A Comparison Between Numerical Methods for Evaluating Ground-Coupled Heat Pump Systems Performance

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Abstract

Ground coupled heat pumps are increasingly used for HVAC systems. The difficulty in sizing and predicting their behaviour and performance is well known. A suitable simulation is often advisable to help in the design choices. The code EnergyPlus is widely used in the field of building simulation and, since it includes a routine dealing with borehole heat exchangers, based on the well-known concept of g-functions, it can be profitably used for the considered purpose. On the other hand a numerical tool, namely CaRM, based on a detailed finite difference model of both the ground and borehole heat exchangers has been developed. A comparison between the use and the results of the EnergyPlus g-functions approach and CaRM in ground subsystem modelling was carried out with particular reference to an office building with quite a critical unbalance between heat extracted from and heat injected into the ground.

1. Introduction

EnergyPlus (U.S. Dept. of Energy, 2016) is a well known computer simulation software widely used for design analysis and certification procedures (e.g. LEED). It allows for a detailed description of the building characteristics and the analysis of several HVAC systems.
Among these characteristics, the borehole ground-coupled heat pumps are nowadays receiving particular attention. An efficient computational handling of the borehole field is not easy because of the complex geometry and the strong significance of its thermal capacitance. For this purpose, the relatively simple and powerful technique of the "transfer functions" has been adopted within the EnergyPlus code to model the borehole heat exchangers and calculate fluid temperatures and related energy fluxes. For this approach a mathematical tool called *g-functions* was introduced by Eskilson (1987).
The downloadable version of EnergyPlus includes precalculated g-functions for only three cases of borehole fields, namely 1x2, 4x4, 8x8 regular grids, with 4.6 m spacing and 0.74 or 1.47 W/(m K) grout thermal conductivity. The effectiveness of the model drops dramatically as the considered characteristics differ even slightly from the default ones.
A specific evaluation of the g-functions, for a given design case, requires an external computer code, and the commercial software GLHEPro (Spitler, 2000) by the Oklahoma State University, is suggested in the EnergyPlus handbook. The latest version of GLHEPro implements the simulation of the whole geothermal system, as it includes the model of the heat pump. The characteristics of the geothermal field can be specified in such a way to allow the simulation with one hour or shorter time step, via EnergyPlus or HVACSYM software. For vertical boreholes the long time-step (LTS) g-functions developed by Eskilson (Eskilson, 1987) using a finite difference model, are used and a data base of 307 precomputed functions is included in the package, and equation fits have been developed to approximate larger rectangular borehole fields. For short-time step (STS) other g-functions (Yavuzturk and Spitler, 1999; Xu and Spitler, 2006) are used to consider the thermal capacitance of the borehole heat

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exchanger when a more detailed simulation is required.

In the past, several researches have been carried out to develop more accurate but less computer time-consuming models. In the literature several analytical models can be found for a simplified sizing of ground heat exchangers, based on the infinite line source (ILS) (Carslaw and Jaeger, 1959) or cylindrical source, or finite line source (FLS) (Zeng et al., 2002) concept. The latter was used by Cimmino (Cimmino and Bernier, 2013) for a simplified calculation of g-functions, as an approximation of Eskilson's ones; this tool is available upon request.

As an alternative to the above mentioned solutions it is possible to simulate the behaviour of the geothermal field by resorting to numerical methods like finite differences, finite elements, or finite volume. These methods require higher computational time, but they describe perfectly the field, as they represent a direct application of Fourier's law. One of such methods is CaRM (CApacity Resistance Model) (Zarrella et al., 2011 and 2013a). With the last release (Zarrella et al., 2013b), the entire ground source heat pump system (i.e. both the heat pump and borehole heat exchangers) can be simulated. The prediction of the performance of the geothermal system is useful for both the design and the energy analysis of the borehole field. Each building requires a specific design of the geothermal field because it has a different impact on the entire building-plant system. Additionally, it is important for the geothermal system simulation to accurately describe the real effect of a different solicitation, e.g., long time and low amplitude or short time and high amplitude.

The purpose of this paper is to compare the results obtained from g-functions and a finite difference algorithm. The comparison starts from a long-term hourly profile of the heating and cooling load of an office building, characterised by an appreciable unbalance between the energy exchanged with the ground in summer and winter. The same load profile, estimated by means of EnergyPlus, has been used in all the cases.

2. Method

2.1 The g-functions

In the last decades, several design tools have been developed to simulate ground heat exchangers. The basic ones rest on some analytical solutions for line source (Carslaw and Jaeger, 1959) and cylindrical source (Ingersoll et al., 1954).

In the approach by Eskilson (Eskilson, 1987) the borehole wall temperature is calculated by making use of transient finite difference method; he proposed dimensionless parameters, the so-called *g-functions*, to describe the performance of a borehole's inhomogeneous ground. Each borehole field configuration is represented by the corresponding g-functions. For each time step the bore wall temperature is calculated according to the following equation:

$$T_{borehole} = T_g + \sum_{i=1}^{n} \left(\frac{q_i - q_{i-1}}{2\pi\lambda} \cdot g\left(\frac{\tau_n - \tau_{n-1}}{\tau_s}, \frac{r_b}{H} \right) \right) \quad (1)$$

Eskilson's model was implemented in the simulation tools EED (Hellström and Sanner, 1994) and GLHEPro (Spitler, 2000), where several configurations of bore fields are considered.

These models are often not suitable to analyse the borehole's short-time behaviour. For example, in his model Eskilson (1987) proposed to apply no variations of the heat extraction–injection rate on a time-scale below the following limit:

$$\tau = \frac{5r_b^2}{a_g} \quad (2)$$

For a borehole in typical applications this time step might lie between 2 and 6 hours. In many cases, this may not be important since the time of interest is in the order of months or even years. In some applications, short-time simulations of ground-coupled systems are needed for a more accurate model dealing with small time intervals (e.g. intermittent operation). Yavuzturk and Spitler (1999) analysed this problem and they solved the numerical heat diffusion problem in the ground by taking into account the heat capacity of the pipe and the grout; their numerical results were expressed in terms of short-time g-functions. This method was then improved by Xu and Spitler (2006) in order to decrease the calculation time. In particular the borehole heat exchanger is modelled as one pipe with grouting material, whose thermal properties are assumed in

such a way to have the same borehole thermal resistance making use of the multipole method (Bennet et al., 1987).
Cimmino and Bernier (2013, 2014) analytically calculated the g-functions using the finite line source method (Zeng et al., 2002). Their approach considers the position of the head of the borehole in the ground and the heat rate can be different for the boreholes of the field; however, as in Eskilson's model, the heat rate is assumed to be constant along the borehole depth.

2.2 The CaRM Approach

The CaRM tool solves the Fourier's equation of the thermal field via a numerical way using the electrical analogy. The most recent version of CaRM (Zarrella et al., 2013a) gives a considerable improvement on the first releases (De Carli et al., 2010). The borehole heat exchanger and ground are discretized with thermal nodes, and the heat balance equations are based on these. The new version (Zarrella et al., 2013a) calculates the heat exchange between the heat-carrier fluid inside the boreholes and the surrounding ground and also accounts for the axial heat conduction within both grout and ground. Convective heat transfer, temperature, and short-long wave radiation exchange at ground surface are also modelled. This approach allows the analysis also of short-borehole heat exchangers that are generally placed where the ground temperature is affected by near-surface effects. The model also considers the shape of the borehole field. Fig. 1 outlines the CaRM approach.
The model resorts to thermal resistances and capacitances in order to solve the unsteady state heat transfer phenomenon. The ground is divided into three main zones: the surface, the borehole, and the deep zones (Fig. 1a). The adopted heat transfer model varies depending on the zone being considered: one-dimensional heat conduction (i.e. along the depth direction) is modelled in both the surface and deep zones, while the heat transfer is in both the radial and axial directions in the borehole (middle) zone. For each thermal node (Fig. 1b-c) of the domain, the heat balance equation is written. The CaRM tool can investigate several types of borehole heat exchangers: single and double U-tube, coaxial pipes, helical shaped pipe, and also energy piles, whose characteristics do not conform to the above g-functions application and require a specific analysis (Zarrella et al., 2017). In CaRM the building load profile is an input, and the tool calculates the ground temperatures and the inlet and outlet heat-carrier fluid temperatures of the boreholes for each time step of the simulation.

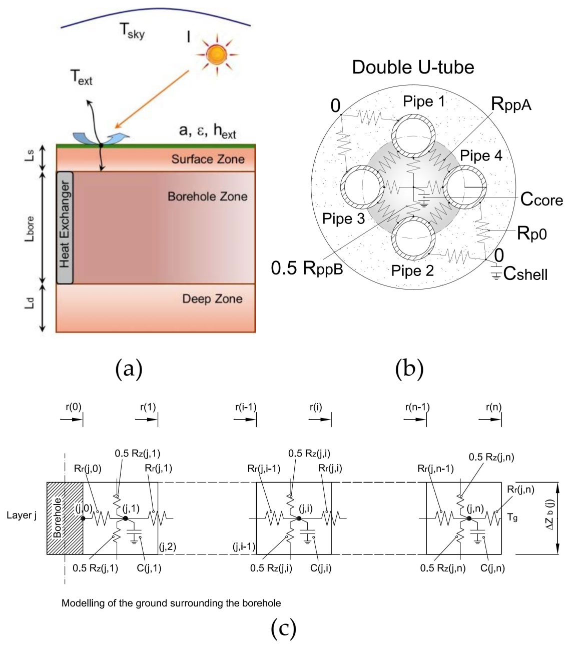


Fig. 1 – Scheme of the modelling approach of CaRM

3. Case Study

The building used as case study is located in the city of Padova, in the north of Italy. It is a four-storey office building with a total floor area of 2,200 m^2. Three floors are above ground and one level is underground (Fig. 2, top). Approximately 90 people work inside this building. The north and south facades are completely glazed (the south is a double-skin type). The west-side wall is opaque with a large central window on the first two floors, while the top west-side floor is fully glazed. The construction was completed in 2003 and the whole building has been operational since 2004. A radiant and primary air HVAC system is installed: during the daytime the air handling unit is on, whereas the thermally activated radiant building system is switched on during the night (Currò Dossi et al., 2003).
The heating and cooling demand of the building is

provided by a 4-step water to water heat pump coupled to 16 borehole heat exchangers, 95 m long and 7 m apart and arranged in an L-shape (Fig. 2, bottom). The heat pump runs with refrigerant R407c and is used for both spaces heating and cooling; its capacities are 111 kW and 93 kW in cooling and heating, respectively. The heat pump operates with one temperature setpoint in heating mode, i.e. 35 °C, and with two different setpoints in cooling mode, i.e. 7 °C and 17 °C in daytime and night time, respectively, to improve the energy efficiency when no air handling is required.

The borehole heads are buried at about 1 m beneath the ground surface. A double U-tube heat exchanger was installed inside the borehole and the outside (inside) diameter of the pipe is 32 mm (26 mm); the borehole diameter is 140 mm. All the circuits (double U-tube) inside each borehole heat exchanger are coupled in parallel. The heat-carrier fluid inside the ground heat exchangers is pure water with a total constant mass flow rate equal to 5.56 kg/s.

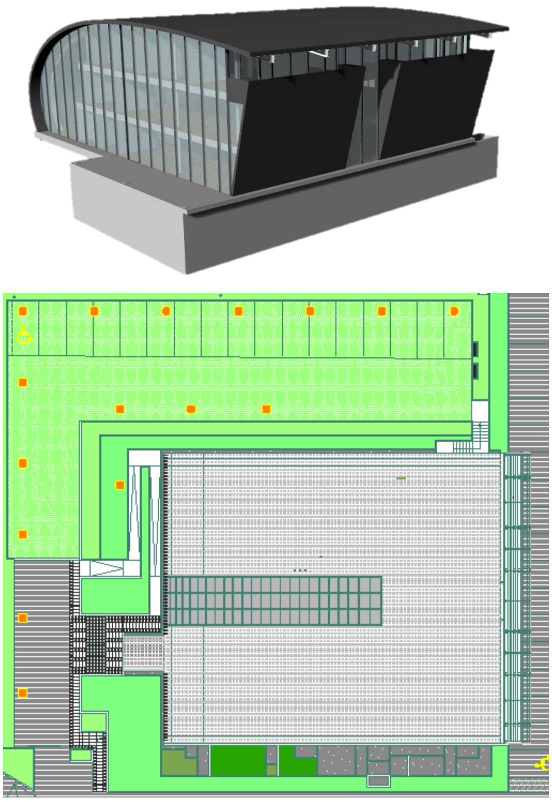


Fig. 2 – North and West view of the building of the EnergyPlus model (top) and plant of the real boreholes field (bottom)

On the building side, the total mass flow rate of water (i.e. the heat-carrier fluid) is equal to 6.10 kg/s. The fluid mass flow rates in the loops were considered constant over the simulation time.

An equivalent ground layer was used to carry out the simulations: the mean weighted thermal conductivity was 1.9 W/(m K) and the volumetric heat capacity was 2.24 MJ/(m³ K). The undisturbed ground temperature was assumed to be 14 °C. The area's groundwater flow effect was considered negligible.

The heating and cooling demand of the building was calculated by means of the EnergyPlus tool over eleven years. To this purpose, real weather data provided by the regional environmental agency ARPAV for the weather station of Legnaro (at about ten kilometers from the building) were used.

The energy model of EnergyPlus was built dividing the whole building in 59 thermal zones, and for each of them, the geometric and thermal properties of the opaque walls, glazed surfaces, and solar shading surfaces were assigned. Then, for each zone the internal heat gains were set.

Fig. 3 shows the thermal loads of the heat pump. The ratio between the annual heating and cooling energy demand ranges from 0.56 initially, to 0.4 at the end of the considered period. This confirms that the building's annual load profile is cooling dominant.

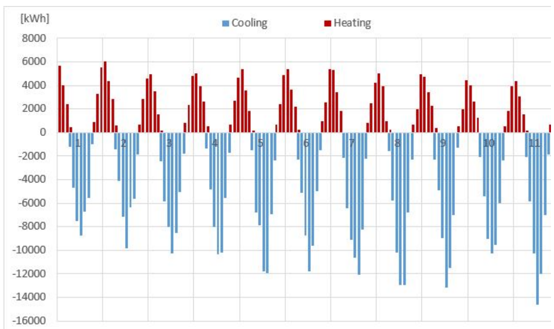


Fig. 3 – Synthesis of building load profile derived from hourly calculations

4. Computer Simulations

The comparison between the models was carried out considering the real layout of the borehole field of the case study. Moreover, two other configurations were assumed in order to make the comparison more complete. In all the layouts considered,

the total borehole length was kept constant and the position of the boreholes was only modified. Table 1 reports the three cases investigated.
The heat pump was simulated considering the data provided by the manufacturer. In particular the energy efficiency was calculated at each time step according to the following equations:

Cooling mode:

$$\frac{Q_c}{Q_{c,ref}} = -0.25 + 7.3574\left(\frac{T_{L,in}}{T_{ref}}\right) - 2.3973\left(\frac{T_{S,in}}{T_{ref}}\right) - \\ -1.5156\left(\frac{\dot{V}_L}{\dot{V}_{ref}}\right) - 2.25\left(\frac{\dot{V}_S}{\dot{V}_{ref}}\right) \tag{3}$$

$$\frac{Power_c}{Power_{c,ref}} = 0.5625 + 1.4518\left(\frac{T_{L,in}}{T_{ref}}\right) + 5.9483\left(\frac{T_{S,in}}{T_{ref}}\right) - \\ -3.125\left(\frac{\dot{V}_L}{\dot{V}_{ref}}\right) - 4.125\left(\frac{\dot{V}_S}{\dot{V}_{ref}}\right) \tag{4}$$

Heating mode:

$$\frac{Q_h}{Q_{h,ref}} = 0.8125 - 1.6888\left(\frac{T_{L,in}}{T_{ref}}\right) + 8.6281\left(\frac{T_{S,in}}{T_{ref}}\right) - \\ -2.8594\left(\frac{\dot{V}_L}{\dot{V}_{ref}}\right) - 3.7187\left(\frac{\dot{V}_S}{\dot{V}_{ref}}\right) \tag{5}$$

$$\frac{Power_h}{Power_{h,ref}} = 3.4375 + 6.1243\left(\frac{T_{L,in}}{T_{ref}}\right) + 1.4024\left(\frac{T_{S,in}}{T_{ref}}\right) - \\ -5.3125\left(\frac{\dot{V}_L}{\dot{V}_{ref}}\right) - 5.1094\left(\frac{\dot{V}_S}{\dot{V}_{ref}}\right) \tag{6}$$

where T_{ref} is a fix value equal to 283.15 K.

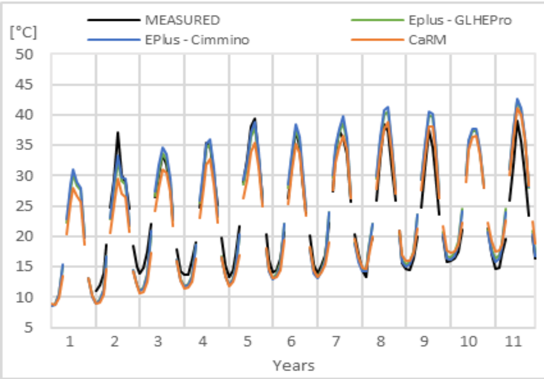
Table 1 – List of simulations

Case	Spacing (m)	Total length (m)
Case A - L shape (Real)	7	1520
Case B - Grid 4 x 4	7	1520
Case C - U shape	7	1520

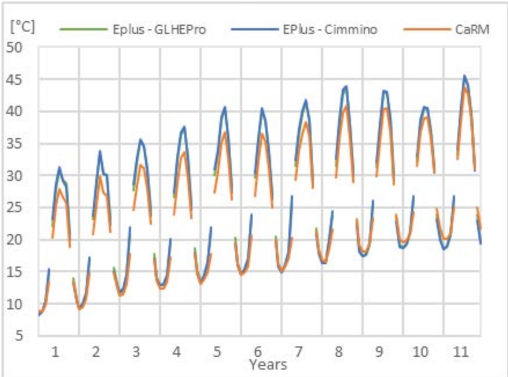
The comparison between the models was carried out in terms of the outlet temperature of the heat carrier fluid from the boreholes, seasonal energy efficiency of the heat pump, and seasonal electrical energy consumption.

5. Results and Discussion

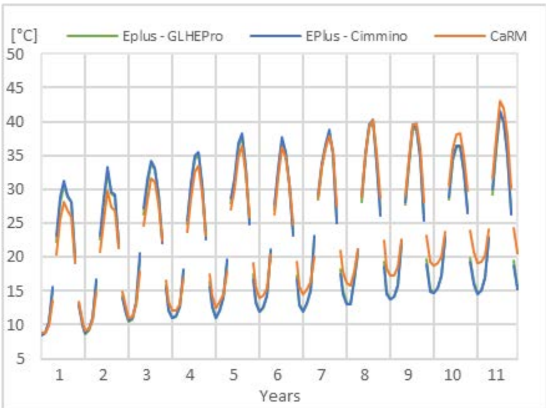
The computer simulations allow to determine several parameters representing the behaviour of the building-plant system. For the purpose of this work the outlet temperature from the borehole heat exchangers and the seasonal performance of the heat pump (S-COP in heating and S-EER in cooling mode) were chosen. In Fig. 4 the monthly average outlet temperatures are reported for the three considered configurations of the borehole field; in particular for the L-shaped case, which is the real one, also the values of the temperature measured and recorded are shown. It can be seen that the agreement is quite good over the full eleven-year period for all the three approaches of ground heat heat exchangers modelling. The actual temperature drift due to the unbalance between heating and cooling loads is well reproduced.
In Fig. 5 the calculated values of the S-COP and S-EER of the heat pump are shown for the same eleven-year period of simulation. The simulations give evidence of an appreciable change in the efficiency of the heat pump over the considered period.



(a)

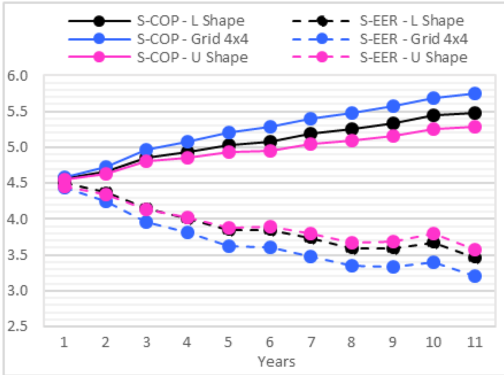


(b)

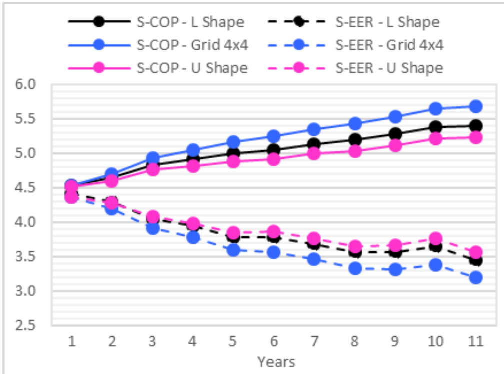


(c)

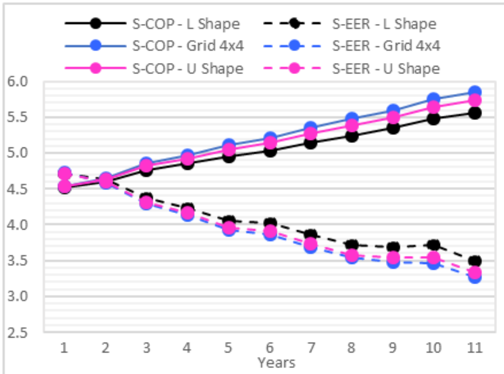
Fig. 4 – Monthly average outlet temperature of the fluid from the boreholes for L-shape (real) (a), grid 4x4 (b) and U shape (c) configurations of field



(a)



(b)



(c)

Fig. 5 – Monthly values of heat pump efficiency calculated with GLHEPro (a), Cimmino (b) and CaRM (c) for the three configurations of field

6. Conclusions

Having ascertained that the predefined default g-functions included in the EnergyPlus original package are not suitable to handle the multiplicity of possible cases, a specific method to determine such functions should be adopted to perform a reliable simulation. In this paper two calculation methods of g-functions have been applied to a significant case study of a real office building showing a multi-year ground temperature drift. These two methods result in more than reasonable agreement, and are in agreement with the long term monitoring of the building as well. Moreover a third method, CaRM, based on the numerical time dependent solution of Fourier's equation applied to the ground field, has been applied, starting from the same heating and cooling loads calculated by EnergyPlus; also this method shows consistency with the measured values of the ground leaving water temperature. It has to be pointed out that the CaRM tool, being based on the mere actual representation of the borehole field, does not exhibit any limits of applicability, as the other methods do due to their preliminary and boundary assumptions. The only penalty is the need to break into two parts the process of simulation.

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Nomenclature

Symbols

$T_{borehole}$	Average borehole temperature (°C)
T_g	Undisturbed ground temperature (°C)
q	Step heat rejection pulse (W/m)
r_b	Borehole radius (m)
τ	Time (s)
$\tau_s=H^2/(9\alpha_g)$	Time scale (s)
α_g	Ground diffusivity (m²/s)
H	Borehole length (m)
λ	Ground thermal conductivity (W/(mK))
Q	Heat pump capacity (W)
$Power$	Heat pump electric power (W)
V	Volumetric flow rate (m³/s)
$T_{L,in}$	Load side inlet temperature (K)
$T_{S,in}$	Source side inlet temperature (K)
S-COP	Seasonal Coefficient Of Performance
S-EER	Seasonal Energy Efficiency Ratio

Subscripts/Superscripts

i	Index of a time step
n	Number of time steps
ref	Reference conditions
c	Cooling value
h	Heating value
S	Source side
L	Load side

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