Finite-element flow and heat transport modelling of Borehole Heat Exchangers

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ABSTRACT

Ground Source Heat Pumps are gradually spreading in Europe, as the price of fossil fuel is increasing at a fast rate. The significant reduction of emissions and the margins for economic saving achievable with this technology are strongly correlated to the long-term sustainability of the exploitation of the heat stored in the soil. The operation of a GSHP over its lifetime should be therefore modelled considering realistic conditions, and a thorough characterization of the physical properties of the soil is essential to avoid large errors of prediction. In this paper, a BHE modelling procedure with the finite-element code FEFLOW is presented. Starting from the governing equations of the heat transport in the soil around and inside the BHE, the most important parameters are individuated and the adopted program settings are explained. A sensitivity analysis is then carried on both the design parameters of the heat exchanger, in order to understand the margins of improvement of a careful design and installation, and the physical properties of the soil, with the aim of quantifying the uncertainty induced by their variability. The relative importance of each parameter is therefore assessed by comparing the statistical distributions of the fluid temperatures and estimating the energy consumption of the heat pump, and practical conclusions are drawn from these results about the site characterization, the design and the installation of a BHE.

1. INTRODUCTION

The use of Ground Source Heat Pumps (GSHP) in Europe is gradually spreading as the price of fossil fuels is increasing rapidly and a strong reduction of greenhouse gases and air pollutants is needed. The most diffused kind of installation are the Borehole Heat Exchangers (BHE), which were introduced in Germany in the 80's (Sanner 2001). According to Saner et al. (2010), a reduction of up to 75% of CO_2 emissions can be achieved, compared to methane furnaces. More than 1.2 million GSHPs are installed in Europe (EUROBSERV'ER 2011), and they are adopted in the 75% of new dwellings in Sweden and Switzerland (Goetzler et al. 2009).

The operation and the efficiency of a BHE depend from the intrinsic design properties (length, grout, heat carrier fluid, etc.), from the operational conditions (thermal load) and the physical properties of the soil (thermal conductivity, groundwater flow etc.), and all these factors should be taken into account for a correct design.

Having in mind this, a thorough sensitivity analysis has been carried in this work, with the aim of understanding the improvement margins of BHEs and the errors in the forecast of their operation which can be induced by the uncertainty about the thermal and hydrogeological properties of the soil.

The finite-element flow and solute/heat transport code FEFLOW 6.0 has been used to simulate the operation of a BHE in heating mode for 30 years. A wide set of simulations has been run, changing one parameter value each time. The resulting fluid temperatures have been compared and processed in order to get an estimate of the overall energy efficiency of the plant.

Practical conclusions have been drawn about the relative importance of each parameter on the efficiency of a GSHP equipped with BHEs.

2. MODELLING FRAMEWORK

The low-enthalpy geothermal system has been modelled dividing it into four sub-domains:

- the heating plant and the thermal load of the building;
- the heat pump and its efficiency, which is strongly correlated to the temperature of the fluid circulated in the BHE;
- the Borehole Heat Exchanger, which extracts heat from the soil;
- the soil, considering the different heat transport mechanisms and the geothermal flux.

The modelling assumptions adopted for them are briefly explained in the ongoing subchapters.

2.1 Building thermal load

For a correct design of BHE fields, knowing the temporal evolution of the building heat load is fundamental, in order to forecast the evolution of the thermal disturb induced by the heat extraction/injection in the soil. For the simulations carried in this analysis, a cyclic annual benchmark load (Fig.1) has been used, which is representative of a house of 150 m^2 in Northern Italy with a good insulation (80 $kWhm^{-2}y^{-1}$).

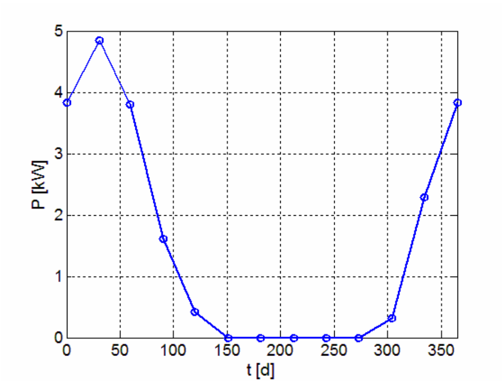

Figure 1: Time series of the benchmark thermal load adopted in the simulations.

2.2 Heat transport in the soil

The heat transport in the soil around the BHE occurs by:

- conduction, which is associated to temperature gradients;
- convection, which is the heat transfer between a solid and a moving fluid;
- dispersion, caused by the heterogeneities of the groundwater flow velocity field.

These mechanisms are described by the heat conservation equation:

$$\frac{\partial}{\partial t}\left[\left(\varepsilon\rho_f c_f+(1-\varepsilon)\rho_s c_s\right)T\right]+\frac{\partial}{\partial x_i}\left(\rho_f q_i^f c^f T\right)+ +\frac{\partial}{\partial x_i}\left(\lambda_{ij}\frac{\partial T}{\partial x_j}\right)=Q_T \quad [1]$$

Where:

- ε is the porosity [-];
- ρ_s and ρ_f are the density of the solid and liquid phase [ML^{-3}];
- c_s and c_f are the specific heat of the solid and liquid phase [$L^2T^{-2}K^{-1}$];
- q_i is the i-th component of the Darcy velocity [LT^{-1}];

λ_{ij} is the heat conductivity porous medium [$MLT^{-3}K^{-1}$], which is the sum of three components (Eq. 2), representing respectively the conductive transport in the solid phase (Eq.3) and in water (Eq.4) and the dispersive transport in water (Eq.5):

$$\lambda_{ij}=\lambda_{ij}^{cond_s}+\lambda_{ij}^{cond_f}+\lambda_{ij}^{disp_f} \quad [2]$$

$$\lambda_{ij}^{cond_s}=(1-\varepsilon)\lambda^s\delta_{ij} \quad [3]$$

$$\lambda_{ij}^{cond_f}=\varepsilon\lambda^f\delta_{ij} \quad [4]$$

$$\lambda_{ij}^{disp_f}=\rho^f c^f\left[\alpha_T V_q^f\delta_{ij}+(\alpha_L-\alpha_T)\frac{q_i^f q_j^f}{V_q^f}\right] \quad [5]$$

Where α_L, α_T are the longitudinal and the transverse dispersivity [L] and V_q is the modulus of the Darcy velocity [LT^{-1}].

A detailed explanation of the modelling assumptions adopted in FEFLOW is reported in Diersch and Kolditz (2002).

2.3 Heat transport in the Borehole Heat Exchanger

The heat transport inside the BHE is quite complex, due to the space variability of the physical properties of the different materials (grout, pipes, heat carrier fluid) and the coexistence of different heat transport mechanisms (advection in pipes and conduction between the pipes and the borehole wall). The “fully discretized approach” (Diersch et al., 2010), which considers the real finite dimension of the BHE, requires an enormous computational effort and it is not sustainable for practical GSHP dimensioning, and it is therefore limited to research applications (Zanchini et al., 2010; Wagner et al., 2012).

FEFLOW introduced the modelling of BHEs as 1D elements in a special program interface (Diersch et al, 2011) to reduce the computational cost of BHE modelling. The BHE is modelled as an electrical circuit (Fig.2): the temperatures of the BHE components (fluid, grout zones, soil at the borehole wall) take the place of potentials, thermal resistances/capacities replace the electrical ones, while currents are replaced by heat fluxes. The heat flux balances are solved in stationary (Eskilson, 1987) or transient (Al-Khoury, 2005) mode, and the fluid temperatures in the inlet and outlet pipes are calculated.

The methods adopted for the calculation of thermal resistance and capacities, which depend from the geometrical setting of the BHE, the physical properties of the different materials and the heat carrier flow rate, are described in Bauer et al. (2011). The most important of these parameters is the borehole thermal resistance (R_b) which was defined by Hellstrom (1991) as:

$$R_b=\frac{T_b-T_f}{q} \quad [6]$$

[6]

Where:

- q is the heat power per unit length exchanged by the BHE [$T^3KM^{-1}L^{-1}$] and it is positive if the heat is extracted from the soil;

- T_b is the temperature at the borehole wall;

- T_f is the mean between the inlet and outlet BHE fluid temperature.

R_b usually ranges between 0.08 and 0.20 mKW^{-1} and a low value is a good indicator of the quality of the BHE installation. For example, in a U-pipe configuration (Fig. 2), the borehole thermal resistance strongly diminishes if the pipes are kept far away and a good grout is used (Fig. 3).

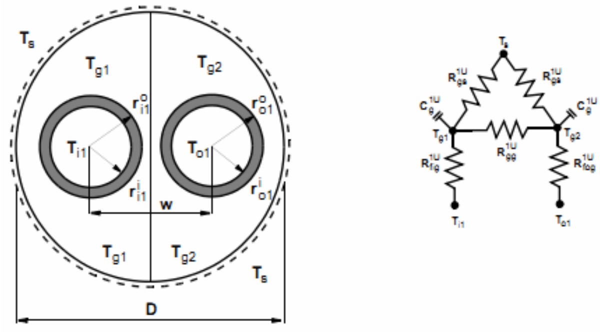

Figure 2: Electric circuit analogy of a single-U inlet BHE (after Bauer et al. 2010).

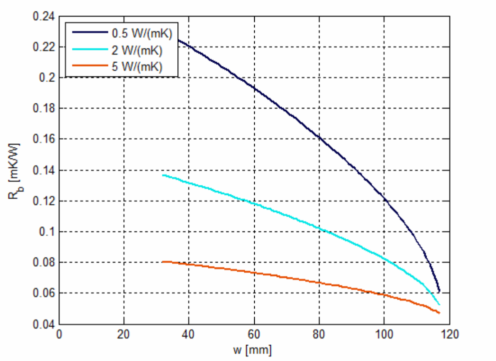

Figure 3: Influence of the pipe spacing on the borehole thermal resistance (R_b).

2.4 Heat pump

The heat pump is a machine that transfers heat from a cold source to a warmer sink, by means of the mechanical work of a compressor. In a GSHP used in heating mode, the cold source is the heat carrier fluid in the BHE, and the sink is represented by the heating plant terminals.

The ratio between the transported heat and the energy consumed by the heat pump is the Coefficient of Performance (COP), which depends mainly from the difference between the source and the sink temperatures, i.e. the smaller it is, the better the heat pump will work and the higher will be the COP.

A linear correlation of COP vs mean fluid temperature has been used, which is typical of heat pumps connected to radiant panels working at a temperature of 35°C:

$$COP = 0.1 \cdot T_f + 4 \qquad [7]$$

The heat pump energy consumption (HPc) is the ratio between the building heating load (BHL) and the COP:

$$HPc = \frac{BHL}{COP} \qquad [8]$$

3.SIMULATION SETTINGS

With the conceptual framework previously described, FEFLOW 6.0 has been used to simulate the transient flow and heat transport in presence of a single U-tube BHE, varying a single parameter each time. Common settings have been adopted for all the simulations, which are hereby described.

3.1 Heat transport boundary conditions

The BHE is modelled in FEFLOW as an internal 4th kind boundary condition (well).

The undisturbed soil temperature is almost equal to the mean annual air temperature: for these simulations, it has been considered equal to 12°C on the surface. Indeed, although seasonal variations occur, their effect on the BHE is negligible (Eskilson 1987), as they disappear at small depths (5 to 20 m). In addition, the temperature of the subsurface usually increases with depth due to the geothermal heat flux. A typical value of the vertical temperature gradient is 0.03 Km^{-1} (Pollack et al., 1993), which is the value that has been used in the simulation. The resulting spatial distribution of the undisturbed soil temperatures is therefore:

$$T_0(x, y, z) = 12 + 0.03z \qquad [9]$$

The soil temperature is altered by the BHE, and the thermal disturb diminishes with the distance: at an infinite distance, it remains at the initial value T_0:

$$T(r = \infty, t) = T_0 \qquad [10]$$

A constant temperature (1st kind b.c.) has been set therefore at the border of each slice of the mesh domain, with the undisturbed temperature value $T_0(z)$. The presence of such a boundary condition would greatly influence the resulting soil temperature field, if the mesh has not an adequate size ("boundary effect"). To avoid this, different mesh sizes have been tried and, finally, a 1000 x 1000 m size has been chosen.

3.2 Flow boundary conditions

An unconfined aquifer has been modelled in the simulation, with a depth to water table of 20m, assigning constant hydraulic head (1st kind) boundary conditions. As the groundwater flow can give an important contribution to the heat transport in the subsoil, also different values of the hydraulic gradient (and hence, subsurface flow velocity) have been used, ranging between 1‰ and 20‰. The initial conditions have been set consistently with the boundary conditions.

4.RESULTS

The results of the simulations have been compared, analyzing the following outputs:

- cumulate distribution of the mean fluid temperature (example in Fig. 4): the time series of the mean BHE fluid temperature have been sorted;
- minimum fluid temperature: the fluid temperature can fall below 0°C if an antifreeze is dissolved in water. Nevertheless, freezing must be avoided, ensuring a sufficient safety margin;
- estimated consumption of electricity for the heat pump (example in Fig. 5): the time series of the mean fluid temperatures have been used to estimate the heat pump COP, and hence its electricity consumption, according to Eq.8.

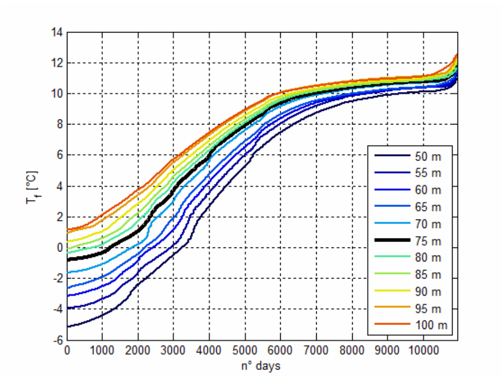

Figure 4 – Cumulate distributions of the mean fluid temperatures (T_f) for different values of the BHE length.

The sensitivity analysis has been carried for two categories of parameters:

- BHE parameters, with the aim of understanding which are the margins of improvement of BHEs for achieving a higher efficiency;
- Physical properties of the soil, with the aim of quantifying the error margins due to the uncertainty of their estimation.

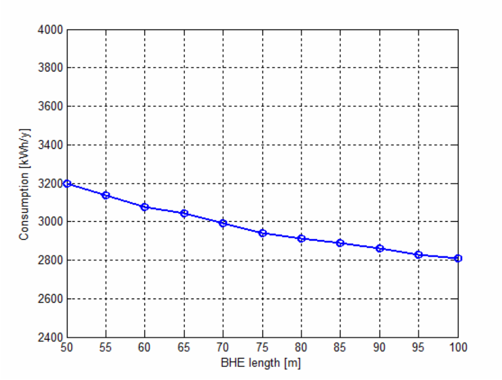

Figure 5 – Estimated heat pump consumption for different values of BHE length.

4.1 BHE parameters

The BHE is composed by:

- pipes, which are usually made of HDPE and exert a negligible influence on the thermal resistance of the exchanger;
- pipe spacers, that should keep the pipes as far as possible in order to avoid the thermal short-circuit (i.e. the heat exchange between the inlet and the outlet pipes) and to reduce the thermal resistance due to the grout between the pipes and the borehole wall (Fig.3);
- the borehole filling material, which is usually a grout made of cement with special aggregates (to ensure a high thermal conductivity) and bentonite (to ensure a perfect sealing of the borehole, avoiding the groundwater exchange between different aquifers);
- the heat carrier fluid usually is a mixture of water and antifreeze additives. The most important parameters are the freezing point, and hence the design value of the minimum temperature of the fluid (which should guarantee a sufficient safety margin), the viscosity and the flow rate, which exert a strong influence on the borehole thermal resistance R_b.

The borehole length is the most influencing property for the efficiency of a GSHP: the longer is the probe, the smaller is the heat power exchanged per unit length and hence the thermal impact on the soil. BHE lengths between 50 and 100m have been adopted in the simulations and, as shown in Fig. 4 and Fig. 5, the effect of the length increment gradually diminishes: adopting a BHE length of 75m instead of 50m permitted to achieve an energy saving of 8.7%, while the gain adopting a length of 100m is equal to the 13.8% (with a further marginal gain of 5.1%). On the other hand, the installation costs increase – more or less linearly - with the drilled depth: this means that an optimization can be achieved minimizing the sum of the installation costs and the maintenance costs due to the heat pump electricity consumption. We provide here an example (Fig. 6) of this optimization. The adopted values of the unit costs are typical of Italy: 6000 € for the heat pump and an electricity rate of 0.22 €/kWh, while the variable costs for installation (drilling, BHE pipes, grouting) have been merged and three different values have been used, which are 50, 60 and 70 €/m. The total cost (installation and maintenance) has been calculated over a period of 30 years. The optimal lengths lie in the range of 60÷80m, therefore a default value of 75 m has set for the other simulations.

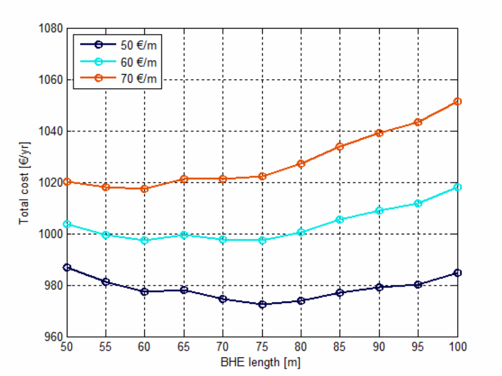

Figure 6 – Economic optimization of the BHE design: annual costs (installation + maintenance) over a lifetime of 30 years.

While the drilled depth accounts for most of the initial investment, the pipe spacers and the grout account for a small part of the installation cost. Nevertheless, their combined influence on the performances of the GSHP can be similar or even larger.

In the simulations, the borehole diameter has been kept equal to 150 mm, and the pipe diameter is 32 mm for all the simulations. Indeed, these values usually do not vary in large ranges. The distance between the pipe centres has been set equal to 35, 55 mm (no spacers), 80, 100 mm (rigid spacers), 117 mm (spring spacers). BHEs are usually filled with a grout of cement and bentonite. Silica aggregates and, recently, graphite powder (Delaleux et al., 2012) are used to enhance the heat transfer between the borehole wall and the pipes. The values of the grout heat conductivity adopted in this sensitivity analysis are 0.5, 1 (poor grouts), 2, 3 (standard grouts), 5 and 10 $Wm^{-1}K^{-1}$ (special grouts). Together, the pipe distance and the grout conductivity heavily influence the borehole resistance and hence the minimum fluid temperature and the electricity consumption of the heat pump. With a grout heat conductivity of 2 $Wm^{-1}K^{-1}$, the minimum temperature varies of about 4°C adopting the extreme values of the pipe distance (35 and 117mm), and the heat pump consumption varies of the 7.2%: this difference is larger with poor grout and smaller with highly conductive fillings. The influence of the grout conductivity is larger with smaller pipe spacing and vice versa.

The heat carrier fluid of BHEs is a solution of water and antifreeze. The most commonly used anti-freeze solutions have been chosen: propylene glycol (PG) at 25% and 33% vol., ethanol (ETH) at 24% and 30% and calcium chloride ($CaCl_2$) at 20%. Observing the results, we see that only calcium chloride reduces the energy expense (-5.8% compared to PG25%), due to its lower viscosity.

4.2 Soil parameters

The thermal and hydrogeological properties of the soil are essential in the design of GSHPs, but most of them are not known with a sufficient precision for a correct modelling. The heat conductivity of the soil can be estimated with Thermal Response Tests (Gehlin 2002), achieving a good precision. The presence of an aquifer enhances the heat transport in the subsurface with a beneficial effect on the efficiency of the system: nevertheless, the hydraulic conductivity, and hence the velocity of the subsurface flow, vary in wide ranges (Di Molfetta and Sethi 2012). The thermal dispersion around a BHE has not been studied yet at a field scale and, generally speaking, scarce references are found in literature.

A set of simulation has been run, exploring wide ranges of soil parameters:

- - thermal conductivity of the solid phase: 0.5, 1, 1.5, 2, 2.5, 3 $Wm^{-1}K^{-1}$;
- - groundwater flow: the Darcy velocity has been varied between 3.15 m/y and 1576.8 m/y (hydraulic conductivity $K=10^{-4}$ m/s; hydraulic gradient i=0.001, 0.002, 0.005, 0.01, 0.02, 0.05; effective porosity $n_e=0.2$);
- heat dispersivity: $\alpha_L=0.1$, 0.2, 0.5, 1, 2, 5, 10 m; $\alpha_T=0.1\ \alpha_L$.

The heat conductivity is the soil physical parameter that exerts the largest influence on the operation of a GSHP. Indeed, most of the design procedures take into account only this parameter, which depends from the lithology, the porosity and the water saturation (Tab. 1) .

Table 1: Thermal conductivity of different soil types, extracted from VDI (2000).

Soil type	λ [$Wm^{-1}K^{-1}$]
Granite	2.4 ÷ 4.1
Limestone	2.5 ÷ 4.0
Sandstone	2.2 ÷ 2.7
Marl	1.5 ÷ 3.5
Gravel (dry)	0.4 ÷ 0.5
Gravel (saturated)	~ 1.8
Moraine	1.0 ÷ 2.5
Sand (dry)	0.3 ÷ 0.8
Sand (saturated)	1.7 ÷ 5.0
Clay/silt (dry)	0.4 ÷ 1.0
Clay/silt (saturated)	0.9 ÷ 2.3

As occurring for the BHE length, also the marginal effect of an increment in the heat conductivity of the soil diminishes for higher values: on the other hand, the results of the simulation showed significant differences for small values. For example, the difference between the minimum temperatures for a values of 2 $Wm^{-1}K^{-1}$ and 3 $Wm^{-1}K^{-1}$ is about 2°C, while a variation of 4.6°C is observed when comparing with a heat conductivity of 1 $Wm^{-1}K^{-1}$. The corresponding heat pump electrical consumption experiences a similar variation: taking a reference value of 2 $Wm^{-1}K^{-1}$, the energy consumed is +9.8% for a heat conductivity of 1 $Wm^{-1}K^{-1}$ and only -4.4% for a value of 3 $Wm^{-1}K^{-1}$. Since the standard values found in literature usually vary in wide ranges (see Tab.1), they are not sufficiently precise for a correct BHE design. Thermal Response Tests are therefore strongly advised for large BHE fields (i.e. more than 5÷10 boreholes).

The groundwater flow activates the advective heat transport, reducing the thermal disturb induced by a BHE. Eskilson (1987) modelled this effect with an equivalent reduction of the thermal resistance of the soil. Chiasson et al. (2000) observed that the advection has a strong effect in the soils with high hydraulic conductivity or in rocks with secondary porosity (i.e. fractures and solution channels), even with low groundwater velocities. Considering a 10m-thick aquifer in a 80m-deep BHE, Signorelli et al. (2007) concluded that a "significant" groundwater movement occurs when the Peclet number is larger than 1, i.e. in sand and gravel aquifers.

The heat transport in the subsoil occurs also by dispersion, which is caused by the heterogeneity of the groundwater flow velocity field. Most authors agree about the scale dependency of the thermal dispersivity, similarly to the solute transport dispersivity (de Marsily 1986, Sauty et al. 1982), a parameter which has been studied and determined in many field sites (Gelhar et al. 1992, Schulze-Makuch 2005). Sethi and Di Molfetta (2007) adopted α_L=10m and α_T=1m for the heat transport simulation in a municipal solid waste landfill. Selcuk (2011) assumed α_L=2m and α_T=0.2m for the simulation of a BHE with a length of 100m. Wagner et al. (2012) used values of α_L between 0 and 2m for a field scale of 10m in laboratory BHE tests.

A wide range of values has been explored in this work, with default values α_L =5m: α_L=0.1÷10m and $\alpha_T=0.1\alpha_L$. The results of the simulations prove that the differences in the BHE fluid temperature distributions with various α_L and α_T values are very strong, and the resulting energy consumption of the heat pump varies in a wide range (Δ=15.4÷17.3% between α_L=0.1m and with α_L=10m, depending from the subsurface flow velocity). As the thermal dispersion is still scarcely known, these results suggest that relying on this transport mechanism would result in a overestimation of the efficiency of the GSHP, and hence to a strong under-dimensioning.

5.CONCLUSIONS

This work was aimed at studying the efficiency of a simple residential heating plant, with a Borehole Heat Exchanger connected to a heat pump.

The flow and solute/heat transport code FEFLOW 6.0 has been used to simulate the operation of a BHE in a period of 30 years, which can be considered long enough to estimate the temperature decay in the soil.

For each simulation the value of a BHE or soil parameter has been changed, in order to quantify its relative importance.

The results of the simulations lead to some considerations about the impact of the technical improvements and about the uncertainty related to soil parameters:

- the length of the Borehole Heat Exchanger is the most important design parameter in the design of a GSHP;
- if we take into account also the installation costs (which are, obviously, larger if we adopt a deeper borehole length), we can find an optimal BHE length, which minimizes the overall cost of the plant over its lifetime;
- together, the pipe distance and the heat conductivity of the grout exert an influence on the performances of the system which is comparable to the one of the borehole length;
- the commonly adopted heat carrier fluids (ethanol and propylene glycol) have similar performances, while the calcium chloride solutions provide an appraisable energy saving;
- the heat conductivity is the most influencing physical parameter of the soil, and literature values are usually given in large ranges, leading to a strong uncertainty in the modelling results. Thermal Response Tests are therefore advised in large installations (say, more than 5÷10 boreholes);
- the presence of a subsurface flow significantly enhances the performance of a GSHP. Also the thermal dispersion is an important heat transport mechanism but, as no field study has been performed on thermal dispersivity in real-scale BHE installations, it is not advised to take it into account.

REFERENCES

Bauer, D., Heidemann, W., Müller-Steinhagen, H., Diersch, H.J.G., Thermal resistance and capacity models for borehole heat exchangers, International Journal of Energy Research, 35 (2011) 312-320.

Chiasson, A.C., Rees, S.J., Spitler, J.D., A Preliminary Assessment of the Effects of Ground-Water Flow on Closed-Loop Ground-Source Heat Pump Systems, ASHRAE Transactions, 106 (2000) 380-393.

de Marsily, G., Quantitative hydrogeology, Academic Press, San Diego (CA, USA), 1986.

Di Molfetta, A., Sethi, R., Ingegneria degli Acquiferi, Springer, 2012.

Diersch, H.-J.G., Bauer, D., Heidemann, W., Ruhaak, W., Schatzl, P., Finite element formulation for borehole heat exchangers in modeling geothermal heating systems by FEFLOW, in: DHI-WASY (Ed.) FEFLOW White Papers, Berlin, 2010.

Diersch, H.J.G., Kolditz, O., FEFLOW Reference Manual, DHI-Wasy, Berlin, 2002.

Eskilson, P., Thermal Analysis of Heat Extraction Boreholes, in, Lund University (Sweden), 1987.

EUROBSERV'ER, The state of renewable energies in Europe - 11th EurObserv'ER Report, in, EUROBSERV'ER, 2011, pp. 254.

Gehlin, S., Thermal Response Test - Method Development and Evaluation, in: Department of Environmental Engineering, Lulea University of Technology, Lulea (Sweden), 2002, pp. 191.

Gelhar, L.W., Welty, C., Rehfeldt, K.R., A critical review of data on field-scale dispersion in aquifers, Water Resources Research, 28 (1992) 1955-1974.

Goetzler, W., Zogg, R., Lisle, H., Burgos, J., Ground-source heat pumps: overview of the market status, barriers to adoption, and options for overcoming barriers, in, U.S. Department of Energy, 2009.

Hellstrom, G., Ground heat storage, thermal analyses of duct storage systems. Part I: theory, Mathematical Physics, University of Lund, Lund (Sweden), 1991.

Hellstrom, G., Sanner, B., Earth Energy Designer, User Manual Version 2.0, 2000.

Pollack, H.N., Hurter, S.J., Johnson, J.R., Heat flow from the earth's interior: analysis of the global data set, Reviews of Geophysics, 31 (1993) 267-280.

Saner, D., Juraske, R., Kübert, M, Blum, P., Hellweg, S., Bayer, P., Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems, Renewable and Sustainable Energy Reviews, 14 (2010) 1798-1813.

Sanner, B., Some history of shallow geothermal use, in: *International Summer School on Direct Application of Geothermal Energy*, 2001, pp. 10.

Sauty, J.P., Gringarten, A.C., Fabris, H., Thiery, D., Menjoz, A., Landel, P.A., Sensible energy storage in aquifers, 2. Field experiments and comparison with theoretical results (Bonnaud, Jura), Water Resources Research, 18 (1982) 253-265.

Schulze-Makuch, D., Longitudinal dispersivity data and implications for scaling behavior, Ground Water, 43 (2005) 443-456.

Selcuk, E., Estimation of heat extraction rates of GSHP systems under different hydrogeological conditions, PhD Thesis, University of Tubingen, 2011.

Sethi, R., Di Molfetta, A., Heat transport modeling in an aquifer downgradient a municipal solid waste landfill in Italy, American Journal of Environmental Sciences, 3 (2007) 106-110.

Signorelli, S., Bassetti, S., Pahud, D., Kohl, T., Numerical evaluation of thermal response tests, Geothermics, 36 (2007) 141-166.

VDI, VDI 4640 - Thermal use of underground, in: Blatt 1: Fundamentals, approvals, environmental aspects, 2000.

Wagner, V., Bayer,. P., Kübert, M, Blum, P., Numerical sensitivity study of thermal response tests, Renewable Energy, 41 (2012) 245-263.

Zanchini, E., Lazzari, S., Priarone, A., Improving the thermal performance of coaxial borehole heat exchangers, Energy, 35 (2010) 657-666.