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Coupling of borehole heat exchangers with solarthermal systems

Couplage d'échangeurs de chaleur de forage avec systèmes solaires thermiques

Oliver Reul, Hannes Räuschel
Department of Geotechnical Engineering, University of Kassel, Germany, o.reul@uni-kassel.de

Dietrich Schmidt
Fraunhofer-Institut für Bauphysik IBP, Kassel, Germany

Janybek Orozaliev
Department of Thermal Energy Systems, University of Kassel, Germany

Petra Gerhold
Department of Urban Planning, City Administration, Kassel, Germany

Jochen Bennewitz
Städtische Werke AG, Kassel, Germany

ABSTRACT: The energy demand of buildings for heating and cooling is responsible for more than one third of the world's final energy consumption. The direct use of solar thermal energy via solar collectors is a cost-effective method for energy supply lacking direct emission of CO2. However, since the seasonal availability of solar energy is limited, a seasonal thermal storage such as for example a borehole heat exchanger (BHE) field storing the heat energy for the winter months is required. In the scope of this paper a heat supply concept for a new housing area, based on a BHE field which supplies heat energy to a central heat pump in combination with a low temperature district heating (40 °C) for space heating is presented. The thermal regeneration of the BHE field is enhanced by means of excess solar heat available in the summer. The sensitivity of the performance of this geothermal system on geothermal material properties and groundwater conditions has been investigated with a numerical parametric study.

RÉSUMÉ: La demande énergétique des bâtiments associée au chauffage et au refroidissement est responsable de plus d'un tiers de la consommation énergétique mondiale. L'utilisation directe de l'énergie thermique solaire, grâce à des capteurs solaires est une solution d'approvisionnement énergétique rentable et sans émissions directes de CO_2. Cependant, puisque la disponibilité de l'énergie solaire est saisonnière, un stockage thermique saisonnier, comme par exemple un champs d'échangeurs thermiques situés dans des trous de forage (BHE) stockant la chaleur pour les mois d'hiver est nécessaire. Dans ce document, nous présentons un concept d'approvisionnement thermique pour une nouvelle zone d'habitation, basé sur un champ de BHE, fournissant de l'énergie thermique à une pompe calorifique centrale, associée à un chauffage urbain à basse température (40 °C). La régénération thermique du champs BHE est améliorée grâce à l'excès de chaleur solaire en été. L'impact du système géothermique sur les propriétés géothermiques principales et la qualité de la nappe phréatique a été analysé avec une approche paramétrique numérique.

KEYWORDS: seasonal thermal storage, borehole heat exchanger, solarthermal systems, numerical study

1 INTRODUCTION

The energy demand of buildings for heating and cooling is responsible for more than one third of the world's final energy consumption. Therefore, the identification of innovative heat supply concepts based on renewable energies is required. The utilization of renewable energies in combination with efficient supply technologies increases the sustainability of new housing areas.

The direct use of solar thermal energy via solar collectors is a cost-effective method for energy supply lacking direct emission of CO_2 or atmospheric particulate matters. However, the heat demand of households is subject to seasonal fluctuations. While domestic hot water (DHW) consumption is almost constant over the year, the heating energy demand rises significantly in the winter half year. On the other hand, in Germany the seasonal availability of solar energy is limited to approximately 160 kWh/m² of global radiation in a summer month and to approximately 20 kWh/m² in a winter month (Deutscher Wetterdienst 2016).

Therefore either an additional energy source (e.g. supplemental boilers) or a seasonal thermal storage for storing the heat energy for the winter months is required (Figure 1).

Figure 2 shows different systems for seasonal thermal storage with the emphasis of this paper on seasonal thermal storage systems applying borehole heat exchangers (BHE). For the example of a new housing area in Kassel, Germany, a seasonal thermal storage concept is presented where seasonal thermal storage by means of borehole heat exchangers will be coupled with solarthermal systems.

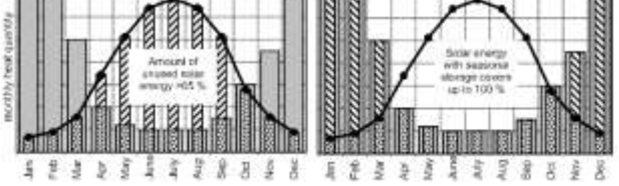

Figure 1. Compensation of heat energy supply and demand by means of seasonal heat storage (after Bauer 2012).

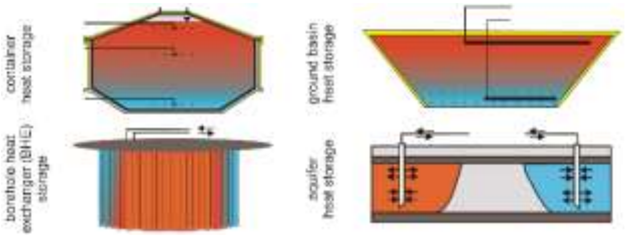

Figure 2. Systems for seasonal thermal storage (after Ochs et al. 2007).

Table 1. Examples for geothermal systems.

Project	Reference	Under-ground	n_{BHE} [-]	L_{BHE} [m]	V_{BHE} [m³]	Q_f [GJ/a]	Q_e [GJ/a]
Kerava, FIN	Peltola 1990	bedrock	54	22-24	11000	2459	2437
Groningen, NL	Wijsman et al. 1983	sand, clay peat layers	360	20	23000	1678	806
Neckarsulm, D	Benner et al. 1999	Gipskeuper, Lettenkeuper	528	30	63360	3924	2671
Attenkirchen, D	Benner et al. 2003	molasse	90	30	9350	691	410
Anneberg, S	Dalenbäck et al. (n.d.)	granite	100	65	60000	2592	1199
Okotoks, CAN	Wamboldt 2009	clay	144	35	34000	2260	1219
Crailsheim, D	Augsten 2005	Gipskeuper, Lettenkeuper	80	55	37500	2473	313*

n_{BHE}, number of BHE; L_{BHE}, length of BHE; V_{BHE}, thermal storage volume; Q_f, energy feeding into the thermal storage; Q_e, energy extraction from the thermal storage; *data from project starting phase

2 SEASONAL THERMAL STORAGE BY MEANS OF BOREHOLE HEAT EXCHANGERS

Borehole heat exchangers (BHE) comprise vertical heat transfer pipes and a footpiece installed in boreholes that usually reach depths of up to 200 m (VDI-Guideline 4640 Part 2). Typically, U-pipes, double U-pipes or coaxial pipes made of a plastic material such as PE are used as heat transfer pipes. After the heat transfer pipes have been placed in the borehole, the connection of the pipes to the subsoil must be produced by means of a perfect grouting from the foot joint to the surface without any gaps. In the heat transfer pipes a heat carrier fluid (e.g. an ethylene glycol water mixture) circulates which extracts or transfers thermal energy from or to the underground, respectively.

The advantages of BHE in comparison to alternative systems (e.g. Figure 2) are the comparatively low costs and the possibility to extend the system if necessary (Al-Addous 2006). On the other hand, large storage volumes are required due to the low heat capacity of soil and rock compared to water. Moreover, BHE storages show relatively high heat losses, since the system can usually only be isolated on the ground surface. The differences between a system without isolation and an isolated system are shown in Figure 6.

As an example, Table 1 summarizes geosolar systems, i.e. systems where solarthermal systems (e.g. solar collectors) have been coupled with a BHE field for thermal storage.

3 GEOSOLAR SYSTEM “ZUM FELDLAGER” KASSEL

3.1 *Geosolar heat supply concept*

The new housing area "Zum Feldlager" comprising 1- and 2-storey detached and semi-detached houses, two-storey terraced houses and large three-storey apartment buildings is located in the city of Kassel (Germany). The total annual energy demand for the housing area amounts to Q_H = 1200 MWh/a for heating and to Q_{DHW} = 365 MWh/a for domestic hot water. Due to the location of the area a connection to the existing district heating network of Kassel is not feasible because of logistical and economic reasons.

As a result of the first project phase a geosolar heat supply concept has been selected. The heat supply concept is based on the central ground source heat pump (estimated seasonal performance factor β_a = 4.9) in combination with a low-temperature district heating with a supply temperature of 40 °C (Figure 3). For the BHE the following configuration has been identified as feasible in the first project phase based on analysis applying the so-called g-functions (Eskilson 1986): number of BHE n_{BHE} = 92; BHE spacing s_{BHE} = 8 m; BHE length L_{BHE} = 120 m; double U-pipes. Due to the relatively large BHE spacing the BHE field does not exclusively store solar thermal energy in the underground but is also able to extract geothermal energy and therefore operates as hybrid system.

Detailed descriptions of the geosolar heat supply concept for the new housing area "Zum Feldlager" in Kassel are given by Schmidt et al. (2016) and Orozaliev et al. (2016).

3.2 *Geothermal site conditions*

According to the data in the geological map (HLUG 1969), residual loess, which can include single quartzite and basalt blocks, can be expected the first few meters below ground level. This layer is followed by claystone and marlstone of the Upper Buntsandstein. The Upper Buntsandstein is underlain by Middle Buntsandstein which comprises mainly sandstone at the site.

The Upper Buntsandstein is characterized by its very low permeability and can practically be considered as an aquitard (HLUG 1969). Small amounts of groundwater can only be expected in thin quartzite or calcareous layers, respectively, embedded in the claystone and marlstone. The Middle Buntsandstein, on the other hand, is an aquifer of major importance for the drinking water supply of Kassel with the groundwater mainly circulating in rock fissures and crevices.

For the investigations of the first project phase the geothermal properties of the underground have been estimated according to VDI-Guideline 4640 Part 1 (Table 2).

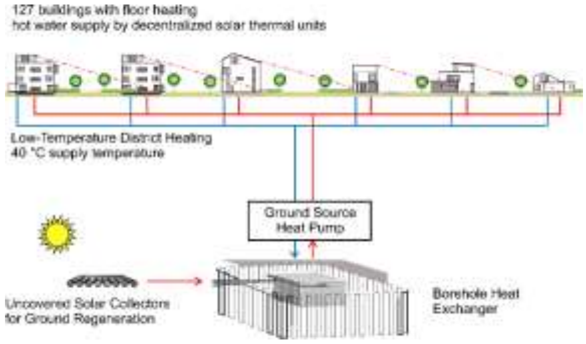

Figure 3. Housing area “Zum Feldlager”: Schematic diagram of the geosolar heat supply concept (Orozaliev et al. 2016).

Table 2. Geothermal properties of the underground (estimated according to VDI-Guideline 4640 Part 1).

Layer	t_L [m]	λ [W/(m·K)]	$\rho \cdot c_p$ [MJ/(m³·K)]
Residual loess	5.5	0.4 to 1.0	1.5 to 1.6
Upper Buntsandstein	125	1.1 to 3.5	2.1 to 2.4
Middle Buntsandstein	90	1.3 to 5.1	1.6 to 2.8

t_L, estimated thickness of the layer at the site; λ, thermal conductivity; $\rho \cdot c_p$, volume related specific heat capacity

In the course of the second phase of the project a geothermal site investigation will be carried out in the first half of 2017 to investigate the geological and hydrogeological site conditions and to establish the geothermal ground properties. The geothermal site investigation will comprise core drillings, geophysical borehole testing and Enhanced Geothermal Response Tests (EGRT) (e.g. Luo et al. 2015).

3.3 *Numerical study*

3.3.1 *Numerical model*

The sensitivity of the performance of the BHE thermal storage on geothermal material properties and groundwater conditions has been investigated with a numerical parametric study. The numerical study has been carried out by means of three-dimensional (3D) coupled finite element analysis with the program FEFLOW (DHI 2015) considering convective as well as conductive heat transfer in the underground.

Figure 4a shows the 3D finite element mesh comprising approximately 614,000 elements und 316,000 nodes with 96 BHE (L_{BHE} = 120 m; s_{BHE} = 8 m) located at the center of the model. The BHE, which do not penetrate into the Middle Buntsandstein, are not discretized in detail but are reduced to internal boundary conditions according to Diersch et al. (2010) applying the Nillert-criterion (Nillert 1976) for the mesh discretization around a BHE (Figure 4b).

In the parametric study simplified loading conditions have been applied with the heat input T_{BHE} = 60 °C and the flow rate of the heat carrier fluid $q_{v,BHE}$ = 0.5 l/s constant over the investigated time period of t = 5 a and all BHE connected parallel.

The temperature at the top surface of the model as well as the normal heat flux at the bottom surface of the model are kept constant at $T_{surface}$ = 10 °C and q = 0.065 W/m², respectively throughout the simulation. The main material properties for the soil and rock layers used in the finite element analyses are summarized in Table 3 for the default model.

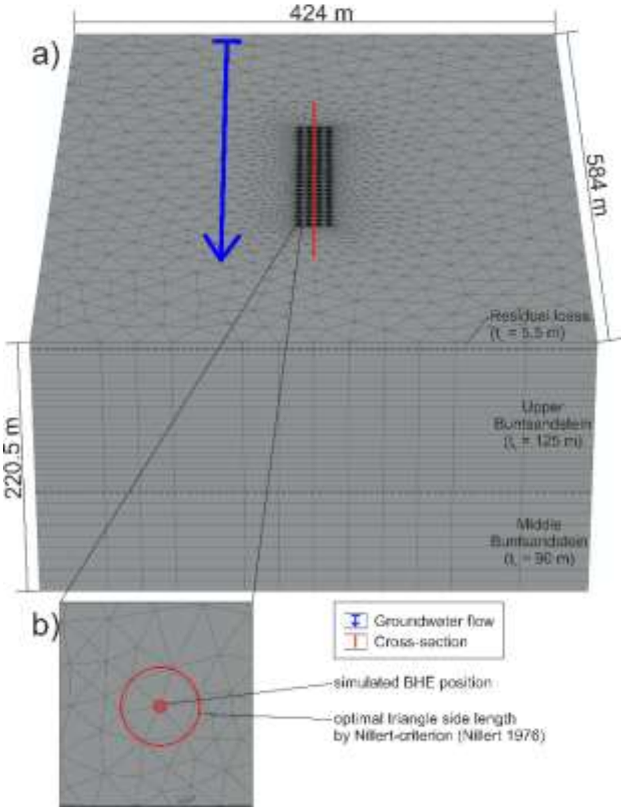

Figure 4. a) Finite element mesh of the system b) Mesh details around a BHE.

Table 3. Material properties in the finite element analyses.

Property	Unit	Residual loess	Upper Buntsandstein	Middle Buntsandstein
$k_{f,h}$ / $k_{f,v}$	[m/d]	3.810/ 0.381	3.46×10^{-4}/ 3.46×10^{-5}	0.259/ 0.130
Φ	[-]	0.100	0.065	0.160
c_V	[MJ/m³/K]	1.55	2.25	2.20
λ	[J/m/s/K]	0.5	2.2	2.8
A_{tc}	[-]	0.800	0.760	0.872

$k_{f,h}$/$k_{f,v}$, hor./vert. permeability; Φ, porosity; c_V, vol. heat capacity; λ, thermal conductivity; A_{tc}, anisotropy of solid thermal conductivity

3.3.2 *Results*

Figure 5 shows the temperature distribution around the BHE field after a time period of t = 5a for a cross section through the finite element mesh (see Figure 4 for definition of cross section).

Figure 6 compares the temperature distribution of the default model (Figure 6a) with a simulation where an 0.5 m thick insulation of foam glass (Φ = 0.41; c_V = 0.136 MJ/m³/K; λ = 0.07 J/m/s/K; A_{tc} = 1.0) is placed on top of the BHE field (Figure 6b). While the model detail plotted in Figure 6, i.e. the residual loess and the top 5 m of the Upper Buntsandstein, show a temperature increase immediately beneath the insulation, evaluation of analysis results in larger depth indicate no significant influence of the insulation.

Figure 7 and Figure 8 show the development of temperature over time at two observation points located in a depth of 60 m below surface in a distance of 5 m and 25 m to BHE field (Figure 5). The variation of the thermal conductivity (Figure 7) as well as the variation of the volumetric heat capacity (Figure 8) document the major influence of these two parameters on the temperature distribution around a BHE field.

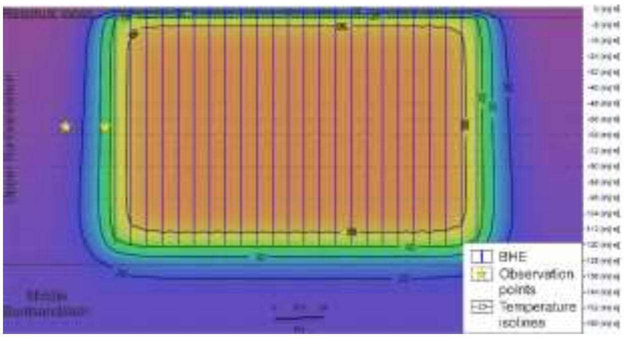

Figure 5. Cross section through the finite element mesh: Isothermal lines for the default model and t = 5 a.

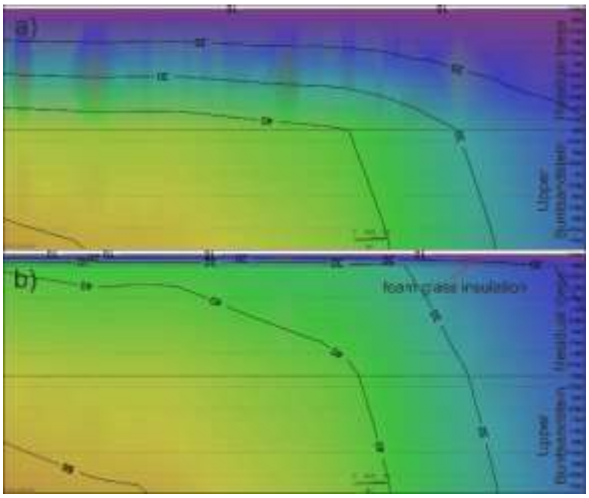

Figure 6. Cross section through the finite element mesh: a) Default model, b) Insulation at the top of the BHE thermal storage; isothermal lines for t = 5 a.

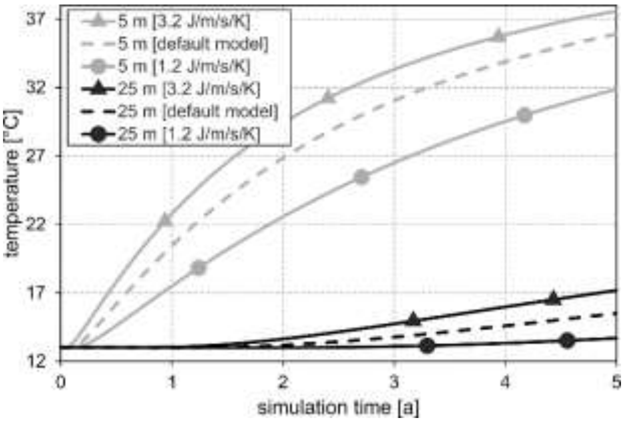

Figure 7. Variation of thermal conductivity: Temperature vs. time.

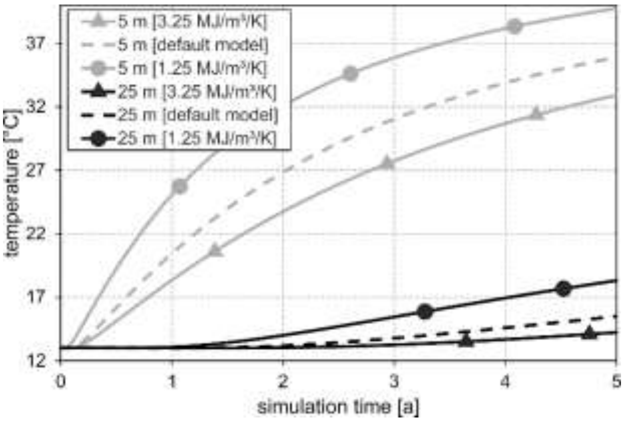

Figure 8. Variation of volumetric heat capacity: Temperature vs. time.

4 CONCLUSION

The results of the numerical parametric study indicate the significant influence of the geothermal material properties thermal conductivity and volumetric heat capacity on the heat flux and temperature distribution around a BHE field. The envisaged geothermal site investigation is therefore of major importance for an economic and sustainable design of the proposed geosolar system.

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