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# Field-scale evaluation of the design of borehole heat exchangers for the use of shallow geothermal energy

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ABSTRACT

A numerical model for the simulation of temperature changes in a borehole heat exchanger (BHE) with fluid circulating through U-tubes is developed. The model can calculate the thermal power transferred from heat pumps to BHEs while considering the nonlinear relationship between temperature of the circulating fluid and the thermal power. The use of the developed model enables the design of a geothermal heat pump (GHP) system with the view of pursuing efficiency and financial benefit. The developed model is validated by comparing two measurement datasets with their respective simulation results. The numerical evaluation of a real GHP system with 28 BHEs and 79 heat pumps involved consideration of a base case and modified cases. In all cases, the temperatures of the circulating fluid at the BHE inlet and outlet, heat pump efficiency, and the heating power and electric power of heat pumps were obtained. The estimated cost of electricity in the year 2030 is 0.146 US$/kW. The most cost-effective system in this case is for there to be 4, 6, and 6 BHEs on the first, second, and third floors, respectively.


## 1. Introduction

Geothermal heat pump (GHP) or ground-source heat pump systems that use shallow geothermal energy resources for heating and cooling purposes have been popular in various parts of the world. The electrical efficiency of the GHP system is better than that of the air-source heat pump system because ground temperature is higher than air temperature in the heating season and lower than air temperature in the cooling season. The vertical closed-loop GHP system is the most popular GHP system [1]. Its advantage is in its applicability to most geographic locations and most system sizes. It has good efficiency for heterogeneous media, such as fractured aquifers in Korea.

The vertical closed-loop GHP system tends to have the highest installation costs of the various GHP systems because of the expense of BHEs [2]. This makes the vertical closed-loop GHP system unattractive financially over the short term. The installation costs are typically returned in energy savings in 5–10 years. Therefore, to reduce the installation cost and increase energy savings, BHE design, including the total number of BHEs, length of each BHE, and spacing between BHEs at the ground surface, should be optimized using a quantitative and reliable assessment procedure. The assessment procedure for the BHE design requires an understanding and corresponding treatment of the physical processes in and around a BHE. In the cooling season, the heat of indoor air is delivered by a heat pump to circulating fluid. The circulating fluid transports heat through a U-tube by advection, and transports the heat to the ground by conduction. The conducted heat raises the temperature of the ground and groundwater. The opposite process occurs in the heating season.

The earliest approaches for calculating the heat transfer around a BHE used Kelvin's line source model [3–5]. Kelvin's line source model assumes the BHE to be an infinite constant-strength line-source within a homogeneous, isotropic, and infinite medium. Kavanaugh [6] developed a cylindrical source model that considers a single isolated pipe surrounded by an infinite solid with constant properties. The model can be used to calculate the temperatures of the circulating fluid at the BHE inlet and outlet. Analytical models such as the line source model and cylindrical source model have the advantages of simplicity of implementation and high calculation speed in comparison with numerical models. However, they have limitations in terms of the ground and BHE conditions affecting the performance of the BHE.

Numerical models have been developed to overcome limitations of analytical solutions. Using a two-dimensional finite-difference model, Eskilson [7] developed a solution for the heat flow using functions for the BHE pattern and geometry, called g-functions. The g-functions are related to the spacing between BHEs and the length

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and radius of each BHE. Eskilson's solution is not accurate when the term for the heat rejection/extraction is less than 3–6 h. Yavuzturk et al. [8] developed a two-dimensional finite-volume model. They used an algebraic algorithm to automatically generate BHE-shaped grids in polar coordinates for the BHE geometry. Gehlin and Hellström's [9] approach to groundwater flow and its effect in the vicinity of a BHE is based on a two-dimensional finite-difference model. To demonstrate the influence of topographical and groundwater effects, Signorelli [10] improved the three-dimensional finite-element model FRACTure [11] so that it was suitable for BHE modeling with a fine BHE-shaped mesh.

However, the fully numerical models have not been applied to the evaluation of the BHE design. Instead, they were applied to evaluate simpler problems such as thermal response tests for measuring *in situ* thermal conductivity. On the basis of the above research, a proper and reliable model for the optimal design of the vertical closed-loop GHP system is developed in this work. The developed model is validated by comparing measurement datasets with simulation results. The model is then applied to the evaluation of BHE design.

## 2. Theory

### 2.1. Physical background

The general form of the basic mass and energy balance equations in a porous medium is

$$\frac{d}{dt}\int_{V_n} M \mathrm{d}V_n = \int_{\Gamma_n} \mathbf{F}\cdot\mathbf{n}\mathrm{d}\Gamma_n + \int_{V_n} q\mathrm{d}V_n, \tag{1}$$

where $V_n$ is an arbitrary subdomain bounded by the closed surface $\Gamma_n$ and $\mathbf{n}$ is a normal vector on the surface element $d\Gamma_n$ pointing inward into $V_n$. The quantity $M$ denotes the mass or energy per unit volume. $\mathbf{F}$ represents the mass or heat flux and $q$ represents sources and sinks [12]. The volume $V_n$ should be big enough to be a "representative elementary volume" including many pores and mineral grains, so that the continuum approximation for the porous medium is valid.

The mass accumulation term ($M_M$) is

$$M_M = \phi\rho, \tag{2}$$

where $\phi$ denotes porosity and $\rho$ denotes density.

The heat accumulation term ($M_H$) is

$$M_H = (1-\phi)\rho_R c_R T + \phi\rho u, \tag{3}$$

where $\rho_R$ is the rock density, $c_R$ is the specific heat of the rock, $T$ is temperature, and $u$ is the specific internal energy. Within each subdomain $V_n$ the fluid and rock have the same temperature.

The advective mass flux ($\mathbf{F}_M$) is

$$\mathbf{F}_M = \rho\mathbf{u} = -\frac{k\rho}{\mu}(\nabla P - \rho\mathbf{g}), \tag{4}$$

where $\boldsymbol{u}$ is the Darcian velocity, $k$ is permeability, $\mu$ is viscosity, $P$ is pressure, and $\boldsymbol{g}$ is the vector of gravitational acceleration.

The conductive and convective heat flux ($\mathbf{F}_H$) is

$$\mathbf{F}_H = -\lambda\nabla T + h\mathbf{F}_M, \tag{5}$$

where $\lambda$ is the thermal conductivity and $h$ is the specific enthalpy.

### 2.2. Model development

The vertical closed-loop GHP system consists of heat pumps, fluid pumps, and BHEs. A heat pump is located indoors and moves heat from indoor air to the circulating fluid using mechanical work. A fluid pump sends the circulating fluid through the BHE and a heat pump. A BHE transfers heat to the ground. Fig. 1 is a schematic diagram of the vertical closed-loop GHP system in cooling mode.

The model presented in this work focuses on the temperature variations in the circulating fluid and in the vicinity of the BHE. Our model is based on a widely accepted three-dimensional numerical simulator for heat and fluid flow in geothermal systems, TOUGHREACT [13]. TOUGHREACT can consider fluid flow occurring under viscous, pressure, and gravity forces according to Darcy's law and heat transport by means of conduction and convection including both sensible and latent heat transport. To take thermal and hydraulic processes related to the vertical closed-loop GHP system into account, three modules are developed and added to TOUGHREACT (Fig. 1 (b)). The developed model is referred to as the modified TOUGHREACT model.

The first module calculates heat flux between the circulating fluid and the U-tube wall in the BHE. The heat transfer coefficient is used in calculating the convective heat transfer between the flowing fluid and solid U-tube wall. The heat flux ($\mathbf{F}_H$) between the fluid and pipe wall is

$$\mathbf{F}_H = -h\left(T_w - T_f\right), \tag{6}$$

where $h$ is the heat transfer coefficient, $T_w$ is the temperature of the pipe wall, and $T_f$ is the temperature of the fluid. The circulating fluid is assumed to be well mixed (i.e., all at the same temperature) across each cross-section of the U-tube. The heat transfer coefficient is obtained using the Dittus-Boelter correlation, which is used for many applications in turbulent flow systems [14]:

$$\begin{aligned} h &= Nu\frac{\lambda}{d}, \\ Nu &= 0.023\,\mathrm{Re}^{0.8}\mathrm{Pr}^{n}, \\ \mathrm{Re} &= \frac{v d\rho}{\mu}, \\ \mathrm{Pr} &= \frac{\rho\mu}{\lambda}, \end{aligned} \tag{7}$$

where $d$ is the pipe diameter and $v$ is the flow velocity in the U-tube. Nu, Re, and Pr denote the Nusselt number, Reynolds number, and Prandtl number, respectively. The superscript $n$ is 0.3 when the temperature of the fluid is higher than the temperature of the pipe wall and is 0.4 when the temperature of the fluid is lower than the temperature of the pipe wall.

The second module considers the fluid pump. TOUGHREACT cannot simulate circulation of the fluid in a closed circuit. To simulate such circulation, the mass source term in Eq. (1) and an infinite-volume element are used. At the BHE inlet, a mass source term generates a fluid with a temperature the same as that of the fluid at the BHE outlet ($T_{Source} = T_{Outlet}$). This fluid passes through the BHE to the BHE outlet, where it flows into an infinite-volume element that has no effect on the other elements and simulation results, effectively acting as a mass sink.

The third module calculates the rate of energy transfer between the heat pump and circulating fluid. The energy transfer rate, $Q$ in Fig. 1 (b), depends on the type of heat pump, indoor air temperature ($T_{Indoor}$), and circulating fluid temperature at the BHE outlet ($T_{Outlet}$). The thermal and electric power of the heat pump varies with the $T_{Indoor}$ and $T_{Outlet}$. The variation data can be obtained from the specification data sheet of the heat pump. Table 1 is an example of a specification data sheet for a heat pump. The $P_T$ is the thermal power carried by the heat pump and the $P_E$ is the electric power supplied to operate the heat pump.