Numerical Modelling of Shallow Geothermal Energy Exploration Process

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Overview

1) Introduction of Ground Source Heat Pump (GSHP) systems

1) Numerical Modelling of heat transport around BHE

2) What are the influencing factors for BHE efficiency?

3) How much energy can be sustainably extracted from shallow subsurface?

4) What will be the potential environmental impacts, e.g. on downstream groundwater temperatures?
Motivation: Building Heating consists of a large part of our Energy Consumption

- Energy consumption in the EU

- 84% of H&C is still generated from fossil fuels
- EU carbon reduction target: 80% by 2050
  - EU renewable energy target: 12% of heat from renewable energy by 2020
- Using shallow geothermal energy for H&C is a viable option.
  - local, clean and efficient!
GSHP – Technical Background

classified in the model

direct BHE boundary condition

COP corrected boundary condition

not yet included in the model

Hot Water Supply

Soil

filled with grout

Circulating Fluid Pump

Heat Pump

Buffer Tank

Floor Heating
Operation Principle of Borehole Heat Exchangers

Distributor and collector with pressure gauge.  
*Q:* which one is the inlet and which one is the outlet?

Open/close valve

Two boreholes are both 2U setup.

De-gassing air releasing valve.

*Q:* think about what is the purpose of this device?

This is the valve to bleed or fill up the system.

Additional weight at the bottom to pull the pipelines down the borehole.

Source: International Geothermal Association, Training Center Bochum
Operation Principle of Borehole Heat Exchangers

Source: BINE Information Services

Source: http://www.groenholland.com
Integration of Data in the numerical model for the process analysis

- Monitoring and Modelling
- Mechanistic Understanding of underlying processes
- Data Driven Model Development
- Visualization and Analysis of Modelling Result
- Model Validation and Parameter Calibration
- Prognosis of System Performance and Environmental Impact
- Data Driven Model Development

[Diagram showing integration of processes]
OpenGeoSys FEM solution with dual-continuum

- Implementation of BHE as a secondary domain, based on the Approach of Al-Khoury (2009) and Diersch (2013).

- Model verified against analytical solution and in-door experiment from Beier (2011) and Beier (2014).
Reference scenario as a single-family house in Leipzig

- Reference scenario built based on the site characteristics of Leipzig.
- Fluctuating surface temperature on the domain surface, according to the metalogic data of Leipzig.
- Thermal flux boundary condition at the bottom, based on a measured geothermal gradient of 0.0384 W/m².
- Building thermal load calculated for a 150 m² single family house.

\[ q_{geo} = \lambda_{soil} \left( \frac{\partial T}{\partial z} \right)_{geo} \]
Configuration of the subsurface structure
Impact of groundwater flow

- It is observed that the recovery ratio increases with increasing Darcy velocity.

- The curve has a sigmoid-like shape. While Darcy velocity increases, also the recovery ratio increases in an exponential manner until reaching a turning point, from which on the recovery ratio converges asymptotically towards full recovery.

- Here, it can be clearly observed that the perturbation of the temperature field in the vicinity of the BHE decreases with increasing groundwater flow velocity.

- Also, it is found that the heat pump COP is further increasing, although almost full recovery is reached with higher groundwater flow velocities.
The two configurations are compared in terms of total cost, which includes the initial installation together with 30 years’ of electricity consumption.

Installation cost is estimated based on the per meter long BHE, and the electricity cost is based on ~0.30 Euro/kWh price in Germany.

The time value of the electricity cost in the future is corrected with an interest rate of 0.05% as in Germany.

\[ C_{\text{current}} = \frac{C_{\text{future}}}{(1 + e)^n} \]

The total cost will be clearly higher for the 46m configuration in Germany.

From 46m to 150m, the total cost first drops quickly, then is smooth. With our setup, the optimal length is a 86m long BHE.
How much energy can we sustainably extract from the shallow subsurface?

Standard approach:
Volume based accounting with a uniform Delta_T value:

\[ E_{geo} = E_S + E_W = V(1 - \epsilon)C_S\Delta T + V\epsilon C_W\Delta T. \]

In the reality:

- Temperature profile in the vicinity of the well is funnel shaped – uneven distribution.
- Temperature profile in the soil changes over season.
- The recovery of the soil temperature must be put into consideration.
Introducing the Equivalent Temperature Drop:

(1) Calculate the average temperature in a controlled volume.

\[ \bar{T}_s = \frac{1}{V} \int_{\Omega} T_s(x, y, z, t) \, dV \]

(2) Find the difference of averaged temperature between one year.

\[ \Delta T_{s,eq} = \bar{T}_s(t_1) - \bar{T}_s(t_0). \]

Figure 3: Visualized soil temperature distribution after 30 years of operation, with data presented at the end of December.

Figure 5: Temperature fluctuation at the BHE wall, measured at the top of the BHE. The initial and quasi steady-state temperatures are marked with dashed lines.
How does the equivalent temperature drop respond to CV size and soil thermal conductivity lambda?

- The boundary of undisturbed temperature is quite far away.
- At the boundary, if temperature change is less than 0.1 dC, the radius is about 110 m (with soil conductivity of 2.0 W/m/K)

- With higher lambda value, the equivalent temperature is smaller. (with a=b fixed at 10 m)
How does the arrangement of multiple BHEs affect the equivalent temperature drop?

- Arrangement of 1x4 and 2x2 BHEs is tested.
- 2x2 arrangement shows larger delta_T drop.
- Large BHE systems needs to be further investigated.
How much energy can we sustainably get from shallow subsurface?

- Single BHE GSHP system: -2.8 dC and -1.8 C for a typical range of subsurface thermal conductivity values over a period of 30 years.

- With a configuration of 4 individual BHE GSHP systems, the equivalent temperature drop ranges between -3.9 dC and -4.4 dC.
A Case Study on the Environmental Impact of Shallow Geothermal Energy Utilization

- 47x closed systems (borehole heat exchangers, BHEs), 4x open systems, closest distance < 10 m
- Measurement of GW levels and temperature
- Unsaturated flow, hydraulic gradient: $6 \times 10^{-4}$ (±35%)
2D GW flow and heat transport model constructed with OpenGeoSys

- assuming fully-saturated flow → depth-averaged model
- finite element mesh, refined around GSHP nodes

Average GW flow velocity: ~11 m/yr
Undisturbed GW temp: 11.6 °C
Calibration of the Numerical Model by Measurement Data
Long-term (25 years) Simulation Result on the GW Temperature Distribution
Will the GW temperature continue decreasing?
- Due to the dispersion effect, probably not.
Impact of the low temperature zone produced by long-term operation

A series of GSHPs along the flow direction adds to downstream cooling!
Summary

• What are the influencing factors for BHE efficiency?

  GW Flow, Specific Thermal Load, Soil Thermal Conductivity

• How much energy can be sustainably extracted from shallow subsurface?

  About 2-4 dC of equivalent Temperature Drop

• What will be the potential impacts on downstream groundwater temperatures?

  In general not much. In places where GSHP systems are lined along with the GW direction, this will cause lower efficiency.