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Evaluation of different heat extraction strategies for shallow vertical ground-source heat pump systems

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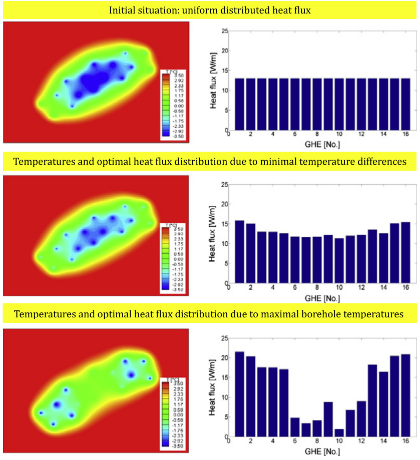
HIGHLIGHTS

- Evaluation of the best heat extraction strategy for GSHPSs.
- Investigation of costs and efficiency impacts on GSHPSs.
- Validation example revealed a sufficient difference of 0.2 °C.
- Improvement of the coefficient of performance (COP) of more than 2%.
- Improvements on energy extraction of approx. 20% and on TAC of approx. 12%.

GRAPHICAL ABSTRACT



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ABSTRACT

Shallow vertical ground-source heat pump systems (GSHPSs) have become a popular alternative to conventional heating systems. Typically more than one vertical ground heat exchanger (GHE) is required along with an increasing heat demand. The higher the number of GHEs, the more a system may benefit from optimal design and operation strategies that focus on costs and efficiencies. However, an optimisation of the heat and fluid flows in these systems, based on discretised models, can be computationally time-consuming and sometimes infeasible. To meet this challenge, one might apply simplified models and identify suitable constraints. In this work an analytical finite line source (FLS) model is compared by RockFlow, a finite element approach. The average absolute difference for a long-term investigation between these approaches is obtained at only approx. 0.2 °C, which was evaluated as sufficient. Subsequently, the FLS model is successfully applied to demonstrate the existence of borehole-specific heat flux distributions. For all case studies optimal solutions were found. These results confirmed the useful application of novel optimisation methods. The impact of the GHE specific heat flux distributions on the time-dependent and spatial temperature course in the vicinity of the GHE is impressively shown. The investigation of the soil and heat pump cycle revealed the system efficiency potential and costs. The efficiency improvement potential, caused by different optimal heat flux distributions, was approx. 2%. The best energy extraction improvement was nearly 20%, which equated to a monetary saving of 12%.

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Nomenclature

Abbreviations

GHE	ground-heat exchanger
Diff.	difference
TAC	total annual cost
GSHPS	ground-source heat pump system
erfc	error function
FEM	finite element method
FLS	finite line source

Indices and subscripts

j	specific case study number
n	specific heat pump number
i	specific borehole number
N	maximal number of boreholes
HP	heat pump
$HP1$, $HP2$	heat pump 1, heat pump 2
el	electric
con	connection
%	percentage
op	operation
b	borehole
f	fluid
in	input (into the HP)
€	euro
tot	total
sp	specific
max	maximal
SC	soil circuit
del	delivered
dem	demand
$crit$	critical
lo	lower limit
up	upper limit
m	mean
1st	first (related to 1st year)
s	long time scale (steady state time)
$*$	non-dimensional
y	year or per year

Parameters

c	specific cost factor (€)
L_b^{tot}	total borehole length (m)
χ, ψ	heat coefficients (kW °C^{-1}, kW)
δ, ε	power coefficients (kW °C^{-1}, kW)
T_0	undisturbed temperature (K)
β	geometrical relation
t	time (s)
t_s	time with a long time scale (s)
z	axial coordinate (m)
k	thermal conductivity (W m^{-1}K^{-1})
γ	substitution factor: $\frac{3}{2}\sqrt{t * t_s^{-1}}$ (–)
α^{th}	thermal diffusivity (m^{2}s^{-1})
R_b	thermal resistance (mKW^{-1})
π	number pi (–)
r_b	radial coordinate (m)
H	single borehole height (m)
$t_{j,y}^{m}$	mean annual operating hours (h y^{-1})
$t_{j,y}^{sp}$	specific annual operating hours (h y^{-1})
t^*	$t * t_s^{-1}$ (Eskilson characteristic data)

Variables

T	temperature (K or °C)
Q	heat (kW or MW)
P	electrical power (kW or MW)
Q_y	heat (kW h or MW h)
P_y	electrical power (kW h or MW h)
COP	coefficient of performance (–)
IC	investment costs (€)
OC	operational costs (€)
q	heat flux (W m^{-1})
g	g-function value (–)

Superscript

–	arithmetic mean

1. Introduction

The ground-depth dependent, nearly constant temperature makes geothermal heat pump systems one of the most efficient, comfortable and quiet heating and cooling technologies available today [1]. To achieve these advantages, ground-source heat pump systems (GSHPSs) require a state-of-the-art design [2]. The thermal properties of the ground are considered as key parameters for the design of GSHPSs [3]. Proper dimensions and arrangements of the vertical ground heat exchangers (GHEs) are required. Installers and engineers are occupied with the design of the optimal number, depth and spacing of the GHEs [2]. The most typical design and simulation models are reviewed by Yang et al. [4]. Thornton et al. [5] compared several practical design programs. They found that the recommended GHE length varied between these programs by 27%. Shonder et al. [6] repeated this comparison with updated computer programs. They showed that the recommended GHE length varied still by 7%. Cho and Mirianhosseinabadi [7] proposed an overview of the general development of GSHPSs and the related analytical models. They presented a chronologically diagram of numerical models, which emphasises the highly complex task of this subject. Do and Haberl [8] proposed a review of analytical and numerical GHE solution methods. They concluded that the closed loop GSHPS model is the most widely used. Koohi-Fayegh and Rosen [9] investigated the modelling of thermally interacting multiple boreholes. As a result, they concluded that mainly the heat needs of these systems should be maintained and that therefore especially the temperature of the circulating fluid needs to be adjusted. Lamarche et al. [10] reviewed and evaluated the thermal resistance. They stated that the thermal resistance can be found in almost all design methods. For GSHPSs with a heat demand of more than approx. 30 kW, a more substantial system analysis may be appropriate [11]. Detailed simulations of planned borefields are convenient for this purpose or can even be required by national regulations, as in Germany [11]. However, most countries have no binding rules or guidelines highlighting the urgent need for further research on the environmental impact and legal management of shallow geothermal installations [12].

GSHPSs typically consist of a circulating water–glycol piping that thermally couples the GHE with the evaporator [1]. The expected life span of the piping is nearly 50 years, and this underground system is often guaranteed for at least 25 years [1]. The systems are durable and require little maintenance. Most components are independent of weather and well protected since they are installed in the underground. A study from Blum et al. [13] revealed that for residential applications in southern Germany, typical GHEs consist of double U-tubes with a mean total length of 190 m for two boreholes, meaning a length of 95 m each. The