**pygfunction**: an open-source toolbox for the evaluation of thermal response factors for geothermal borehole fields

Massimo Cimmino

Département de génie mécanique, Polytechnique Montréal, Montréal, Canada

**Abstract:** Thermal response factors, or g-functions, are used in energy simulation software to simulate geothermal systems and evaluate their energy performance. When using such software, the user is however restricted to the bore field configurations provided with the software. The aim of this study is to provide an efficient and versatile toolbox, called pygfunction, to generate g-functions for fields of arbitrarily positioned and sized boreholes. The toolbox implements analytical methods, based on the finite line source (FLS) solution, to generate g-functions for the 3 main boundary conditions at the borehole wall found in the literature: (1) uniform heat extraction rate along the boreholes, (2) uniform borehole wall temperature and (3) equal inlet fluid temperature into the boreholes. pygfunction allows the calculation of g-functions for all 3 boundary conditions. pygfunction is implemented into the Python language and also supports the simulation of geothermal systems using load aggregation methods.

**Keywords:** Thermal response factors, g-functions, Ground-source heat pump systems, Geothermal

**INTRODUCTION**

Thermal response factors, or g-functions, are used in both the simulation and the design of ground-source heat pump systems. Ground-source heat pump systems consist in an array of geothermal boreholes typically connected in parallel, as shown on Figure 1. A heat pump is used to transfer heat between the fluid circulating in the boreholes and the building to satisfy the heating and cooling loads. In simulation methods, g-functions are used to predict fluid and ground temperatures and then evaluate the energy consumption of the heat pump. In design methods, g-functions are used to find the borehole length that is required to satisfy the building loads while maintaining the fluid temperatures within prescribed limits.

By definition, g-functions give the relation between the heat extraction rate in the bore field and the average temperature variation at the borehole walls. For a constant heat extraction rate in the bore field:

\[
\bar{T}_b(t_k) = T_g - g(t_k) \frac{\bar{Q}'}{2\pi k_s} \quad (1)
\]

where \(\bar{T}_b\) is the average borehole wall temperature in the bore field, \(T_g\) is the undisturbed ground temperature, \(\bar{Q}'\) is the constant average heat extraction rate per unit borehole length in the bore field, \(k_s\) is the ground thermal conductivity and \(g\) is the g-function.

The concept of g-functions was introduced by Eskilson (1987). Eskilson’s g-functions are obtained numerically using an explicit finite difference method. Using this method, each borehole is modelled individually in a 2D radial-axial grid. The temperature fields around each borehole are superimposed in space to obtain the total temperature variation. This necessitates a dedicated code implementing the numerical finite difference method and may require very long calculation times for bore fields with
large numbers of boreholes. For these reasons, g-functions are often included in databases of pre-set bore field configurations in simulation and design software. This has the advantage of increasing the calculation speed by avoiding the calculation of g-functions. These databases also spare the user the arduous task of defining the numerical spatial grids and time steps. However, it has the disadvantage of limiting the bore field to the standard configurations included in the database, which can limit design choices and cause errors due to interpolation between g-functions curves (Malayappan and Spitler 2013).

The analytical finite line source (FLS) solution (Zeng, Diao, and Fang 2002) is often employed to evaluate the g-functions of geothermal bore fields. For boreholes experiencing pure conduction in homogenous isotropic ground, the FLS solution can accurately reproduce Eskilson’s g-function, as will be presented in the following section. The FLS solution has been extended to consider groundwater advection (Molina-Giraldo et al. 2011), anisotropic ground thermal properties (Li and Lai 2012), and vertically layered ground thermal properties (Abdelaziz et al. 2014; Hu 2017). Analytical methods have the advantage of enabling the calculation of g-functions of irregular bore field configurations at relatively small calculation times. They can however require important calculation times when implemented incorrectly.

The objective of the paper is to present an open-source toolbox for the evaluation of g-functions based on the FLS solution. The toolbox is currently limited to fields of parallel-connected vertical boreholes in homogenous isotropic ground without groundwater advection. It is designed to be extensible and facilitate the implementation of new analytical solutions and new methods for the evaluation of g-functions. It is publicly available on github (Cimmino 2018a). The paper first presents the theoretical background of the toolbox, then the structure of the toolbox, and finally some examples demonstrating its use for irregular bore field configurations.

**LONG-TERM G-FUNCTIONS**

G-functions are dimensionless and are represented as a function of the logarithmic time ln(t/t₀), where t₀ = L²/9α, is the characteristic time of the bore field, L is the borehole length and α is the ground thermal diffusivity. The g-functions of a U-shaped field of 6 × 4 boreholes are shown on Figure 2. Each g-function curve is associated with a specific set of dimensionless parameters: B/L is the spacing ratio, rₕ/L is the borehole radius ratio and D/L is the buried depth ratio. Whenever any of these parameters change or the bore field shape changes, the g-function needs to be re-evaluated.

For a piecewise constant heat extraction rate, the average borehole wall temperature is obtained from temporal superposition of the g-function:

\[ T_b(t_k) = T_g - \sum_{p=1}^{k} g(t_k - t_{p-1}) \frac{\dot{Q}'(t_p) - \dot{Q}'(t_{p-1})}{2\pi k_s} \]  

(2)

where \( \dot{Q}'(t_p) \) is the average heat extraction rate per unit borehole length in the bore field, constant over \( t_{p-1} < t \leq t_p \).

The difference between short-term and long-term g-functions is that long-term g-functions typically neglect the transient effects inside the boreholes (i.e. fluid travel time and thermal capacities of the fluid, pipe and grout materials). Short-term g-functions typically neglect the effects of axial conduction in the ground and the thermal interaction between the boreholes. Eskilson (1987) estimated that long-term g-functions are valid for times \( t > 5r_h^2/\alpha \).

The evaluation of g-functions using analytical methods is done by representing each of the boreholes in a bore field by a series of \( n_q \) finite line source segments of equal length \( L_{i,u} = L_i/n_q \) (Cimmino and Bernier 2014). The g-function is obtained by assembling three sets of equations: (1) the superposition of the FLS solution, (2) the global energy balance, and (3) the boundary condition at the borehole walls. The following sections describe each set of equations. Matrix notation is adopted to simplify the formulation.
Superposition of the FLS solution

The borehole wall temperature along each of the borehole segments in the bore field is obtained from the temporal and spatial superpositions of the FLS solution. In matrix notation:

\begin{equation}
T_b(t_k) = T_b'(t_k) - H(\Delta t_k) \frac{Q'(t_k)}{2\pi k_s} 
\end{equation}

\begin{equation}
T_b'(t_k) = T_b - \sum_{p=1}^{k-1} [H(t_k - t_{p-1})
- H(t_k - t_p)] Q'(t_p) / 2\pi k_s 
\end{equation}

where \(T_b(t_k)\) is the vector of borehole wall temperatures along all borehole segments, \(Q'(t_k)\) is the vector of heat extraction rates per unit length of all borehole segments, \(T_b'(t_k)\) is the vector of borehole wall temperatures along all borehole segments from temporal superposition of all loads preceding time step \(t_k\), \(H(t)\) is the thermal response factor matrix.

The thermal response factor matrix is built from the FLS solution for all pairs of borehole segments in the bore field. The thermal response factor matrix is obtained from the temporal and spatial superpositions of the FLS solution. In matrix notation, this boundary condition can be employed by Eskilson to evaluate the original g-functions, especially for large values of times and for fields with large numbers of boreholes. They are presented here in increasing order of modelling complexity: (1) uniform heat transfer rate, (2) uniform borehole wall temperature, and (3) equal inlet fluid temperature.

Uniform heat extraction rate

The boundary condition of uniform heat extraction rate corresponds to the classical superposition of the FLS solution, as presented by Zeng et al. (2002) and simplified by Lamarche and Beauchamp (2007) and Claesson and Javed (2011). Under this boundary condition, all boreholes extract heat at equal and uniform rates over their length. In matrix notation, this boundary condition is expressed:

\begin{equation}
Q'(t_k) = \tilde{Q}' \mathbf{1}
\end{equation}

where \(\mathbf{1}\) is a vector of ones of size equal to the total number of borehole segments in the bore field.

Since the heat extraction rate is constant, temporal superposition (Equation 4) is not necessary and only \(n_b = 1\) segment per borehole is sufficient. The g-function is obtained directly by Equation 3, with \(\tilde{Q}' = -2\pi k_s\). This boundary condition has been shown to overestimate g-function values when compared to the original g-functions of Eskilson (Fossa 2011; Cimmino, Bernier, and Adams 2013).

Uniform borehole wall temperature

The boundary condition of uniform borehole wall temperature corresponds to the boundary condition employed by Eskilson to evaluate the original g-functions (Eskilson 1987). It is meant to represent the condition of boreholes connected in parallel in a single fluid network. Since fluid temperature variations inside boreholes tend to be small, the borehole wall temperature variations along the boreholes also tend to be small. By dividing each of the boreholes into segments, this boundary condition can be reproduced using the FLS solution (Cimmino and Bernier 2014; Lazzarotto 2016).

In matrix notation, this boundary condition is expressed:

\begin{equation}
T_b(t_k) = T_b'(t_k) \mathbf{1}
\end{equation}

The combination of Equations 3, 8 and 10 forms a system of equations that can be solved sequentially at every time step.
step $t_k$. Per Equation 1, for $\bar{Q}' = -2\pi k_s$, the uniform borehole wall temperature is equal to the g-function of the bore field.

**Equal inlet fluid temperature**

In reality, heat extraction rates are driven by the temperature differences between the fluid and the borehole walls. In these conditions, both the heat extraction rate and the borehole wall temperature vary along the borehole lengths. The thermal coupling between the fluid and the ground needs to be considered to accurately represent the variation of the two quantities.

For the evaluation of long-term g-functions, steady-state analytical solutions to the fluid temperature profiles inside boreholes can be used to express the relation between the heat extraction rates and the borehole wall temperatures. A steady-state solution to fluid temperature profiles in single U-tube boreholes was obtained by Eskilson and Claesson (1988). A solution for symmetrical double U-tube boreholes was obtained by Zeng et al. (2003). A general solution for boreholes with any number of U-tubes in any position was presented by Cimmino (2016).

In all cases, a linear equation can be written for the relation between the heat extraction rates, the inlet fluid temperature and the borehole wall temperature. In matrix notation:

$$Q'_i = a_{Q,i}T_{f,in} + b_{Q,i}T_b$$

where $Q'_i$ is a vector of the heat extraction rates per unit borehole length along each of the segments of the $i^{th}$ borehole, $T_{f,in}$ is the inlet fluid temperature shared by all parallel-connected boreholes and $T_b$ is a vector of the borehole wall temperatures along each of the segments of the $i^{th}$ borehole. $a_{Q,i}$ and $b_{Q,i}$ are coefficient vectors and matrices that depend on the fluid mass flow rate, on the physical properties of the fluid, and on the internal thermal resistances between the fluid circulating through U-tube pipes and between the fluid and the borehole wall. These thermal resistances are in turn dependent on the thermal conductivities of the ground, the grout, the fluid and the pipes, the fluid physical properties, the fluid mass flow rate and the configuration and number of pipes inside the boreholes.

The combination of Equations 3, 8 and 11 forms a system of equations that can be solved sequentially at every time step $t_k$. For $\bar{Q}' = -2\pi k_s$, the average borehole wall temperature is equal to the g-function of the bore field. g-functions with equal inlet fluid temperatures were presented by Cimmino (2015) for single U-tube boreholes. It was shown that g-function values approach the condition of uniform temperature when the borehole thermal resistance is small and the condition of uniform heat extraction rate when the borehole thermal resistance is large.

**STRUCTURE OF THE TOOLBOX**

`pygfunction` is developed in Python 2.7 and is compatible with Python 3.6. The toolbox is divided into modules that each serve a specific purpose in the evaluation and use of g-functions. The main module, `gfunction`, evaluates the g-function curves for any of the previously presented boundary conditions. The `heat_transfer` module builds the thermal response factor matrix based on the FLS solution. The `Borehole` class in the `boreholes` module contains the geometric information associated with the position and size of a borehole. The `UTube` classes in the `pipes` module handle the calculation of fluid temperature profiles inside a borehole. The `utilities` module contains supporting functions used throughout all modules. Finally, the `load_aggregation` module allows the simulation of geothermal systems. Each of the modules are described in the following sections.

**boreholes module**

The `boreholes` module contains the `Borehole` class. An instance of the `Borehole` class defines the geometric characteristics of a borehole: its position $(x, y)$, its radius $r_b$, its length $L$ and its buried depth $D$. In `pygfunction`, a bore field is simply defined as a list of boreholes. Listing 1 presents three ways to define a bore field using the `boreholes` module. The bore field can be defined by creating a list of individual borehole objects, by calling any of the implemented functions for regular bore field configurations, or by loading the bore field data from an external text file. The regular configurations implemented into `pygfunction` include rectangular fields, box-shaped fields, U-shaped fields, L-shaped fields and circular fields. Figure 3 shows the visualization of a bore field imported from an external file.

**pipes module**

The `pipes` module contains `UTube` classes associated with different pipe configurations inside the boreholes. An instance of a `UTube` class defines the geometric characteristic of the pipes and the physical properties of the borehole: the position of the pipes within the borehole, the inner and outer radiuses of the pipes, the thermal conductivities of the grout and the ground, and the thermal resistance between the fluid and the outer pipes wall. Class methods return the coefficient vectors and matrices necessary for the evaluation of g-functions using equal inlet fluid temperature (Equation 11) based on fluid mass flow rate and specific heat capacity. Internal thermal resistances
are calculated using the multipole method (Claesson and Hellström 2011).

Listing 1: Defining a bore field

```python
import pygfunction as gt

# 1 - Define bore field from list of boreholes
bore0 = gt.boreholes.Borehole(H=150, D=4, r_b=0.075, x=0, y=0)
bore1 = gt.boreholes.Borehole(H=150, D=4, r_b=0.075, x=10, y=0)
bore2 = gt.boreholes.Borehole(H=150, D=4, r_b=0.075, x=8, y=5)
field0 = [bore0, bore1, bore2]

# 2 - Define bore field from function
field1 = gt.boreholes.rectangle_field(N_1=3, N_2=2, B_1=7.5, B_2=7.5, H=150, D=4, r_b=0.075)

# 3 - Define bore field from text file
filename = './data/custom_field.txt'
field2 = gt.boreholes.field_from_file(filename)

# Visualize bore field
gt.boreholes.visualize_field(field2)
```

Figure 3: Custom defined bore field of 40 boreholes

Two steady-state analytical models are currently implemented in pygfunction: the single U-tube model of Eskilson and Claesson (1988), and the multiple U-tube model of Cimmino (2016). In addition to returning the coefficient vectors and matrices for the relation in Equation 11, the UTube classes also provide a series of methods to evaluate fluid temperatures and heat extraction rates during simulation. Listing 2 presents the definition of a double U-tube borehole. Figure 4 shows the pipe configuration associated with the double U-tube borehole.

Listing 2: Defining U-tube pipes

```python
import pygfunction as gt

borehole = gt.boreholes.Borehole(H=150, D=4, r_b=0.075, x=0, y=0)
UTube = gt.pipes.MultipleUTube(pos=[(-0.05, 0), (0, -0.05), (0.05, 0), (0, 0.05)], r_in=0.015, r_out=0.02, borehole=borehole, k_s=2, k_g=1, R_fp=0.1, nPipes=2)
UTube visualize_pipes()
```

Figure 4: Double U-tube borehole

heat_transfer module

The heat_transfer module is built around the FLS solution (Equation 6). It implements functions to evaluate the thermal response factor matrix (Equations 6 and 7). The module recognizes “similarities” in the evaluation of the FLS solution and uses multiprocessing to accelerate the evaluation of the matrix (Cimmino 2018b). It is called by the gfunction module to build the necessary system of equation for the evaluation of g-functions.

gfunction module

The gfunction module implements specialized functions to evaluate the g-functions for each of the previously presented boundary conditions. The functions in this module assemble the sets of equations for the superposition of the FLS solution, the global energy balance, and the boundary condition. Then, they evaluate the g-function values sequentially by solving the assembled system of equations at every time step. Listing 3 presents the calculation of the g-function of a rectangular field of
10 × 10 boreholes with the boundary condition of uniform borehole wall temperature. The only required inputs to the evaluation of the g-function using this boundary condition are the list of boreholes constituting the bore field, the time values at which to evaluate the g-function and the ground thermal diffusivity.

Listing 3: Calculating the g-function of a bore field

```python
import pygfunction as gt
# Calculate g-function over 3000 years with
# geometrically expanding time steps
dt = 3600.
time = gt.utilities.time_geometric(dt=dt, tmax=3000*8760*dt, Nt=50)
boreField =
gt.boreholes.rectangle_field(N_1=10, N_2=10,
B_1=7.5, B_2=7.5, H=150., D=4, r_b=0.075)
gFunc =
gt.gfuction.uniform_temperature(boreField, time, alpha=1.0e-6)
```

load_aggregation module

The classes in the load_aggregation module implement different algorithms for the temporal superposition of the g-function (Equation 2) for the evaluation of borehole wall temperatures during the simulation of a ground-source heat pump system. The currently implemented algorithms are that of Bernier et al. (2004), Liu (2005), and Claesson and Javed (2012). This module is not used during the evaluation of the g-functions. It gives basic support for simulation using pygfunction. Alternatively, pygfunction can export the g-function to be called by another simulation program that relies on g-functions for the simulation of ground-source heat pump systems.

EXAMPLES

The functionalities of pygfunction are demonstrated through the examples presented in this section. In all cases, the examples use the bore field configuration presented in Figure 3. This bore field corresponds to a 8 × 5 configuration that has been adjusted to cover a non-rectangular land surface area. The total land surface area is \( A = 3938 \, \text{m}^2 \). The minimum spacing \( B_{min} = 7.5 \, \text{m} \) appears along the left-most column and the maximum spacing \( B_{max} = 19.9 \, \text{m} \) appears along the right-most column. The borehole dimensions, the pipe dimensions, the thermal properties of the materials and the physical properties of the fluid are presented in Table 1. This field is used to compare the different boundary conditions in the evaluation of the g-function, to analyse the effect of the irregular spacing on the g-function values and to predict the variation of fluid and ground temperatures.

**Table 1: Parameters used in g-function evaluation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Borehole dimensions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (L)</td>
<td>150</td>
<td>m</td>
</tr>
<tr>
<td>Buried depth (D)</td>
<td>3.75</td>
<td>m</td>
</tr>
<tr>
<td>Radius (( r_b ))</td>
<td>0.75</td>
<td>m</td>
</tr>
<tr>
<td><strong>Pipe dimensions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner radius (( r_{in} ))</td>
<td>0.015</td>
<td>m</td>
</tr>
<tr>
<td>Outer radius (( r_{out} ))</td>
<td>0.020</td>
<td>m</td>
</tr>
<tr>
<td>Shank spacing (( d_s ))</td>
<td>0.050</td>
<td>m</td>
</tr>
<tr>
<td>Pipe surface roughness (( \varepsilon ))</td>
<td>10^{-6}</td>
<td>m</td>
</tr>
<tr>
<td><strong>Thermal properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground thermal conductivity (( k_s ))</td>
<td>2.0</td>
<td>W/m-K</td>
</tr>
<tr>
<td>Ground thermal diffusivity (( \alpha_s ))</td>
<td>10^{-6}</td>
<td>m^2/s</td>
</tr>
<tr>
<td>Grout thermal conductivity (( k_g ))</td>
<td>1.0</td>
<td>W/m-K</td>
</tr>
<tr>
<td>Pipe thermal conductivity (( k_f ))</td>
<td>0.4</td>
<td>W/m-K</td>
</tr>
<tr>
<td><strong>Fluid physical properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass flow rate per borehole (( m_b ))</td>
<td>0.25</td>
<td>kg/s</td>
</tr>
<tr>
<td>Specific heat capacity (( c_f ))</td>
<td>4000</td>
<td>J/kg-K</td>
</tr>
<tr>
<td>Density (( \rho_f ))</td>
<td>1015</td>
<td>kg/m^3</td>
</tr>
<tr>
<td>Dynamic viscosity (( \mu_f ))</td>
<td>0.002</td>
<td>N/m-s</td>
</tr>
<tr>
<td>Thermal conductivity (( k_f ))</td>
<td>0.5</td>
<td>W/m-K</td>
</tr>
</tbody>
</table>

Comparison of boundary conditions

The g-functions of the bore field are evaluated for each of the boundary conditions of uniform heat extraction rate, uniform borehole wall temperature and equal inlet fluid...
temperature. The equal inlet fluid temperature boundary condition is evaluated for 2 different pipe configurations: a double U-tube borehole as presented in Figure 4, and a single U-tube borehole using only pipes 1 and 3 in Figure 4. The g-function curves are presented on Figure 5. The maximum and minimum g-function values are obtained for the uniform heat extraction rate and uniform borehole wall temperature boundary conditions, respectively. The difference between these two curves increases with the dimensionless time \( t/t_s \) and reaches 4.5% at \( t/t_s = 0.1 \) (\( \ln(t/t_s) = -2.3 \)). At the same time, the g-function values for the single U-tube and double U-tube boreholes are 1.2% and 0.9% greater than the uniform borehole wall temperature boundary condition, respectively. The double U-tube configuration is expected to have lower g-function values than the single U-tube configuration since the effective borehole thermal resistance is lower. The g-function obtained with the uniform borehole wall temperature boundary condition is compared to the g-function obtained with the numerical method of Eskilson (1988), which also uses a boundary condition of uniform borehole wall temperature. At \( \ln(t/t_s) = 3.6 \), the difference between the g-function with uniform borehole wall temperature and the numerical g-function is 0.02%.

In terms of calculation time, the g-function using the uniform heat extraction rate boundary condition is the fastest to evaluate, with a calculation time of 17.2 seconds. Each of the boundary conditions of uniform borehole wall temperature and equal inlet fluid temperature for single and double U-tube boreholes are slower to evaluate, with calculation times of 127 seconds in all three cases. The uniform heat extraction rate boundary condition should not be used as it can greatly overestimate the g-function values, especially at large values of time. When information on the pipe configuration is available, the equal inlet fluid temperature boundary condition should be used. Otherwise, the uniform borehole wall temperature boundary condition gives sufficient accuracy.

### Irregular bore field configuration

G-functions of regular bore fields are often used to predict temperature variations in irregular bore field, since simulation and design software rarely implement g-functions for irregular bore fields. Here, the g-function of the irregular bore field is compared to the g-function of a regular bore field of equivalent land surface area. Since the bore field in Figure 3 is dense, it is approximated by a rectangular field of 8 × 5 evenly spaced boreholes. The equivalent borehole spacing is then:

\[
B_{eq} = \sqrt{A/[(N_1 - 1)(N_2 - 1)]}
\]

where \( B_{eq} = 11.9 \) m is the equivalent borehole spacing, \( A = 3938 \) m² is the land surface area, and \( N_1 = 8 \) and \( N_2 = 5 \) are the numbers of columns and rows in the bore field, respectively. With this equivalent borehole spacing, a bore field of 8 × 5 evenly spaced boreholes covers the same land surface area as the irregular bore field shown in Figure 3.

The g-functions of the irregular field and of the equivalent field are presented on Figure 6 for a boundary condition of uniform temperature. It is shown that the g-function values of the equivalent field are close to that of the irregular field at large values of time. At \( t/t_s = 10 \) (\( \ln(t/t_s) = 2.3 \)), the equivalent field overestimates the g-function by 0.5%. However, at smaller values of time, the equivalent field is shown to underestimate the g-function. The maximum difference is found at \( \ln(t/t_s) = -3.7 \) where the g-function is underestimated by 2.4%. This difference is related to the change in the distribution of borehole spacings between the irregular and the equivalent bore fields. In the irregular bore field, some boreholes are closer together than in the equivalent spacing. Thermal interactions thus start sooner for the irregular bore field and the g-function values are greater at smaller values of time. The dimensionless time \( \ln(t/t_s) = -3.7 \) corresponds to a time of the order of 1 to 2 years for boreholes of lengths between \( L = 100 \) m and \( L = 150 \) m with a ground thermal diffusivity \( \alpha_g = 10^{-6} \) m²/s. This shows that approximating an irregular bore field configuration by a regular bore field configuration will have an impact on predicted temperatures in yearly simulations.
Simulation of fluid temperatures

Once known, the g-function of the bore field can be used to simulate the fluid and ground temperatures variation of a ground source heat pump system. Listing 4 presents the use of the load_aggregation module to calculate the fluid and ground temperatures. Listing 4 presumes that the g-function is already evaluated and that a U-tube model has already been defined for the boreholes in the field (i.e. from Listings 1, 2 and 3). The simulation uses a synthetic load profile (Bernier et al. 2004). The ground loads are balanced: the maximum heat extraction and injection rates are 177 kW and the total thermal energy extracted from and injected into the ground is 76000 kWh/year. Borehole wall and fluid temperatures during the 20th simulation year are shown on Figure 7. Figure 8 shows the fluid and borehole wall temperatures during the last 7 days of the 20th year. The calculated borehole wall temperatures are validated against the values calculated using an exact convolution method based on Fast Fourier Transforms (Marcotte and Pasquier 2008). The calculation times are 48.6 seconds for the evaluation of the g-function and 80.5 seconds for the simulation of fluid and ground temperatures.

CONCLUSION

An open-source Python toolbox, pygfunction, is presented. pygfunction allows the calculation of g-functions of irregular bore fields using different boundary conditions, including a boundary condition of equal inlet fluid temperature into the boreholes. This boundary condition relies on analytical steady-state models of the heat transfer inside the boreholes, valid for any number of arbitrarily positioned U-tubes. The calculation time using this boundary condition is equivalent to the calculation time for a uniform borehole wall temperature. The toolbox is hosted on github (Cimmino 2018a). In the future, the toolbox will be extended to allow tilted boreholes and to account for the effects of groundwater movement and inhomogeneous ground.
Figure 7: Simulation of fluid temperatures (20th year)

Figure 8: Simulation of fluid temperatures (last 7 days of 20th year)

ACKNOWLEDGEMENT

The author received a start-up subsidy from the Fonds de recherche du Québec – Nature et Technologie (FRQNT).

REFERENCES


