Energy Conversion and Management 166 (2018) 106–119

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Global sensitivity analysis of borehole thermal energy storage efficiency on the heat exchanger arrangement

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ARTICLE INFO

Keywords:
Borehole thermal energy storage
BTES
Global sensitivity analysis
Borehole heat exchanger
Numerical model
Thermal energy storage

ABSTRACT

Global sensitivity analysis of the efficiency of borehole thermal energy storage (BTES) during long-term operation on the borehole heat exchanger (BHE) arrangement was investigated to advance understanding of the system's thermal performance. Three parameters were assessed to determine the BHE arrangement: the first parameter designate the distance between BHE axis in x direction, the second in y direction and the third an angle between top surface of the rock mass and boreholes axis. Conducting research on the real system is extremely expensive, so it was decided to conduct simulation studies utilising a finite element method. The ANSYS software with a newly implemented heat and mass transport model in BHE was used. Based on conducted numerical simulations, and according to the design of the experiment, a multidimensional response surface was achieved. The global sensitivity was conducted based on a response surface model. It was found that the BHE inclination (S_{Eeff}^{P3} = 0.97 – FAST algorithm) has a crucial impact for the BTES efficiency. The area on response surface, where the optimal BHE arrangement to maximise BTES efficiency could be reached, is an inclination $P3 = 0°$ and BHE spacing in the range of $P1 = P2 = (1.5–3\text{ m})$.

1. Introduction

The seasonal and random nature of renewable energy sources is a problem which occurs in numerous technological fields. These include heat from solar collectors, various technological processes, and waste heat. It is globally estimated that approximately 56% of residential and 42% of commercial buildings final energy is consumed for heating [1]. Therefore, there is a great potential in storage of this energy and the use of thermal energy storage (TES) systems has become more popular in recent years. The thermal energy could be stored for several methods as sensible heat, latent heat of melting or evaporation and as heat of chemical reactions [2]. The TES systems are generally divided into two groups defined by their storage period: short term thermal energy storage (STTES) and seasonal thermal energy storage (STES) systems. The main types of STES are tank thermal energy storage (TTES), pit thermal energy storage (PTES), borehole thermal energy storage (BTES), cavern thermal energy storage (CTES) and aquifer thermal energy storage (ATES) [3]. The TES method having the most economic significance is BTES. The seasonal storage of energy in the rock mass is the most interesting and promises the greatest hope as example of TES [4]. BTES is found to be a favourable method for storing large amounts of thermal energy [5].

The first large scale high temperature BTES was built at Lulea University of Technology, in 1983. Its 120 boreholes were drilled through 120,000 m^3 of crystalline rock. The heat was delivered from the local steel and coke plants [6]. Another well-known project, is the BTES system in the Drake Landing Solar Community (DLSC) in Okotoks, Canada. The BTES in DLSC consists of 144 boreholes, each stretching to a depth of 37 m and planned in a grid with 2.25 m between them [7].

BTES system consists of an array of boreholes heat exchanger. A typical BHE consists of a plastic pipe inserted into the vertical or inclined borehole. To provide good thermal contact with the surrounding soil, the borehole is then filled with a high thermal conductivity grouting material. Then, water or non-freezing liquid (in installation with heat pump) flow is added in a closed loop pipe circuit. The most common construction of an exchanger used in boreholes is a single U-tube (which consists of an inlet, outlet pipe and grouting material), with a double U-tube and concentric pipe also utilised. BHE are used as the heat exchanger in ground source heat pump (GSHP) installations, in which the rock mass is the only source of heat. In GSHP installation rock mass are required to be regenerated during the summer months. Another application of BHE are BTES systems, in which the rock mass is the TES. There are several parameters which determine the efficiency of a BTES and they can be classified as follows:

- basic design and material parameters, i.e. the pipe diameter and

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https://doi.org/10.1016/j.enconman.2018.04.009
Received 9 March 2018; Received in revised form 29 March 2018; Accepted 4 April 2018
Available online 03 May 2018
0196-8904/

Nomenclature

b	thickness of the pipe wall, m, heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
c	specific heat, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
D	diameter, m
E	energy, J
H,h	depth, m
k	distance between pipe axes, m
P	parameters,
q	heat flux, $W{\cdot}m^{-2}$
R^2	determination coefficient
R	rank of parameters
r	radius, m
S	sensitivity
T	temperature, K
t	time, s
u,V	fluid flow velocity, $m{\cdot}s^{-1}$
$\dot{V}$	volume flow, $m^3{\cdot}s^{-1}$
x,y,z	Cartesian coordinates, m
y	parameters value predicted from response surface or simulation

Greek Symbols

λ	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
ρ	density, $kg{\cdot}m^{-3}$
μ	dynamic viscosity, $Pa{\cdot}s$

Subscripts

a	air
b	borehole
f	fluid
eff	efficiency
g	grout
i,in	inner, inlet
o,out	outer, outlet
p	pipe
s	rock mass

wall thickness, distance between pipes axes, BHE depth, arrangement in the subsurface, arrangement on the surface, moisture content of the soil, infiltration and ground water flow, rock mass and grout thermal properties, and distance from consumers,

- operating parameters, i.e.: the type of flow (turbulent or laminar), temperature of the fluid, type of work, and local climatic conditions.

To the best of the author's knowledge, there has not been a study on the sensitivity of BTES efficiency on the BHE arrangement including inclined BHE. Most of the published research has focused solely on the vertical arrangement BHE or GSHP systems. For example, Bayer et al. [8] presented the mathematical procedure for optimization of a BHE field. The proposed approach sequentially reduces the least effective BHEs in the BHE-field. Ciampi et al. [9] conducted a sensitivity analysis by simulating 27 configurations obtained by varying solar collectors area, volume of STTES and volume of BTES. An life cycle assessment (LCA) of BTES in district heating systems and optimal system designs with and without BTES was carried out by Welsch et al. [10]. Several pieces of research have focused on the design or operating parameters. The influence of the parameters such as: BHE depth, diameter of the heat exchanger pipe, inlet temperature, and Reynolds number, on the BHEs thermal efficiency was studied by Khalajzadeh et al. [11]. The effects of parameters such as: BHE length, pipe spacing, types of fluid, fluid flow rates and soil thermal properties was analysed by Casassno and Sethi [12]. Kurevija et al. [13] presented how the spacing of adjacent boreholes and thermal interferences influences the required BHE

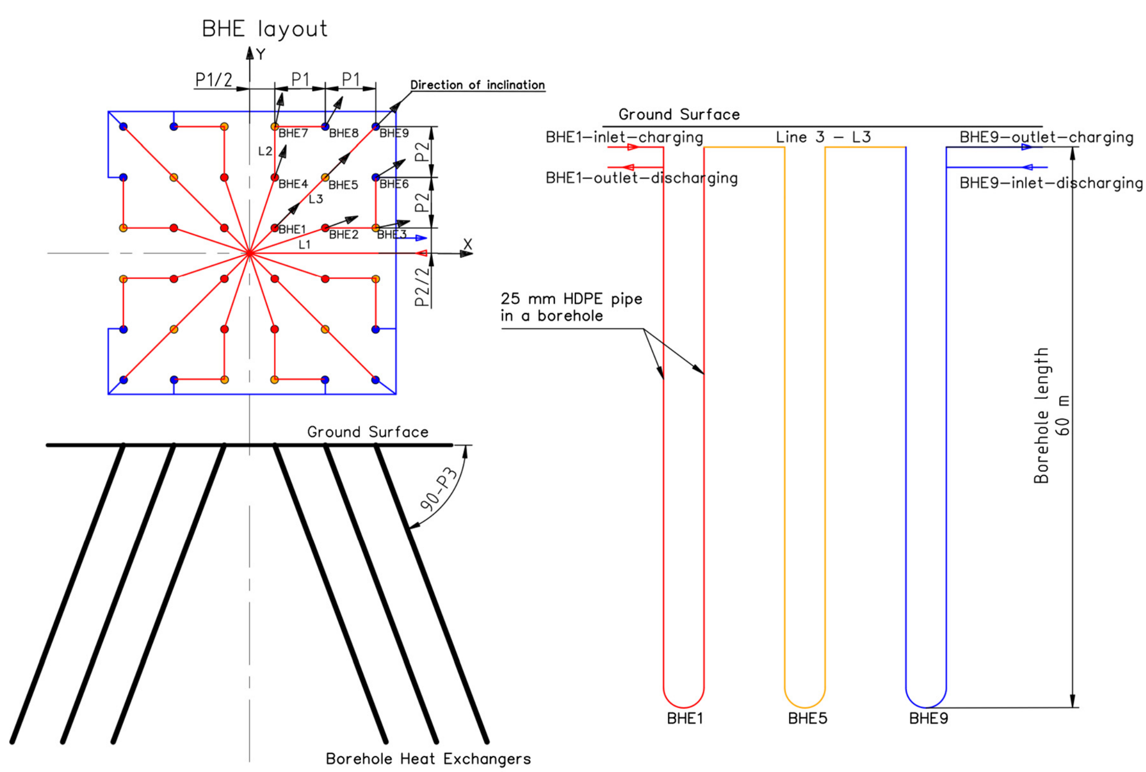

Fig. 1. The description of the BTES system.