Renewable Energy 96 (2016) 65–79

Contents lists available at ScienceDirect

Renewable Energy

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

Formulation of a 1D finite element of heat exchanger for accurate modelling of the grouting behaviour: Application to cyclic thermal loading

B. Cerfontaine [a, *], G. Radioti [a, b], F. Collin [a], R. Charlier [a]

[a] University of Liege, Geomechanics and Engineering Geology, Chemin des chevreuils, Liege, Belgium
[b] F.R.I.A., Fonds de la Recherche Scientifique - FNRS, Brussels, Belgium

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form
30 March 2016
Accepted 19 April 2016

Keywords:
Borehole heat exchanger
Ground source heat pump
Finite element
Short-time step
Numerical modelling

ABSTRACT

This paper presents a comprehensive formulation of a finite element for the modelling of borehole heat exchangers. This work focuses on the accurate modelling of the grouting and the field of temperature near a single borehole. Therefore the grouting of the BHE is explicitly modelled. The purpose of this work is to provide tools necessary to the further modelling of thermo-mechanical couplings.

The finite element discretises the classical governing equation of advection-diffusion of heat within a 1D pipe connected to ground nodes. Petrov-Galerkin weighting functions are used to avoid numerical disturbances. The formulation is able to capture highly transient and steady-state phenomena.

The proposed finite element is validated with respect to analytical solutions. An example consisting of a 100 m depth U-pipe is finally simulated. A first continuous heating simulation highlights the non-symmetric distribution of temperature inside and near the borehole. An estimation of the error on the results as a function of the resolution parameters is also carried out. Finally simulations of cyclic thermal loading exhibit the need to take into account all daily variations if the grouting behaviour must be modelled. This is true especially in case of freeze-thaw damaging risk.

1. Introduction

Among the different possibilities that geothermal energy offers, energy extraction through geothermal heat pumps is the most frequent worldwide application and increasing over the last years [1]. Shallow geothermal heat pump systems exchange heat with the ground either by circulating the groundwater through two separate wells (open-loop) or by using heat exchangers embedded in the ground mass (closed-loop). Vertical closed-loop geothermal systems, also known as Borehole Heat Exchangers (BHEs), are widely used since they have a small footprint at the surface for installation and can be applied in many hydrogeological contexts [2,3]. BHEs consist typically of one or two loops of high-density polyethylene pipes installed in a borehole. A heat carrier fluid is circulated in the pipe loop and heat is transferred between the fluid and the surrounding ground. A grouting material is usually injected in the borehole to enhance the heat transfer between the circulating fluid and the surrounding ground and to prevent environmental risks. These systems are widely used for heating and cooling of buildings and small compounds [4]. In winter heat is extracted from the ground (heating of the building) while in summer heat is injected in the ground (cooling of the building).

The long-term use of BHE may have many technical and environmental consequences [5] such as the influence on groundwater quality or the reduction of efficiency of the injection/extraction process. Sustainability of BHE is a crucial issue [6]. This consists in finding the maximum level of energy production allowing a constant production for a very long time. Therefore the optimisation of single or fields of BHE is carried out in order to limit their impact or increase their efficiency [7–9]. Limitations of temperature variations within the soil, the carrier fluid and the grouting is another constraint. Indeed the freeze-thaw cycles may affect the thermal properties of the grouting [10–12] or the shallow aquifer quality [5]. The evaluation of these consequences requires the development of analytical and numerical models able to capture all the features of BHE-ground interactions.

Analytical and semi-analytical solutions are widely used for the BHE design and optimisation [7–9] especially due to their low

* Corresponding author.
E-mail address: b.cerfontaine@ulg.ac.be (B. Cerfontaine).

http://dx.doi.org/10.1016/j.renene.2016.04.034

computational cost. Early solutions are developed to analyse the long-term behaviour of BHE [13,14]. They are limited to conduction only and drop vertical effects or pipe interactions [15]. extend one of these methods to take into account short-term behaviour which is proven important for some applications. The basic infinite line source, finite line source and infinite cylindrical source models are compared in Ref. [16] and their applicability is classified with respect to the duration of the simulation.

Refinements of analytical methods are more and more developed. Heat advection in the surrounding soil is taken into account in Ref. [17] despite the proposed solution is in 2D. The interaction between pipes is included in Ref. [18–20]. propose a model dealing with vertical conduction as well as advection-diffusion in the soil and discontinuous loading. A classification procedure of these models is proposed in Ref. [21].

Finally some other authors try to better estimate the variation of temperature within the pipe only in order to simplify the resistance parameter identification procedure. For instance [22] propose to use a so called p-approximation of the temperature profile within U-pipes [23,24]. develop other analytical solutions taking into account interactions between the pipes. However despite the high efficiency of all these methods, they are still limited in geometry, soil configuration and complexity of couplings.

The last decade gives birth to a large number of different numerical models of BHE. These models allow more flexibility on thermal properties distribution within the soil, modelling of an advection flow around the BHE, varying geometries, short-term description of the temperature variations … They could be classified with respect to different criteria [25].

1. numerical method: finite element (most of the following papers), finite differences [26,27], finite volumes [25,28];
2. 2D or 3D simulations;
3. treatment of circulating fluid transport;
4. representation of the grouting;
5. possible advection in the soil [29];
6. single or multiple borehole(s).

Fully coupled 3D models of BHE are most of the time very computationally demanding. However the continuous increase of computational power allows their intensive use. Indeed, many case studies are inherently 3D, especially when multiple boreholes are involved, the soil is heterogeneous or in case of waterflow in the ground.

Advection of heat within the pipe and diffusion within the soil are two phenomena with distinct time constant and numerical requirements (time step or mesh limitations). A pioneering work of [30] and [31] early distinguishes the BHE from the soil finite elements. In this model, the BHE (including one or two U-pipes and the grouting) is modelled as a 1D finite element. This was extended to higher number of pipes in the grouting [32,33] or to multiple dof representing the grouting [34]. This decomposition of the pipes and the volume element becomes classical in the modelling of BHE. Another model describes the BHE as an assembling of resistances and thermal capacity [26,35]. The enumeration of the different models is not the purpose of this paper but interested reader should refer to [25] as a starting point.

Many models deal with steady-state solutions for the temperature distribution within the pipe. However it appears that the dynamic modelling of BHE is a crucial issue in their design [36–39]. conclude that alternative and discontinuous operation modes can strongly increase the heat transfer efficiency. Heat pump are often used in alternative modes and periods ranging from a year to less than a day. In the first case, heat extraction (winter) and injection (summer) modes alternate over a year [40,25]. In the second case, the heat pump may work only for a part of the day and be switched off otherwise [41,19]. Subsequently there is a need of a model able to reproduce highly transient effects with a minimum error and computer cost. Indeed, the error accumulation may be a critical issue [42] in case of cycle thermal loading.

The objective of the paper is to present the formulation of a versatile finite element of heat exchanger. The classical basic idea consists in dissociating the advective problem within the pipes and the dispersive problem within the grouting and the soil. The focus is placed here not on the large-scale modelling of multiple BHE but on the accurate modelling of a single BHE in the near and far fields. The grouting around the pipes is then explicitly modelled in order to well reproduce the gradients of temperature inside it and to avoid any hypothesis on the grouting thermal resistance or the interaction between different pipes. The geometry of the grouting section may also evolves with depth due to the heterogeneity of the soil. The model must accurately reproduce long and short term variations of temperature around the borehole.

The finite element is implemented in the non-linear finite element code LAGAMINE developed at the University of Liege [43,44]. This software is able to take into account all thermo-hydro-mechanical couplings in a fully coupled manner. However only thermal effects are considered here. The formulation of the element is adapted to highly transient simulations. Moreover the error control is a major concern. Indeed, the integration scheme and parameters are of crucial importance for advection problem.

In the following, the coupled heat exchanger finite element is firstly described in a general manner. It is validated on a classical example and verified with respect to a line source analytical solution. Numerical examples are then presented. A short-term heat injection scenario is investigated to prove the capabilities of the model and to estimate the error due to time integration parameter. A short-period discontinuous heat extraction scenario is presented and the influence of the operation scheme is analysed. Finally a one year simulation is carried out taking into account daily variations of the thermal demand.

2. Heat exchanger finite element

In the following it is decided to represent the pipe inside the BHE as a 1D finite element. Contrary to many models, the 1D finite element only models the flow into the pipes and does not include the grouting. This allows a very flexible formulation where the number, the disposition and the interaction of the pipes inside the borehole is arbitrary. The fluid flow is supposed to be in steady-state and the fluid velocity is constant all along the pipes.

Each node of the pipe element is related to a node, representative of the surrounding ground temperature. Here the ground is a generic denomination of the volume surrounding the pipe irrespectively of its actual nature (grouting, soil …). The volume 8-node finite elements describing the ground are classical and defined in Ref. [45] for thermo-hydro-mechanical couplings. They take into account thermal conduction into the soil and could also deal with advection, despite this is not considered in the following.

2.1. Governing equations

Let us assume a pipe is embedded into a ground volume of arbitrary shape, as depicted in Fig. 1. A fluid is circulating within the pipe and there is a difference of temperature between the fluid and the surrounding ground. It is assumed that the cross-section of the pipe is constant all over the pipe. Moreover the temperature of the fluid is assumed uniform over each cross-section and the velocity of the fluid is constant all along the pipe. The incoming longitudinal heat flux q_z [W/m^2] into the pipe is composed of a conduction and