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Sensitivity analysis on the performance of a ground source heat pump equipped with a double U-pipe borehole heat exchanger

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Abstract

Ground Source Heat Pumps (GSHP) are economically and environmentally advantageous for the heating and cooling of buildings, provided that the long-term sustainability of the thermal exploitation of the soil is ensured. In particular, the performance of a closed-loop Borehole Heat Exchanger (BHE) strongly depends on the geometrical and physical properties of its components and on the thermo-hydrogeological properties of the surrounding soil. In this work, we present the results of a series of simulations of a double U-pipe Borehole Heat Exchanger, carried out with the finite-element flow and heat transport modelling software FEFLOW to assess the relative influence of these parameters on the operation of a GSHP. The analysis confirms that the length of the borehole is the main design parameter, but the thermal conductivity of the grout, the pipe spacing, the heat carrier fluid and its flow rate also have an important effect on the energy efficiency of the system. The thermal conductivity of the soil is another fundamental variable in the design of a GSHP, and hence it is better to rely on site-specific data, rather than adopting values from the literature. Although most design methods neglect it, the presence of a subsurface flow results in an enhancement of the performance of the system. Thermal dispersion also enhances the efficiency of the system but, since it has not yet been adequately studied, relying on it is not advised for the design of BHE fields.

Keywords: Low-enthalpy geothermal energy; Borehole Heat Exchanger; Ground Source Heat Pump; Heat transport; Groundwater

1. Introduction

Ground Source Heat Pumps, which rely on thermal exchange with the shallow subsoil, are economically and

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environmentally sustainable systems for the heating and cooling of buildings. Heat can be exchanged directly with groundwater extracted by a well (open loop or Ground Water Heat Pump) or through the circulation of a heat carrier fluid into a pipe loop (closed loop or Ground Coupled Heat Pump). Open loop is more suitable for large plants, while closed loop is much more widespread for small installations. The most diffused closed loop configuration is the Borehole Heat Exchanger and, in particular, the double U-pipe version has become the standard in the last years thanks to its smaller thermal resistance (and hence, a higher efficiency) and the possibility of a backup in case of failure of one of the circuits.
The performance of a closed loop GSHP depends mainly on:

- The temperature of the heat carrier fluid, which in turn depends on the design parameters and on the physical properties of the soil
- The circulation pump, which can absorb a large quantity of electric power
- The heating/cooling terminals and their operating temperatures

The existing literature on BHEs deals with the influence of one or more of these parameters, but few studies with a global analysis are available. Chung and Choi [1] stressed the importance of optimizing the flow rate of the heat carrier fluid, without increasing it indiscriminately. Delaleux et al. [2] simulated how super-conductive grouts can enhance the thermal exchange capacity of a BHE. Michopoulos and Kiriakis [3] studied the correlation between the borehole length and the total life cost of the plant (installation and maintenance), developing a method that can be used to optimize the length of the boreholes to be drilled. Various works deal with the beneficial effect of the groundwater flow on the thermal exchange in closed-loop geothermal plants [4, 5]. Recently, Casasso and Sethi [6] have conducted a comprehensive study on single U-pipe BHEs, assessing the relative influence of the main design parameters and the main thermo-hydrogeological properties of the soil on the operating fluid temperatures and hence on the energy consumption of the heat pump.

The study presented in this paper deals with double U-pipe BHEs, with the aim of assessing the margins of improvement of the efficiency of the design and installation and the margins of uncertainty caused by an imprecise knowledge of the physical properties of the soil.

2. Flow and heat transport modelling

The energy efficiency of a GSHP can be assessed by modelling the heat transport in the soil in response to the stimulus induced by the heat extraction and injection. The flow and solute/heat transport simulation code FEFLOW 6.0, which includes a specific BHE simulation package [7], was used for this purpose. In this chapter, the fundamentals of heat transport modelling and the settings adopted in the simulation are explained.

2.1. Heat transport in the soil and inside the BHE

The heat transport in the subsoil occurs by means of three mechanisms: conduction (induced by temperature gradients), advection (due to the groundwater flow) and dispersion (due to the heterogeneity of the groundwater flow field). These phenomena are described by the heat conservation equation in porous media:

$$\frac{\partial}{\partial t}\left[\left(\varepsilon\rho_w c_w+\left(1-\varepsilon\right)\rho_s c_s\right)T\right]+\frac{\partial}{\partial x_i}\left(\rho_w c_w q_i T\right)+\frac{\partial}{\partial x_i}\left[\left(\lambda_{ij}^{\ cond}+\lambda_{ij}^{\ disp}\right)\frac{\partial T}{\partial x_i}\right]=H \tag{1}$$

where ε is the total porosity [-], ρ_s and ρ_w are the densities of the solid and the fluid phase respectively [kg m^{-3}], c_s and c_w are their specific heats [J kg^{-1} K^{-1}], T is the temperature (assumed to be equal in the solid and in the fluid phase), x_i is the i-th axis (i.e. x_1=x, x_2=y, x_3=z), q_i is the i-th component of the Darcy velocity [m s^{-1}] and H is the heat power per unit volume abstracted or injected by the BHE [Wm^{-3}].

The first term of Equation 1 describes the time variation of the temperature in the porous medium, and it is function of its porosity ε and its thermal capacity (ρc). The second term describes the advection, while the third term describes the conduction (see Equation 2) and the dispersion (see Equation 3):

$$\lambda_{ij}^{cond} = \begin{cases} (1-\varepsilon)\lambda_s + \varepsilon\lambda_w & for\, i = j \\ 0 & for\, i \neq j \end{cases} \tag{2}$$

$$\lambda_{ij}^{disp} = \rho_w c_w \left[\alpha_T q \delta_{ij} + (\alpha_L - \alpha_T) \frac{q_i q_j}{q} \right] \tag{3}$$

where λ_s and λ_w are the thermal conductivity of the solid matrix and of groundwater respectively, α_L and α_T are the longitudinal and transverse thermal dispersivity (with respect to the groundwater flow direction), and q is the modulus of the Darcy velocity vector [ms^{-1}].

The temperature of the soil at the borehole wall, calculated by solving the heat conservation equation in the soil domain, is the boundary condition for the thermal exchange inside the spatial domain of the BHE, which is a combination of advection (the heat carrier fluid that flows inside the pipes) and conduction (from the pipe wall to the borehole wall). Simplified 1D models have been developed, since a full finite element simulation of the thermal exchange inside the probe would be very time consuming. The TRCM (Thermal Resistance and Capacity Model) according to Bauer et al. [8] is based on an analogy with electrical circuits and it was implemented in FEFLOW starting from version 5.4 [7]. The elements of the geothermal probe (inlet/outlet pipes, grout, borehole wall) are the nodes, connected by thermal resistances and capacities which are function of the geometrical setup and of the physical properties of the materials. By solving the thermal balance equations at the nodes, the fluid temperatures are calculated.

2.2. Mesh size and spatial resolution

The size of the domain is an essential aspect for numerical simulations, since it is important to avoid boundary effects. A mesh convergence study was therefore performed, and no appraisable differences were found for the chosen mesh dimension (1000 x 1000 m) when comparing the calculated fluid temperatures with those obtained with smaller domains (e.g. 500 x 500 m, 200 x 200 m etc.).

The depth of the 3D domain was set to 150 m for all the simulations, larger than the simulated BHE depth (50÷120 m), in order to take into account the vertical component of the thermal exchange of the soil [9]. A total of 31 slices (one every 5 m) was set, each one composed of 501 nodes (total number: 15531 nodes).

A regular hexagonal arrangement of the nodes around the BHE was used as suggested by Diersch [7].

2.3. Boundary conditions

A constant value of 12°C was imposed on the boundary of the first slice, which represents the ground surface, while the temperatures of the slices below were set according to a geothermal gradient of 0.03°C m^{-1}. Indeed, the oscillations of the temperature on the ground surface are dampened in the shallow subsoil (i.e. 5÷10 m), and their effect on the operation of a geothermal probe is negligible [10].

First kind hydraulic boundary conditions (imposed hydraulic head) were adopted to reproduce a constant groundwater flow. The water table of the phreatic aquifer was set to 20m below ground surface, the hydraulic conductivity is 10^{-4} m/s, while the hydraulic gradient ranges from 0 to 1% and the saturated depth is comprised between 10 and 50m.

A variable thermal load was imposed, with a total heat extraction of 12 MWh/year that is representative of a well-insulated detached house in Northern Italy.

2.4. Simulations and processing of the results

The operation of a single BHE for 10 years was simulated, changing one parameter each time in order to assess its relative influence on the operating fluid temperatures. The results confirm that the adopted simulation time is enough for the soil to reach the maximum thermal alteration.

The adopted values for the main BHE design parameters (length, pipe distance, heat carrier fluid and circulation flow rate, thermal conductivity of the grout), hydrogeological (groundwater flow velocity, saturated thickness of the aquifer) and thermal properties (conductivity and dispersivity) of the soil are summarized in Table 1.

To compare the results, two different methods were adopted, as described in Casasso and Sethi [6]:

- Sorting the inlet fluid temperatures during the heating seasons, a cumulate curve is obtained, that represents the operating range of a BHE
- The COP of the heat pump (COP_1) depends on the inlet fluid temperature (T_{in}) and the operating heating terminal temperature (T_t), and it was estimated as 40% of the Carnot theoretical COP. The temperature of the heating terminal was set to 35°C, which is typical of radiant panels
- The COP_2 is the ratio between the heating power delivered to the heating plant and the quantity of electric power consumed by the heat pump and the circulation pump [11]. This coefficient should be used, rather than COP_1, when comparing the performance of a GSHP and a boiler. The quantity of electric power absorbed by the circulation pump was estimated through the calculation of the friction losses along the BHE pipes (the Blasius' formula was used for this purpose) and considering a pump energy yield of 50%

The values of COP_1 and COP_2 were averaged over the whole simulated periods (10 years), thus obtaining the Seasonal Performance Factors SPF_1 and SPF_2.

Table 1 - Values of the BHE and soil properties adopted in the simulations.

Parameter	Values
Length of the BHE [m]	50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120
Pipe distance [mm]	50, 60, 70, 80, 100
Heat carrier fluid	Pure water, Propylene Glycol (PG) at 25% and 33%, Calcium Chloride ($CaCl_2$) at 10 and 20%
Thermal conductivity of the grout [$Wm^{-1}K^{-1}$]	0.5, 1, 1.5, 2, 3, 5
Thermal conductivity of the soil [$Wm^{-1}K^{-1}$]	0.5, 1, 1.5, 2, 2.5, 3
Hydraulic gradient of the aquifer [‰]	0, 1, 2, 5, 10
Saturated thickness of the aquifer [m]	10, 20, 50
Longitudinal thermal dispersivity [m]	0, 0.1, 0.2, 0.5, 1, 2, 5

3. Results

The results of the simulations were compared to assess the relative influence of each parameter on the performance of the GSHP. The discussion is subdivided into two paragraphs, one about the BHE design parameters (for which the improvement margins are sought) and one about the soil parameters (for which the aim of the analysis is to assess the margins of error due to an under/overestimation).

3.1. BHE design parameters

The length and the number of BHEs are the main design parameters, since half of the total cost of installation of a GSHP usually are due to the drilling and installation of the probes [12]. On the other hand, longer BHEs achieve a better performance, since the thermal disturb per unit depth of soil is smaller.

Usually, a minimum temperature constraint is imposed for BHEs operating in heating mode to avoid the freezing of the fluid inside the pipes. The curves in Fig. 1 show how the marginal increment of the fluid temperature is reduced for increasing length: for example, an increment from 50 to 80m brings to a temperature increment of 8.9°C, while an additional length of 30m (from 80 to 110m) results in a much smaller gain (4.3°C), and the same occurs for the SPF_2 (+14.6% and +9.1% respectively).

The costs of installation of the BHEs and the variation of the SPF_2 (and hence of the maintenance costs) have different growth rates with the installed probe length. The sum of these costs can be minimized, finding an optimal probe length that depends on the unit costs of drilling and installation, the unit cost the electricity and its expected rate of increase in the next years, and the possible regimes of incentive, that can be based on the energy production or on the cost of the installation. Examples of such an evaluation are reported in Casasso and Sethi [6,13].

Other factors are worth to be taken into account for the optimization of the design of BHEs. Indeed, it is possible to achieve an appraisable gain of SPF with a small expense by adopting a good geothermal grout, a large pipe spacing, a proper heat carrier fluid and the optimal flow rate, thus reducing the borehole thermal resistance R_b [10]. A wide range of grout thermal conductivities was investigated, representing special high-performance products (λ_g=3÷5 $Wm^{-1}K^{-1}$), common geothermal grouts (λ_g=2 $Wm^{-1}K^{-1}$) and low grade borehole fillings (λ_g=0.5÷1 $Wm^{-1}K^{-1}$), e.g. with excessive water-to-cement ratio or with void spaces. The thermal conductivity of the grout exerts a combined effect with the pipe reciprocal distance: a large pipe spacing can partially compensate the negative effect of a low grade grout, and the performance of a BHE filled with a highly conductive grout is almost insensitive to pipe spacing (Fig. 2). The performance of common geothermal grouts can be slightly improved with special grouts, while the use of bad fillings results in a strong reduction of the performance (e.g. SPF_2 is reduced of 4.2÷9.2% with λ_g=0.5 $Wm^{-1}K^{-1}$, compared to λ_g=2 $Wm^{-1}K^{-1}$) due to a large increment of R_b.

The heat carrier fluid and its flow rate have a smaller impact on the performance of a GSHP, compared to the parameters described above. Usually, a mix of water and antifreeze is adopted, with different concentrations depending on the prescribed minimum fluid temperature. Using pure water to avoid the contamination of aquifers seems to be an excessive precaution, because common antifreeze additives are not toxic [14], and a large additional borehole depth is required to avoid freezing in the inlet pipe during the heating load peaks. In contrast, the use of water is advised for a prevailing cooling mode, since water is the least viscous heat carrier fluid. Calcium chloride solutions are less viscous than propylene and ethylene glycols, allowing a larger SPF_2 to be achieved (Fig. 3). In addition, $CaCl_2$ is much cheaper than glycols, although special anti-corrosion hydraulic components must be used. The circulation flow rate (Q_f) also plays an important role, in particular R_b strongly diminishes when switching from the laminar (Re<2300) to the turbulent (Re>10000) regime. The heat carrier fluid cannot usually be circulated in fully turbulent regime, since the required flow rate would be too large. An optimal flow rate can be found, for which the value of SPF_2 reaches a peak (Fig. 3), thus confirming the conclusions of Chung and Choi [1].

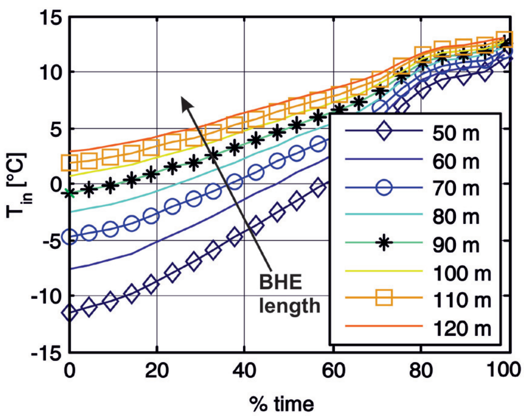

Fig. 1. Cumulate distributions of the inlet fluid temperature (T_{in}) for different values of the BHE length.

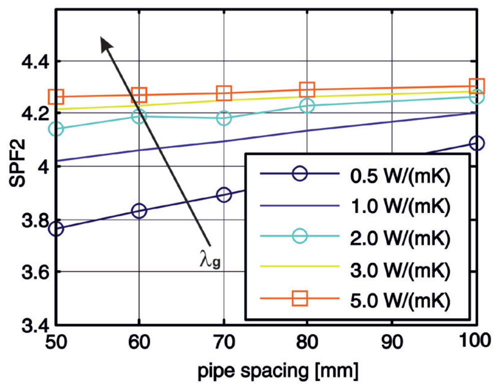

Fig. 2. GSHP Seasonal Performance Factor (SPF_2) for different values of the pipe spacing and of the thermal conductivity of the grout (λ_g).

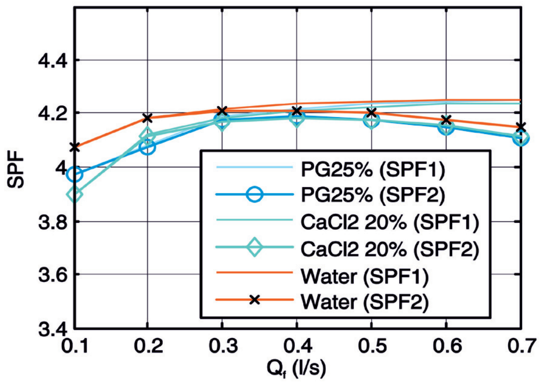

Fig. 3 – SPF_1 and SPF_2 for different heat carrier fluids and flow rates.

3.2. Soil properties

The soil properties are usually a critical aspect of the design phase, especially for small plants, since a thorough characterization is not affordable and hence the dimensioning often disregards the thermal properties of the soil [12].

Conduction is the main heat transport mechanism in the soil for closed loop geothermal plants and the thermal conductivity may vary in wide ranges even for the same lithology. This means that, if values from the literature are used rather than performing field tests, unreliable simulation results are obtained. For example, the thermal conductivity of a water-saturated sand may vary between 1 and 2.5 $Wm^{-1}K^{-1}$ [15], with a difference of minimum fluid temperature equal to 12°C (Fig. 4) and a very large variation of SPF_2 (3.45 and 4.26, respectively). Such an uncertainty often leads to an under/over-dimensioning of plants, impairing their economical attractiveness. Thermal Response Tests are strongly advised for large BHE fields (e.g. >50kW), while some research projects have been focused on mapping the thermal properties of the shallow subsoil for the design of smaller plants [16].

Thermal advection due to groundwater flow may have a beneficial effect on the performance of BHE, depending on the flow velocity and on the saturated thickness of the aquifer [4,5]. The Darcy velocity (q) ranged between 0 and 31.56 m/y in the simulation carried out for this study, with a hydraulic conductivity $K=10^{-4}$ m/s (typical of a fine sand [17]) and a hydraulic gradient i=0÷10‰. An example of the role of advection is that the SPF_2 achieved by a 75m long BHE with q=15.78 m/y over a saturated thickness of 50m are similar to those of a 90m long BHE without groundwater flow, i.e. the effect of advection can be compared to an additional length of 15m (+20%) in this case. The saturated thickness is also important (Fig. 5), but it is usually known with an acceptable precision. In contrast, the hydraulic conductivity (and hence the groundwater flow velocity) may vary over wide ranges and hence it is crucial to estimate it with reliable methods (i.e. pumping tests or slug tests [17]).

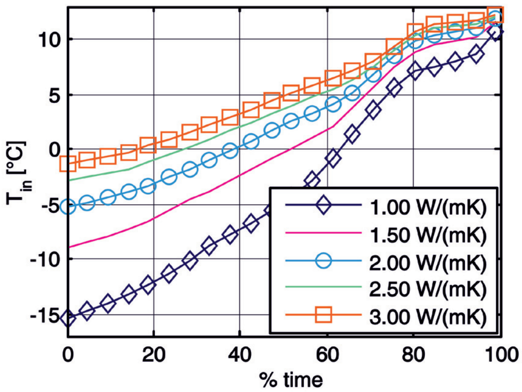

Fig. 4. Cumulate distributions of the inlet fluid temperature (T_{in}) for different values of the soil thermal conductivity (λ^{cond}).

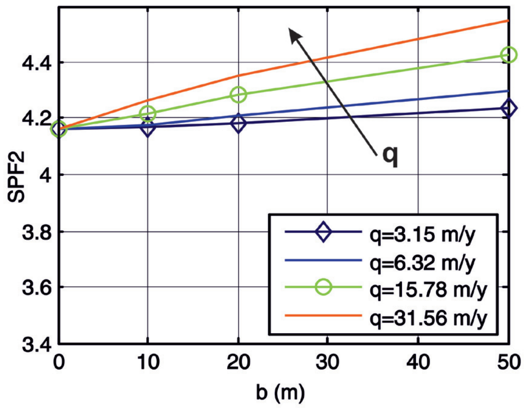

Fig. 5. SPF_2 for different values of the groundwater flow Darcy velocity (q) and of the aquifer saturated thickness (b).

Thermal dispersion, which is induced by the heterogeneity of the groundwater flow field, depends on the scale of the phenomenon [18]. Different formulae are available in literature, usually with a linear dependence on the scale [17,19], but the real issue is that the scale of a BHE may vary if we consider its cross-section (i.e. 10÷20 cm), its length (i.e. 50÷200 m) or, in a BHE field, the reciprocal distance (i.e. 5÷10m). Different values of the dispersivity were therefore adopted over a wide range (α_L=0÷5m, α_T=0.1α_L), which are typical of the aforementioned scales, and a high degree of variability was found for results, especially in case of large groundwater velocities. For this reason, it is not advised to rely on thermal dispersion when modelling BHE fields.

4. Conclusions

In this paper, we present the results of a sensitivity analysis conducted on the main factors that affect the performance of a double U-pipe Borehole Heat Exchanger. A series of finite-element flow and heat transport simulations with FEFLOW were carried out, and the resulting fluid temperatures were processed in order to assess the performance with different plant setups and different soil properties.

Large margins of improvement were found for the design of BHEs. The length of the probe, which is the main parameter of this category, should be optimized considering both the installation and the maintenance costs. The thermal conductivity of the grout and the pipe spacing exert a combined influence that can be compared to the one of the BHE length. The influence of the heat carrier fluid on the performance of the GSHP depends on the fluid's viscosity, and the flow rate should be optimized in order to reduce the thermal resistance of the borehole without increasing the energy consumption of the circulation pump too much.

Thermal conductivity is confirmed as the most influent parameter among the soil properties. It should be determined with in situ tests (Thermal Response Tests) rather than using values from the literature, which present a high degree of variability. The advection may provide an appraisable performance gain in permeable aquifers with a large hydraulic gradient. Thermal dispersion could also enhance the efficiency of BHEs but, since it has as yet insufficiently studied on the field scale, relying on it is not advised in the design phase.

The sensitivity analysis took into account a GSHP with a single BHE. The results reveal useful indications for the optimization of geothermal probes and can easily be extended to larger plants. In this case, other variables should be taken into account, i.e. reciprocal distance, arrangement, number and depth of boreholes.

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