operation scenarios. It represents a versatile simulation tool, which includes models for the three most common BHE types: U-pipe, double U-pipe and coaxial pipe BHEs. In a dual-continuum approach, the simulator couples a numerical subsurface model with an analytical solution for the BHEs, which facilitates an efficient, but detailed consideration of thermophysical and operational variables.
The models are set up by self-explanatory Excel sheets, which define all relevant parameters. Furthermore, the finite element mesh is created by a MATLAB routine that allows for a user-defined size and geometry of the BHE array . In return, BASIMO provides time series of the BHEs' outlet temperatures and subsurface temperature distributions.

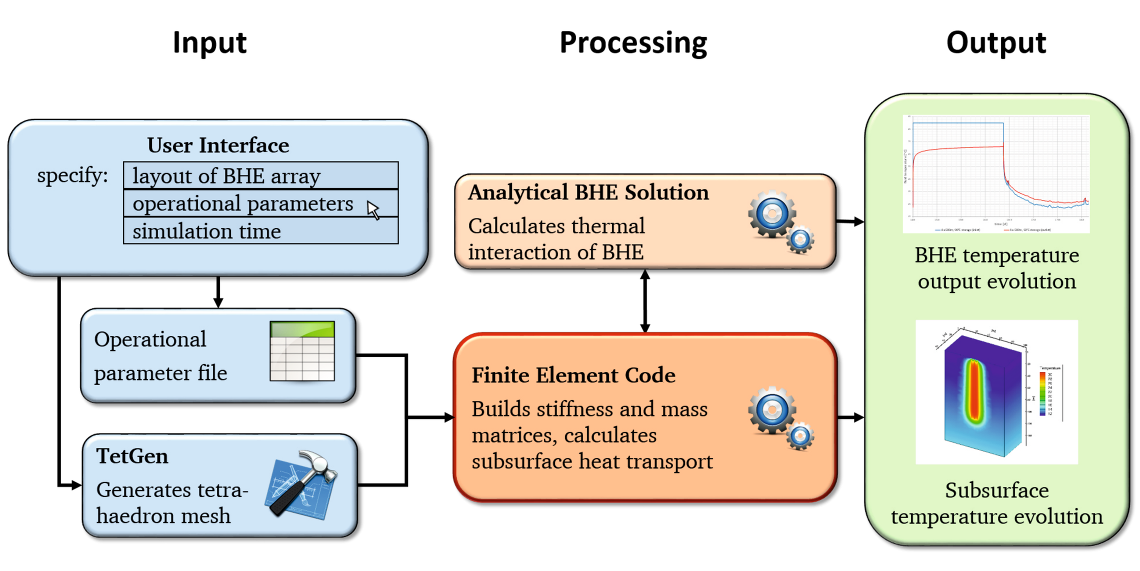

Figure 2: *Toolbox structure of the model simulator*

In contrast to most commercial simulation tools, BASIMO can also consider partially insulated boreholes, which are an important feature of BTES systems (Schulte et al., 2016b). Additionally, BHE array geometries are not restricted due to the use of an unstructured tetrahedron mesh: the modeling of inclined or even curved borepaths is possible.
Furthermore, BASIMO is readily configured for the use with the MATLAB Global Optimization toolbox to allow for mathematical optimization of BHE array design and operation. (Schulte et al., 2016a, 2016c)

Coupled Numerical Simulation

The BHE array operation is simulated with a set of MATLAB functions, which dynamically calculate the conductive 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 BHEs. 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.

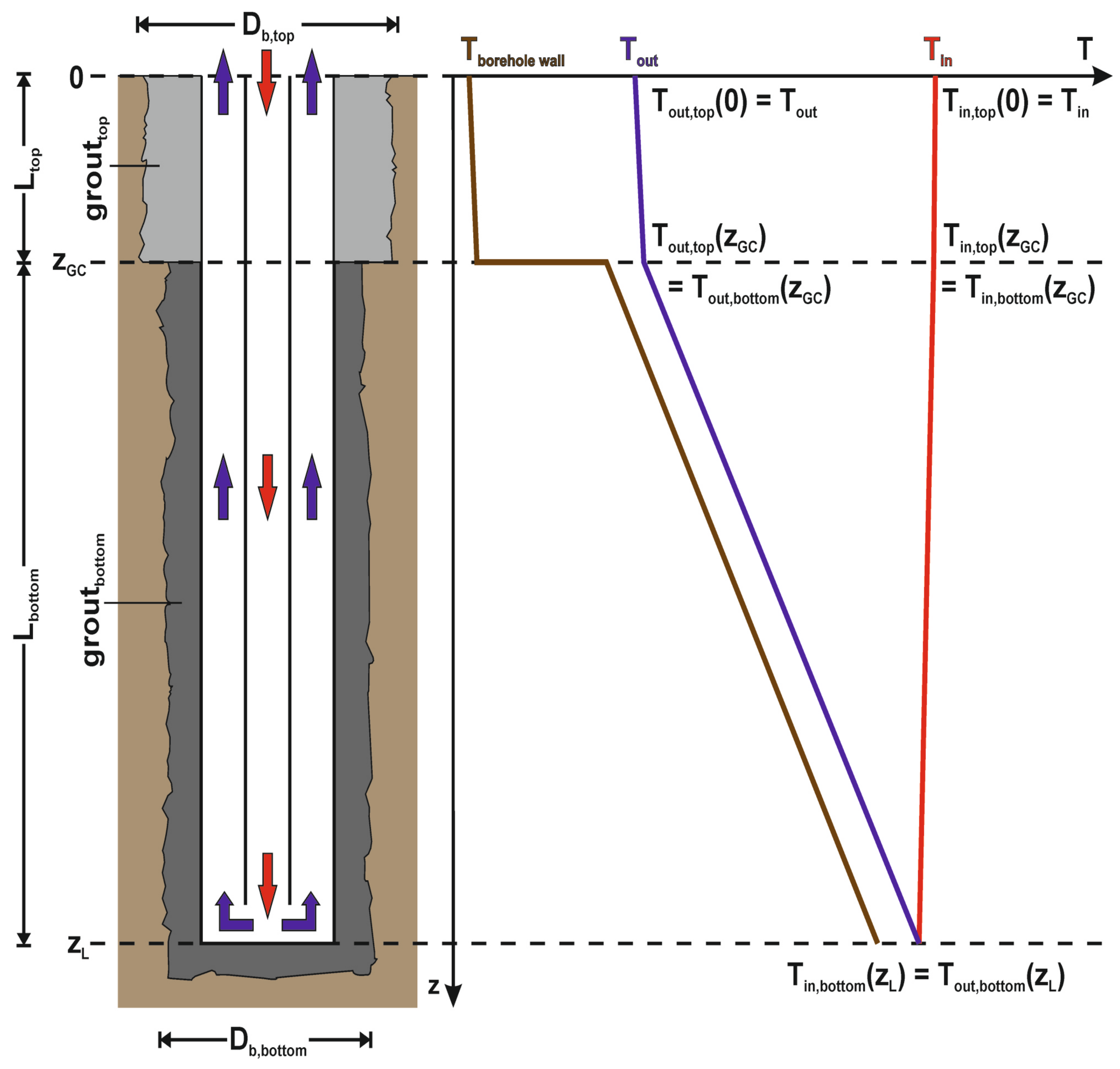

Figure 3: *Schematic of a partially insulated coaxial BHE and the corresponding temperature profile calculated with BASIMO.*

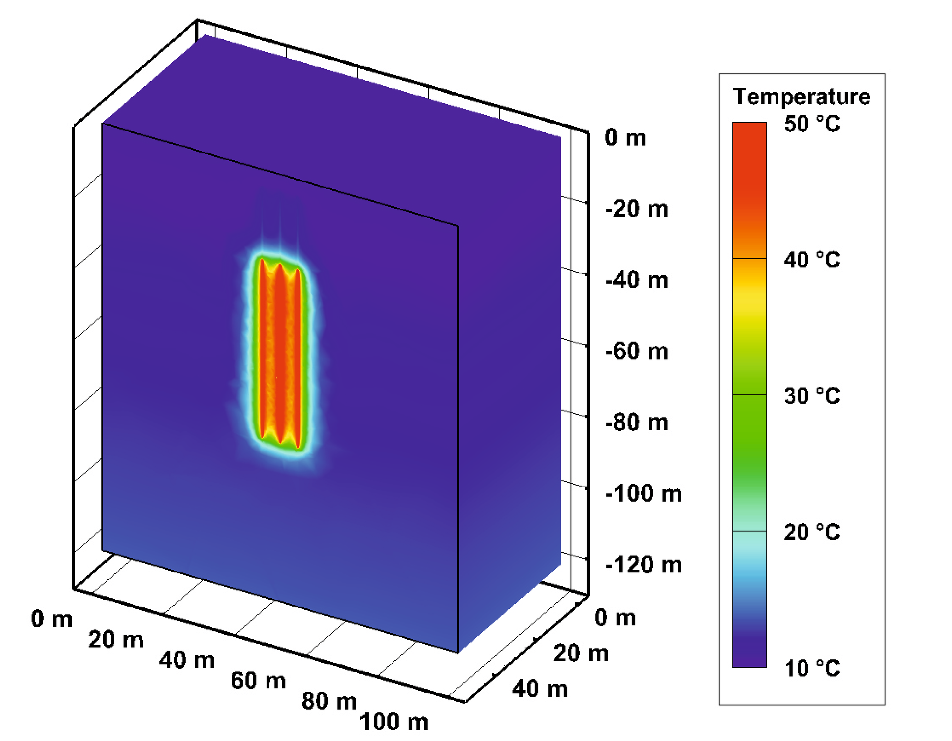

Figure 4: *Subsurface heat plume of a 100 m BTES with 7 partially insulated BHEs after a 6 months charging cycle.*

The thermal interaction of the BHEs is determined by a 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 taking into account the thermophysical parameters of the BHE materials as well as the borehole wall temperature. Two differently parameterized sections can be considered along the borehole length to allow for partially insulated BHEs. 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 BTES. 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.

Mathematical Optimization

BASIMO can be readily embedded in a subroutine called as an objective function or as a nonlinear constraint function in the MATLAB Global Optimization Toolbox. This way, various design or operational parameters can be optimized with regard to characteristic performance indicators.
For example, BASIMO can optimize the length of a thermally insulated section of a BHE (see Figure 5). Such an insulation inhibits the heat exchange with the shallow subsurface and is required for groundwater protection in high temperature heat storage applications like BTES. As a beneficial side effect, the heat losses in this section of the borehole are reduced, as well. Consequently, the outlet temperature in heat extraction operation is maximized, which represents an improvement of the heating performance.
Despite the advantages of BASIMO over other programs, simulations of large systems can still be lengthy. This can pose an impasse for some optimization problems that require a large number of function calls to converge on a solution. The problem can be overcome by generating a proxy model from considerably fewer training simulations (Schulte et al., 2016a). Whereas the computational effort for large models is still high, they only have to be computed once. The resulting proxy model can be evaluated by the optimization algorithm in a matter of seconds, as it consists only of a polynomial instead of a numerical model.

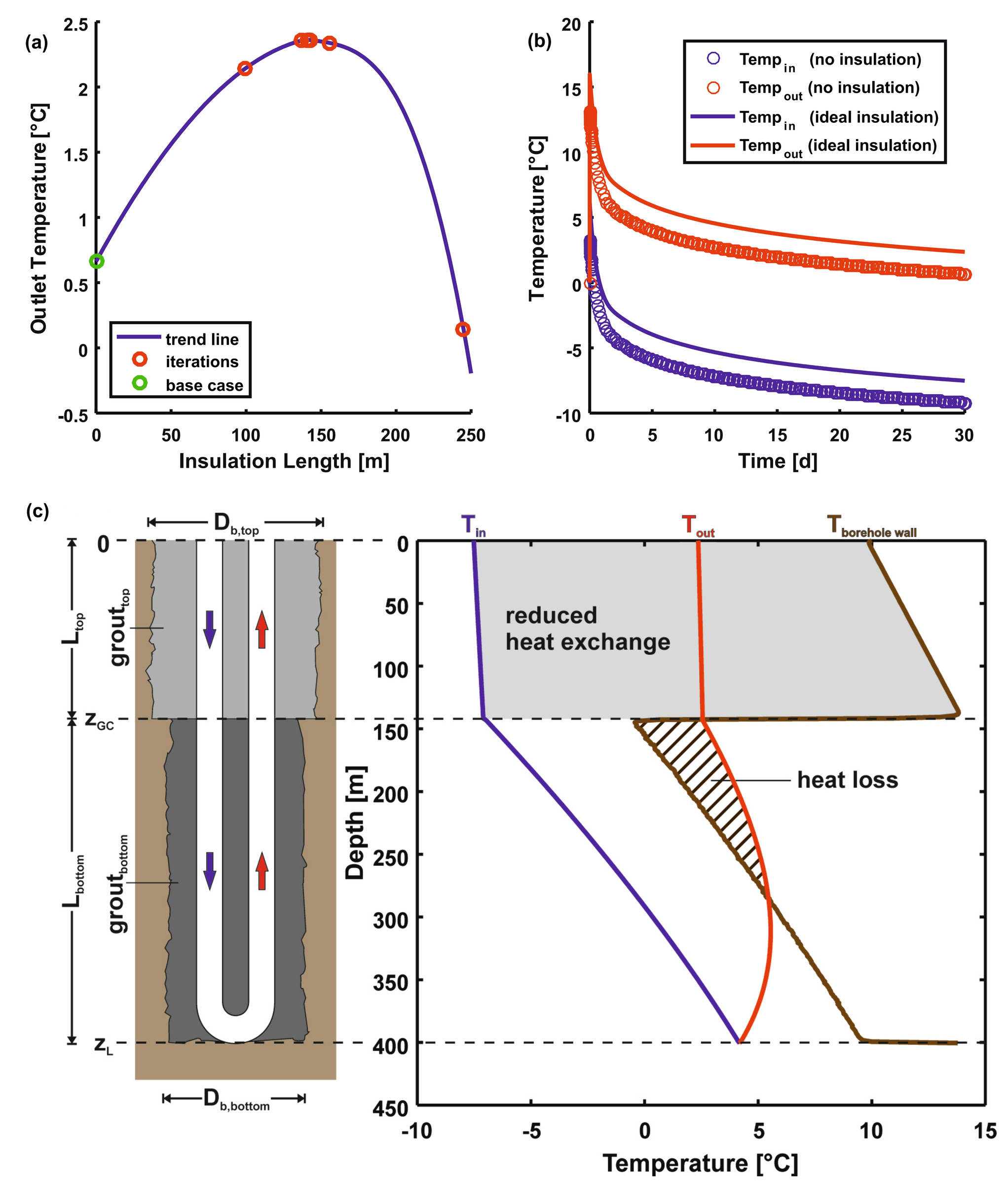

Figure 5 (to the right): *Optimizing an insulated double U-pipe BHE: (a) final outlet temperature of all simulation iterations, (b) uninsulated vs. insulated temperature outlet, (c) schematic of the ideally insulated BHE and according temperature profile calculated with BASIMO.*

Outlook

BASIMO is a versatile tool specifically tailored for the simulation and the optimization of BTES systems. It closes capability gaps of currently available simulators like the consideration of borehole insulation and unrestricted bore path geometries, while still maintaining reasonable computational performance. The adaptability of the MATLAB code not only enables its use in optimization algorithms. With only a few simple changes to the code it is possible to couple BASIMO with building models, which consider the heating infrastructure like heat pumps and buffer storages on the surface. Heat demand profiles with a high temporal resolution can be taken into account. This way, the dynamic interplay of the involved system components can be simulated with unprecedented and realistic detail.

Acknowledgement

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