Advanced Hybrid Model for Borefield Heat Exchanger Performance Evaluation, an Implementation in Modelica

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Abstract

Accurate and computationally efficient borefield models are important components in building energy simulation programs. They have not been implemented in Modelica so far. This paper describes the implementation of an innovative approach to model borefields with arbitrary configuration having both short-term (minutes) and long-term accuracy (decades) into Modelica. A step response is calculated using a combination of a short-term response model which takes into account the transient heat transfer in the heat carrier fluid, the grout and the immediately surrounding ground, and a long-term response model which calculates the boreholes interactions. Moreover, an aggregation method is implemented to speed up the calculations. Validation shows good results and very high computational efficiency.

Keywords: Borefield; short- and long-term; Modelica; Aggregation method;

1 Introduction

Building energy simulations have gained significant importance in the last decades resulting in several dynamic simulation platforms such as EnergyPlus [1] and TRNSYS [2]. Modelica might become the next generation tool for energy system simulations in buildings and communities as is the aim of the IEA EBC Annex 60 project. To achieve this goal, libraries are developed to simulate a wide variety of energy systems in buildings. Accurate and computationally efficient borefield models have not been implemented in Modelica so far, even though they play and will play an important role in recent and future buildings.

The open-source Modelica Buildings library developed by the Lawrens Berkeley National Laboratory (LBNL, US) is the only freely available library which has a U-tube single borehole model [18]. The borehole model is similar to the EWS model implemented in TRNSYS (type 451, [17]). The model solves the transient heat flux in the ground by discretizing the surrounding ground in several cylindrical layers up to a radius of 2 meters from the borehole center. The layer temperature at this outer radius is calculated using an approximation of the line-source theory together with superposition. This temperature is updated every week in order to avoid too intensive calculations. The heat carrier fluid (HCF) and the grout (i.e the filling material of the borehole) are simulated dynamically but their capacities are lumped. A triangle thermal resistance network is used to describe the heat transfer into the borehole heat exchanger (BHX) (i.e. from the HCF to the borehole wall). In the vertical direction, the borehole and the surrounding ground are divided into adiabatic horizontal layers. The model is not suited for multiple borehole simulation.

The E.ON Energy Research Center (Germany) also developed a single borehole model for single U-tube and coaxial type [11]. The pipe model is connected to an axially and radially discretized cylindrical ground model. A fixed temperature boundary condition is used for the ground model. The model does not take the dynamics of the grout into account and multiple borehole simulation is not possible.

Several models are implemented in TRNSYS. The Superposition Borehole Model (SBM), developed by Hellström, gives a detailed three-dimensional model for the transient thermal process in a borefield which has been implemented into TRNSYS [16]. The model can simulate single or multiple, vertical or inclined boreholes. The dynamics of the BHX is not taken into account and the computation time is very high. The Duct Heat Storage model (DST), developed by Hellström, calculates the transient thermal process for multiple borehole configurations, uniformly positioned in a cylindrical volume. The model does not take the dynamics of the BHX into account but it is fast and it calculates the interaction between the boreholes (it uses pre-computed g-functions obtained by the SBM). Its TRNSYS implementation (type 557) can be used together with a separate program called BORE to calculate the borehole thermal resistance depending on the flow rate and the temperature [16].

To the author's knowledge, no model has been implemented in building simulation programs so far, which (i) is able to simulate any arbitrary configuration of boreholes, (ii) allows coaxial, U-tube type or double U-tube type BHX, (iii) has short- and long-term accuracy for minute-based year-long simulations, and (iv), is numerically efficient. The aim of this paper is to propose a new model, implemented in Modelica, which meets the above mentioned requirements. No ground water flow is taken into account.

Section 2 describes the model and Section 3 handles the computation of the response function and an aggregation method to speed up the computation. Finally Section 4 and 5 validate the model and give an example including a CPU-time comparison with the existing borehole model of the Buildings library. The main conclusions are summarized in section 6.

2 Bore field model

The proposed model is a so-called hybrid step-response-model (HSRM). This type of model uses the borefield's temperature response to a step load input. An arbitrary load can always be approximated by a superposition of step loads. The borefield's response to the load is then calculated by superposition of the step-responses using the linearity property of the heat diffusion equation. The most famous example of HSRM for borefields is probably the *g-function* of Eskilson [9]. The major challenge of this approach is to obtain a HSRM which is valid for both minute-based and year-based simulations. To tackle this problem, a HSRM has been implemented. A long-term response model (LTM) is implemented in order to take into account the interaction between the boreholes and the ground temperature evolution of the surrounding ground. A short-term response model is implemented in order to describe the transient heat flux in the BHX to the surrounding ground. The two models are merged into one HSRM in order to achieve both short- and long-term accuracy.

In this section, the long-term and the short-term response models are described.

2.1 Long-term response model

The long-term temperature response of the borefield is calculated using the model of Javed and Claesson [12]. This model is the current state-of-the-art and it proposes a compact expression to calculate the mean temperature of the borehole wall (average over the different boreholes of the borefield and over the length of each borehole).

The model is based on the spatial superposition of finite line-sources of equal length, each representing one borehole of the borefield. The finite line-source is calculated from the convolution of a point source of constant power along the depth of the borefield. The mirror of the solution at z=0 is subtracted to ensure that no heat transfer occurs between the ground and the ambient air. After several mathematical manipulations to simplify the calculation, Javed and Claesson obtain the following compact expression for the mean borehole wall temperature:

$$\bar{T}_{mbhw}(t) = \frac{q_0}{4\pi\lambda} \int_{1/\sqrt{4\alpha t}}^{\infty} \left(\sum_{i=1}^{N} \sum_{j=1}^{N} e^{-r_{i,j}^2 s^2} \right) \frac{\mathrm{I_{ls}}(Hs)}{Hs^2} ds \tag{1}$$

where q_0 is the heat flux per meter length, λ is the ground heat conductivity, α is the ground heat diffusivity ($\lambda/(\rho c_p)$), N is the number of boreholes and H is the depth of the borefield. $\mathrm{I_{ls}}$ is defined by Eq. 2-3 and $r_{i,j}$ by Eq. 4:

$$\mathrm{I_{ls}}(h) = 4\ \mathrm{ierf}(h) - \mathrm{ierf}(2h) \tag{2}$$

$$\mathrm{ierf}(x) = \int_0^x \mathrm{erf}(u) du = x\ \mathrm{erf}(x) - \frac{1}{\sqrt{\pi}}(1 - e^{-x^2}) \tag{3}$$

where *erf* is the error function,

$$r_{i,j} = \begin{cases} r_b & \text{if } i = i \\ \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} & \text{if } i \neq j \end{cases} \tag{4}$$

where r_b is the BHX radius and (x_i, y_i) are the spatial coordinates of the center of each borehole from an arbitrary reference point.

Eq. 1 is valid for $t > \frac{5r_b^2}{\alpha}$, i.e after the transient part of the heat transfer through the BHX is completed [9]. The model also makes an important approximation by assuming uniform heat flux for all boreholes. The (long-term) accuracy of the model decreases for long simulation times for configurations with non-uniform heat fluxes, e.g. densely packed rectangular grid. For

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more information about this approximation, we refer to Malayappan and Spitler [14]. Finally, the analytical solution assumes a uniform initial ground temperature equal to its average value.

Eq. 1 is implemented as a Modelica function. The integral of Eq. 1 and Eq. 2 are evaluated using the adaptive Lobatto rule implemented in the `Math.Nonlinear` of the Modelica Standard Library. The error function, however, is not implemented in Modelica. The publicly available c-code of Okumura [15] is compiled using the ability of Modelica to call external code.

2.2 Short-term response model

The short-term response model (STM) should be able to calculate the transient thermal response of the HCF, the grout and the surrounding ground accurately for time periods ranging from minutes to $t = \frac{5r_b^2}{\alpha}$ (typically < 200 hours). The interaction between the boreholes for these short times can be neglected, therefore a single borehole model is used.

The implemented STM is able to simulate boreholes with a co-axial, single-U-tube or double-U-tubes configuration. The model can compute the step response of a single borehole or that of a set of boreholes in series. Vertical discretization is also possible in case of an initial ground temperature gradient but no vertical heat transfer is computed except through the HCF. The main STM elements are the HCF, the pipes, the grout, the surrounding ground and the undisturbed ground temperature. Fig. 1 illustrates the model structure for a set of single-U-tube boreholes in series.

The dynamics of the HCF is calculated using the `Fluid` base classes of the open-source Buildings library [18] (`PartialFourPortInterface`, `PartialTwoPortInterface`, `TwoPortFlowResistanceParameters`, `LumpedVolumeDeclarations`) and the `Media` library from the Modelica Standard Library. The convection resistance between the HCF and the pipe is calculated by the correlation for smooth pipe in turbulent flow regime of Dittus-Boelter in the case of single- and double-U-tubes. For the circular-tube annulus, the correlation of Petuhkov and Roizen is used. For more information about the correlations we refer to Hellström [10].

The transient heat transfer from the internal wall of the pipes to the borehole wall is calculated using the thermal resistive-capacitive models (TRCM) derived by Bauer et al. [3]. These authors propose to extend the resistance model of Hellström for heat transfer in the BHX (see [10]) to a dynamic model by adding capacities to it. For the case of a single U-tube, they also propose an empirical formula to approximate the multipole method of Bennet et al., using heat conduction shape coefficients and correction terms depending on the shank spacing divided by the borehole diameter. The correction terms are derived from an extensive set of simulations. The method is developed for coaxial, single U-tube and double U-tube types of borehole. The position of the capacities is calculated to be at the area center of the borehole with an equivalent single pipe.

Finally, the heat transfer from the borehole wall to the surrounding ground is calculated by discretizing the ground using a TRCM. The mesh is generated according to Eskilson's guidelines [9]:

$$\begin{aligned}\Delta r &= \left[\Delta r_{min}, \Delta r_{min}, \Delta r_{min}, \beta \Delta r_{min}, \beta^2 \Delta r_{min}, \cdots\right] \ , \\ \Delta r_{min} &= \min(\sqrt{\alpha \Delta t_{min}}, H/5) \ ,\end{aligned}$$

with α the diffusivity of the ground, H the depth of the borehole, Δt_{min} the minimum resolution time and Δr the size of the cell. The discretization has been tested with the analytical Cylindrical Source Model developed by Carslaw and Jaeger [7] and it shows very good agreement when the mesh is chosen fine enough. The width of the ground layer is by default equal to three meters but it can be adapted. The heat port at the external side of the layer is connected to a constant prescribed temperature equal to the initial undisturbed ground temperature. The heat flux at the external side of the ground layer is indeed very low from short simulation time.

3 Computation of the response function and aggregation method

The STM gives an accurate step response of the borefield as long as the diffusion length of the thermal process is small compared to the radius of its ground layer model or to the distance between the boreholes. The LTM is able to correctly compute the step response of the ground for a long time horizon as well as the interaction between the boreholes. It does not calculate, however, the borehole thermal resistance and its transient behaviour, contrary to the STM. The full response function is then obtained by lifting the LTM response to the STM response in the time interval where both models are still valid as shown in Fig. 2. As Javed mentions in his work [12], this interval is quite large (default value in model = 200 hours). Physically,

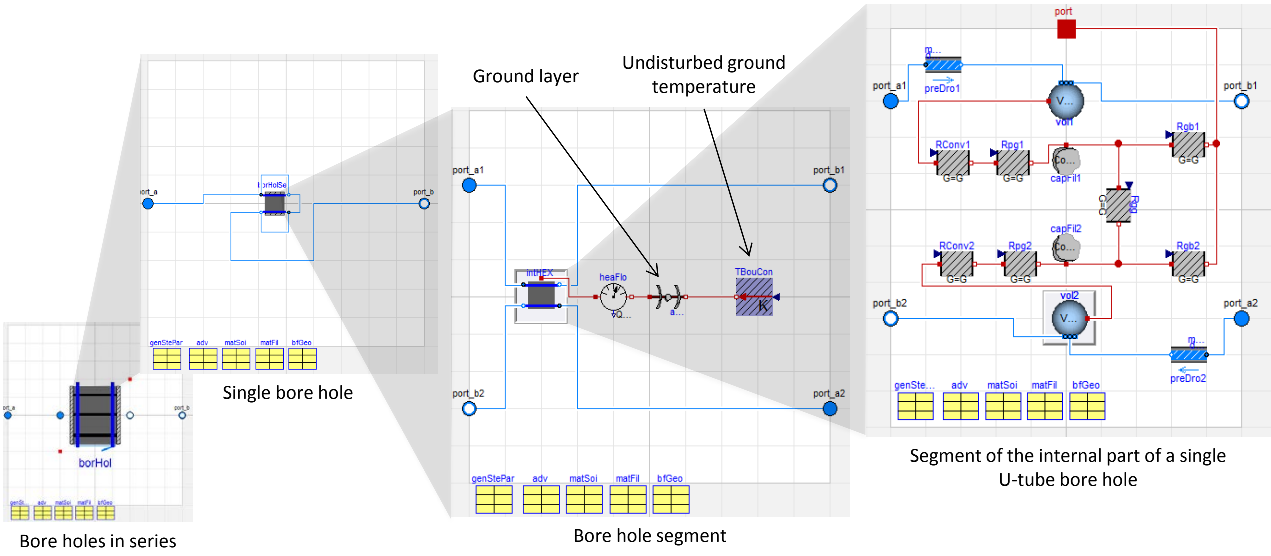

Figure 1: Implementation of the short-term model for boreholes in series in Modelica.

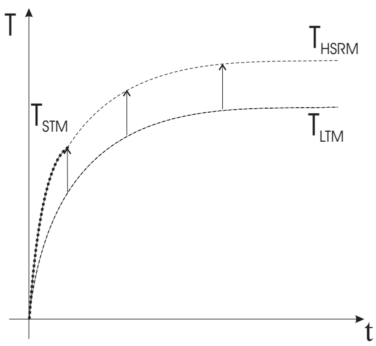

Figure 2: Combination of the long-term temperature step response (T_{LTM}) with the short-term temperature step response (T_{STM}) to compose the global temperature step response (T_{HSRM}).

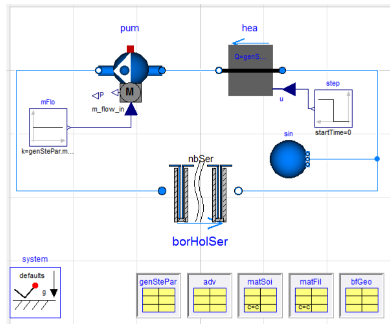

Figure 3: Model for the short-term temperature step response. The boreholes in series (*borHolSer*) are connected to a pump (*pum*) and to an ideal heater (*hea*). All the parameter values are stored in the records (bottom of the figure).

this interval begins when the transient behaviour of the BHX is over and it lasts until the interactions of the boreholes start to appear. The combination of both STM and LTM gives an accurate response function for both short- and long-term.

The response-function can be calculated at the start of each simulation or it can be priorly saved with a sample time equal to time resolution of the model. Until now, only the response of the STM is priorly saved in the implemented model in order to increase the computational speed but to avoid large files containing the full response function. The STM is connected to a pump and a prescribed heater/cooler from the `Buildings` library (see Fig. 3). A script-function automates the simulation of the STM and it writes the sampling values of its temperature response in the `Data` package of the model as .txt file. The file is read at the initialization of the model in order to build the full response function of the HSRM.

As described above, g-functions and most of the analytical models give only a step response solution for the borefield. In order to model arbitrary input signals, the inputs need to be represented by a sum of time-shifted step signals and their responses should be superposed.

For minute-based multi-year simulations where the individual step response of each input step should be summed, this approach leads to enormous calculations. This problem is solved by using an aggregation method. The following paragraphs describe the technique of Claessons and Javed [12]. The notation has been adapted to gain clarity.

Assume that the discrete load input to the borefield is Q and the HCF temperature is T_f. Q and T_f can be written as:

$$Q_{\nu}^{(n)} := \begin{cases} Q\left[(n+1-\nu)h\right], & \text{if } \nu \leq n. \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

$$T_f(nh) - T_f(0) = \sum_{\nu=1}^{\nu_{\max}} \frac{Q_{\nu}^{(n)}}{Q_{\text{step}}} \left[T_{f,\text{step}}(\nu h) - T_{f,\text{step}}(\nu h - h)\right] \tag{6}$$

with $\nu_{\max} \geq n$, h the discrete time-step, Q the discrete load and $T_{f,\text{step}}$ the response function from HSRM with step load Q_{step}. Notice that the model assumes a uniform temperature at time 0.

The idea behind this aggregation is the following: the HCF temperature difference of the borehole system (from an initial steady state) at $t = nh$ depends on the nh load pulses which have been applied to the borehole system from $t = 0$ to nh. However, the influence of the pulses on the HCF temperature decreases the further they are from the observation time nh. If the pulses happened long before the observation time, the transient behaviour of the BHX has faded out, and only the net energy injection of extraction of the pulse is important. This net energy injection or extraction will indeed increase or decrease the global temperature of the borefield. An accurate profile of the load, far away from the observation time, is therefore not necessary. On the contrary, the load profile at times close to the observation time is important because they still influence the transient behaviour of the borefield and immediate surrounding ground.

Claesson and Javed proposed an aggregation algorithm grouping (i.e. taking the average of) the load pulses and their coefficients into cells of exponentially increasing size. The cells are themselves grouped into q levels. Each level has a given number of cells $p_{\max}$ and each cell of a same level contains the same amount of load pulses R_q. Javed and Claesson propose to double the size of the cells at each level, in order to have the same number of cells in each level and finally in order to choose this number of cells per level according to the desired accuracy (a higher number of cells per level gives a more detailed load profile but penalizes the computational efficiency).

Eq. 6 is now rewritten to implement the aggregation method. Notice that the temperature difference of the HCF between two time steps in Eq. 6 divided by the amplitude of the step load Q_{step} can be considered as the transient thermal resistance of the borehole for that particular time. Let us define the transient thermal resistance R_ν and the dimensionless factor κ_ν as:

$$R_\nu = \frac{T_{f,\text{step}}(\nu h) - T_{f,\text{step}}(\nu h - h)}{Q_{\text{step}}} \tag{7}$$

$$\kappa_\nu = \frac{T_{f,\text{step}}(\nu h) - T_{f,\text{step}}(\nu h - h)}{T_{f,\text{step}}(\infty)} = \frac{R_\nu}{R_{ss}}. \tag{8}$$

Eq. 6 can now be rewritten as:

$$T_f(nh) - T_f(0) = R_{ss} \sum_{\nu=1}^{\nu_{\max}} Q_{\nu}^{(n)} \kappa_\nu \,. \tag{9}$$

with R_{ss} the steady state thermal resistance.

As explained above, the aggregation is consisting of $q_{\max}$ levels, each composed of $p_{\max}$ cells which have a level-dependent width R_q defined as:

$$R_q := 2^{q-1} \quad \text{for } q = 1, ..., q_{\max} \,. \tag{10}$$

The number of pulses covered by the aggregation is then:

$$\nu_{\max} := \sum_{q=1}^{q_{\max}} R_q\, p_{\max} \quad \geq n_{\max} \,. \tag{11}$$

Define $\nu_{q,p}$ as the number of pulses covered from cell 1 at level 1 till (including) cell p at level q:

$$\nu_{q,p} := p\, R_q + \sum_{i=1}^{q-1} R_i\, p_{\max} \,. \tag{12}$$

Define the function $\nu(q, p, r)$ numbering each pulse, starting from pulse 1 in cell 1 at level 1:

$$\nu(q,p,r) := \nu_{q,p} - R_q + r \quad \text{for } \begin{array}{l} q = 1, \ldots, q_{\max} \,, \\ p = 1, \ldots, p_{\max} \,, \\ r = 1, \ldots, R_q \,. \end{array}$$

These different definitions are illustrated in Fig.4.

Using these definitions, Eq. 9 can be rewritten as:

$$T_f(nh) - T_f(0) = R_{ss} \sum_{q=1}^{q_{\max}} \sum_{p=1}^{p_{\max}} \sum_{r=1}^{R_q} Q_{\nu(q,p,r)}^{(n)} \kappa_{\nu(q,p,r)} \tag{13}$$

Now we apply the aggregation technique by approximating the last sum of Eq. 13 by

$$\sum_{r=1}^{R_q} Q_{\nu(q,p,r)}^{(n)} \kappa_\nu \approx \left[\frac{\sum_{r=1}^{R_q} Q_\nu^{(n)}}{R_q}\right] \sum_{r=1}^{R_q} \kappa_{\nu(q,p,r)} := \bar{Q}_{\nu(q,p)}^{(n)} \bar{\kappa}_{\nu(q,p)} \tag{14}$$

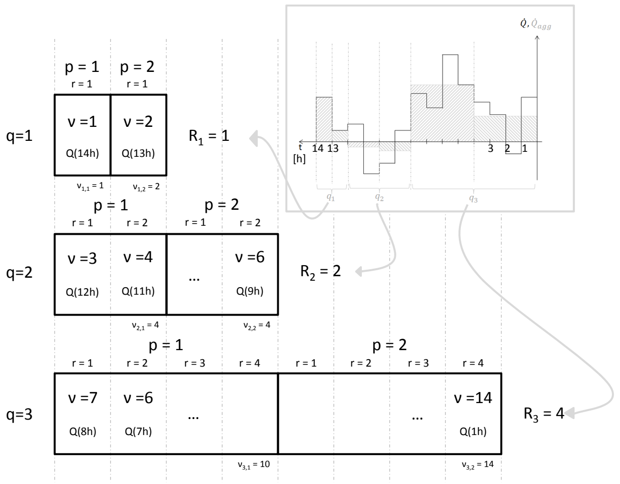

Figure 4: Illustration of the aggregation method for a load of 14 hours with time steps (pulses) of one hour. The number of levels is three and each level has two cells. The size of the cells is doubled at each level.

Finally the aggregation of Eq. 9 gives:

$$T_f(nh) - T_f(0) \approx R_{ss} \sum_{q=1}^{q_{\max}} \sum_{p=1}^{p_{\max}} \bar{Q}^{(n)}_{v(q,p)} \bar{\kappa}_{v(q,p)} \,. \qquad (15)$$

The term $\bar{\kappa}_{v(q,p)}$ is a matrix with the transient thermal resistance of each cell of the aggregation and it is independent of the load. This matrix is currently calculated at the initialization of each simulation. For repetitive simulations using the model and the same simulation length, the matrix can be priorly calculated and saved to gain significant calculation time. The term $\bar{Q}^{(n)}_{v(q,p)}$ is a vector with a length equal to the number of aggregation cells and which is composed of the aggregated past load pulses. At each new discrete simulation time, a new load pulse needs to be added and the previous pulses need to be shifted in the $\bar{Q}^{(n)}_{v(q,p)}$ vector. This means re-calculating the whole vector. Claesson and Javed developed a method which avoids this time consuming re-calculation by updating instead the load vector from the previous time step. The method is based on the shift of each cell to the next one and it has been applied to our model. An error, however, is introduced due to mixing in the cells. Claesson and Javed concluded after a detailed study that the error can be neglected. For example, in case of a simulation of 20 years using the aggregation method with each level having 5 cells, the error compared to the non-aggregated solution is lower then 0.1 K (for more information about the method and accuracy, see Claesson and Javed [8]).

Note that the left-hand term of Eq. 15 is only an approximation of its right-hand term due to the approximation made in Eq. 14. The error, however, is negligible if the number of cells is sufficiently high. By default, the number of cells by level is five and the size of the levels increase exponentially with base two.

4 Model validation

The STM and the LTM have been verified by their respective developers. To avoid coding error and to check and generalize the validity of the model, the model verification has been extended.

The STM is compared to the widely used sandbox experiment of Beier et al. [5]. These authors have carefully performed a thermal response test using a U-tube BHX. The U-tube is grouted into an aluminium pipe of 18 meters long which is placed into a box filled with homogeneous sand. An electrical heater injects a constant heat rate to the HCF and a pump insures a constant flow rate. All ground and grout properties are presented in the paper, except the heat capacities. The ground capacity has been estimated by Beier using a best fit method ($c_v = 3.2MJ/m^3K$) [4]. For the grout a heat capacity of $4MJ/m^3K$ is used. The HCF temperature is measured at the in- and outlet as well as the BHX wall and sand temperatures at various depths. It should be noted that the aluminium pipe around the grout acts as a thermal fin which reduces the borehole thermal resistance by evening out its wall temperature. The HCF temperature should therefore be lower for the experiment than for the models which do not take this fin effect into account (see Lamarche 2010 [13]). Fig. 5 compares the average of the in and outlet temperatures of the HCF for the case of the experiment, the Buildings model, TRNSYS model (type 557a, DST) and the implemented HSRM. The Buildings model dynamics is clearly to slow. This is due to the position of the lumped capacity of the grout, as illustrated by Bauer et al [3]. In the Buildings model, the grout capacities are positioned at the pipe wall instead of the area center of each grout zone. Adapting the capacity location (which requires also the adaptation of the resistances), the problem is solved (*Buildings adapted*). TRNSYS DST model and HSRM give similar results. DST, however, does not incorporate the short-term thermal dynamics of the fluid, contrary to the new model HSRM.

The LTM is verified using the well known g-function developed by Eskilson and the infinite cylindrical heat source (CHS) solution for different configurations (the data are taken from the paper of Bertag-

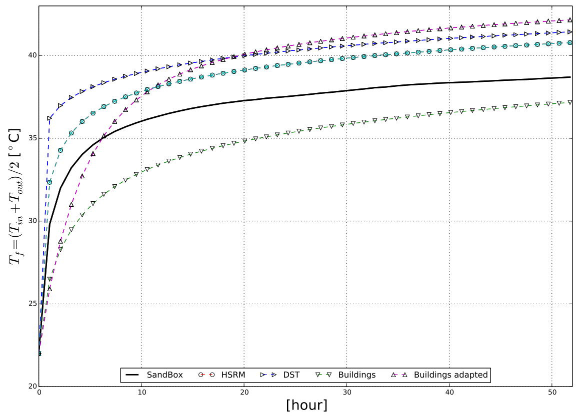

Figure 5: Comparison between the heat carrier fluid temperature from the sandbox experiment ([5]), the borehole model from the Buildings library and its adapted version, type 557a of TRNSYS (DST) and the new hybrid model (*HSRM*).

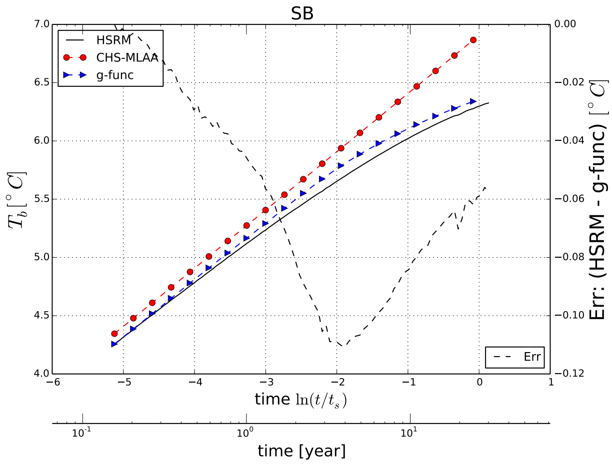

Figure 6: Average temperature step response of the borehole wall of a single borehole calculated by the g-function (*g-func*), the infinite cylindrical source with aggregation method (*CHS-MLAA*) and the new hybrid model (*HSRM*).

nolio [6]). Fig. 6 illustrates the case of a 110 meter deep single borehole. The error of the implemented model compared to the g-function never exceeds 0.11 K during the 25 year-long simulation. The difference is caused by the so-called end effect of the borehole because the analytical solution uses a finite line-source approximation whereas the Eskilson finite volume model is three-dimensional (boundary difference at the foot of each borehole). The CHS model is clearly unable to model the end effect. Fig. 7 illustrates the case of a borefield with a square 8x8 configuration, respectively. The length of the boreholes is 110 meters and the relative distance between the boreholes to length ratio equals 0.05. Due to the very compact configuration, a large error appears, as Malayappan and Spitler warned for [14]. The error comes from the assumption that each borehole injects or extracts the same amount of heat, regardless of its relative position in the borefield. In reality, the boreholes at the edge of the borefield will inject/extract more than the center ones and as a consequence, the average borefield temperature will be lower. The end effect error is negligible compared to the large error ($>$ 7K after 25 years for this case) introduced by the homogeneous heat source approximation. However, if the borefield is dissipative enough, the model shows very good results (e.g. see Fig. 8 for a line configuration of eight boreholes). For simulation with yearly thermal ground balance (amount of injected heat = amount of extracted heat), the configuration error is partly counteracted and it will not cause significant accuracy issues.

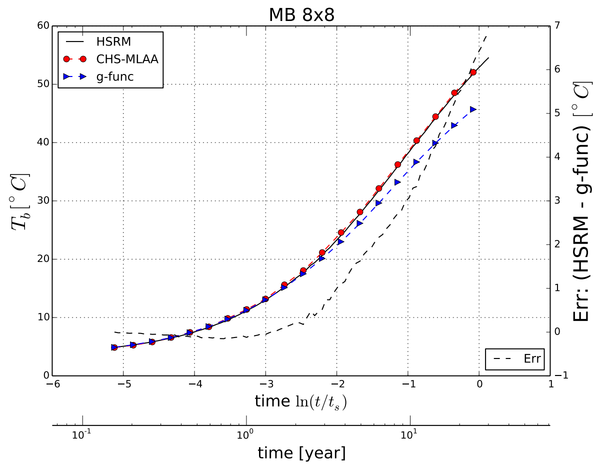

Figure 7: Average temperature step response of the borehole walls of a borefield with 64 boreholes in filled square configuration (B/H=0.05) calculated by the g-function (*g-func*), the infinite cylindrical source with aggregation method (*CHS-MLAA*) and the new hybrid model (*HSRM*).

5 Example

This section describes an example of a borefield subjected to a varying non-symmetric load with a time-step of 4 hours proposed by Bernier et al [6]. The CPU and the fluid temperature of the Buildings model and those of the HSRM model are compared for a simulation of one year in the case of a single borehole and the case of three boreholes in series (Fig. 11). The Build-

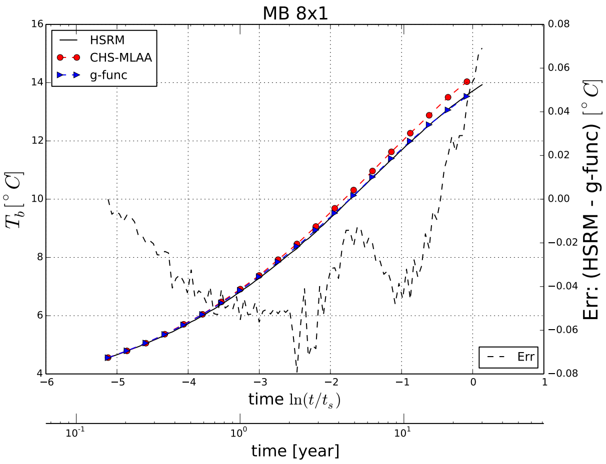

Figure 8: Average temperature step response of the borehole walls of a borefield with 8 boreholes in line configuration (B/H=0.05) calculated by the g-function (*g-func*), the infinite cylindrical source with aggregation method (*CHS-MLAA*) and the new hybrid model (*HSRM*).

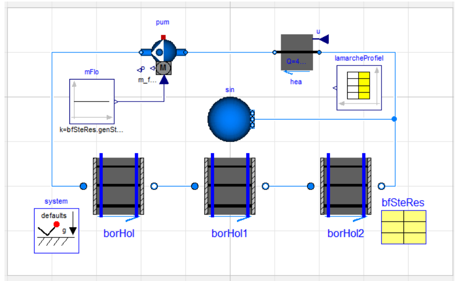

Figure 9: Model of three boreholes in series with a variable heat load (described by Bernier et al. [6]) and a constant mass flow rate, using components of the Buildings library.

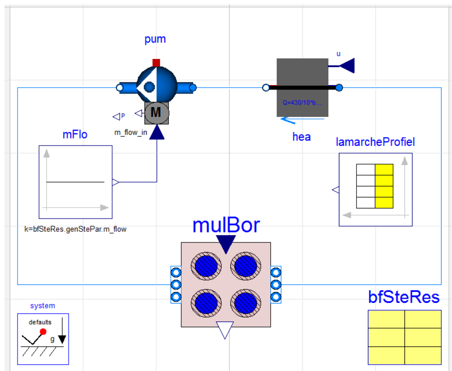

Figure 10: Model of three boreholes in series with a variable heat load (described by Bernier et al. [6]) and a constant mass flow rate, using the new borefield (*multBor*) model and components of the Buildings library.

ings model is composed of the Buildings component `Boreholes.UTube`, an ideal heater and a pump (see Fig. 9 for the case of three boreholes in series). The HSRM model uses the same setup but the Building boreholes are replaced by the HSRM (Fig. 10). A step response of 200 hours is calculated with the STM prior to the simulation, in order to calculate the short term part of the response function. The interaction between the boreholes is taken into account by the HSRM but not by the Buildings model.

As seen above, the Buildings model underestimates the borehole resistance which is also visible in Fig. 11 where the fluctuations of HCF temperature of the Buildings model have a smaller amplitude than those of the HSRM model.

The analysis of the CPU times illustrates very clearly the difference between the models. In the case of a single borehole, the HSRM model is about twelve times faster than the Buildings model. The HSRM has a longer initialization time due to the calculation of the aggregation matrix, but it calculates the temperature response very fast. In the case of three boreholes in series, the HSRM is about 60 times faster. The initialization time is longer than for a single borehole because the superposition of the temperature field of the boreholes needs to be calculated. However, once the aggregation matrix is calculated, the calculation time is the same for any configuration. This is not the case for the Buildings model.

6 Conclusion

A new hybrid model for borefields with arbitrary configuration having both short-term (minutes) and long-term accuracy (decades) has been successfully developed and implemented in Modelica. The model has been validated for both short- and long-term. Thanks to its aggregation method, the implemented model is about twelve times faster than the borehole model of the Buildings library for the case of a single borehole and about 60 times faster for the case of three boreholes in series. The long-term accuracy of the model decreases for compact borefield configuration. This can be solved by plugging a g-function in the model instead of calculating the temperature step response.

7 Acknowledgment

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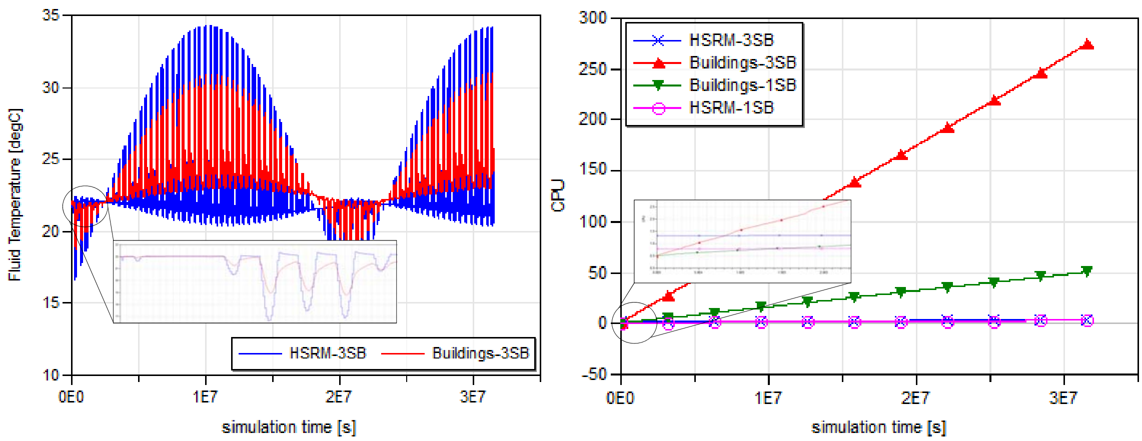

Figure 11: Left: CPU comparison between the new model (*HSRM*) and the model form the Buildings library (*Buildings*) for a single borehole (*1SB*) and for three boreholes in serie (*3BH*). Right: heat carrier temperature for *HSRM-3BH* and *Buildings-3BH*.

SMART GEOTHERM focusing on integration of thermal energy storage and thermal inertia in geothermal concepts for smart heating and cooling of (medium) large buildings. Moreover this study is part of the development work performed within IEA-ECB-Annex 60 on new generation computational tools for buildings and community energy systems based on the Modelica and Functional Mockup Interface standards.

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