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# A hybrid reduced model for borehole heat exchangers over different time-scales and regions

Eui-Jong Kim [a,*], Michel Bernier [b], Odile Cauret [c], Jean-Jacques Roux [a]

[a] Université de Lyon, CNRS, INSA-Lyon, CETHIL, UMR5008, F-69621 Villeurbanne, France
[b] Polytechnique Montréal, Département de Génie Mécanique, Case Postale 6079, Succursale "Centre-ville", Montréal, Que. H3C 3A7, Canada
[c] Research and Development Division, Electricité de France (EDF), Les Renardières, 77818 Moret sur Loing, France

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ABSTRACT

Accurate modeling of heat transfer in the ground and inside the borehole is crucial to correctly size and assess performance of ground coupled heat pump systems. The model proposed here uses a hybrid approach combining two techniques. First, the rapid transient behavior inside the borehole is handled numerically with a fine grid in combination with a model size reduction technique to reduce computation time. Secondly, the surrounding ground is modeled using modified g-functions. The resulting HR (hybrid reduced) model is implemented as a TRNSYS type using a load aggregation algorithm. Results show that differences between the proposed model and a well-known non-capacity model are within an acceptable range of the order of ±0.8 °C. The differences are partly attributed to the simplification methods. However, they are mainly due to the fact that the HR accounts for the thermal capacity in the borehole. In simulations over a heating season, the inclusion of borehole thermal capacity results in outlet fluid temperatures that can be up to 2 °C higher than when thermal capacity is not accounted for. In terms of computation time, the HR model is about 37 times faster than a complete hybrid model, but with almost no loss in accuracy.

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## 1. Introduction

Accurate modeling of heat transfer in the ground and inside the borehole is crucial to correctly size and assess performance of GCHP (ground coupled heat pump) systems [1,2]. Each region reacts with a different time-scale to a change of boundary conditions (such as a change in the inlet fluid temperature). For example, the borehole region requires short-time steps to accurately model the rapid changes occurring in that region. On the other hand, long time steps may be sufficient for the ground domain where a change of inlet fluid temperature may be felt only after several days or weeks. Most models either account for borehole dynamics or ground heat transfer but very few do both. It has generally been assumed that the borehole transient behavior can be neglected in annual simulations because it has a negligible impact on the annual heat pump energy consumption [3]. However, a recent study shows that it is important to account for borehole thermal capacity for infrequent heat pump operation [4].

The borehole region, which comprises the pipes, the grout, and the fluid has relatively complex geometries, so effective models that use equivalent parameters are generally used to easily account for the thermal capacity. For example, Rottmayer et al. [3] approximated the *U*-tube cross-section by a pie sector shape. Since they used relatively coarse grids, errors of the order of 5% in heat transfer rate were found when compared to a circular tube solution obtained by an analytical solution in the steady state regime. Then, a more detailed mesh was proposed [5] to describe accurately the pipe geometry which reduced the average error to 1%. However, the fine mesh increased computation time.

Another technique often used is to replace the *U*-tube by an equivalent single tube. Bose [6] was one of the first to suggest such an approximation. Another form of the equivalent diameter approach was proposed by Gu et al. [7] to account for the center-to-center distance between pipes. These equivalent diameter models neglect the two-dimensional temperature variations over the borehole cross-section by simplifying the problem to a one-dimensional radial heat transfer problem. This approximation may lead to over-sizing of the ground heat exchanger [8]. Shirazi and Bernier [4] considered thermal storage effects in the borehole using an equivalent cylinder approximation. Ten radial grids were used in the cylinder thickness to represent the grout.

* Corresponding author. Tel.: +33 472 437 488; fax: +33 472 438 522.
*E-mail addresses:* eui-jong.kim@insa-lyon.fr, euijong.a.kim@gmail.com (E.-J. Kim).

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Lamarche and Beauchamp [9] developed a closed-form analytical solution that takes into account different materials inside and in the vicinity of the borehole allowing for short-time responses. The heat transfer problem in the resulting concentric cylinder was solved by Laplace transformation under different boundary conditions. They also remarked that the non-capacity approximation in the grout and fluid are strictly valid only when the borehole operates in quasi-steady state which may be of the order of 3–6 h after a step change in the inlet conditions.

For the surrounding ground portion, some well-known analytical solutions have been used. One of them is the ILS (infinite line source) model, proposed by Ingersoll et al. [10], which assumes one-dimensional (radial) heat transfer from an infinite line source. Similarly, the CHS (cylindrical heat source) solution has been employed to calculate cases where heat is transferred radially at the borehole wall [11,12], Another analytical solution is the FLS (finite line source) method [13]. It can predict two-dimensional (radial and axial) heat transfer from a finite line source subjected to a constant heat transfer rate and positioned in a semi-infinite medium.

In his pioneering work, Eskilson [14] developed thermal response factors called g-function that were obtained from a 2-D (radial and axial) numerical model. The use of pre-defined g-function for a specific bore field configuration allows faster simulations to be performed. The original g-function did not provide responses for short time scales. Yavuzturk and Spitler [15] proposed to extend Eskilson's g-function to short time steps. A fine mesh covering the borehole and the ground was used in a two-dimensional numerical model in radial coordinates ($r$, $\theta$). In a particular configuration assuming constant heat injection at the *U*-tube wall, temperature differences between the borehole wall and the far-field were estimated using this model. Then, g-functions were extended to cover the time range from 2.5 min to 200 h.

The DST (duct ground storage) model [16] is a 3D model which uses both numerical and analytical solutions to simulate axi-symmetric cylindrical bore fields. As a result, bore fields that are regularly arranged have to be approximated by a cylindrical storage. The DST model has been used as a benchmark to evaluate various design software tools [17] and in a comparison exercise with analytical methods [18].

Lee and Lam [19] developed a three-dimensional finite difference model using the rectangular coordinate system with an irregular grid scheme. With this grid, several boreholes can be simulated but in limited flexibility.

The ground models mentioned above can provide average borehole wall temperatures for given heat transfer rates, so they may be useful in combination with a dynamic-behavior borehole model. Some have handled both borehole and ground domains. Most of them are three-dimensional and use a detailed unstructured mesh to correctly describe the circular forms in the borehole. Li and Zheng [20] used a detailed mesh to develop a 3D finite volume method model for a single borehole case. Kim et al. [21] developed a 3D model with a detailed mesh structure that can simulate simultaneously the inside of the borehole as well as the overall bore field. Even though the technique used model reductions techniques, it still required almost 18 h of computations for annual simulations with a 10-min time steps. This level of computation time is inadequate for annual simulations of large bore fields.

A few models treat both the borehole and ground thermal behavior with reasonable computational time. Most of them combined a numerical model for the borehole region and an analytical approach for the ground portion. One such model is the 2D thermal capacity model implemented into TRNSYS (TRaNsient SYstem Simulation program) [22] as Type 451 [23] where the entire grout is modeled as a single node for each axial layer. The model describes the axial heat transfer in the borehole as well as in the ground in the vicinity of the borehole using a two-dimensional ($r$, $z$) grid. The borehole capacity model proposed by Shirazi and Bernier [4] used 10 radial grids in the grout coupled to the CHS model for the ground portion. Yavuzturk et al. [24] used the FEM (finite elements method) for a one-dimensional single radial grid to approximate the grout portion. The model was coupled to the g-function that was extended to short-time scales.

As can be seen from this literature review, very few models can handle both the borehole and ground thermal behavior in an efficient way. The objective of this work is to attempt to fill this gap. The borehole and ground are characterized by different time scales and require distinct solution methodologies. In this work, the borehole portion is obtained using a FEM (finite element method) with an unstructured fine mesh. The resulting model is "reduced" in size using a state model reduction technique to perform annual hourly simulations with a reasonable computational time. This is coupled to a ground model which uses g-functions that can be calculated for any bore field configuration. The resulting HR (hybrid reduced) model is described in detail in the following section followed by a comparison exercise and an application.

## 2. HR (hybrid reduced) model

The HR (hybrid reduced) model proposed in this work consists of a numerical borehole model combined with g-functions obtained using the FLS (finite line source) analytical solution [25]. For the borehole portion, the numerical model is based on the FEM and uses reduction techniques [21,26,28]. Unstructured fine meshes are used to describe the irregular geometry found inside the borehole. Then, the FLS based g-function is used to provide the borehole wall temperature boundary to the numerical model. The HR model is based on the following assumptions:

- Ground and grout properties ($\rho$, $c$, $k$) are considered constant and homogeneous.
- A perfect thermal contact between the materials is assumed.
- Two-dimensional ($x$, $y$) heat transfer is assumed for the borehole domain (grout).
- The borehole wall temperature is assumed uniform along the height and circumference.
- The thermal capacity of the *U*-tubes is neglected.

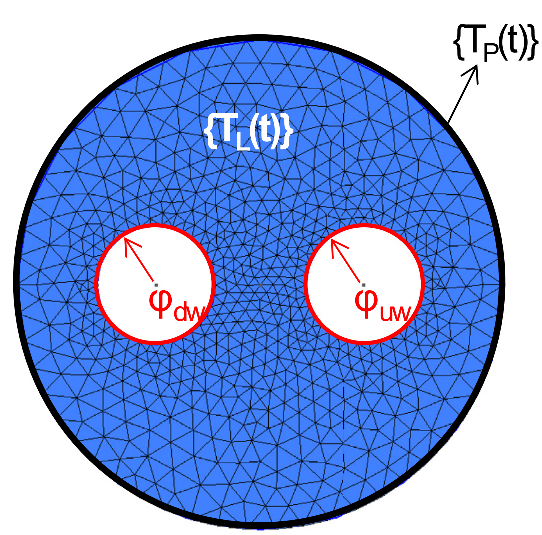


**Fig. 1.** Delaunay triangulation mesh for the borehole (single *U*-tube case).

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