FLOW THROUGH A POROUS MEDIUM AND GROUND HEAT EXCHANGERS

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Summary The thermal response of vertical Ground Heat Exchangers (GHEs) is examined when the ground sublayer involves underground water flow. A numerical model constructed to allow for the presence of porous media regions and a consequent validated computational finite elements model in FlexPDE software lead to an analysis of several factors effecting the efficiency of the GHE, such as summer and winter mode of operation, underground temperature variation in small depths, borehole radius, borehole grout properties, U-tube diameter, U-tube leg and borehole centers distance, groundwater flow velocity.

INTRODUCTION

Geothermal energy, the thermal energy generated and stored in the Earth, is a fast-growing Renewable Energy Source. It has been used since Paleolithic times for bathing, through the use of water from hot springs, as well as since ancient Roman times for space heating. It is nowadays used for electricity generation as well, in addition to district heating, space heating, spas, industrial processes, desalination and agricultural applications. Depending on the depth geothermal energy systems (GES) can be classified as deep or shallow. One of the most common approaches for lower and mid-depth applications for shallow GES is the borehole vertical Ground Heat Exchanger (GHE), where using a Ground Source Heat Pump (GSHP) fluid circulates through pipes (U-tubes) and an indirect thermal contact is achieved between the fluid and the subsurface. GHE technology is of higher efficiency for air-conditioning compared to conventional systems as the underground environment provides lower temperature for cooling and higher temperature for heating, with the underground temperature being approximately equal to the mean annual atmospheric temperature of the year [1–2].

A GHE system is controlled by the effective area, the thermal conductivity of the subsurface, the velocity of the circulating fluid, the equipment involved, (type and size of pipes, the grouting material, etc.), the presence of underground water in the form of an aquifer, and so on. A parametric analysis of the aforementioned factors using simulations and validation tools can lead to the optimization of the GHE system. For more on the design aspects of GHEs the reader is referred to [3]. An aquifer is the saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients [4]. In order to describe the flow through a porous medium, Darcy's law needs to be applied. The theory, allowing the estimation of the velocity or flow rate within an aquifer was firstly established by Darcy [5] based on experimental results. Model results with various seepage velocities (i.e. Darcy's velocity over porosity) indicate that groundwater flow influences the average GHE temperature, and in the water-baring layer the average temperature is lower than in the dry regions [6]. It is also noteworthy that the temperature of the affected ground layer reaches a steady-state much sooner than in other regions.

The effect of an aquifer on a GHE is examined in this paper through numerical modeling in the FlexPDE software based on the convection-diffusion equation and Darcy's law. FlexPDE is a general-purpose software that builds a mesh, constructs a system finite-elements model (FEM), solves it, and presents an easy to use graphical output for steady-state, time-dependent and free boundary problems.

MATHEMATICAL MODEL OF GHEs IN POROUS MEDIA

The basic three-dimensional equation governing the convective and conductive heat transfer is given as

$$\rho c_p \frac{\partial T}{\partial t} + \rho_f c_{pf} u_{in} \cdot \nabla T + \rho_w c_{pw} u_p \cdot \nabla T + \nabla \cdot (-\lambda \nabla T) = Q, \tag{1}$$

where ρ denotes the density [kg m^{-3}], u the velocity [m s^{-1}], T the temperature [K], c_p the specific heat capacity [J kg^{-1} K^{-1}], λ the thermal conductivity (W m^{-1} K^{-1}), Q the power density of the heat source [W m^{-3}]. Subscript f denotes fluid, w denotes water, *in* denotes inside tube and p denotes porous media. At the boundary between the fluid and the tubes (Darcy's regime) the convective heat flux is $h\Delta T$, where h is the convective heat transfer coefficient of the process [W m^{-2} K^{-1}] and ΔT is the temperature difference at the boundary. The convection heat transfer coefficient h can be estimated to be $h = \lambda \mathrm{Nu}/D_H$, where D_H is the hydraulic diameter (in this case the tube-inside diameter) and Nu is the Nusselt number. The Nusselt number in this case can be expressed through the Dittus–Boelter correlation as $\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{n}$, where $\mathrm{Pr} = \mu c_p/\lambda$ is the Prandtl number, $\mathrm{Re} = \rho c_p d_{in}/\mu$ is the Reynolds number, μ is the dynamic viscosity [kg m^{-1} s^{-1}, and porosity n = 0.4 for heating and 0.33 for cooling. For more on the fluid properties necessary for the application of the equations above and the various boundary layers of the GHE the reader is referred to [7–8].

COMPUTATIONAL MODEL AND RESULTS

The desired model based on the numerical model above was created in the FlexPDE environment with the following meshed ground layers (zones) from top to bottom: 80 m of dry well area; 25 m of high water-velocity area (0.00005 m s^{-1}); 55 m of low water-velocity area (0.0000000116 m s^{-1}); 5 m of base area shown in purple. The configuration above is a model for an existing borehole GHE in Lakatameia area, Cyprus, and has been validated through Thermal Response Testing (TRT) [7]. The underground temperature in the Lakatameia BH, for depths over 7 m is 22°C, with 1°C increase per 100 m. The best-fit equations for the temperature gradient were imposed on the numerical model to match the ground

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temperatures used in simulations to the actual temperatures of the ground during the experiments (Figure 1 for deep zone). The results for the computational model show a good agreement with TRT measured values (Figure 2).

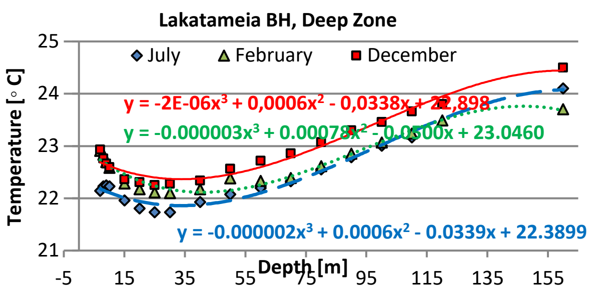

Figure 1. Recorded underground temperature at the Lakatameia borehole (BH) deep zone (7–160m), shown is the best-fit equation.

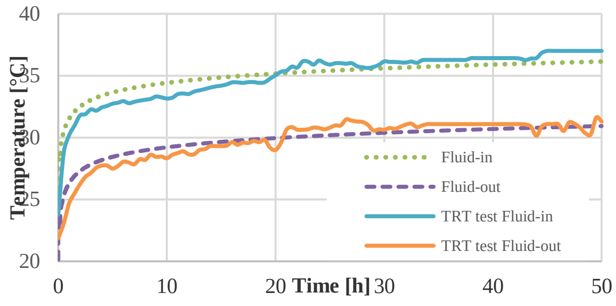

Figure 2. TRT recorded temperatures (December) at the Lakatameia BH (TRT Fluid-in/out) in comparison with the FlexPDE script calculated values (Fluid-in/out).

The thermal response of the GHE can then be examined with confidence for both cooling and heating regimes (see [7] for details). For cooling, one can conclude that the greater the difference between the input water temperature and the ground temperature, the greater the rejected heat to the ground, while the higher the exiting water temperature, the greater the rejected heat to the ground. Similarly, for heating, the greater the difference between the input water temperature and the ground temperature, the greater the absorbed heat from the ground, while the lower the exiting water temperature, the greater the absorbed heat from the ground.

The effect of the groundwater velocity is examined through a parametric analysis for various BH radiuses. Results show that a smaller BH radius keeps a lower temperature of the fluid of the GHE (cooling mode) due to the thermal properties of the grout used in the specific geological formation. It turns out that the relation of the absorbed power per m ($= mc_w\Delta T$) of BH length to the BH radius (Figure 3), reveals that although the total power absorbed by the ground is kept the same (5710 W) in all cases, the dry layer and the low underground water-velocity layer respond rather uniformly in absorbing power, as opposed to the high underground water-velocity layer that decreases exponentially with radius.

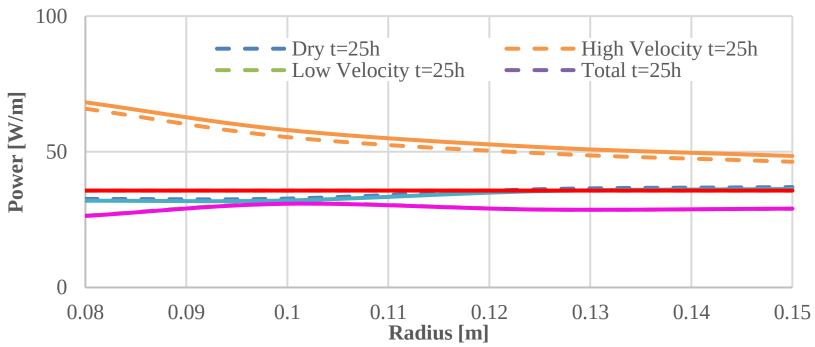

Figure 3. Absorbed power per m against the BH radius for the three layers of the BH for 25h of GHE operation.

CONCLUSION AND DISCUSSION

A more complete parametric analysis, for the cooling mode of the GHE, can involve the analysis of (i) the grout thermal conductivity, (ii) the U-tube size, (iii) the distance between BH and tube leg centers, (iv) underground water velocities [7]. The study presented in here is an important step toward investigating the importance of the presence of an aquifer in the construction of a BH GHE and can be further extended for factors such as the summer and winter mode of operation, the underground temperature variation due to seasonal changes, the BH thermal resistance and multiple BHs [6].

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