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Influence of spatially variable ground heat flux on closed-loop geothermal systems: Line source model with nonhomogeneous Cauchy-type top boundary conditions

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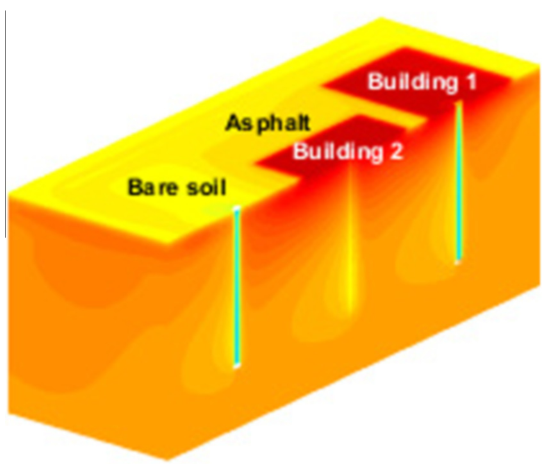
HIGHLIGHTS

- A new model for simulation of land surface effects on BHEs is introduced.
- A nonhomogeneous Cauchy-type top boundary conditions is implemented in the line source equation.
- The model considers linear heat exchange at the ground surface and groundwater flow.
- It is numerically verified and discrepancies with existing analytical models are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Borehole heat exchangers (BHEs) utilize the shallow ground to extract geothermal energy. Mostly they are installed in urbanized areas, where the thermal regime is strongly influenced by pavements, buildings and other urban infrastructures. In order to account for the spatial and temporal variability in the above-ground urban temperatures, a new semi-analytical model with a Cauchy-type top boundary is introduced. With this model, it is possible to estimate the transient three-dimensional temperature field in the near-surface ground influenced by the interaction of BHEs, horizontal groundwater flow, land use type and associated surface air temperature (SAT). It is verified with a numerical model and sensitivity analyses are conducted to examine the relevance of the prevailing thermal regime. By adopting a dimensionless formulation, it is shown that the decoupling between temperature fields at the ground surface restraints heat fluxes and penetration depth of thermal signals above ground. A systematic comparison with traditional Dirichlet-type boundary conditions shows that a fixed temperature formulation generally overestimates the thermal effect of land surface signals on thermal plumes of BHEs. This is also addressed by investigating the ground energy balance during operation of the geothermal system.

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Nomenclature

A	specific land use area (m^2)
a	thermal diffusivity ($m^2\ s^{-1}$)
c	volumetric heat capacity ($MJ\ m^{-3}\ K^{-1}$)
f	vertical fluxes at the ground surface ($W\ m^{-2}$)
F	dimensionless form of f
Fo	Fourier number
G	Green's function
h	coupling coefficient (m^{-1})
H	borehole length (m)
H_h	dimensionless product $H \cdot h$
I	linear heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	natural geothermal gradient ($°C\ m^{-1}$)
n_e	effective porous medium porosity
p	power (W)
P	dimensionless form of p
Pe	Péclet number
D	Darcy velocity ($m\ y^{-1}$)
Q_T	dimensionless number $q \cdot \lambda \overline{T_s}^{-1}$
q	heat flow rate per unit length ($W\ m^{-1}$)
r_d	horizontal radial distance from the borehole (m)
R	dimensionless form of r_d
s	phase shift of T_s
t	time (s)
t_o	period of T_s (s)
T	temperature in the porous medium (°C)
T_k	ground surface temperature corresponding to the geothermal gradient k (°C)
T_m	reference initial and surrounding temperature (°C)
T_s	above-ground temperature (°C)
T_{sA}	amplitude of T_s (°C)
$\overline{T_s}$	mean value of T_s (°C)
v	effective thermal velocity ($m\ s^{-1}$)
$\boldsymbol{x}$	coordinates vector where temperature is evaluated (m)
$\boldsymbol{x}'$	coordinates vector where a heat source is released (m)
x, y, z	single space coordinates where temperature is evaluated (m)
x_a, x_b, y_a, y_b	boundary coordinates of the specific land use (m)
x', y', z'	single space coordinates where heat sources are released (m)
$\boldsymbol{X}$	dimensionless form of $\boldsymbol{x}$ (m)
$\boldsymbol{X}'$	dimensionless form of $\boldsymbol{x}'$ (m)
X, Y, Z	dimensionless form of x, y, z
X', Y', Z'	dimensionless form of x', y', z'

Greek symbols

β	solution to the homogeneous boundary-value problem
B	dimensionless form of β
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
κ	substitution function
K	dimensionless form of κ
τ	time at which a heat pulse is released (s)
θ	dimensionless temperature
ω	solution to the nonhomogeneous boundary-value problem
Ω	dimensionless form of ω

Subscripts

β	referring to the HBVP β
C	referring to Cauchy-type boundary conditions
D	referring to Dirichlet-type boundary conditions
κ, K	expressed in terms of the functions κ, K
ω	referring to the NHBVP ω
T	referring to the temperature T

Abbreviations

BC	boundary condition
BHE	borehole heat exchanger
GST	ground surface temperature
HBVP	homogeneous boundary-value problem
MFLS	moving finite line source
NHBVP	nonhomogeneous boundary-value problem
RS	reference scenario
SAT	surface air temperature
TDP	temperature depth profile

1. Introduction

Especially in urban areas, pristine natural land is rare and land surfaces are considerably modified. The strong heterogeneity in land use, together with micro-climatic conditions specific to individual cities and global climate trends [1], yields spatially and temporally variable thermal conditions above the ground surface and in the subsurface [2,3]. Implementation of numerical models for simulating heat transport across the ground surface is often a difficult task, mainly because of the multi-scale and spatiotemporal variability of parameters specifying the governing physical processes (e.g. [4–10]). Often, comprehensive numerical model development and the associated computational cost are not justified, given the quality and resolution of the data available to calibrate such models. Alternatives to this are simplified simulation techniques that focus on the most relevant processes, and which are on a par with the limited detail of case-specific information (e.g. [11–13]). These techniques can also be utilized to reveal, which key features should be explicitly resolved in more detailed models. In this context, analytical models have proven to be a keystone, not only because of their relatively simple implementation, but also because of their straightforward usability in parameter studies and sensitivity analyses.

Analytical models are widely accepted for simulating geothermal systems that use the shallow urban ground [14,15], especially for sizing, optimizing and analyzing vertical borehole heat exchangers (BHEs) [16–22]. Usually, these analytical models are based on the superposition of Green's functions [23,24], which have been derived for several model configurations including line, spiral and cylindrical sources with (in-)finite lengths, with or without groundwater flow in (an-)isotropic media, or even considering phase-change [25]. Yet, available analytical models loosely consider the effect of complex top boundary conditions. Commonly, the temperature at the ground surface is assumed constant and is set equal to an initial temperature prevailing in the whole domain (e.g. [26,27]). This, however, is unsatisfactory in view of the land use variability in urbanized areas and the associated impact on the heat transport across the ground surface.

Bandos et al. [28] relaxed the constant temperature assumption at the top boundary in an analytical framework for investigating the influence of seasonal ground surface temperature (GST) signals in thermal-response testing with BHEs. Rivera et al. [29] generalized this approach by implementing Green's functions to simulate specific features in urban environments. Their results show the potentially strong effect of long-term changes in GST on the thermal conditions around a BHE. Both models, by Bandos et al. [28] and Rivera et al. [29], assume a spatially and temporally variable GST implemented as 1st kind or Dirichlet-type boundary condition (BC). However, a spatially resolved GST field is rarely available in practice. Best estimation is derived from punctual temperature-time series measured by sensors installed a few centimeters below the ground surface (e.g. [11,30–32]). Therefore, as a surrogate,