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Research Paper

A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems

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HIGHLIGHTS

- A numerical BHE model was enhanced to include heat pumps characteristics.
- Surface temperature and geothermal gradient are necessary for realistic simulation.
- The benefit of groundwater flow and injection of excess heat is quantified.
- Usage of thermally enhanced grout materials will always result in financial benefit.
- It was found that BHE coupled GSHP systems are extremely sensitive to design errors.

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ABSTRACT

To utilize shallow geothermal energy, ground source heat pump systems (GSHPS) are often coupled with borehole heat exchangers (BHE). In recent years, some GSHPSs are experiencing a gradual decrease in BHE outflow temperatures and thus have to be shut down. In this work, a comprehensive numerical model was constructed to include flow and heat transport processes, together with the dynamics of heat pump efficiency. The model parameters are based on local conditions in the Leipzig area. Different scenarios were simulated to observe the evolution of BHE outflow and soil temperatures subject to various factors of influence. In the first year, the recovery of shallow geothermal energy only accounts for about 89% of the energy extracted. Over the following years, outflow and soil temperature will gradually drop until they reach a quasi-steady-state. It was also found that groundwater flow and using BHE for cooling will be beneficial to the energy recovery and efficiency of the heat pump. In comparison to other factors, the soil heat capacity and thermal conductivity are considered to have a minor impact on the sustainability of the system. In contrast, it is very likely that undersized systems are the cause of strong system degradation.

1. Introduction

For the purpose of heating and cooling buildings, borehole heat exchanger (BHE) coupled ground source heat pump systems (GSHPS) have gained increasing interest in recent years. In heating applications, energy is extracted from the shallow subsurface by a fluid (usually water with antifreeze) circulating through pipes in one or multiple BHEs. In the upper 10–15 meters of the shallow subsurface, the ground temperature is controlled by surface temperature variation and also the heat flux through the soil. Below this depth, the temperature field is controlled by the geothermal gradient and the vertical geothermal heat flux. The heat from the subsurface is carried by the circulating fluid, lifted by a heat pump, and then supplied to the building.

It is known that in summer when the GSHPS is switched off, the subsurface temperature will recover. This recovery can also be facilitated by providing cooling to the building. Over the course of a year, a thermal balance of the subsurface can only be achieved if heating and cooling loads are balanced; otherwise, the subsurface around a BHE will be cooled down until a quasi-steady-state is reached. Basetti et al. [1] reported several cases in which the subsurface and BHE outlet temperature considerably decreased after a couple of years of operation. Since heat pumps operate most efficiently at high temperatures, the drop of BHE outlet temperature will lead to the efficiency decrease of GSHPS as well. In extreme cases, the BHE outlet temperature is so low that it causes a breakdown of the heat pump. Therefore, to maintain a sustainable system,

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the temperature drop in the vicinity of BHE must be as small as possible.

The overall behavior of BHE-coupled GSHPS depends on a wide range of factors. First, the site conditions, including local geothermal gradient, surface temperature variation, soil saturation and groundwater flow, have to be considered. Bandos et al. [2] presented an analytical solution, which takes into account the initial temperature field due to the geothermal gradient, as well as the fluctuating surface temperatures. Kurevija et al. [3] found in their study that the geothermal gradient will influence the sizing of BHEs. Molina-Giraldo et al. [4] presented analytical solutions considering the advective heat transport due to groundwater flow. Rivera et al. [5] investigated the effects of groundwater flow and land surface on the thermal regime of the underground by means of an analytical solution. They also analyzed the ground energy balance subject to groundwater flow and vertical heat fluxes [6]. A numerical study on the thermal impact and performance of BHEs due to groundwater flow has been performed by Angelotti et al. [7], while Zhang et al. [8] investigated the effect of groundwater advection on BHE fields.

In addition to the site conditions, the subsurface characteristics, such as soil thermal conductivity, density and specific heat capacity, also need to be considered. Luo et al. [9] analyzed the performance of BHEs in a layered subsurface. They concluded that the system design, thermal load of the building, BHE length and cooling demand also have considerable effects on long-term system performance. Another widely-ignored effect is that the heat pump *coefficient of performance (COP)* is dynamically regulating the thermal load on BHE. De Rosa et al. [10] presented an analytical BHE model, which is coupled to a heat pump model in the commercial building simulation code TRNSYS. Further studies that take the coupling between BHE and heat pump into account were presented by Capozza et al. [11] and Retkowski et al. [12] The effect of unbalanced thermal load during heating and cooling season was investigated by You et al. [13], Mehrpooya et al. [14], and Yu et al. [15] Casasso et al. [16] performed a sensitivity analysis on the efficiency of BHE-coupled GSHPS by performing a series of numerical simulations. Also based on 3D numerical models, Lee [17] and Dai et al. [18] analyzed the response of BHEs when subject to quick change of thermal load within short period of time.

In the aforementioned studies, only a single or a few factors that influence the sustainability and efficiency of a GSHPS were investigated. The relative importance of these factors, especially their impact on the long-term running cost of GSHPS, is a critical topic of interest for the GSHPS industry. For designers and contractors, they would like to know which of these factors must be carefully controlled so that the failing cases reported in Basetti et al. [1] can be avoided. Therefore, in this work a general numerical model was established to include all relevant phenomena in a realistic scenario. The model considers inhomogeneous subsurface properties, groundwater flow, the geothermal gradient and heat flux as well as varying surface temperatures. More importantly, a heat pump model is included to consider dynamically-changing loads due to specific COP characteristics. With the heat pump feature, the electrical energy consumption can be determined and thus allowing for financial analysis. By utilizing this model, a systematic study based on a single-house GSHPS was carried out to investigate its sustainability and efficiency. Also, the impact of design and operational errors were analyzed, which to our knowledge has not been investigated by other researchers.

The numerical approach adopted in this work is described in section 2.1. As a heat pump is utilized, the thermal load of the BHE depends on both the building heat demand and the performance characteristics of the specific pump. This feature was integrated into the numerical BHE model (see section 2.2). A reference scenario with realistic heating and cooling loads was adopted (section 3.1), based on the scenario of a single-family house in the area in and around Leipzig, Germany. A number of model simulations were performed in order to investigate the influence of different system parameters (section 3.2 and 3.3). The simulation results are presented (section 4) and discussed (section 5). Finally, we conclude this study in section 6 and give an outlook to potential future topics.

2. Methods

In this work, the dual-continuum approach, originally proposed by Al-Khoury et al. [19] and extendend by Diersch et al. [20,21], was adopted and implemented in the open-source finite element code *OpenGeoSys* (OGS) (cf. Kolditz et al. [22], Zheng et al. [23]).

2.1. Dual-continuum approach

Here, the subsurface is modeled as a 3D continuum, while the BHE is represented by 1D line elements as the second continuum. The heat transfer between different BHE compartments, namely the circulating fluid within the pipes, the grout zones and the borehole wall, is modeled by means of a thermal capacity-resistor-network in analogy to electrical circuits. The heat fluxes q (cf. Eq. (1)) are driven by the temperature difference ΔT between these components and the heat transfer coefficient $\Phi = \frac{1}{RS}$, which is the inverse of the product of thermal resistance R and specific exchange area S.

$$q = \Phi \Delta T. \tag{1}$$

Both the heat convection of the fluid f (groundwater) in the soil and heat conduction through the soil matrix s contribute to heat transport in the subsurface. With ρ_s, ρ_f, c_s and c_f referring to density and specific heat capacity of soil and fluid in a fully-saturated soil matrix with porosity ε_s, subject to a vector of Darcy velocity $\mathbf{v_D}$, the thermal energy conservation equation reads:

$$\frac{\partial}{\partial t}[\varepsilon_s \rho_f c_f + (1-\varepsilon_s)\rho_s c_s] T_s + \nabla \cdot (\rho_f c_f \mathbf{v_D} T_s) - \nabla \cdot (\mathbf{\Lambda_s} \cdot \nabla T_s) = H_s. \tag{2}$$

Here, $\mathbf{\Lambda_s}$ denotes the tensor of thermal hydrodynamic dispersion and H_s denotes the heat source and sink term. For the BHE, there are two governing equations: one for pipes and the other for the grout. For the pipes, the heat transport is dominated by the convection of the circulating fluid r with flow velocity vector $\mathbf{u}$. For a single U-tube (1U) type BHE, with $i1$ denoting the inflow pipe and $o1$ the outflow one, the heat balance of circulating fluid reads:

$$\begin{aligned} &\rho_r c_r \frac{\partial T_k}{\partial t} + \rho_r c_r \mathbf{u} \cdot \nabla T_k - \nabla \cdot (\mathbf{\Lambda_r} \cdot \nabla T_k) = H_k \text{ in } \Omega_k \text{ for } k = i1, i2 \\ &\text{with Cauchy type of BC:} \quad -\Phi_{ig}(T_{g1} - T_{i1}) = q_{nT_{i1}} \text{ on } \Gamma_{i1} \text{ and} \\ &\qquad -\Phi_{og}(T_{g2} - T_{o1}) = q_{nT_{o1}} \text{ on } \Gamma_{o1}. \end{aligned} \tag{3}$$

$\mathbf{\Lambda_r}$ stands for the hydrodynamic thermodispersion tensor of the circulating fluid,

$$\mathbf{\Lambda_r} = (\lambda_r + \rho_r c_r \beta_L \|\mathbf{u}\|)\mathbf{I}. \tag{4}$$

Here λ_r, ρ_r, and c_r are the thermal conductivity, density and heat capacity of the circulating fluid. β_L is the longitudinal thermal dispersivity, and $\mathbf{I}$ is the unit matrix. Inside the grout zones $g1$, $g2$ of a 1U-type BHE, heat transport is dominated by dispersion:

$$\begin{aligned} &(1-\varepsilon_g)\rho_g c_g \frac{\partial T_k}{\partial t} - \nabla \cdot [(1-\varepsilon_g)\lambda_g \cdot \nabla T_k] = H_k \text{ in } \Omega_k \text{ in } k = g1, g2 \\ &\text{with Cauchy type of BC:} \end{aligned} \tag{5}$$