

# Heat Transfer in Borehole Heat Exchangers from Laminar to Turbulent Conditions

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**Abstract:** Borehole heat exchangers (BHE) in connection with heat pumps and floor heating in many countries are becoming an alternative to conventional heating or cooling systems using fossil resources. They are one building block of the suite of alternative low-carbon, sustainable and renewable energy sources. Modeling is a convenient tool in order to understand and optimize the heat transfer between the technical system, consisting of borehole, pipes and grout, and the surrounding ground, which is crucial for the performance of the BHE. We describe how 1D model components for flow and heat transport in the technical part can be coupled with a 2D or 3D component for the ground. With appropriate borehole conductances so coupled model is capable to cope with laminar, turbulent and transitory conditions in the pipes.

**Keywords:** borehole heat exchanger (BHE), heat transfer, thermal conductance

## 1. Introduction

Geothermal energy is a renewable, locally available, low-carbon energy (Ashby *et al.* 2012). In comparison to other alternative energies geothermics is independent of season, weather and climate and thus is available permanently. Depending on the depth below the surface, where the installation is placed, one may distinguish between near-surface and deep utilization of geothermal energy. Shallow, near surface systems usually do not reach a depth of more than 100 m, while deep geothermal systems utilize reservoirs in several 1000 m depth. Two applications for intermediate depths are presented here briefly.

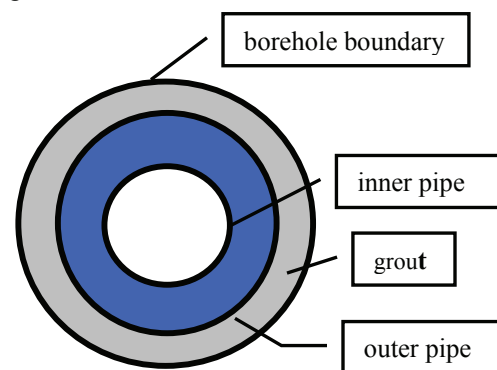
Shallow geothermics can be used for heating and cooling, and for both heating and cooling (Stauffer *et al.* 2013). For electricity generation higher temperatures are needed, which, except in high-enthalpy regions, can be found in greater depths only. Geothermal heat pumps are an integral element within heating, ventilation and air conditioning systems (HVAC), discussed in the framework of green energy concepts (Egg & Howard 2010). Using BHEs the connection of geo- and solarthermics (for example:

Oberdorfer *et al.* 2012, 2013) shapes the way towards a sustainable heating/cooling sector.

Technically one may distinguish between open and closed systems. In closed systems, borehole heat exchangers for example, a fluid is circulating in closed pipe systems, and only conductive heat transfer from the ground is utilized. In contrast open systems use the heat of the subsurface water directly.

With the widespread distribution of BHEs, energy piles or doublettes, questions raise about the capacity, longterm potential of these shallow geothermal resources. Some approaches have been developed based on numerical modeling (Al-Khoury 2011, Stauffer *et al.* 2013, Laloui & di Donna 2013). The FEFLOW code for groundwater flow and transport has been extended especially for BHEs (FEFLOW 2014). Hecht-Méndez *et al.* (2010) present a model based on the solute transport code MT3DMS.

There are various types of BHEs, concerning the pipe design. Major types are the U-pipe, double-U-pipe, and the coaxial type (Oberdorfer *et al.* 2011). Here we focus on the latter type, for which a cross-sectional view through the borehole is depicted in Figure 1.



**Figure 1.** Sketch of cross-section through a co-axial heat exchanger

There are three main components CXA-design: the inner pipe, the outer pipe and the grout. Water flows through the inner pipe and the annular cross-section. At the bottom the inner cylinder is open and connects to the annular space between the inner and outer cylinders. A technical fluid, in some cases just water,

circles through this pipe system, from the inlet at the ground surface to the nearby outlet.

The outermost part between outer pipe and borehole boundary may be filled with water, but is often filled by a suited material, often cement, here called grout. There are two operation modes for the co-axial BHE: there can be downflow in the inner cylinder and upflow in the annular part (CXC) or in the other direction: downflow in the annular and upflow in the inner cylinder (CXA).

## 2. Components and Couplings

The BHE itself is modelled by 1D models directed along the borehole, one for downflow and one for upflow. The coupled 1D models can be embedded in a 2D vertical cross-section or 3D model of the surrounding porous medium. Details of these couplings are described in the next chapter. For the consideration of the grout there are several alternatives. It can be either modelled similar to the porous medium, i.e. in a 2D vertical cross-section or in 3D. It could be treated similar to the water filled pipes, i.e. in a vertical 1D geometry. Finally it is also possible to consider grout as an additional resistance in the calculation of the conductances; see end of this chapter.

In the presented approach the temperature  $T$  in the pipes is described by the 1D differential equation for heat transport:

$$(\rho C)_f \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}((\rho C)_f T v) = -\frac{\partial}{\partial x} \cdot \lambda_f \frac{\partial T}{\partial x} + j$$

with heat capacity of fluid  $(\rho C)_f$ , fluid thermal conductivity  $\lambda_f$ , flow velocity  $v$  and sinks/sources  $j$ . The different terms of the equation consider storage, advection, conduction and additional sinks or sources. The thermal regime in the ground is described similarly by the equation:

$$(\rho C) \frac{\partial T}{\partial t} + \nabla \cdot ((\rho C)_f T \mathbf{q}) = -\nabla \cdot \lambda \nabla T$$

with specific heat capacity of the fluid-solid system  $(\rho C)$ , its thermal conductivity  $\lambda$  and groundwater velocity  $\mathbf{q}$ . In case of stagnant groundwater, the second term of the equation can be omitted. The equation is valid in 1D, 2D or 3D. In case of groundwater flow the hydraulics affects heat transport in the advection term via Darcy velocity  $\mathbf{q}$ :

$$\mathbf{q} = -\nabla \cdot \mathbf{K} \nabla h$$

with piezometric head  $h$  and the tensor of hydraulic conductivities  $\mathbf{K}$ . The piezometric head can be obtained by solving the groundwater flow equation:

$$S \frac{\partial h}{\partial t} = \nabla \mathbf{K} \nabla h + Q$$

with storage coefficient  $S$  and general sink/source term  $Q$ .  $h$  is the dependent variable in the equation. Details concerning the link between hydraulics and thermics can be found elsewhere (Holzbecher 2014). Heat transfer at the interfaces between grout and pipes, and at pipe boundaries of the pipes is calculated using conductances  $h$ :

$$j_s = -h(T - T_{ext})$$

with external temperature  $T_{ext}$ . Conductances  $h$  are calculated as inverses of resistances  $R$ . As heat flow is mainly normal across the interfaces, resistances can be added (Al-Khoury 2011). For pipe and annular flow resistances depend on the Nusselt numbers  $Nu$ :

$$R^{-1} = \begin{cases} Nu \cdot \lambda \cdot \pi & \text{for cylinder flow} \\ Nu \cdot \lambda \cdot \pi \cdot r_i / d & \text{for inner boundary annular flow} \\ Nu \cdot \lambda \cdot \pi \cdot r_o / d & \text{for outer boundary annular flow} \end{cases}$$

The Nusselt-numbers are calculated differently for laminar flow ( $Re < 2300$ ), transition regime ( $2300 < Re < 10000$ ) and turbulent flow ( $Re > 10000$ ). For laminar flow for example the calculation is done according to the formulae:

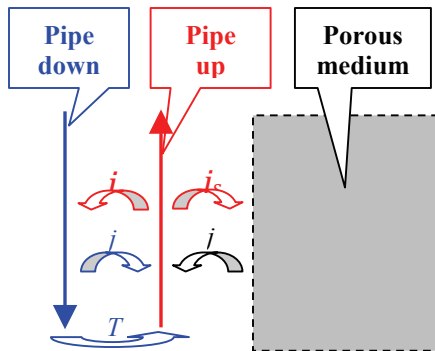
$$Nu = \begin{cases} 4.364 & \text{for cylinder flow} \\ 3.66 + \left( 4 - \frac{0.102}{0.02 + r_o / r_i} \right) \left( \frac{r_o}{r_i} \right)^{0.04} & \text{for annular flow} \end{cases}$$

For  $Re > 2300$  the Nusselt-number depends on the Prandtl-number  $Pr$  in addition. For this study we adopted the formulae from FEFLOW (2014), which are well established for smooth pipe boundaries. Similarly they can be specified for other BHE-designs, as U-pipes or double U-pipes. Alternative formulae can be implemented easily, which surely is necessary for pipes with rough surfaces.

## 3. Model Set-up

As noted already the entire model consists of three components: downflow, upflow and ground. The former two are 1D, the latter can be 2D or 3D. The connection between downflow and upflow, the U-turn itself at the very bottom of the BHE is neglected.

COMSOL Multiphysics (2014) is surely the most convenient software to treat such a multi-component set-up.



**Figure 2.** Sketch of components and extrusions

In all components we utilize heat transfer modes. For downflow and upflow we use heat transfer in fluids, for the ground heat transfer in porous media. The components are coupled in various ways by extrusions, which are sketched in Figure 2.

Upflow and downflow are coupled in two ways. (1) The calculated bottom temperature of the downflow leg is the inflow temperature for the upflow leg. (2) At all depths the temperatures of both components are utilized to compute the heat exchange between inner and outer leg, using conductances, as outlined in the previous chapter. The exchange term is considered in the differential equation as additional source or sink.

Finally the coupling between the 2D/3D region and the outer pipe is realized as follows: (1) the temperature from the outer pipe is considered in a general flux boundary condition in the 2D/3D component; (2) the temperature from the 2D/3D model is considered in an additional source term for the outer pipe model.

To complete the boundary conditions some further notes are necessary. The 1D components have a Dirichlet condition at the inlet, and the usual Neumann condition at the outlet. The multidimensional model has a Dirichlet condition at the outer boundary, in which the geothermal gradient is taken into account. For inhomogeneous geological settings, as treated in our applications below, the correct (piecewise linear) profile can also be obtained by a steady state pre-run with the model - without BHE heat withdrawal. At the bottom of the porous medium model we require a Dirichlet temperature condition. At the top we use a Dirichlet condition, too, in order to account for temporally

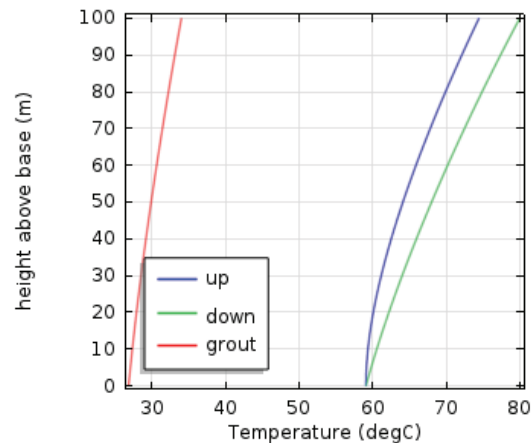
changing conditions. In general a Neumann condition may also be adequate there – see the verification case.

For a verification exercise of our approach we compared output from COMSOL Multiphysics with published results; see details in the next chapter. Applications of the presented approach are described and presented in a further chapter below.

#### 4. Verification

For the verification of the chosen approach a first test model was set up for a benchmark specified in a FEFLOW white paper (FEFLOW 2014). As in a thermal response test heated water enters a co-axial BHE. In the test the steady state is examined within the grout under a constant temperature boundary condition at the borehole walls. The entire constellation requires a 2D approach for the grout region as the porous medium component of Figure 2. The ground around the borehole itself is not considered in this benchmark.

For the numerical calculations we took standard elements with quadratic shape functions. The 1D components consist of 100 elements. For the 2D region we chose a rectangular (mapped) mesh with 161 elements on the long (vertical) sides and 50 elements on the short (horizontal) sides. In the horizontal direction the elements become smaller when approaching the inner boundary.



**Figure 3.** Results for the CXA verification case: heated borehole; temperatures in downflow and upflow part of CXA heat exchanger

Reynolds numbers are 8551 and 3634 for the circular and the annular cross-sections. Concerning thermal conductances we are thus in the transition regime between laminar and turbulent conditions.

Figure 3 depicts the temperature profiles in the up- and downflowing legs of the BHE as well as at the interface to the grout. The result is quite different from the profiles of the original proposal. This is most likely due to the different geometries in the two models. However, the benchmark allows a check of the heat flux balance along the borehole. This is depicted in Figure 4, where total flux in upflow (out) agrees perfectly with the balance from flux out of the 2D grout model and the total flow in the downflow (in).

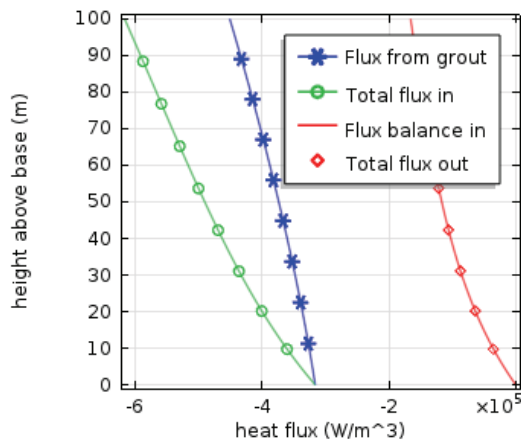


Figure 4. Flux verification for test model CXA heat exchanger

## 5. Applications

The presented method was utilized for the calculation of the thermal potential of two field sites. The two sites have in common that they are located in Lower Saxony, Northern Germany, that they are of intermediate depth (1000-1500 m) and that they are partially drilled in a salt formation.

Subsurface salt formations in form of salt domes appear quite frequently in the North-German lowlands. They are advantageous for geothermal installations, as salt is a good heat conductor. With 4 W/m/K the thermal conductivity of salt is double the size of the usual saturated porous medium. The increased conductivity is generally connected with a steeper geothermal gradient. The second advantage is that a higher capacity of the geothermal facility can be obtained.

For the location Hambühren a feasibility study is terminated, while the location Göttingen is still in the first investigating stage. In Hambühren salt dominates the geological profile: the overlying cap-layer has a thickness of 130 m, only. In Göttingen the thickness of the salt layer is expected to have a

thickness of 350 m. Aside from the salt there are two further layers considered in Hambühren. In the Göttingen model there are seven different geological formations.

Using the before described approach models are used that simulate the operation of a geothermal facility for both sites. Here we present results for the CXA pipe design, which is favoured at both sites currently. The circulating technical fluid has a lower freezing point, a density slightly lower than  $1000 \text{ kg/m}^3$  and a dynamic viscosity of  $1.793 \cdot 10^{-3} \text{ kg/(m}\cdot\text{s)}$ . For the Hambühren case from the feasibility study we assumed that the heat pump is operating in the cold season 211 days of the year, while for the second site we took a constant pumping rate for simplicity. For the temperature difference between inflow and outflow from the pump, we assumed a typical heat pump characteristic of  $6^\circ\text{C}$ .

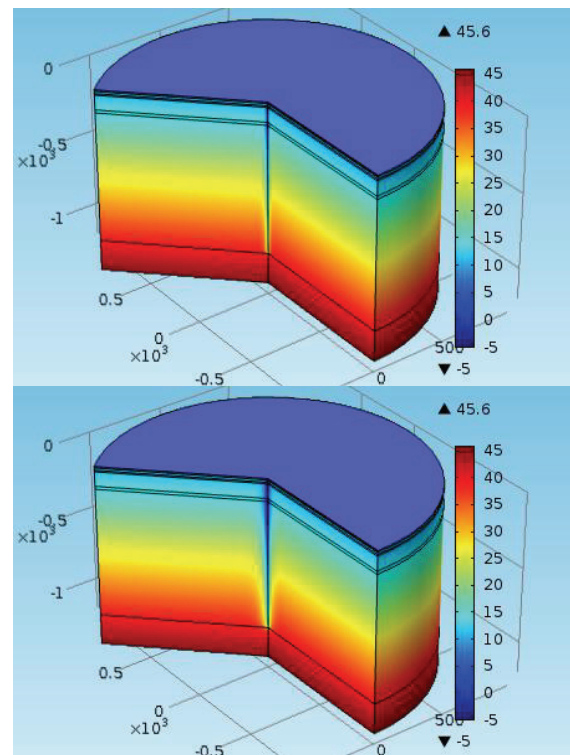


Figure 5: Temperature [°C] field at planned installation in Hambühren, after 5 a (top) and 30 a (bottom)

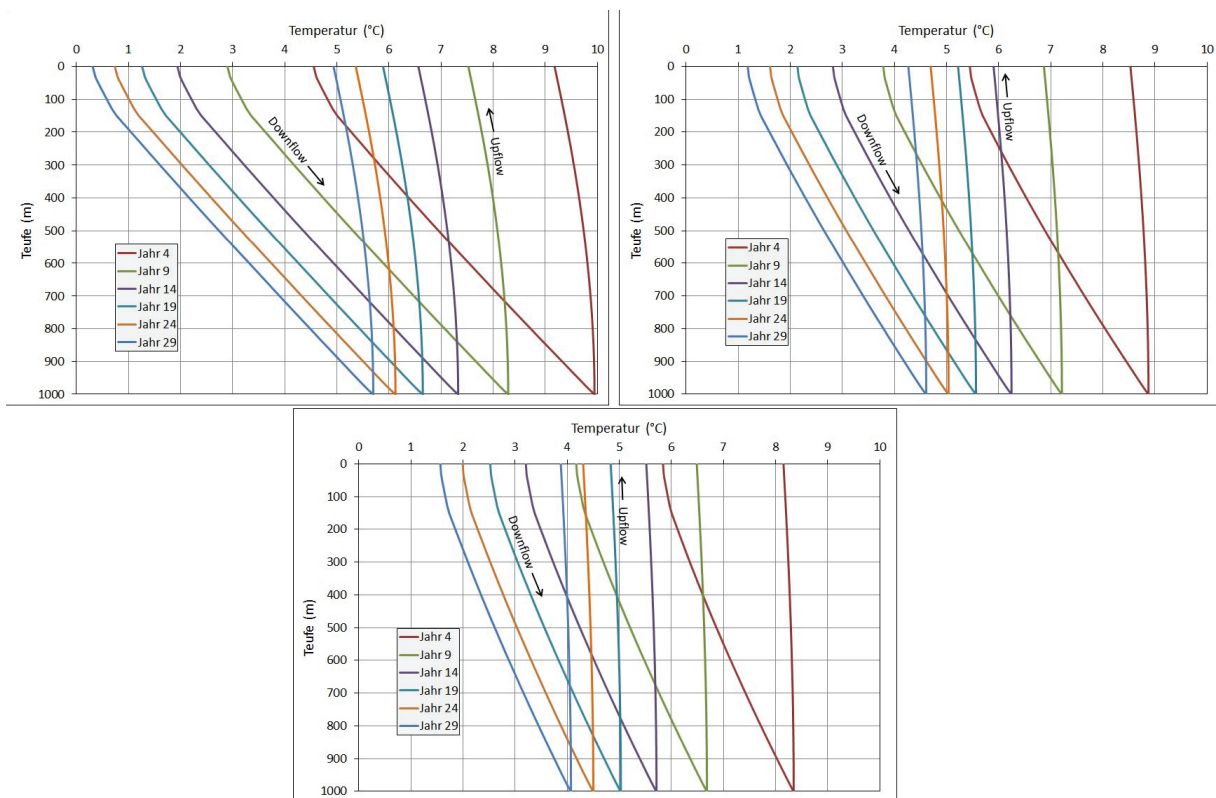
Concerning the surrounding ground a 2D approach was assumed to be sufficient. However, currently there are no data concerning varying geological conditions at the deeper depth anyway. All geological layers extend horizontally and have a constant thickness. There are no data concerning groundwater

flow. Thus the hydraulic coupling was not considered in the model. Within the dominating salt formation there is almost no water and thus the neglect of fluid flow is surely justified. In the following we focus on the Hambühren site, for which more geological and technical data are available at the current state.

The model region extends 360 m around the borehole. In addition seasonally fluctuating surface temperatures were considered at the upper boundary. We use a sinusoidal development of temperatures for a time period of 1 year with minimum temperature of 1.4°C and a maximum of 18.7°C. However, this may be of importance in (very) shallow geothermics, only. Moreover in the uppermost near-surface part of the model region the groundwater table was taken into account. Above the water table the porespace is filled by air, below by water, which is of influence for the thermal conductivity and for the heat capacity. The initial condition was determined in a pre-study run of the model for steady-state conditions without withdrawal of the geothermal heat. At the outer boundary we assume no change of the initial state, considered by a Dirichlet condition.

The Reynolds-numbers are 28095 for downflow and 12482 for upflow, and thus in the turbulent regime. The inner pipe is of polypropylene, the outer of steel. For meshing of the 2D region this time free triangular elements we chosen. Refinements were required at the top boundary (in order to resolve the effects of seasonal oscillations) and at the inner borehole boundary. The total number of elements is 25702. Figure 5 shows the temperature distribution in the vicinity of the borehole after 5 and 30 a of constant operation.

Figure 6 depicts the temperature profile in the downflow and upflow legs of the BHE for the Hambühren. The results show heating up in the downflow leg and a very small cooling in the upflow leg, due to contact with the surrounding upflow leg. For longer operation times the V-curves of temperature profiles move towards colder temperatures. Gradually the shift from one year to the next becomes smaller, but a steady state is not reached after 30 years of operation.



**Figure 6:** Temperature [°C] profiles in downflow and upflow pipes; in dependence of operation time (Jahr=year); three subfigures for different flow rates (4, 6, 8 l/s); for planned geothermal facility at Hambühren (Germany)

However, temperatures are above freezing point. The three sub-figures show the dependence on flow rate, here 4, 6 and 8 l/s. With increasing flow rate the temperature differences between upflow and downflow decrease, i.e. the inclination of the V-curves.

Additional simulations reveal that the capacity of the BHE for a salt-dominated site, as in Hambühren, is almost twice the capacity of an identical installation in a no-salt porous medium with lower heat conductivity.

## 6. Discussion and Conclusions

Using COMSOL Multiphysics a model concept is developed that enables the simulation of coupled heat transfer in pipes and surrounding porous medium. The grout, that may be used to fill the borehole, can be included either explicitly as another component (see verification exercise) or implicitly by using an additional resistance term for calculating thermal conductances. Concerning the conductances we distinguish between laminar, turbulent and transitory regimes, valid for pipes with smooth walls.

The 1D pipe concept can be applied within 2D or 3D porous medium domains in cartesian or axisymmetric coordinates, for steady-state as well as for transient problems. Advective processes resulting from groundwater or seepage flow can be included (not shown here), using 3D domains. In parameter studies a 1D advection field can be used. In general the 3D heat transfer model can be coupled with a 3D model for groundwater hydraulics, based on the equations given above. It is even possible to treat high temperature gradients, when changes of fluid properties, density and viscosity, have to be taken into account; thus using a two-way coupled TH-model (thermal-hydraulic; see for example: Holzbecher 1998).

Geological layers, complex geometries, inhomogeneities, anisotropies of the porous medium can be accounted for. It is possible to use the here presented concept for heat exchangers of different design (U-pipe, double U-pipe). For rough pipes these should be altered accordingly. The transient response of the system due to varying pumping regimes can be simulated. Finally it is possible to take different conditions at the boundaries into account. For shallow boreholes changing conditions, i.e. of temperatures and/or fluxes, at the ground surface can be important. The presented model concept, coupling 1D heat transfer to higher

dimensional components, is quite general, as it can be utilized to all mentioned settings and influences.

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