Renewable Energy 62 (2014) 265–275

Contents lists available at ScienceDirect

Renewable Energy

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

Technical note

A network-based methodology for the simulation of borehole heat storage systems

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ARTICLE INFO

Article history:
Received 11 February 2013
Accepted 8 July 2013
Available online

Keywords:
Borehole heat exchanger
Finite line source
Ground heat storage

ABSTRACT

The optimization of strategies to operate borehole thermal energy storage systems can play an important role for the exploitation of this technology. Available tools utilized for the design of borehole fields don't consider these aspects in the calculation. For this reason a network-based methodology which gives a sufficient level of detail to describe different system operation strategies has been developed. In particular, the method allows to calculate how the heat is distributed among the borehole heat exchangers in the field according to the way the brine is supplied to the borehole heat storage system. This enables to test the same borehole field configuration pattern for different piping arrangement. An example of application where a simultaneous need of heating and cooling is met by extracting and injecting heat in different region of the ground storage is considered to illustrate the potential of the method.

1. Introduction

A large share of the energy used in the world is utilized for heating and cooling of buildings. Ground source heat pump systems are among the most energy efficient systems for heating and cooling of dwellings and their broader application can reduce end-use energy and contribute to the mitigation of CO_2 emissions.

Vertical ground heat exchangers have been utilized in Sweden since the early eighties and their diffusion took place in the second half of the nineties [1]. While during the diffusion phase their main utilization took place in the residential sector with small size installation (between 5 and 30 kW), recently there has been a growing interest towards larger installation for office buildings and multifamily houses.

Large installations have the advantage of greater density of energy exchanged with the ground for a given footprint available. On the other hand, they need a more careful design compared to small installations due to the fact that an improper design might have a greater impact on the system performance. In fact, as the size of the system increases there is also a rise of the thermal influence that a borehole heat exchanger experiences within the borehole field due to the presence of several heat sources in the surrounding ground volume. Therefore a variation on the design parameters might have a larger effect on the ground temperature compared to a single borehole installation, with a consequent variation of system performance. Tools for the simulation of the dynamic thermal behavior of borehole fields have been developed and they give a robust basis for the design of these systems. However, due to the simplification introduced to reduce the complexity of the problem, these methods lack of details on the description of the strategy utilized to operate the system. This is a limitation since in large installation the ground storage system consists in multiple boreholes that could potentially be operated independently and an appropriate management of the heat storage might have beneficial effects on the performance of the system.

Aim of this paper is the introduction of a methodology for the thermal analysis of ground heat storage system giving a sufficient level of detail to address this issue.

2. Background on convolution methods for the thermal analysis of vertical ground heat exchangers

An established method to perform the thermal analysis of vertical a ground heat exchanger consists in dividing the system in two parts: a region inside the borehole and a region outside the borehole [2,3]. In this paper these two parts will be referred to as a *local* and a *global* problems as showed in Fig. 1. The connection between the two problems takes place at the borehole wall interface.

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http://dx.doi.org/10.1016/j.renene.2013.07.020

Nomenclature

a	coefficient defined in Eqs. (25) and (31)
b	memory term
c_p	specific heat capacity (J kg^{-1} K^{-1})
F_n	coefficients defined in Eqs. (28) and (34)
g	g-function
H	borehole length (m)
k	thermal conductivity (W m^{-1} K^{-1})
$\mathscr{L}^{-1}$	inverse Laplace operator
$\dot{m}$	mass flow (kg s^{-1})
q	heat flux (W)
q'	heat flux per unit length (W m^{-1})
r_b	borehole radius (m)
R'_b	unit length borehole resistance (K m W^{-1})
t	time (s)
$\tilde{t}$	non dimensional time $\alpha t/r_b^2$
T	temperature (°C)
u	function defined in Eqs. (26) and (32)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

b	borehole
in	inlet
f	fluid
out	outlet
0	undisturbed conditions

2.1. Local analysis

The *local analysis* addresses the thermal interaction between the fluid flowing in the pipe and the borehole wall. The heat transfer depends on the flow regime within the pipes, and on geometric and thermal properties of the borehole and of the ground heat exchanger. A common assumption for the analysis of this region is considering quasi-steady state conditions. Given this assumption, the relation between mean fluid temperature $\overline{T}_f$, borehole temperature $T_b(t)$ and heat flux per unit of length $q'_b(t)$ can be described by means of resistance models as in Eq. (1).

$$\overline{T}_f(t) - T_b = R_b\, q'_b(t) \tag{1}$$

Expressions for the calculation of the borehole resistance R_b are given by Hellström [4] and Zeng [5]. The analysis of the internal region is completed with the expression of Eq. (2), which consists in the heat balance at the ground heat exchanger. This allows to establish a relation between the total heat exchanged and the fluid temperature difference between inlet and outlet for a given mass flow.

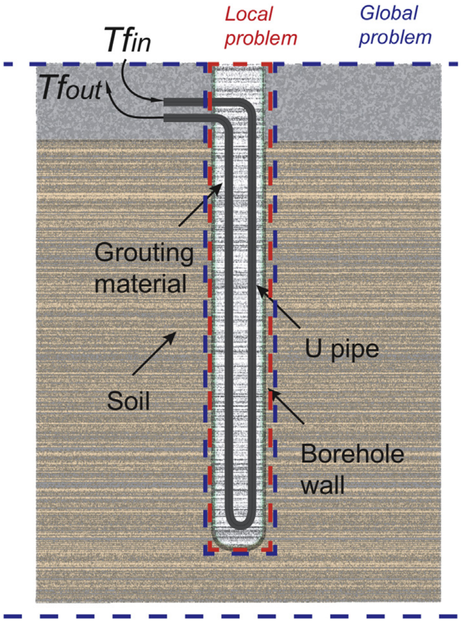

Fig. 1. Borehole heat exchanger model.

$$q'_b(t)\, H = \dot{m}\, c_p \left(T_{f_{in}}\left(t\right) - T_{f_{out}}(t)\right) \tag{2}$$

2.2. Global analysis

The *global problem* is the analysis of the thermal interaction between the borehole wall and the surrounding ground region. In particular, for a single borehole this consists in determining the evolution in time of the temperature at the borehole wall $T_b(t)$ while the borehole is exchanging the heat $q'(t)$ with the rock, given a domain at the initial temperature T_0. This dynamic heat transfer analysis is an inhomogeneous initial value problem with zero initial conditions which, given that the system is linear, can be solved by means of the convolution product of the impulse response function $h(t)$ and the loading condition $q'(t)$ as derived from the Duhamel theorem:

$$T_b(t) - T_0 = \int_0^t q'(t) h(t-\tau) \mathrm{d}\tau \tag{3}$$

A usual approach to calculate numerically the result of Eq. (3) is to decompose the load as being the superposition of a number of heat steps and superimpose the response of each heat step.

$$T_b(t_n) - T_0 = \sum_{k=1}^{n} \left(q'(t_k) - q'(t_{k-1})\right)\ g\left(\frac{\alpha(t_n - t_k)}{r_b^2}\right) \tag{4}$$

This consists in the numerical convolution between the step decomposed load $q'_{sd}(t_k)$ and the step response function g. A graphic representation of the procedure is given in Fig. 2.

$$q'_{sd}(t_k) = q'(t_k) - q'(t_{k-1}) \tag{5}$$

$$T(t_n) - T_0 = (q'_{sd} * g)(t_n) \tag{6}$$

The step response function g is the non dimensional borehole temperature evolution in time that takes place while the ground heat exchanger is injecting a unitary heat step $q'_b(t)$. Several approaches have been utilized to model the heat source. In particular this has been modeled as an infinite line source (ILS), infinite cylindrical source (CLS) [6] or as a finite line source (FLS) (Fig. 3).