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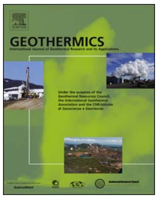

# Efficiency analysis of borehole heat exchangers as grout varies via thermal response test simulations

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## ABSTRACT

Grout is normally used in borehole heat exchangers, in part for separating different water layers. Grout can also enhance heat transfer with the ground when it has high thermal conductivity. In this article, thermal response test results from simulations of borehole heat exchangers are presented. The work is undertaken to enhance understanding and predictions of the heat transfer effectiveness and energy efficiency of borehole heat exchangers as grout varies. The following borehole heat exchanger types are considered: coaxial, single U-tube and double U-tube. The results quantitatively describe the effect of grout on energy efficiency and indicate if it is reasonable to incur the higher costs of using grouts of high thermal conductivity to enhance borehole heat exchanger performance.

## 1. Introduction

The borehole heat exchanger (BHE) is being applied increasingly to manage energy and heat in buildings (Dincer and Rosen, 2011). Underground thermal energy storage (UTES) is the subject of much recent research made (Kizilkan and Dincer, 2015; Kurevija et al., 2012; Li et al., 2014a; Jaszczur et al., 2015; Sliwa and Rosen, 2015). Heat extraction can often be more easily accomplished from boreholes than from geothermal waters (Tomaszewska and Pająk, 2012).

The main geological parameters of a BHE are the characteristics of the local ground (at the surface and including all layers drilled through to creating the borehole). Such characteristics affect BHE energy effectiveness and include (Sliwa and Kotyza, 2003):

- geothermal gradient,
- heat flux of natural earth,
- thermal conductivity and density of rocks,
- anisotropy of thermal conductivity of orogenic belt,
- thermal capacity, porosity, saturation and hydrodynamic characteristics of layers,
- type of deposit material filling pore and fracture spaces,
- natural speed of deposit medium filtration.

The energy flux reaching the surface of the earth due to BHE operation is largely dependent on its construction, which requires equipment for reaching the desired well location and use of thermal energy. Construction characteristics are set largely during the design and implementation of a BHE. Typical BHE construction types include:

- single U-tube,
- multi U-tube,
- coaxial (Sliwa and Rosen, 2015),
- helical BHE (Zarrella and De Carli, 2013; Zarrella et al., 2013), and
- BHE in piles (Li and Lai, 2012).

The construction can carried out in vertical boreholes, using the same approach for BHEs as used in the technology of Geothermal Radial Drilling (GRD), which permit the installation of directional (oblique) wells (Knez, 2014).

A borehole heat exchanger can also be developed from abandoned wells originally used for other tasks (oil and gas wells, for example). Existing wells can be converted to deep BHEs (Sapinska-Sliwa et al., 2015). Some important construction and design characteristics follow (Sliwa and Kotyza, 2003):

- depth of packer or insulation cork in wells,
- diameters of wells,
- internal and external diameters and lengths of insulation casings,
- number, length and diameter of casings,
- quality and condition of material insulating casings,
- heat resistance of material of the internal column,
- drill axis,

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**Nomenclature**

| | |
|---|---|
| $C_p$ | Specific heat at constant pressure (J kg$^{-1}$ K$^{-1}$) |
| $D_b$ | Borehole diameter (m) |
| $d_{in}$ | Inside diameter of U-tube (m) |
| $d_{out}$ | Outside diameter of U-tube (m) |
| $H$ | Depth of BHE (m) |
| $k$ | Theoretical directional factor of TRT |
| $k_{TRT}$ | Empirical directional factor of TRT |
| $P$ | Thermal power of TRT (W) |
| $q$ | Unit thermal power (W m$^{-1}$) |
| $r$ | Radius (m) |
| $R_b$ | BHE thermal resistance (m K W$^{-1}$) |
| $R_{tr}$ | Contact heat transfer resistance (associated with material discontinuity) (m K W$^{-1}$) |
| $T$ | Temperature (K) |
| $t$ | Time (s) |
| $\alpha_{in}$ | Heat convection coefficient (W m$^{-2}$ K$^{-1}$) |
| $\lambda$ | Thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $\lambda_g$ | Thermal conductivity of grout (W m$^{-1}$ K$^{-1}$) |
| $\lambda_p$ | Thermal conductivity of U-tube material (W m$^{-1}$ K$^{-1}$) |
| $\rho$ | Density (kg m$^{-3}$) |
| $\gamma$ | Euler constant ($\gamma = 0.5772156$) |

- centricity of internal column,
- distances separating BHEs.

These parameters are affected by the geological and construction characteristics already noted, and influence the profitability of using drills to make BHEs. Exploitation parameters include the following (Sliwa and Kotyza, 2003):

- mean annual heat production,
- heating power (maximum instantaneous and long-term),
- type, temperature and volume flux of heat carrier,
- flow resistance of heating medium,
- time for ground temperature restoration (i.e., energy resource renewal),
- temperature of compressed heat carrier (which depends on carrier cooling in receiving installation),
- time of usage,
- distance between heat consumer and well,
- consumer type, heat rate, operating time and heat consumption,
- local climate.

The mean BHE energy efficiency for depths up to approximately 200 m is about 50 W m$^{-1}$ or, conversely, the depth required per unit power is approximately 20 m kW$^{-1}$. However the value of the BHE energy efficiencies deviate significantly from case to case, with values typically within the range 20–100 W m$^{-1}$. This value range is mainly representative of the thermal conductivity of rocks, and applies mainly to properly constructed BHEs. An important factor in BHE design and construction, which affects significantly the energy transfer between the working fluid in the BHE (e.g., propylene glycol) and the rock mass, is the kind of grout used and its connection with heat exchanger U-tube and borehole wall. Yet, the quantitative information available on the effect of grout is sparse. The purpose of this article is to analyse the effects of grout type on effective thermal conductivity $\lambda_{eff}$ of a BHE, for various kinds of grout, so as to improve understanding of the heat transfer and efficiency of BHEs and thereby help enhance the design of BHE systems.

Grout has an impact on thermal resistivity. Many types of sealing materials have been investigated in drilling research (Stryczek and Gonet, 1998; Stryczek et al., 2013).

## 2. Thermal response test

Numerous nations have experienced in the last decade significant increases in the use of heat pumps and BHEs for heating and cooling. The thermal response test (TRT) provides an accurate means of evaluating BHE thermal properties. TRTs are usually performed on the first hole, especially for large installations with thermal capacities exceeding 100 kW. TRT results for a BHE determine the number of boreholes required to satisfy heating and/or cooling demands. A variant of the TRT is described by Acuña and Palm (2013).

The TRT methodology is founded on the thermal interaction as determined by the partial differential equation for the dynamic relationship $T = T(r, t)$, where $r$ denotes the radius extending from the center of the BHE, and $t$ the test duration. The form of the expression follows:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{\rho C_p}{\lambda}\frac{\partial T}{\partial t}, \tag{1}$$

This expression corresponds mathematically to the Theis equation, which in hydrogeology considers the distribution of pressure $p = p(r, t)$, instead of the distribution of temperature $T = T(r, t)$. This type of partial differential equation can be solved with the method of substitution, reducing to an ordinary differential equation the partial differential of Eq. (1). The following terms are substituted:

$$u = \frac{r^2 \rho C_p}{4t\lambda} \tag{2}$$

**Table 1**
Technical parameters for BHEs at Laboratory of Geoenergetics, Drilling, Oil and Gas Faculty, AGH University of Science and Technology, in Krakow, Poland.

| BHE type and construction | Parameter symbol | Parameter | Value(s) |
|---|---|---|---|
| BHE construction | $D_b$ | Borehole diameter | 0.143 m |
| | $H$ | Borehole depth | 78.0 m |
| | $\lambda_t$ | BHE tube conductivity (polyethylene) | 0.42 W m$^{-1}$ K$^{-1}$ |
| Coaxial | $D_{out}$ | Outer tube outer diameter | 0.0582 m |
| | $D_{in}$ | Outer tube inner diameter | 0.053 m |
| | $d_{out}$ | Inner tube outer diameter | 0.04 m |
| | $d_{in}$ | Inner tube inner diameter | 0.0348 m |
| | $\lambda_g$ | Grout (filling) material conductivity | 1.0, 1.5, 2.0 and 2.5 W m$^{-1}$ K$^{-1}$ |
| Single U-tube | $d_{out}$ | U-tube outer diameter | 0.04 m |
| | $d_{in}$ | U-tube inner diameter | 0.0352 m |
| | $\lambda_g$ | Grout (filling) material conductivity BHE-2 | 1.0, 1.5, 2.0 and 2.5 W m$^{-1}$ K$^{-1}$ |
| Double U-tube | $d_{out}$ | U-tube outer diameter | 0.032 m |
| | $d_{in}$ | U-tube inner diameter | 0.0272 m |
| | $\lambda_g$ | Grout (filling) material conductivity | 1.0, 1.5, 2.0 and 2.5 W m$^{-1}$ K$^{-1}$ |