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Research Paper

Efficiency and economic analysis of utilizing latent heat from groundwater freezing in the context of borehole heat exchanger coupled ground source heat pump systems

Tianyuan Zheng [a,b], Haibing Shao [a,d,*], Sophie Schelenz [a], Philipp Hein [c,a], Thomas Vienken [a], Zhonghe Pang [e], Olaf Kolditz [a,b], Thomas Nagel [a,f]

[a] Helmholtz Centre for Environmental Research – UFZ, Permoserstraße 15, 04318 Leipzig, Germany
[b] Applied Environmental Systems Analysis, Dresden University of Technology, Germany
[c] Faculty of Mechanical and Energy Engineering, Leipzig University of Applied Sciences – HTWK, Germany
[d] Faculty of Geosciences, Geoengineering and Mining, Freiberg University of Mining and Technology, Germany
[e] Geothermal Research Center, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[f] Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland

HIGHLIGHTS

- A numerical model was developed to simulate BHE induced soil freezing.
- Latent heat from freezing slows down the BHE outlet temperature drop.
- COP corrected boundary condition produces more realistic estimation.
- Longer BHE do not always lead to a better financial performance over 30 years.
- Total cost of GSHPS depends heavily on electricity price and interest rate.

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ABSTRACT

To utilize the shallow geothermal energy, heat pumps are often coupled with borehole heat exchangers (BHE) to provide heating and cooling for buildings. In cold regions, soil freezing around the BHE is a potential problem which will dramatically influence the underground soil temperature distribution, subsequently the inlet and outlet circulating fluid temperature of the BHE, and finally the efficiency of the heat pump. In this study, a numerical model has been developed to simulate the coupled temperature evolution both inside the BHE, and the propagating freezing front in the surrounding soil. The coupled model was validated against analytical solutions and experimental data. The influence of the freezing process on the overall system performance is investigated by comparing one long BHE configuration without freezing and another short one with latent heat from the frozen groundwater. It is found that when freezing happens, the coefficient of performance (COP) of the heat pump will decrease by around 0.5, leading to more electricity consumption. Furthermore, analysis of the simulation result reveals that the exploitation of latent heat through groundwater freezing is only economically attractive if electricity price is low and interest rate high, and it is not the case is most European countries.

1. Introduction

In recent years, ground source heat pump systems (GSHPS) are increasingly employed as a new technology for heating and cooling of buildings. In the heating mode, the general principle of a GSHPS is to extract heat from the shallow subsurface by circulating heat-carrying fluid through single or multiple borehole heat exchangers (BHE), which are typically operating at a relatively low temperature [1]. The energy carried by the circulating fluid is then lifted

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* Corresponding author at: Helmholtz Centre for Environmental Research – UFZ, Permoserstraße 15, 04318 Leipzig, Germany.

E-mail addresses: tianyuan.zheng@ufz.de (T. Zheng), haibing.shao@ufz.de (H. Shao), sophie.schelenz@ufz.de (S. Schelenz), philipp.hein@ufz.de (P. Hein), thomas.vienken@ufz.de (T. Vienken), z.pang@mail.iggcas.ac.cn (Z. Pang), olaf.kolditz@ufz.de (O. Kolditz), thomas.nagel@ufz.de (T. Nagel).

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Nomenclature[1]

Greek symbols

α	non negative freezing coefficient (kg m^{-3} s^{-1} K^{-1})
$\boldsymbol{\alpha}_L$	diffusivity tensor (m^2 s^{-1})
Φ	heat transfer coefficient (W m^{-2} K^{-1})
$\boldsymbol{\lambda}$	heat conductivity tensor (W m^{-1} K^{-1})
$\boldsymbol{\lambda}_{\alpha R}$	real heat conductivity tensor of phase α (W m^{-1} K^{-1})
$\boldsymbol{\Lambda}$	thermal hydrodynamic dispersion tensor (W m^{-1} K^{-1})
ϕ_α	volume fraction of constituent α (–)
ρ_α	apparent density of constituent α (kg m^{-3})
$\rho_{\alpha R}$	real (effective) density of constituent α (kg m^{-3})

Operators

$H(\bullet)$	Heaviside step function
$(\hat{\bullet})_\alpha$	production term of quantity $(\bullet)_\alpha$ due to local interaction with other constituents
$\nabla\cdot$	spatial divergence operator
∇	spatial gradient operator
$(\dot{\bullet})_\alpha$	time derivative of quantity α

Roman symbols

c	coefficient of exponential function (–)
$c_\mathbf{p}$	specific isobaric heat capacity (J kg^{-1} K^{-1})
D	borehole diameter (m)
D	pipe diameter (m)
h	entropy (J)
Δh	heat of reaction per unit mass (J kg^{-1})
R	heat resistance (W^{-1} K)
H_s	heat source (J m^{-3} s^{-1})
k	coefficient of sigmoid function (–)
L_l	latent heat (J kg^{-1})
r	pipe radius (m)
T_α	temperature of phase α (K)
T_m	freezing point temperature (K)
$\mathbf{v}_\alpha$	velocity of phase α (m s^{-1})
$\mathbf{u}$	fluid circulating velocity (m s^{-1})
x	distance between the pipes (m)
X	the location of phase change front (m)

[1] Throughout the article bold face symbols denote tensors and vectors. Normal face letters represent scalar quantities.

by heat pump to a level suitable for domestic applications. For cooling applications, the system can be reversed, and the excess heat can be removed from the building and stored in the ground. As the temperature in the shallow subsurface remains constant, GSHPS are very efficient in comparison to other technologies [2]. For example, if 1 kW h of energy is required to heat the building, only 0.25–0.3 kW h of electricity are consumed to drive the heat pump [3]. The substitution of coal and gas burning boilers by GSHPS will not only reduce fuel costs, but also lead to substantially lower emission of CO_2 and air pollutants. Therefore, GSHPS have become a very attractive technology for domestic heating and hot water supply. In cold regions, the undisturbed soil temperature itself is already low (sometimes less than 10 °C). Typically, the circulating fluid inside the BHE is a mixture of water and anti-freezer. It allows its temperature to fall below zero and cause the freezing of groundwater surrounding the BHE [4]. This will strongly affect the soil temperature distribution, and the heat pump efficiency as well.

In practice, the length of BHE is designed based on the thermal conductivity and diffusivity of the soil, which can be measured by a thermal response test. Roth et al. [5] made the first in-situ thermal response test by installing BHE in Latin America. Wang et al. [6] proposed a novel constant heating-temperature method for the test, and also improved TRT equipment and presented a mathematical model to interpret the measured data. In order to improve the performance of GSHPS, both analytical and numerical modeling techniques have been applied to simulate the dynamic temperature evolution inside and around the BHE. Classically, Carslaw and Jaeger's line source model [7] with Kelvin's theory of heat sources is widely used to identify conductivity value in the thermal response test. Duhamel's theorem efficiently helps develop solutions with transient boundary condition [8]. Beier et al. employed the numerical Laplace transformation technique and developed a semi-analytical solution for single U-tube type BHE [9]. His model is capable of predicting the transient temperature profile within and around the BHE, which is installed in homogeneous soil and operated under a constant heat extraction rate [10]. Later on, he also extended this solution to coaxial types of BHEs [11]. Being aware of the limitation of the analytical approach, Lee and Lam [12] developed a numerical model for BHE with finite difference method, which can predict the dynamic temperature profile. Boockmeyer and Bauer [13] have managed to simulate the thermal response of the entire BHE, with the U-tube, grout material and the surrounding soil matrix all explicitly represented in the finite element mesh. These models are very accurate, but require significant computational resources. Following a different approach, Al-Khoury et al. [14,15] presented a model where the BHE is represented by a second 1D domain, which is coupled to the heat transport processes in the soil. Diersch et al. [16,17] followed the same idea and implemented the algorithm into the commercial software FEFLOW [18]. Such dual continuum models are still flexible enough to accept varying boundary conditions and heterogeneous soil properties, yet they are much more efficient in terms of computational time.

When freezing happens around the BHE, complex effects will occur. On one hand, the latent heat produced by the phase change can provide large amounts of extra energy for heating up the buildings. On the other hand, however, the freezing process will expand the soil which may damage the pipe and even the foundation of the buildings. To simulate freezing and thawing processes around the BHEs, a coupled model including both the BHE and the freezing feature is required. In other words, the numerical model has to capture the phase change between water and ice, and must also explicitly account for the associated latent heat. The mathematical description of freezing processes was first described by Stefan [19], and improved by Neumann [20] and Lunardini [21]. Afterwards, McKenzie et al. introduced a clear benchmark for the calibration of numerical models [22]. Bluhm and Ricken [23] proposed a mathematical and numerical model to simulate freezing in thermo-elastic porous media based on the porous media theory of De Boer [24]. Yet, none of these models considered the interactions between a BHE and the surrounding soil. To investigate such effects, several researchers have made important contributions. Wang et al. [25] experimentally investigated the pipe deformation during freezing at the interface between grout and soil. Eslami-nejad and Bernier [26] set up an experiment to examine the thermal consequences of freezing in the vicinity of BHEs and compared the result with a 1D numerical model. They found that soil freezing plays an important role in cold districts and delays the soil temper-