Renewable Energy 85 (2016) 195–205

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A spectral model for transient heat flow in a double U-tube geothermal heat pump system

Rafid Al-Khoury [a,*], Sara Focaccia [b]

[a] Faculty of Civil Engineering and Geosciences, Computational Mechanics, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] CERENA – Centre for Natural Resources and the Environment, Instituto Superior Técnico, Lisbon Technical University, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal

ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form
12 May 2015
Accepted 13 June 2015
Available online xxx

Keywords:
Borehole heat exchanger
GSHP
TRT
Spectral analysis
FFT

ABSTRACT

This paper introduces a semi-analytical model based on the spectral analysis method for the simulation of transient conductive-convective heat flow in an axisymmetric shallow geothermal system consisting of a double U-tube borehole heat exchanger embedded in a soil mass. The proposed model combines the exactness of the analytical methods with an important extent of generality in describing the geometry and boundary conditions of the numerical methods. It calculates the temperature distribution in all involved borehole heat exchanger components and the surrounding soil mass using the fast Fourier transform, for the time domain; and the complex Fourier and Fourier-Bessel series, for the spatial domain. Numerical examples illustrating the model capability to reconstruct thermal response test data together with parametric analysis are given. The CPU time for calculating temperature distributions in all involved components, pipe-in, pipe-out, grout, and soil, using 16,384 FFT samples, for the time domain, and 100 Fourier-Bessel series samples, for the spatial domain, was in the order of 3 s in a normal PC. The model can be utilized for forward calculations of heat flow in a double U-tube geothermal heat pump system, and can be included in inverse calculations for parameter identification of shallow geothermal systems.

1. Introduction

Geothermal heat pump (GHP) is an important source of energy for heating and cooling of buildings. It saves energy by making use of the relatively constant temperature conditions at small depths of the earth. This system, also known as borehole heat exchanger (BHE) or ground source heat pump (GSHP), works by circulating a fluid (refrigerant), mostly water with antifreeze solution, through a closed loop of polyethylene pipe that is inserted in a borehole in a soil mass. The borehole is filled with some grouted materials to fix the polyethylene pipe and to ensure a good thermal interaction with the soil. Several types of GHP are available in practice. In this publication, the GHP system is assumed to consist of a vertical double U-tube BHE embedded in a soil mass and subjected to an inlet temperature coming from the heat pump, air temperature, and a temperature coming from the bottom of the earth.

The borehole heat exchanger is a slender heat pipe with dimensions of the order of 30 mm in diameter for the U-tube, and 150 mm in diameter and 100 m in length for the borehole. The U-tube carries a working (circulating) fluid that collects heat from the surrounding soil via convection-conduction heat flow mechanisms. Physically, the heat flow process in such a system is well understood, but computationally, and in spite of the bulk of existing models, still creeping due to the combination of the slenderness of the boreholes heat exchangers and the involved thermal convection. This combination constitutes the main source of computational challenges in this field. Consequently, several theoretical and computational assumptions and approximations have been introduced in order to circumvent this problem and obtain feasible solutions. All known solution techniques, such as analytical, semi-analytical and numerical, have been utilized for this purpose. However, in spite of the versatility of the numerical methods, analytical and semi-analytical solutions are yet preferable because of their comparatively little demands on computational power and ease of use in engineering practice. In this publication, focus is placed on analytical and semi-analytical solution techniques.

In the last three decades, several analytical and semi-analytical models for the simulation of heat flow in geothermal heat pump

* Corresponding author.
E-mail address: r.i.n.alkhoury@tudelft.nl (R. Al-Khoury).

http://dx.doi.org/10.1016/j.renene.2015.06.031
0960-1481/

systems with different complexities and rigor have been introduced. Based on their treatment of heat flow inside the U-tubes, these models can be classified into three categories: 1. No heat convection; 2. Implicit convection; and 3. Explicit convection.

Models belonging to the first category are those based on the work of Carslaw and Jaeger [1], who seem to be the first to introduce a comprehensive treatment of heat conduction in solids. Heat flow in finite, semi-infinite and infinite domains subjected to point, line, plane and cylindrical heat sources were extensively studied in their work between 1947 and 1959. In the meanwhile, and on the basis of Carslaw and Jaeger work, Ingersoll et al. [2] made a significant contribution to the field of heat conduction in solids and provided a practical framework for modeling geothermal systems. Currently, most of the analytical and semi-analytical models for heat flow in geothermal heat pumps are based on these two sources. These models calculate heat flow in a soil mass subjected to a heat source, representing the borehole heat exchanger, regardless of the convective heat flow in the fluid inside the U-tubes and the thermal resistance between the different components. Philippe et al. [3] gave a perceptive review of these models and the researchers who employed them.

Along the same category, but different representation of the geometry, there are several other models in use. In such models, the convective-conductive heat flow in the U-tubes is replaced by a constant cylindrical heat source, and the geometry is described by a concentric two-dimensional (radial) composite domain. Gu and O'Neal [4] gave an elaborate literature review on analytical solutions of radial heat conduction in a composite domain. They utilized this technique to simulate transient heat flow due to a constant heat source, resembling U-tubes, surrounded by a backfill (grout) and a soil mass bounded by a far field boundary. The cross sectional areas of the two branches of the U-tubes are replaced by an equivalent cross sectional area. They utilized the eigenfunction expansion to solve the governing partial differential equation that gave rise to solving an eight degree transcendental equation for determining the involved eigenvalues. Apparently, solving an eight degree transcendental equation is difficult and might be a source of numerical oscillations and computational inefficiency. In this model, summing up to 1000 terms was needed for the series to converge.

Based on Gu and O'Neal's approach, a number of models have been introduced using different mathematical formulations and solution techniques. Lamarche and Beauchamp [5] solved Gu and O'Neal's composite problem using Laplace transform. They solved both forward and inverse Laplace transforms analytically. Bandyopadhyay et al. [6] solved the same problem using dimensionless equations by means of Laplace transform. They utilized Gaver-Stehfest numerical algorithm to solve the inverse Laplace transform. Such models, together with those employing the finite, infinite and cylindrical line sources, can also be classified as a no thermal resistance models.

Models belonging to the second category are those which calculate the BHE fluid temperature implicitly, i.e. without really simulating fluid flow along the axial axis of the U-tubes. In such models, a mean fluid temperature is specified to indicate the average temperature in the U-tubes. It is calculated by first computing the soil temperature at the borehole wall, using any of the known analytical models, then adjusting the borehole thermal effective resistance to obtain equilibrium. Marcotte and Pasquier [7] introduced such a model for a transient pseudo convective problem using the fast Fourier transform for discretizing the time domain, and the cubic spline for interpolating results obtained at selected samples of the analytical function. They utilized the principle of superposition method to simulate the response to multiple heat fluxes. Javed and Claesson [8] solved Gu and O'Neal's problem using a similar pseudo convective approach.

Yet another type of models has also been introduced that implicitly accounts for the fluid heat flow in the U-tubes. In this kind of models, heat flow in a geothermal heat pump is described by an assembly of interconnected resistances and capacitors. De Carli et al. [9] and Zarrella et al. [10] proposed what is known as the Capacity Resistance Model (CaRM) for the calculation of transient temperature distributions in borehole heat exchangers, including those for the grout and the circulating fluid. In this model, the geometry is discretized by nodes representing slices in the vertical and radial directions. Heat flow in a slice is described by calculating the temperature difference between adjacent slices, controlled by the thermal resistance between them. Bauer et al. [11] extended the idea of the CaRM model by dividing the grout thermal resistance over the number of the involved U-tubes in the borehole. Their model is known as the Thermal Resistance Capacity Model (TRCM). Pasquier and Marcotte [12] extended Bauer et al. [11] model by incorporating the circulating fluid and the pipe thermal capacity. They also introduced a better account for the pipe spacing. This kind of models, and in spite of their apparent ease of formulation, is sensitive to the number of nodes utilized to discretize the geometry, making them sensitive to the thermal parameters, the definition of thermal resistance and the time steps. Such models can also be classified as thermal resistance models.

Models belonging to the third category are those which calculate the BHE fluid temperature explicitly, i.e. simulating fluid flow along the axial axis of the U-tubes. Eskilson and Claesson [13] introduced a semi-analytical model for ground source heat pumps that approximates heat flow in the borehole heat exchangers by two interacting channels conveying a circulating fluid in the vertical axis and embedded in an axisymmetric soil mass. Heat flow in the channels is assumed steady state convective, and in the soil, transient conductive. They utilized Laplace transform to solve the involved heat equations of the channels, and the explicit forward difference method to solve the heat equations of the soil mass. Zeng et al. [14] solved the same problem but using dimensionless heat equations for the channels. This kind of models, in spite of its realistic physical representation of heat flow in the GHP system, is mainly suitable for long term analyses. As for the second category models, this kind of models can also be classified as thermal resistance models.

Alongside this category, Al-Khoury [15,16] introduced a semi-analytical model for transient conductive-convective heat flow in a single U-tube borehole heat exchanger embedded in a soil mass. The model calculates the temperature distribution in all involved borehole heat exchanger components (pipe-in, pipe-out and grout), and the surrounding soil mass using eigenfunction expansion in terms of the spectral analysis method. The fast Fourier transform is utilized for discretizing the time domain, and the complex Fourier series and Fourier-Bessel series are utilized for discretizing the spatial domain. The main advantage of this model is that it solves the governing partial differential equations of the system directly, making it physically sound. Additionally, the use of the spectral analysis makes it computationally efficient.

In this paper, this model is extended to describe heat flow in a double U-tube borehole heat exchanger embedded in an axisymmetric soil mass. Detailed mathematical formulation of the double U-tube together with eigenvalue determination and spectral analysis are given. The mathematical formulation and solution of heat flow in the soil mass are adopted from Al-Khoury [16] but, for completeness, the general solution is described in this paper. The proposed model is utilized to simulate a thermal response test (TRT).