

Comparison of effective thermal conductivity in closed-loop vertical ground heat exchangers

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ABSTRACT

Performing a series of in-situ thermal response tests, the effective thermal conductivity of six vertical closed-loop ground heat exchangers was experimentally evaluated and compared to each other, which were constructed in a test bed in Wonju, South Korea. To compare thermal efficiency of the ground heat exchangers in field, the six boreholes were constructed with different construction conditions: i.e., different grouting materials (cement vs. bentonite), different shape of heat exchange pipe-sections (conventional U-loop type vs. new 3 pipe-type), and different additives (silica sand vs. graphite). One observation borehole was installed in the middle of the test site to measure a subsurface temperature change during performing the in-situ thermal response test. From the test results, it can be shown that cement grouting has a higher effective thermal conductivity than that of bentonite grouting, and graphite better performs over silica sand as a thermally enhancing additive. In addition, a new 3 pipe-type heat exchanger yields less thermal interference between the inlet and outlet pipe than the conventional U-loop type heat exchanger, which results in superior thermal performance.

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1. Introduction

With the rapidly increasing worldwide energy demand, it is necessary to develop new and renewable energy resources, which can be alternatives to universally used fossil fuels such as oil, gas and coal. Among the various types of new and renewable energy resources, geothermal energy is considered to be a relatively clean and inexhaustible resource. Geothermal energy can be used at suitable sites for electrical power generation, or directly used as heat for numerous applications such as: ground-source heat pumps; space and district heating; greenhouse heating; agricultural drying; and industrial process, etc.

Recently, ground-source heat pump (GSHP) systems have been increasingly used around the world, because they are among the most energy- and cost-efficient heating and cooling systems for residential and commercial buildings. They use less electricity and produce a much smaller amount of greenhouse gas emission than conventional HVAC systems and provide a comfortable indoor environment for building occupants. According to the US Environmental Protection Agency [1], GSHP systems can reduce energy consumption and corresponding greenhouse gas emission by up to

44% compared to air-source heat pumps and by up to 72% compared to electric resistance heating with standard air-conditioning equipment for residential applications.

A typical GSHP system mainly consists of a conventional water-source heat pump unit coupled with a group of ground heat exchangers (GHEXs) where heat exchange occurs between a working fluid circulating through the GHEX and the ground formation. A GHEX, where heat extraction or injection of thermal energy occurs from/into the ground, is an important device that determines the performance of a GSHP system and its initial installation cost. A vertical closed-loop ground heat exchanger, shown in Fig. 1 and also known as a borehole heat exchanger (BHE), has been largely used in Korea [2]. The performance of this device is closely related to the heat transfer between a working fluid circulating in the pipe of the GHEX and soil or rock around the borehole.

For optimum sizing or simulating the performance of a GHEX, the thermal properties of ground formation in the vicinity of the GHEX must be estimated. The thermal response test (TRT) method is an effective method for the in-situ determination of the effective thermal conductivity of the ground formation. In this test, a known thermal load is applied to the GHEX along with accurate measurements of temperature and flow rate of the working fluid. Since Mogensen [3] first proposed the concept and detailed analysis method for the TRT, it has been used to evaluate effective ground thermal conductivity in recent years [4–10].

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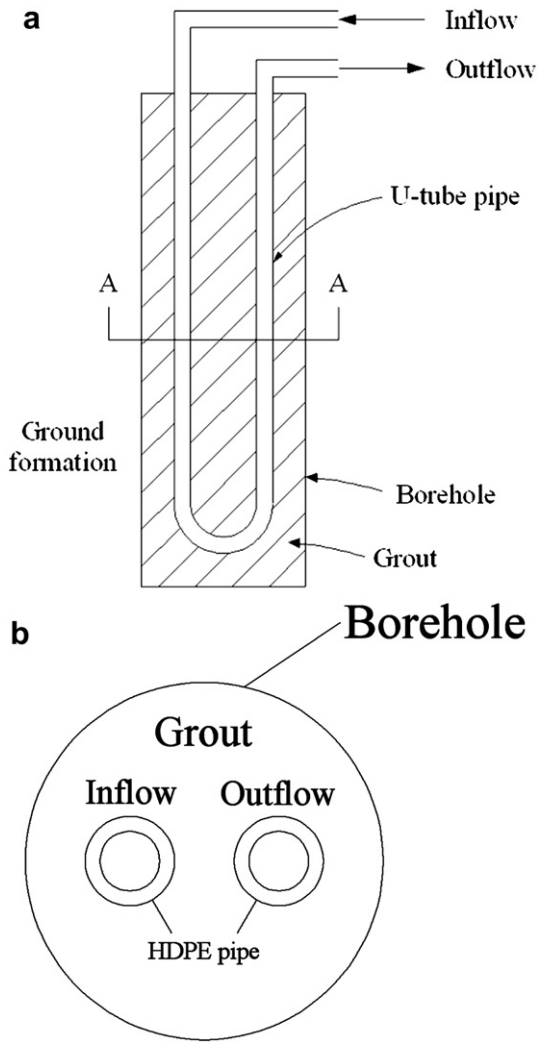


Fig. 1. Closed-loop vertical ground heat exchanger.

The well-known influence factors on heat exchange are summarized as the thermal conductivity of grout backfilling boreholes, HDPE pipes and adjacent geologic formations. The thermal efficiency of the ground heat exchanger can be improved by increasing the thermal conductivity of grout and HDPE pipes. This leads to saving to some extent construction cost along with reducing the required length of the heat exchange pipe. In this paper, another factor, thermal interference between the inlet and outlet pipe, is introduced as shown in Fig. 2, which is discussed in detail later.

To evaluate the effective ground thermal conductivity and investigate the thermal efficiency of the GHEX, six test boreholes were constructed with different installation conditions: such as different grouting materials (cement vs. bentonite), different shape of pipe-sections (conventional U-loop type vs. new 3 pipe-type), and different additives (silica sand vs. graphite), at a test bed in Wonju, South Korea. Thereafter, the thermal efficiency of each borehole is evaluated by conducting a series of in-situ thermal response tests.

- (a) Schematic of closed-loop vertical ground heat exchanger.
(b) Cross-section of closed-loop vertical ground heat exchanger (A–A section).

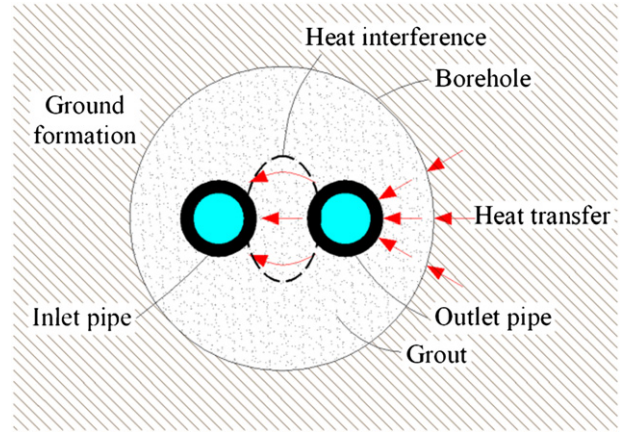


Fig. 2. Mechanism of heat transfer in geothermal heat exchanger (heating mode).

2. Method

2.1. Line source model

There have been a number of models for calculating the thermal properties of the GHEX. These models, which are based on Fourier's law of heat conduction, include the analytical line source model [11], the cylindrical source model [12] and several numerical models [13–15]. In this study, the line source model is applied, which is the most widely used analytical procedure when interpreting the in-situ TRT data. The approach adopts the analytical solution for the response to an infinite constant-strength line source within a homogeneous, isotropic, infinite medium. When constant lateral heat flow is maintained from the line source with negligible vertical heat flow along the borehole, the temperature field around the GHEX is only dependent on time (t) and radial distance (r) from the borehole axis. Using the so-called exponential integral Ei , the temperature distribution is described as follows [12]:

$$T(r, t) - T_i = \frac{q}{4\pi\lambda} \int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} du = \frac{q}{4\pi\lambda} Ei\left(\frac{r^2}{4\alpha t}\right) \quad (1)$$

where, q is the heat injection rate per active length of borehole [W/m], λ is the effective thermal conductivity of the ground [W/m·K], α is the thermal diffusivity of the ground [m²/s], and T_i denotes the undisturbed initial ground temperature [K].

For large values of the parameter $\alpha t/r^2$, the exponential integral can be approximated with the following simple relation:

$$Ei\left(\frac{r^2}{4\alpha t}\right) \approx \ln\left(\frac{4\alpha t}{r^2}\right) - \gamma \quad (2)$$

where γ is Euler's constant [0.5772...]. The maximum error of this simplification is less than 2.5% for $\alpha t/r^2 \geq 20$ and 10% for $\alpha t/r^2 \geq 5$ [16].

Evaluating the line source temperature at the borehole radius ($r = r_b$) and introducing the effect of the borehole thermal resistance (R_b) between the fluid and the borehole wall, the average fluid temperature of the circulation fluid as a function of time can be written as:

$$T_f(t) = \frac{q}{4\pi\lambda} \left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma \right] + qR_b + T_i \quad (3)$$

Eq. (3) can be rearranged in a linear form as

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