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## A New Borefield Dymola Model Accounting for Groundwater Flow and Complex Borefield Geometries

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### ABSTRACT

In order to support the development of shallow geothermal energy and geothermal energy storage, accurate modelling of ground heat transfer is key. This is particularly true for borehole heat transfer, where the dynamical response of the borehole can greatly affect the overall performance of the surface energy system. Project ANR Sunstone, funded by the French National Agency for Research, aim to optimise the integration of solar heat production and geothermal energy storage, with a practical application on the district heating network of Chateaubriant, Brittany. In this context, the French national survey, BRGM, developed a new borefield Dymola model to contribute to the accuracy of borehole heat transfer modelling. The new borefield model allows considering groundwater flow in the borefield, and heat loss at the surface. It simplifies the declaration of borefield configuration, and allows choosing between rectangular shape on a square base, and hexagonal shape on a hexagonal base. The dynamic heat transfer occurring in a borefield is a complex dynamic process, with time scales involved varying by several order of magnitudes, from the minutes to several decades. The first section of this paper reports the development of new g-functions describing the heat transfer in the borehole, while the second section is focused on its practical implementation in Modelica.

## 1. BOREFIELD HEAT TRANSFER MODELLING

### 1.1 Borefield modelling approaches

Heat transfer in the borefield can be split into three main domains of interest. Firstly, the transfer inside the borehole, secondly, the transfer in the ground locally, around each borehole taken individually, and thirdly the thermal interactions between the boreholes inside the borefield at the global level.

Leaving apart the fully discretized models, the transient processes inside the borehole are modelled via an equivalent Thermal Resistance Model (TRM) or Thermal Resistance and Capacity Model (TRCM) (Bauer et al. 2011), depending on the characteristic

time focus of the developed model. TRM is used to simplify the modelling of the short-term behaviour and focus on the long-term processes, while TRCM take into account the influence of the grout thermal capacity and its ability to model the short-term heat transfer, at the expense of the computation time.

The local heat transfer in the ground can be modelled by a discretization of the domain and a corresponding thermal resistance and capacity model. Another approach has been introduced by Eskilson (1987), using a so-called g-function representing the step response of the ground to a constant heat source. The temperature of the ground can be expressed as follows:

$$T - T_0 = \frac{q_l}{\lambda_g} \cdot g \quad [1]$$

Where  $T_0$  is the initial temperature of the ground,  $q_l$  is the constant linear heat input in the ground, and  $\lambda_g$  the thermal conductivity of the ground. The step response  $g$  can have different expression depending on the geometry of the considered heat source. The simplest one is an Infinite Line Source (ILS) exchanging a constant linear heat flux  $q_l$  with the ground. However, the ILS model is suitable only for intermediate time. For short-term behaviour modelling close to the borehole, where the cylindrical nature of the source must be taken into consideration, the Infinite Cylindrical Source (ICS) can be used, and for long-term and long-distance behaviour where the finite nature of the borehole has an impact on the results, the Finite Line Source (FLS) is more suitable. A comprehensive comparison of these basic g-functions and their respective validity domain can be found in Philippe, Bernier, and Marchio (2009).

A wide variety of g-functions has been developed in order to take into account other geometries or boundary conditions, including groundwater flow and boundary condition at the ground surface (Conti 2016). The g-functions are evaluated before any dynamical modelling, and aggregation methods have been developed in order to use this step-response in the case of varying heat flux input between the borehole and the ground (Laferrère et al. 2020).

Some g-functions have an analytic expression, but as the modelling hypothesis become more and more general, the difficulty of finding such an expression becomes important.

At the global level, g-functions can also be used to compute the thermal interactions between boreholes. Another approach, generally implemented when the Borefield is used as a Borehole Thermal Energy Storage (BTES), consists of a discretization of the ground inside the storage, and the computation of an average ground temperature for each sub-domain, based on a local modelling of a borehole heat transfer and the interaction with the adjacent sub-domain. This approach proceeds by a wide approximation of the heat transfer processes in the ground but can be very timesaving and sufficiently precise if carefully parameterized. Furthermore, it allows the calculation of the mean temperature of the borefield ground, which is a valuable information for the control of the charge and discharge cycles of the borefield when taken as a heat storage medium.

### 1.2 Borefield modelling in Modelica language

The Modelica language is particularly efficient for complex equation based multi-physics modelling and simulation. It supports acausal connection and object-oriented construction of components and is therefore adapted for complex energy systems simulation such as the ground source heat pump dynamic modelling and borefield thermal performances optimisation.

Two borefield models have already been implemented in the Modelica language. The first and more widely used is the Hybrid Step Response Model (HSRM) developed by Picard and Helsen (2014), and included in the IBPSA and BUILDINGS model libraries. It uses a TRCM model for short-time accuracy, and an asymptotic matching between ICS and FLS g-functions for the local heat transfer in the ground (Li et al. 2014), allowing the resulting g-function to be accurate at both short-term and long-term delay. Interactions between boreholes are calculated using only the FLS method, since the boreholes are separated by several meters. An aggregation method is used to evaluate varying heat flux in a timesaving way, but the calculation of the g-function step response during the initialisation can be time consuming for large borefield.

Another model is the MOBTES library developed by Formhals et al. (2020). Its main difference is the global level which is based on the discretisation approach in the same way that the Duct Ground Storage model (DST) implemented in the dynamic modelling software TRNSYS and developed by Pahud and Hellström (1996).

These two models do not take into account the influence of groundwater flow. Formhals et al. (2020) justify this omission by the fact that BTES are generally installed in areas where there is no groundwater flow, since its impact is largely negative on the BTES thermal performances. That is indeed true, but the MOBTES

model is therefore not capable of modelling the actual impact of groundwater flow and considering possible mitigation actions. There are also cases where the borefield is not considered as a thermal energy storage system but rather as a heating and cooling system connected to Heat Pump, that can be installed in areas where groundwater flow is present. It is therefore important to be able to consider the effect on the borefield thermal performance.

It is possible to analytically derive a model of Moving Finite Line Source (MFLS) or Moving Infinite Line Source (MILS) from the FLS and ILS models respectively. It is however impossible to do so with a Moving Infinite Cylindrical Source (MICS) from the ICS model. Conti, Testi, and Grassi (2018) perform a numerical study based on the same assumptions than the MICS and give g-functions approximation for the temperature difference from the initial temperature at the borehole surface for discrete values of Peclet number. However, discrete g-functions do not allow for accurate representation of the temperature step response over the entire spectrum of groundwater velocities, and the MICS model is accurate for short-term modelling only since the influence of the finite length of the borehole can have major impact on the step response for long-term modelling.

### 1.3 Numerical calculation of a Moving Finite Cylindrical Heat Source model

The Finite Element based simulation software COMSOL Multiphysics v4.2a was used to evaluate the temperature step response at the borehole wall of a finite cylindrical heat source with groundwater flow and mixed boundary condition at the surface (MFCSm). The characteristic length of the problem is the borehole radius  $r_b$ . The Fourier number, the non-dimensional borehole depth, the Peclet number and the Biot number between the convective heat transfer coefficient  $h$  at the surface and the ground conductivity  $\lambda_g$  are defined as follows:

$$Fo = \frac{\alpha_{eq} t}{r_b} \quad [2]$$

$$H^* = \frac{H}{r_b} \quad [3]$$

$$Pe = \frac{u_T r_b (\rho c_p)_g}{\lambda_g} \quad [4]$$

$$Bi = \frac{h r_b}{\lambda_g} \quad [5]$$

With  $\alpha_{eq}$  the equivalent heat diffusivity of the water-filled ground, function of the porosity of the ground,  $H$  the borehole length and  $u_T$  the effective heat transport velocity, defined from the Darcy velocity  $u$  in the principal direction of the flow:

$$u_T = u \frac{(\rho c_p)_w}{(\rho c_p)_g} \quad [6]$$

Where the subscript  $w$  refers to the physical quantities for water and the subscript  $g$  refers to the ground.

Figure 1 shows the influence of the Peclet number on the g-function step-response at the borehole wall for the numerical solution from COMSOL, the analytical solution MFLS with imposed temperature at the surface (i.e.  $Bi \rightarrow \infty$ ), and the ICS solution with no groundwater flow. Groundwater flow has no impact on the step-response at low Fourier number but leads to the establishment of asymptotes for high  $Fo$ . Figure 1 shows a good agreement between ICS and the COMSOL solution for low  $Fo$ , and good agreement between COMSOL and MFLS for high  $Fo$  number. The COMSOL model is thus a good approximation for both short time and long-time calculation of the step-response of the borehole wall.

Figure 2 displays the g-function step-response of the borehole wall temperature for different values of Biot number with no groundwater flow and  $H^* = 100$ , from the COMSOL numerical solution and from a MFLS model with mixed thermal conditions at surface (MFLSm). The analytical, quite complex, expressions of this later model can be found in Rivera, Blum, and Bayer (2016). Figure 2 shows a good agreement between the numerical and analytical solutions for high Fourier numbers. However, the numerical solution is more accurate at low Fourier number.

#### 1.4 Meta-model derivation of the MFCSm model from the COMSOL numerical model

Four hundred and thirty numerical evaluations of the g-function step-response of the MFCSm model with parameters chosen using a Latin hypercube sample in the following ranges:

$$5 < H^* < 4000 \quad [7]$$

$$5 \cdot 10^{-5} < Pe < 6 \quad [8]$$

$$10^{-6} < Bi < 10 \quad [9]$$

Each of these step-responses were approximated using modified sigmoids:

$$G_{MFCSm}(H^*, Pe, Bi, Fo) = \frac{G_{max}(Y)}{2} \left( 1 + \tanh\left(\sum_{n=0}^2 B_n(Y) (\log_{10}(Fo))^n\right) \right) \quad [10]$$

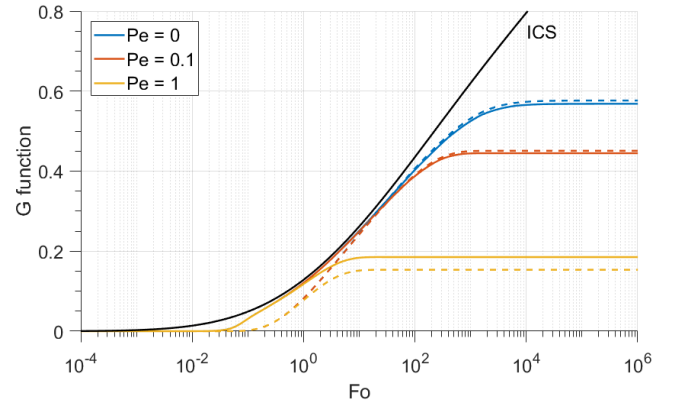
$$Y = [\log_{10} H^* \quad \log_{10} Bi \quad \log_{10} Pe] \quad [11]$$

The coefficients  $B_n$  ( $n = 0, 1, 2, 3$ ) and the asymptote  $G_{max}$  are computed as a polynomial function of  $Y$ :

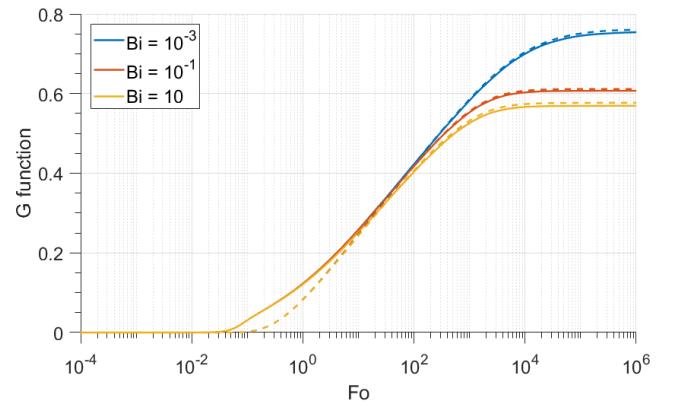
$$B_n(Y) = \sum_{j=1}^{35} (a_{B_n})_j \prod_{i=1}^3 Y_i^{m_{ij}} \quad [12]$$

$$G_{max}(Y) = \sum_{j=1}^{35} (a_{G_{max}})_j \prod_{i=1}^3 Y_i^{m_{ij}} \quad [13]$$

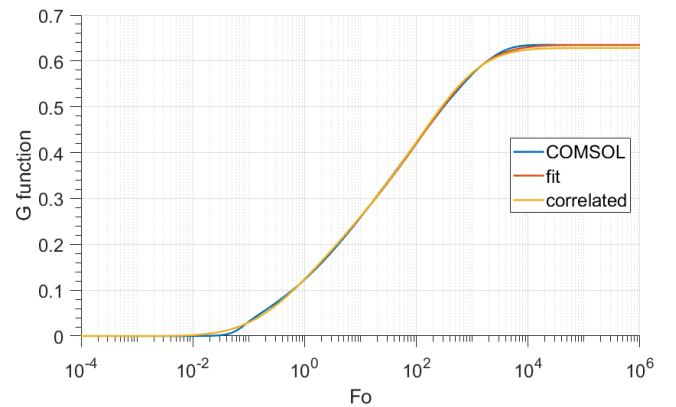
The vectors  $a_{B_n}$  and  $a_{G_{max}}$  contain 35 coefficients.  $[m_{ij}]$  has 35 lines and 3 columns: for instance, a line with  $[0 \ 1 \ 2]$  corresponds to  $\prod_{i=1}^3 Y_i^{m_{ij}} = Y_1^0 Y_2^1 Y_3^2$  in equation [12] and [13]. The coefficients are found numerically by minimising the standard deviation between the g-function computed by COMSOL and eq. 10.



**Figure 1: ICS model (black) vs COMSOL solution (solid-coloured lines) vs MFLS (dashed) function of the Fourier number for large Biot number (imposed surface temperature) and  $H^* = 100$ .**



**Figure 2: COMSOL solution (solid) vs MFLSm (dashed) function of the Fourier number for  $Pe = 0$  and  $H^* = 100$ .**



**Figure 3: COMSOL solution of the temperature wall step-response vs fitted function based on eq (10) vs correlated function from the meta-model.  $H^* = 320$ ;  $Pe = 0.03$ ;  $Bi = 0.48$ .**

A meta-model is then set up to find each vector  $a_{B_n}$  and  $a_{G_{max}}$  from the values of the parameters  $[H^*, Pe, Bi]$ . It is therefore possible to obtain the values of the before-mentioned vectors for any given value of  $[H^*, Pe, Bi]$ , hence the value of the wall temperature step response without the need to perform a COMSOL calculation. The meta-model is validated by comparing the COMSOL solution, the fitted curve on this solution, and the result of the meta-model for several parameter sets not used for the elaboration of the meta-model. Figure 3 shows an example of this validation.

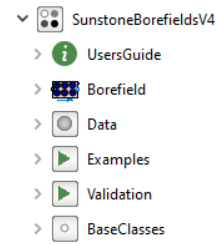
The draft of a review article presenting details about the COMSOL model, and the elaboration of the meta-model is currently under way.

## 2. IMPLEMENTATION OF THE MOVING FINITE CYLINDRICAL SOURCE

The meta-model derived in section 1.4 is implemented in a new Modelica library. This library is based on the same structure than the HSRM model developed by Picard and Helsen (2014), since the calculated function is the borehole wall temperature response to a step of power in both cases. The MICSm meta-model calculates the g-function for a single borehole in the borefield, and the MFLS model calculates the interactions between boreholes, since the cylindrical nature of the heat source is negligible at such distances. This modification allows for the consideration of groundwater flow in the borefield, and mixed boundary conditions at the surface.

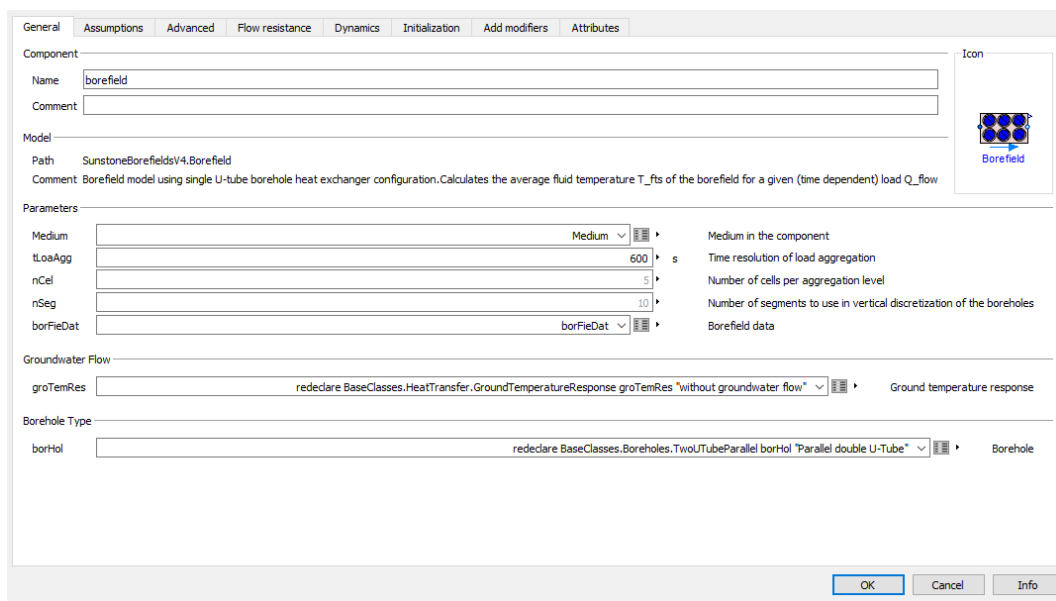
At the difference with the HSRM model, only one model is proposed at the top level of the arborescence (Figure 4). The user can then choose in the parameter tab of this model (Figure 5) the type of borehole used between three choices: single-U, parallel double-U or series double-U. It is also possible to choose if there is

a groundwater flow. If no groundwater flow is chosen, the HSRM model is used.



**Figure 4: Arborescence of the new Modelica borefield module.**

Moreover, the borefield configuration definition in the HSRM model can only be achieved by providing the cartesian coordinates of all the boreholes, which can be time consuming and cumbersome, or require elaborate function declaration in the configuration record. The new borefield Modelica model presented here does not change the calculation process of borehole interactions, so the calculus core still requires the coordinates of the entire borefield, but it simplifies the declaration process and give access to two different patterns on which the boreholes are placed: rectangular borefield on a square base, or hexagonal borefield on a hexagonal base (Figure 6). The first configuration requires the following parameters: number of rows (x-direction), number of columns (y-direction) in the borefield, and distance between the boreholes. By default, the direction of groundwater flow is parallel to the rows. It is to this date not possible to specify a direction of groundwater flow with respect to the row direction. The second configuration requires the following parameters: number of boreholes, and distance between boreholes. The borefield is then constructed by progressively filling the concentric annular, on a hexagonal base, around a central borehole.



**Figure 5: Parameter display of the borefield model.**

The screenshot shows a software interface for configuring a borefield model. It is divided into several sections:

- General:** Name: conDat; Comment: [empty]; Path: SunstoneBorefieldsV4.Data.Configuration.Template; Comment: Template for configuration data records.
- Parameters:** use\_Rb: false; Rb: 0.0 (m·K)/W. Description: true if the value borehole thermal resistance Rb should be given and used. Borehole thermal resistance Rb. Only to fill in if known.
- Nominal condition:** mBor\_flow\_nominal: 0.278 kg/s; mBorFie\_flow\_nominal: mBor\_flow\_nominal\*nBor kg/s; dp\_nominal: 10000 Pa.
- Borehole:** choixGeom: Hexagonal (hexa base) selected. hBor: 100 m; rBor: 0.06 m; dBor: 0 m; nBor: if choixGeom == 1 then size(cooBor, 1) else choixGeom == 2 then nxBor; dSGV: 4 m; nxBor: 4; nYbor: 4; cooBor: if choixGeom == 1 then {{0,0},{0,10},{10,0},{10,10}} else choixGeom.
- Tubes:** rTub: 0.0125 m; kTub: 0.25 W/(m·K); eTub: 0.002 m; xC: 0.0354 m.

Figure 6: Parameter display of the configuration data record in the new Modelica borefield module.

### 3. CONCLUSIONS

The Modelica language is particularly adapted for dynamic multi-physics energy system simulation. Shallow geothermal energy systems need to rely on accurate modelling of the heat transfer occurring between the borehole and the ground. However, the available borehole and borefield Modelica models in the commonly used libraries do not consider the impact of groundwater flow on the temperature step-response of the borehole or the borefield.

The new borefield Modelica module presented here considers groundwater flow and mixed boundary conditions. It is based on a meta-model derived from COMSOL simulations of the temperature step-response at the borehole wall function of the non-dimensional borehole height, the Peclet number and the Biot numbers.

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