Hein et al 2016

GSHP are often coupled with borehole heat exchangers (BHE) to extract geothermal energy, but some GSHP system recently experiences gradual decrease in BHE outflow temperature and had to be shut down. Here the authors built a comprehensive numerical model including:

* flow and heat transport processes (i.e. model considers inhomogeneous subsurface properties, groundwater flow, geothermal gradient, heat flux, varying surface temperature.
* the dynamics of heat pump efficiency (i.e. Heat pump model included to consider varying heat loads due to specific **COP** characteristics of the HP + building heat demand)

The model parameters are based on scenario of a single-family house GSHP in the Leipzig area, Germany. Model used to assess the sustainability and efficiency of the system + impact of design and operational errors were analyzed

The scenarios are modelled to observe the evolution of BHE outflow and soil temperatures under various factors of influence (i.e. thermal rock properties, GW flow impact, system design).

Results:

* recovery of shallow geothermal energy only accounts for about 89% of the energy extracted in the first year and then outflow and soil temperature decrease until quasi-steady-state.
* Groundwater flow and using BHE for cooling will be beneficial to the energy recovery and efficiency of the heat pump.
* soil heat capacity and thermal conductivity are considered to have a minor impact on the sustainability of the system
* undersized systems are the cause of strong system degradation.

Novelty: consider realistic simulations of BHE coupled GSHPS including site-specific conditions like geothermal gradient and heat flux, ground surface temperature fluctuation + COP curves and corresponding energy consumption.

Main findings: potential of reducing the BHE length if sufficient groundwater flow helps the subsurface thermal recovery. Heat from cooling application during the summer will always improve the system performance.

Implication and outlook: Model simulations suggest that the soil conductivity and building thermal load should be determined as accurately as possible to guarantee a sustainable and efficient operation of BHE-coupled GSHPS. Small underestimation in these two values is very likely to cause the over-exploitation of the subsurface and consequently the breakdown of heat pump system.

Model modules:

* dual-continuum approach (Al-Khoury et al., extendend by Diersch et al.[20,21], adopted and implemented in the OGS (cf. Kolditz et al. [22], Zheng et al.)
  + Subsurface = 3d continuum
  + BHE = 1D line elements
* heat transfer between different BHE compartments (i.e circulating fluid within the pipes, the grout zones and the borehole) modeled by means of a thermal capacity-resistor network
* heat fluxes q driven by the temperature difference ΔT between these components and the heat transfer coefficient (i.e. inverse of the product of thermal resistance R and specific exchange area S.

In the subsurface: both the heat convection of the fluid f (groundwater) in the soil and heat conduction through the soil matrix s contribute to heat transport.

For the BHE, 2 main equations:

* Convection in pipe (inflow and outflow pipe with circulating fluid at velocity v), Cauchy BC
* Dispersion in grout zone with Cauchy BC

BC for BHE always imposed in terms of Tinlet but it is more convenient to prescribe BHE thermal load in terms of power and heat flux through BHE



So Tinlet calculated iteratively using prescribed Qbhe and Qr (flow rate) and T0 from preceding iteration

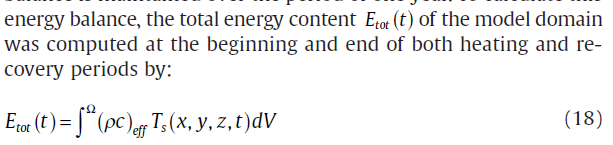
Here, COP of the HP integrated in the equations by assuming linear relationship between outlet temperature and COP (Kahraman and Celebi [24], Casasso and Sethi [16] and Sanner et al.)

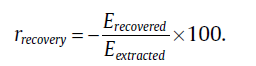
Model set up:

* BC: qgeo value turns out to be 0.0384Wm−2 and is applied as a Neumann bottom BC. As a result of this heat flux, energy can permanently accumulate in the model domain, which is not realistic, so a ground surface BC is applied accordingly.

Bortoloni et al. [31] compared the influence of different BC at the ground surface in modeling shallow horizontal ground heat exchangers. They found out that applying the surface temperature (Dirichlet) in contrast to heat flux (Neumann) and mixed (Cauchy) boundary conditions is appropriate with respect to the BHE fluid temperature. Here the stepwise function of monthly mean temperatures imposed as a Dirichlet type BC on the ground surface.

* **IC adapted to maintain an energy balance over a year, based on mean annual surface temperature and bottom HF (reference model with no extraction is thermally balanced, so Etot= cst)**





**Same model was also simulated with:**

* **ground surface temperature boundary condition only and**
* **bottom heat flux boundary condition only.**

**It turned out that after the first year, the ground surface temperature contributes approx. 98% to the energy balance, while the bottom heat flux contributes only approx. 2%.**