Numerical Evaluation of Long-Term Performance of Borehole Heat Exchanger Fields

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Abstract: The long-term performance of double U-tube Borehole Heat Exchangers (BHEs) is studied numerically by considering three different time-dependent heat fluxes exchanged between each BHE and the ground. Reference is made to the following geometrical configurations: a single BHE surrounded by infinite ground; a field of 4 BHEs surrounded by infinite ground; the limiting case of a field of infinite BHEs. Since the temperature distribution along the vertical direction has a negligible influence on long-term BHE performance, the problem is studied by means of a 2D conduction model, where the energy transfer due to water flow is replaced by a uniform, time dependent, heat generation. The fluid mean temperature in the BHE is determined as a function of time. Results point out that, in the absence of groundwater movement, when a BHE field is considered, at least a partial compensation of the thermal load is necessary to avoid long-term system breakdown.

Keywords: Ground Coupled Heat Pumps; Borehole Heat Exchangers (BHEs); BHE Field; Long-Term Operation; Finite Element Simulations.

1. Introduction

Strongly insulated buildings, heated and cooled by ground coupled heat pumps (GCHPs), are now applied in several countries to achieve sustainability of the built environment.

GCHPs employ heat transfer between the ground and a fluid, typically a water-based solution, which flows in tubes buried into the soil. Two different configurations are used: horizontal heat exchangers and vertical ones, also called Borehole Heat Exchangers (BHEs). The most commonly employed BHEs are composed of two U-bent polyethylene tubes, placed in a borehole which is then grouted.

The total length of the BHEs necessary for a plant is usually determined by a method recommended by ASHRAE [1], developed by Ingersoll and Zobel [2] and by Kavanaugh [3].

In designing a BHE installation, a special attention must be given to the choice of a correct heat extraction rate, since an excessive exploitation of the ground could lead to system collapse [4]. On this subject, Axelsson et al. [5] suggested the following definition of sustainable production from a geothermal system: *for each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for a very long time (100 – 300 years).*

Few studies on long-term performances of BHEs can be found in the literature, and also direct experience is lacking, due to the fairly recent use of this technology.

Rybach et al. [6] studied the long-term performances of a coaxial BHE, used only in heating mode for the need of a single family house. They showed that, during the considered working period of 30 years, the temperature of the ground around the BHE decreases, especially during the first few years. After the shut-down of heat extraction, regeneration of the ground starts: the ground temperature increases steeply at the beginning and then tends asymptotically to the undisturbed initial value after 30 years.

Signorelli et al. [7] simulated the long-term thermal behavior of an array of six double U-tube BHEs considering an operation period of 30 years, working only in heating mode. They concluded that in a BHE array the recovery time is longer than for a single BHE (70 years).

To limit the ground heat depletion which decreases the system performances after several years of operation, some authors suggest the combined use of GCHPs both for heating during wintertime and for cooling during summertime [8, 9]. Trillat-Berdal et al. [9] proposed the coupling of thermal solar collectors with the BHEs, to enhance the natural ground recovery and maintain a stable temperature in the ground.

In the present paper, the long-term performance of double U-tube BHEs is studied with reference to some typical time-periodic working conditions and to three different BHE fields: a single BHE surrounded by infinite ground; a square field of 4 BHEs surrounded by infinite ground; the limiting case of a square field of infinite BHEs.

2. Numerical model

Double U-tube BHEs placed in a homogeneous ground, with high density polyethylene PE-Xa tubes, have been considered. The effects of groundwater movement have been assumed as negligible and all the physical properties of materials have been considered as temperature-independent. Table 1 summarizes the values chosen for both the geometrical parameters and the material properties, as well as the prescribed working conditions. Since the temperature distribution along the vertical direction has a negligible influence on long-term BHE performance, the real 3D heat transfer problem has been studied by means of a 2D unsteady conduction model of the BHE cross-section, as shown in Figure 1. Thus, the water-ethylene glycol 25% solution flowing in the BHE has been replaced by an equivalent solid with the same density and the same specific heat capacity as the solution, but with a very high thermal conductivity, in order to present a uniform temperature distribution in the cross-section. A uniform power generation or absorption has been considered in the solid, to reproduce the heat load of the BHE [10]. The properties of the water-glycol solution have been evaluated at a reference temperature of 6°C and the thermal conductivity of the equivalent solid has been assumed equal to 1000 W/(m K). Moreover, the thermal resistance due to the convective heat transfer between the water-glycol flow and the tube wall has been taken into account by considering an effective thermal conductivity k_{peff} of the PE-Xa tube, namely:

$$k_{peff} = \frac{\log(r_e/r_i)}{\frac{1}{r_i \cdot h} + \frac{1}{k_p} \cdot \log(r_e/r_i)} , \tag{1}$$

where h is the convection coefficient at the internal wall, $r = r_i$. For the considered working conditions, the Reynolds number is $Re = 2525$ and the flow is in the transition regime. The value to be assigned to the Nusselt number and, therefore, to h, has been determined by means of the Churchill correlation [11] and is reported in Table 1.

Starting from an initial instant in which the BHE and the ground are in mutual thermal equilibrium at temperature T_0, three different time periodic heat loads, with period of one year and maximum power 30 W/m, have been considered. The heat load has been assumed as positive if heat is collected by the BHE (*i.e.*, the solid in the tubes is a heat sink) and supplied to the house (winter working conditions), negative in the opposite case (summer working conditions). Plots of the heat loads are represented in Figure 2. Plot 1 (blue line, Q_1) holds for a BHE working both in winter and in summer, with a vanishing value of the total energy exchanged during one year (full compensation case); plot 2 (red line, Q_2) holds for a BHE working both in winter and in summer, with a positive value of the total energy exchanged during one year (partial compensation case); finally, plot 3 (green line, Q_3) represents the case of a BHE working only in winter (no compensation case). In detail, the considered heat loads are:

$$Q_1 = A_1 \cdot \sin(\varphi \cdot \tau) \quad , \tag{2}$$

$$Q_2 = A_{2A} \cdot \sin(\varphi \cdot \tau) + \left| A_{2B} \cdot \sin(\varphi \cdot \tau) \right| \quad , \tag{3}$$

$$Q_3 = A_3 \cdot \sin(\varphi \cdot \tau) + \left| A_3 \cdot \sin(\varphi \cdot \tau) \right| \quad , \tag{4}$$

where

$$\varphi = \frac{2\pi}{P} = 1.9924 \cdot 10^{-7} \text{ s}^{-1} \tag{5}$$

is the pulse of oscillation, P = 1 year = 31536000 s is the period, τ is time and $A_1 = 30$ W/m, $A_{2A} = 22.5$ W/m, $A_{2B} = 7.5$ W/m, $A_3 = 15$ W/m are the amplitudes. In the partial compensation case, the absolute value of the maximum load during summer is one half of that during winter, as typically occurs for residential buildings in Northern-Central Italy (Padana flat).

The long-term performance of double U-tube BHE fields has been studied with reference to the following configurations:

I) a single BHE surrounded by an infinite ground;
II) a square field of 4 BHEs, with a spacing of 6 m, surrounded by an infinite ground;
III) the limiting case of a square field of infinite BHEs, with a spacing of 6 m.

For case I, a circular portion of ground with 100 m radius has been considered, to model the infinite ground; for case II, a portion of ground with 150 m radius has been considered, for the same purpose. In order to grant that the results are independent of the chosen domain size, two boundary conditions have been considered at the external ground surface: uniform and constant temperature $T = T_{gd}$; zero heat flux. The comparison between these boundary conditions always gave a very good agreement, up to 5 significant digits.

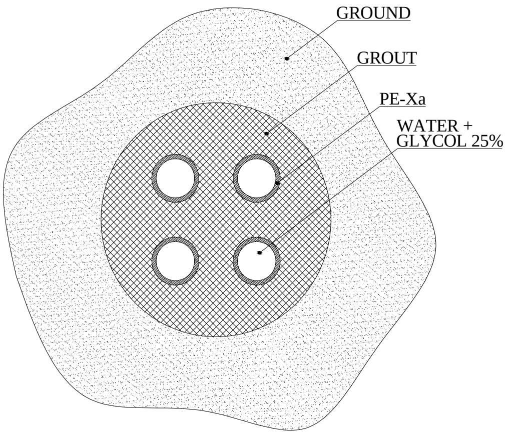


Figure 1. Sketch of the double U-tube BHE cross-section.

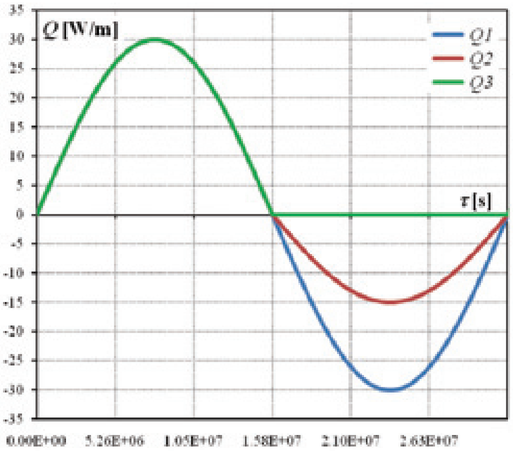


Figure 2. Prescribed time-periodic heat fluxes.

Table 1. Geometrical parameters, material properties and working conditions.

SYMBOL	VALUE	QUANTITY
Geometrical data of double U-tube BHE		
r_i	13	Internal radius of PE-Xa tube [mm]
r_e	16	External radius of PE-Xa tube [mm]
r_b	78	External radius of grout layer [mm]
Thermal properties of high density polyethylene PE-Xa		
c_1	2300	Specific heat capacity [J kg^{-1} K^{-1}]
k_1	0.4	Thermal conductivity [W m^{-1} K^{-1}]
ρ_1	940	Density [kg m^{-3}]
Thermal properties of grout		
c_2	1600	Specific heat capacity [J kg^{-1} K^{-1}]
k_2	1.08	Thermal conductivity [W m^{-1} K^{-1}]
ρ_2	1000	Density [kg m^{-3}]
Thermal properties of ground		
$(\rho c)_3$	2.5	Heat capacity per unit volume [MJ m^{-3} K^{-1}]
k_3	1.8	Thermal conductivity [W m^{-1} K^{-1}]
Thermal properties adopted for water-ethylene glycol 25%		
c_{wg}	3823	Specific heat capacity [J kg^{-1} K^{-1}]
k_{wg}	1000	Thermal conductivity [W m^{-1} K^{-1}]
ρ_{wg}	1084.5	Density [kg m^{-3}]
μ_{wg}	6.31	Dynamic viscosity [mPa s]
Working conditions		
T_0	14	Initial water-glycol temperature [°C]
T_{gd}	14	Undisturbed ground temperature [°C]
$\dot{V}$	18	Water-glycol flow rate [dm^3 min^{-1}]
h	100.76	Convection coefficient [W m^{-2} K^{-1}]

Finally, to study case III, a square portion of ground with 6 m side, centered on the BHE, has been considered. Also in this case, two different conditions have been imposed on the external boundary and compared: spatially periodic condition and adiabatic condition. Again, the check gave the same results for both boundary conditions up to 5 significant digits.

For the polyethylene tubes, the grout and the ground, the equation to be solved is the Fourier equation without generation

$$\rho_j c_j \frac{\partial T}{\partial \tau} = k_j \nabla^2 T \quad , \quad j = 1, 2, 3 \quad , \tag{6}$$

where ρ_j, c_j and k_j are the density, the specific heat capacity and the thermal conductivity of the j-th solid material.

In the solid which replaces the water-glycol solution, the equation to be solved to obtain the temperature distribution T_f is

$$\rho_{wg} c_{wg} \frac{\partial T_f}{\partial \tau} = k_{wg} \nabla^2 T_f + q_{gi} \quad , \tag{7}$$

where q_{gi} is the power generated per unit volume, given by

$$q_{gi} = -\frac{Q_i}{4 \cdot \pi r_i^2} \quad , \quad i = 1, 2, 3 \quad . \tag{8}$$

In Eq.(8), Q_1, Q_2, Q_3 are the heat fluxes per unit length given by Eqs. (2–4) and represented in Figure 2.

A period of 15 years of operation is considered and a uniform time step of 1 day is adopted in computations.

In order to ensure the grid independence of the results, three unstructured meshes have been tested for each configuration: a comparison of the results is illustrated in Table 2, where the values of T_f, for the case of adiabatic boundary condition with heat flux Q_3, are reported for some time intervals after the start-up. The results show a good agreement among the tested meshes and in particular between Mesh 2 and Mesh 3. Therefore, Mesh 2 has been adopted for the final computations.

Simulations have been performed by means of the linear system solver (Direct UMFPACK) available in COMSOL Multiphysics 3.4, with default tolerance settings.

3. Results

The effect of the prescribed thermal load on a BHE field performance is shown in Figures 3-5, with reference to the first year of operation (a) and to the whole period of 15 years (b).

Table 2. Mesh independence test: values of T_f for adiabatic boundary condition and heat flux Q_3, in the case of single BHE (case I), field of 4 BHEs (case II), field of infinite BHEs (case III).

T_f [°C], case I			
Time	***Mesh 1 (4436)***	***Mesh 2 (7442)***	***Mesh 3 (9612)***
1 year	13.42	13.42	13.40
5 years	12.80	12.81	12.81
10 years	12.48	12.49	12.51
15 years	12.38	12.38	12.38
T_f [°C], case II			
Time	***Mesh 1 (8186)***	***Mesh 2 (11020)***	***Mesh 3 (14146)***
1 year	12.55	12.56	12.55
5 years	10.51	10.47	10.45
10 years	9.37	9.37	9.41
15 years	8.75	8.78	8.78
T_f [°C], case III			
Time	***Mesh 1 (3954)***	***Mesh 2 (6950)***	***Mesh 3 (9212)***
1 year	10.64	10.63	10.61
5 years	-2.90	-3.22	-3.30
10 years	-20.04	-19.96	-19.95
15 years	-36.92	-36.61	-36.70

Figure 3 refers to the case of a single BHE surrounded by an ideally infinite ground. In this case, the long-term depletion of the BHE performance is nearly negligible, in a period of 15 years, even if no load compensation during each year is adopted (load Q_3). The minimum value of the water-glycol temperature T_f is nearly the same, after each winter. On the other hand, the peak load of 30 Wm^{-1} appears rather high for the ground considered, because it yields a difference of about 28 °C between the highest and the lowest value of T_f, during each year.

The case of a small field with 4 BHEs is illustrated in Figure 4. The results show that, in this case, if no seasonal compensation is adopted (load Q_3), the long-term depletion of the BHE efficiency is considerable. However, a partial compensation between winter and summer loads (load Q_2) is sufficient to ensure an acceptable long-term performance.

Finally, Figure 5 shows that for a very large BHE field, the distance of 6 m between two boreholes, here assumed, usually employed and recommended as a minimal one by ASHRAE, is sufficient to ensure an acceptable long-term performance only if a total compensation between winter and summer loads is provided.

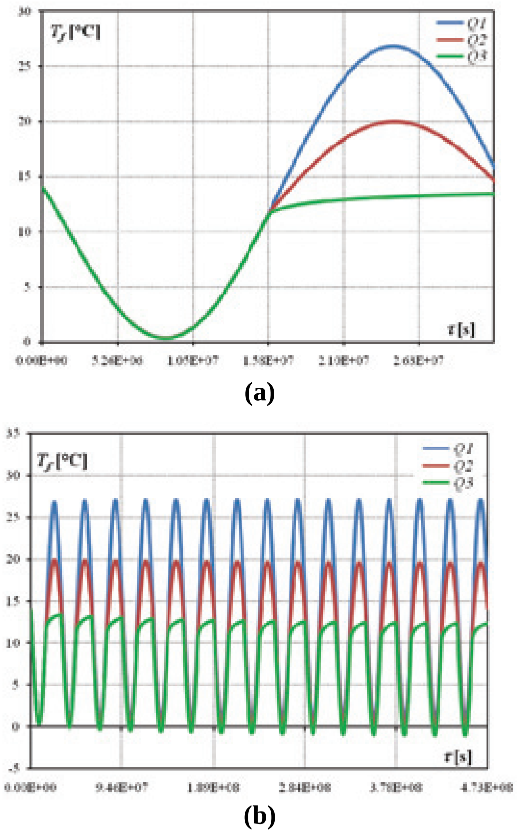
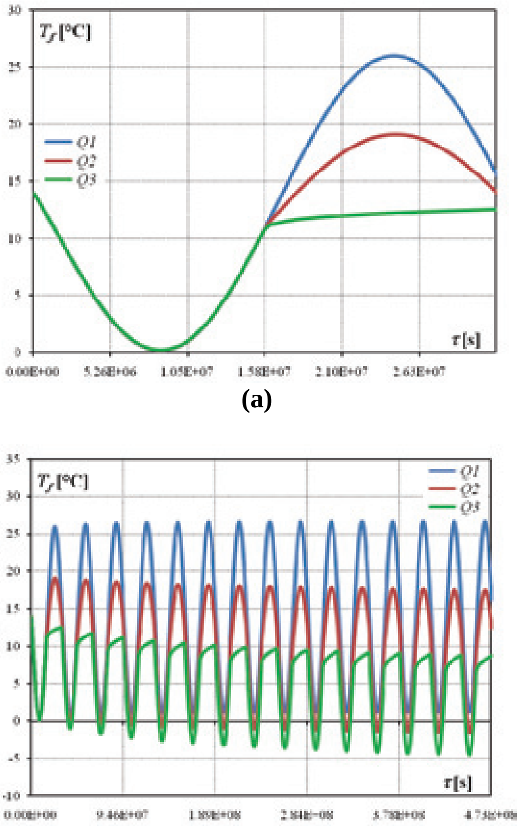


Figure 3. Fluid temperature T_f versus time in case I, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.



(a)

(b)

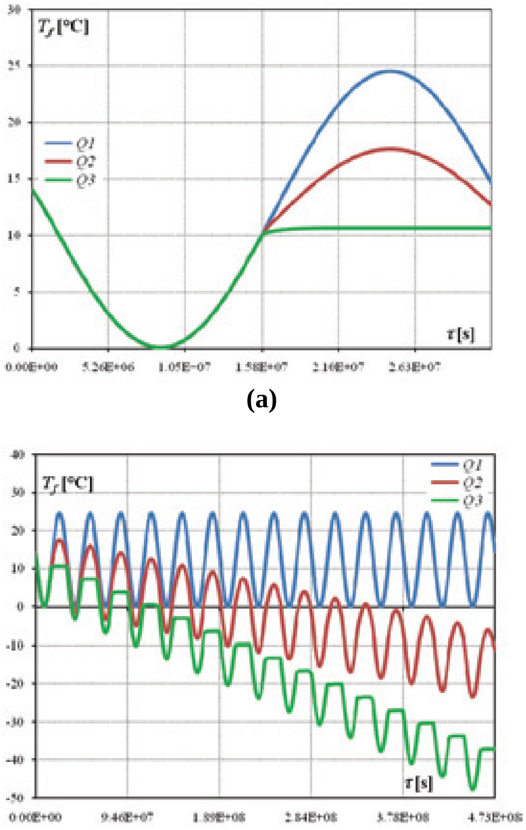
Figure 4. Fluid temperature T_f versus time in case II, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.

The results reported above agree qualitatively with those obtained by Kälin and Hopkirk [12], Pahud et al. [13], Signorelli et al. [7]. In Ref. [12], the authors conclude that a spacing of 15 m is needed to yield no noticeable influence between BHEs. Signorelli et al. [7] suggested that the minimum distance between two adjacent BHEs in a field should not fall below 8 m to provide sustainable heat exchange with ground. For a very large and square BHE field, this distance seems to us sufficient only for a full compensation load (Q_1).

A parametric analysis of the effects of BHE spacing on the long-term performance of very large BHE fields, for partial compensation or no compensation loads, has been performed. Figure 6 shows the results of this analysis: Figure 6(a) illustrates the case of an infinite BHE field subject to the partial compensation load Q_2, whereas Figure 6(b) refers to the same field subject to the no compensation load Q_3; both cases have been studied with different distances between adjacent BHEs: 6, 8, 10 m.

Figures 6(a) and 6(b) point out the improvement of thermal performance which is obtained by increasing the distance between the BHEs; the enhancement is more relevant for the spacing increase from 6 m to 8 m. However, for both loads Q_2 and Q_3, even a distance of 10 m between boreholes is insufficient to grant a good long term performance of the BHE field. Thus, for very large BHE fields, the only possible solution seems to be an almost complete seasonal compensation of the thermal load.

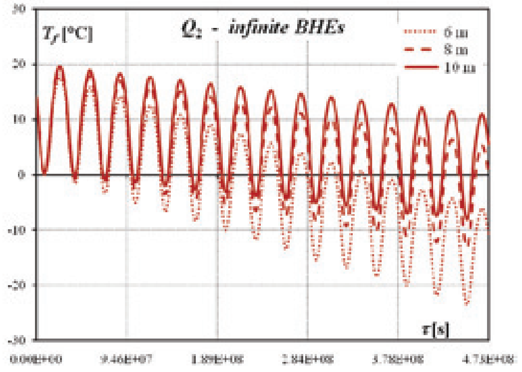
All the results presented in this paper hold under the assumption of negligible effects of groundwater movement.



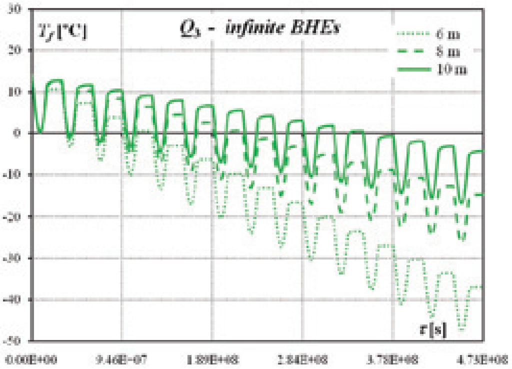
(a)

(b)

Figure 5. Fluid temperature T_f versus time in case III, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.



(a)



(b)

Figure 6. Fluid temperature T_f versus time for a field of infinite BHEs, with different distances between adjacent BHEs (6, 8, 10 m): (a) Q_2; (b) Q_3.

4. Conclusions

The long-term performances of double U-tube borehole heat exchanger fields has been studied numerically by means of the finite element software package COMSOL Multiphysics 3.4 (©Comsol, Inc.). A simplified 2D unsteady conduction model has been used to reproduce the real 3D conduction and convection heat transfer problem. Three different time-periodic heat loads have been considered, as well as three BHE field configurations: a single BHE surrounded by infinite ground; a square field of 4 BHEs, with a spacing of 6 m, surrounded by infinite ground; the limiting case of a square field of infinite BHEs, with a spacing of 6 m. Finally, a parametric analysis of the effects of BHEs spacing on the long-term performance of a square field of infinite BHEs has been carried out. The following main conclusions have been drawn, with reference to the case of negligible groundwater movement effects:

- for a single BHE, no compensation between winter and summer loads is necessary;
- for a small field of 4 BHEs with a mutual distance of 6 m, a partial compensation of the winter load by means of an opposite-sign summer load with 50% peak power is sufficient to grant an acceptable long term performance;
- for a very large and square BHE field, the only solution is an almost complete seasonal compensation of the thermal load.

5. References

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