Renewable Energy 83 (2015) 1341–1351

Contents lists available at ScienceDirect

Renewable Energy

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

Review

Ground energy balance for borehole heat exchangers: Vertical fluxes, groundwater and storage

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ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
22 May 2015
Accepted 26 May 2015
Available online 23 June 2015

Keywords:
Geothermal energy
Heat transport
Sources of power
System recovery

ABSTRACT

Borehole heat exchangers (BHE) are the most frequent applications for extracting low-enthalpy geothermal energy. Their effect on shallow ground is commonly assessed by modeling the in-situ thermal conditions with little attention on the transient heat flux regime stimulated by BHEs. Here, we characterize these heat fluxes using analytical models. The approach is applied to a field site with long-term monitoring of the ground temperature development around a BHE. Our major findings are that advective transport shapes vertical heat fluxes and the power provided to the system from groundwater and from storage substantially varies over time. Examination of power sources reveals that during early operation phase, energy is extracted mainly from the storage. Then, local depletion enhances the vertical fluxes with the relative contribution from the bottom reaching a limit of 24% of the total power demand, whereas that from the ground surface becomes dominant for $Fo > 0.13$. Long-term energetic analysis, including the time after system shutdown, highlights that recovery may take much longer than the operation time. However, axial heat fluxes accelerate recovery and the ground surface then becomes even more dominant providing about two thirds of the power over the full life-cycle of the studied standard system.

1. Introduction

The consumption of low-enthalpy energy for heating and cooling has led to accelerated depletion of fossil fuels and is a main contributor to the carbon footprint of countries. In search of alternative and preferably renewable energies, the shallow ground has evolved as an increasingly popular source, which has a great advantage: it is directly accessible and available everywhere. Worldwide, the capacity of shallow geothermal applications is rising, and only in the European Union, geothermal heat pumps provided around 1400 ktoe (16 Mio. MWh) in 2011, with estimated greenhouse gas (GHG) emissions savings of around 4 Mio. tons CO_2. [1,2]. The most common variants of geothermal heat pumps utilize vertical boreholes of 50–400 m depth, with installed plastic tubes that exchange energy with the ground. These borehole heat exchangers (BHEs) are well-controlled closed systems without mass transfer, where energy is exchanged by pumping a carrier fluid through the plastic tubes loops [3].

With the huge number of installed BHEs, meanwhile technical design follows routine recipes [4,5]. For each case, BHE numbers, configurations and individual lengths are oriented at the energy demand, expected lifetime, ground properties and performance of the heat pump [6–8]. Still, routine practices bear the risk of neglecting opportunities in case-specific system design, dynamic control and fine-tuning [9,10]. This was for example demonstrated for multiple BHE fields, with improved performance potential through optimization of individual BHEs operation mode and position [11,12]. A crucial point in standard planning is that the heat transport processes in the ground are often roughly approximated, assuming uniform heat conduction only. This may lead to the misconception that extracted shallow geothermal energy originates exclusively from the ground and is supplied by conduction from the earth's interior only. However, for instance, neglecting top boundary effects, disregards typically pronounced thermal gradients at the ground surface [13]. These gradients delineate potentially relevant thermal fluxes towards a BHE. If they are not accounted for, this may lead to inaccurate system design and wrong estimations of the magnitude of the induced thermal anomalies [14,15]. As another process, heat advection by groundwater can play a substantial role. It shapes thermal plumes and can potentially

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http://dx.doi.org/10.1016/j.renene.2015.05.051
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Nomenclature

Symbol	Description
a	thermal diffusivity (m^2 s^{-1})
c	volumetric heat capacity of porous medium (MJ m^{-3} K^{-1})
Fo	Fourier number
f	vertical heat flux distribution (W m^{-2})
F	dimensionless form of f
G	Green's function
H	borehole length (m)
n_e	effective porous medium porosity
p	power (W)
P	dimensionless form of p
Pe	Péclet number
q_d	Darcy velocity (m y^{-1})
q	heat flow rate per unit length (W m^{-1})
r_h	horizontal radial distance from the borehole (m)
R	dimensionless form of r_h
t	time (s)
T	temperature in the porous medium (°C)
T_o	reference temperature (°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', y', z'	single space coordinates where heat sources are released (m)
X, Y, Z	dimensionless form of x, y, z

Greek symbols

Symbol	Description
λ	thermal conductivity of porous medium (W m^{-1} K^{-1})
τ	time at which a heat pulse is released (s)
φ, φ_H	intermediate or substitution variables

Subscripts

Symbol	Description
w	wetting phase
s	solid phase

Abbreviations

Abbreviation	Description
BHE	borehole heat exchanger
CV	control volume
CS	control surface in the CV
FLS	finite line source
GWF	groundwater flow
GSHP	ground source heat pump
MFLS	moving finite line source

replenish generated ground energy deficits [16–18]. Altogether, the relevant contributors to the energy sourced from the ground and their respective shares in the energy balance are defined by site-specific conditions. These shares, however, have not yet been analyzed in detail. Our objective is to shed light on these geothermal energy sources and their time-dependent contributions. By quantification of heat fluxes and power supply, we understand how the different physical mechanisms interact, and ultimately can provide fundamental criteria for balanced und hence sustainable BHE operation.

Sustainability is in fact an issue that spans the entire lifetime of ground source heat pump (GSHP) systems. This lifetime typically comprises decades when extraction and injection of heat is rarely balanced [13,19]. This could be achieved for instance by optimized seasonal operation or by combining heat extraction with heat injection [20–22]. Given an imbalance, thermal anomalies in the ground often grow over the years. As they potentially entail a decline in a geothermal system's performance, pronounced thermal anomalies are not desirable. Aside from this, induced thermal disturbances of the ground and groundwater are frequently restricted, to minimize environmental impacts and to give equal prospects to neighboring applications [23,24]. In some studies, long-term operation as well as ground recovery time after hypothetical shutdown of the system was examined. Ungemacht et al. [25] and Rybach et al. [26] estimated that the (approximated) initial thermal state can be reached after a time span similar to the operation period. This regeneration time span, however, is sensitive to the system size (single or multiple BHEs), configuration and specific site conditions [27,28]. After the shut-down, the rate of regeneration is fastest, driven by pronounced thermal gradients. At later times, this rate declines while the temperature around the BHE asymptotically approaches the initial state. Thus, judging regeneration based on the evolution of ground temperature is plausible, but it does not give direct insight in the replenishment of the bulk ground energy deficit.

Since long-term field measurements are rare, models serve as key tools for predicting the ground thermal evolution around BHEs. A broad range of different variants exists, from fast temperature response functions (g-functions) and exact, but simplifying analytical models, to demanding numerical models [29–35]. In this work, we set up an analytical modeling framework, which is customarily based on Kelvin's line source theory for prediction of in-situ ground temperatures. However, in our study, we do not focus on the temperature. Rather, and this is original, we examine the heat fluxes stimulated by long-term BHE operation for heat extraction. This includes basal fluxes, those from the ground surface and by reservoir depletion.

By utilizing a versatile analytical model framework, general and specific findings can be obtained. For example, it is feasible to characterize the influence of groundwater flow on the spatial and temporal distribution of vertical heat fluxes. Despite the fact that many previous studies have pointed out the positive influence of groundwater flow on BHEs performance [18,36–39], it is unclear under which conditions advection enhances vertical fluxes. Our model framework allows quantifying heat fluxes at the top boundary and borehole toe. Furthermore, by direct integration of these fluxes over their thermally influenced area, simple closed analytical equations can be obtained for the associated power supply. With these, an overall ground energy balance is performed. This is important, firstly, to highlight the relevance of considered heat flux processes and, secondly, because it represents an efficient tool to analyze the long-term ground temperature behavior during BHE operation and subsequent recovery from a power-supply perspective.

In the following, we first present the analytical tools for estimating vertical heat fluxes and total power at the top boundary and the BHE toe based on an alternative form of the moving finite line source [40]. Then, a dimensional analysis is performed to describe the spatial and temporal dynamics of these fluxes while changing variables such as groundwater flow and heat exchanger length. This is fundamental for the subsequent analysis of the temporal evolution of the dimensionless power from different sources. The presented models are also applied to the previously studied Elgg site [41,42], where long-term temperature data is available and analytical models have successfully been validated [15]. Finally, a simulation of the power dynamics after hypothetical BHE shutdown is presented.