Short review of Borehole Heat Exchanger BHE thermal models implemented in Modelica

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Introduction

The main aim of this document is to compile the thermal models available in the open source Modelica library Buildings v.8.0.0 (University of California, 2021) to simulate Borehole Heat Exchangers BHE. Besides, it is further investigated whether these models are suited to model energy piles. The content of this document is expected to be used in the conference paper "Implementing ground-source heat pumps in novel district heating and cooling networks: A holistic modelling approach" whose abstract has been admitted for the European Geothermal Congress 2022.

Borehole Heat Exchanger BHE thermal models implemented in Modelica

The open source Modelica library Buildings v.8.0.0 (University of California, 2021), called "Buildings Library" hereon for brevity, contains two main BHE modules implemented in its Fluid/Geothermal package: the "Boreholes" model and the "Borefields" model.

The "Boreholes" model bases its temperature response g-function on the transient heat conduction in cylindrical coordinates for the spatial domain. The analytical formula of Hart & Couvillion (1986) for constant heat extraction is adapted to a non-constant heat flux. The borehole thermal resistance and capacity network inside the borehole is computed according to Bauer et al. (2011) and it only allows to simulate single-U pipe configurations. The model uses as inputs fluid temperature and mass flow rate.

On the other hand, the "Borefields" model bases its temperature response g-function on the hybrid model described in Picard & Helsen, (2014). Here, the long-term response model uses the spatial superposition of the finite line source FLS presented in Claesson & Javed (2011) to account for thermal interaction between boreholes.

The borehole thermal resistance Rb and capacity network inside the borehole is computed according to Bauer et al. (2011). The thermal resistance Rb can also be directly provided by the user. However, the main documentation provided does not seem to correspond with the input parameters requested. I.e., the borehole model appears to follow Section 3.4.2 (pp. 72-74) of Advances in Ground-Source Heat Pump Systems by Rees (2016), based on the empirical method from Paul (1996). It allows considering single U-tube, double U-tube in parallel and double U-tube in series configurations.

The "Borefields" model can consist of one or many boreholes. Each borehole can be positioned at an arbitrary location in the field using cartesian coordinates. E.g., a file with (x, y) positions can be imported. The model is limited to the simulation of borehole fields with boreholes connected in parallel. All boreholes have the same length, the same radius and are buried at the same depth below the ground surface. The model uses as inputs heat power rate q [kW] and mass flow rate.

The Buildings Library has, apart from the FLS (Claesson & Javed, 2011), more g-functions implemented, namely: the cylindrical heat source and the infinite line source, both from Carslaw & Jaeger (1959). Modelica allows to use the heat source model that most suits our problem.

Besides, the "Borefields" model uses a load aggregation technique to reduce the time required to calculate the borehole wall temperature changes resulting from heat injection or extraction. In this case, the method presented in Claesson & Javed (2012) is implemented.

Suitability of BHE models implemented in Modelica to simulate energy piles

The long-term thermal aspects of either borehole fields or energy pile foundations are governed by the axial effects and the thermal interaction between ground heat exchangers. Therefore, these can be considered by using, e.g., the FLS model together with spatial superposition, without the need to use tailored models for energy piles, in a similar manner to what Picard & Helsen (2014) presented.

However, the main aspect considered when modelling energy piles, which is not usually considered in BHE modelling, is the thermal inertia of the pile concrete, primarily, in the short term. According to Loveridge & Powrie (2013, 2014) including the transient temperature change in the concrete results in a reduction of the range of calculated fluid temperatures and, therefore, 10% more energy is available in the system, compared to steady state approaches. I.e., steady state approaches overestimate the range of temperature response. This is relevant for energy piles because their operational temperature range is tighter than that of BHEs: 2 °C to 30 °C and <0 °C to >50 °C for energy piles and BHEs, respectively.

In this sense, the “Borefields” model presented in the previous section can consider the effect of the thermal capacitance of the filling material placed in the boreholes (by activating the dynamics within the borehole model and treating the filling material as concrete). This attribute could be useful to model energy piles and this section further investigates whether the built-in models are suited for this. To assess this aspect, several short-term pile temperature response functions (g-functions) are plotted together in Figure 1. Table 1 provides the basis for reproducing Lower Bound and Upper Bound pile g-functions with the “Borefields” framework (Picard & Helsen, 2014). Besides, these other g-functions are shown, in a similar way as it was done in Loveridge & Powrie (2013): line source, solid cylinder source, pile g-functions generated with steady state heat transfer through the pile and semi-empirical precast pile g-function for 2U pipe configuration (LB) presented in Alberdi-Pagola (2018).

Table 1: Upper Bound (UB) and Lower Bound (LB) temperature responses as for the cases shown in Figure 1.

	Pile Diameter, $2r_b$ [m]	Number of Pipes, n	Concrete cover, c [mm]	Concrete thermal conductivity λ_c [W/m/K]	Concrete volumetric heat capacity ρ_{cp} [MJ/m^3/K]	Ground thermal conductivity λ_s [W/m/K]	Ground volumetric heat capacity ρ_{cp} [J/m^3/K]
Upper Bound UB	1.0	4	100	2	1.6	1	1.6
Lower Bound LB	1.0	2	400	1	1.6	2	1.6

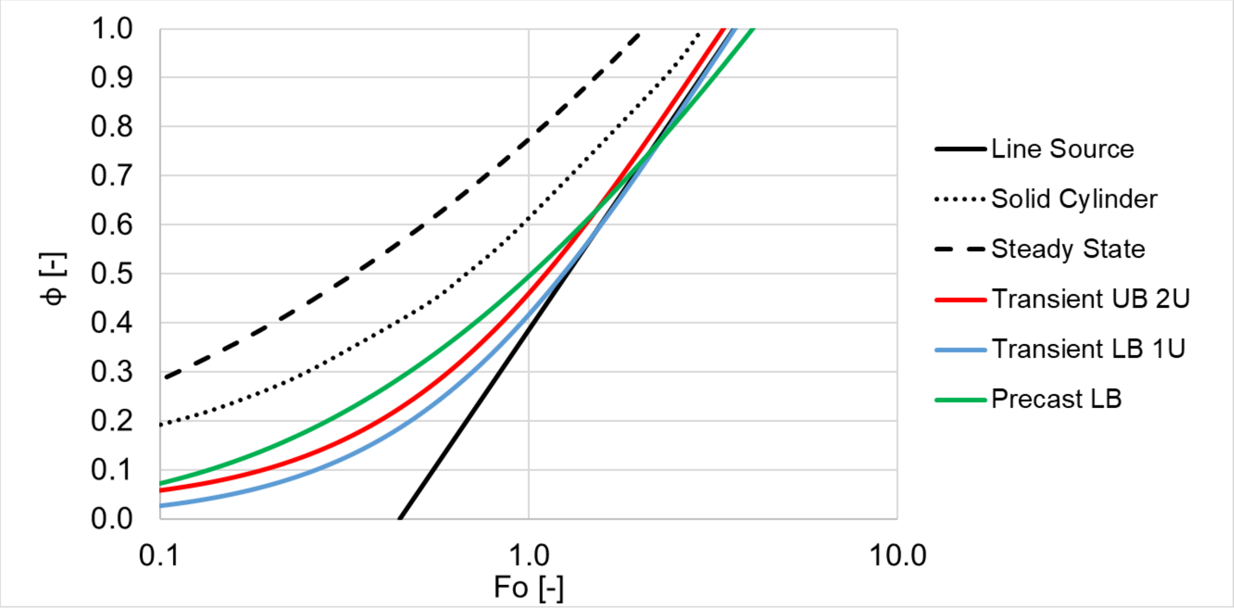

Figure 1: Range of short-term pile temperature response functions for the cases given in Table 1, based on the FLS model implemented in the Buildings Library in Modelica (Picard & Helsen, 2014) and on the semi-empirical precast pile g-function presented in Alberdi-Pagola (2018).

The curves shown in Figure 1 depend on the number and position of the geothermal pipes, the size of the pile and the relative properties of the pile concrete and the surrounding soil. The energy pile responses fall between two analytical solutions, as it was observed in Loveridge & Powrie (2013): the line source and the solid cylinder solution. The steady state pile g-function (dashed black line) gets close to the hollow cylinder heat source (not presented here), and it is considered not suited to model energy piles. Steady state approaches are, hence, more conservative. In any case, it can be concluded that the "Borefields" model can be used to model energy piles when the thermal dynamics of the filling material are considered.

On top of this, the fact that the "Borefields" package can accommodate arbitrary position of ground heat exchangers is an important attribute as piles do not always follow a regular grid.

There are, of course, some limitations to the "Borefields" model:

- Only single-U and double-U pipe configurations can be considered. Large energy piles (> 1.0 m in diameter) would, usually, accommodate mode pipes in their cross section. To consider the resulting decrease in the thermal resistance new models would have to be incorporated into Modelica, or external functions called.
- Only cylindrical piles can be considered. However, Figure 1 shows that the precast pile g-functions are not that far from the pile g-function generated with the "Borefields" model.

The "Borefields" package seems to offer a good option to model energy piles and their influence in the overall performance of the GSHP system.

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