Numerical Investigation of Thermal Interference in Adjacent Geothermal Systems

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ABSTRACT

This paper presents a numerical investigation of thermal behavior of an element-scale borehole heat exchangers to understand the thermal interactions between them. Thermal interaction between adjacent geothermal systems is a growing concern in urban areas where multiple geothermal systems are in proximity to each other. These interactions potentially have adverse impacts on the system by reducing the system performance and efficiency. Understanding the interaction at an element-scale system is necessary to assess these interactions at larger scales. In this study, a three-dimensional coupled thermo-hydraulic numerical model based on the finite element was developed using COMSOL Multiphysics to simulate the thermal interactions in a 2x2 borehole field. A parametric study was conducted to investigate the impact of pipe diameter, fluid-flow velocity, and injection temperature on the performance of the borehole heat exchangers. The results showed that the predicted ground temperature increases with increasing pipe diameters and higher fluid velocities. Understanding the complexity of the subsurface is an important consideration for an accurate ground temperature estimation. The thermal plume resulting from heat injection extends approximately 3 m away from the heat exchangers. Accordingly, delineating the influence area of the thermal plume is a critical parameter for designing siting nearby geothermal systems.

Keywords: geothermal energy, community-scale network, thermal interference, sustainable energy, cities

1. INTRODUCTION

Building decarbonization solutions are recognized as a primary strategy in cities for mitigating future climate change impacts, that also leads to improved air quality, ensures equitable energy access, and enhances building operational resiliency and adaptability (Jello et al., 2022). Vertical borehole heat exchangers have been shown to be a cost-effective solution for decarbonizing buildings by capturing the ambient thermal resources underground that the heating, cooling, and hot water needs of residential and commercial buildings (Reiter et al., 2023; Jello and Baser, 2023). In urban cities, Goetzl et al. (2023) suggested that geothermal energy can replace both electric and fossil fuel supplied loads.

In densely populated areas, where multiple geothermal systems are installed in proximity as shown in Figure 1, thermal interference becomes a major concern. This interaction between thermal plumes could negatively affect the borehole heat exchanger performance and efficiency of the geothermal systems and has the potential risk of negatively impacting the long-term sustainable utilization of underground resources.

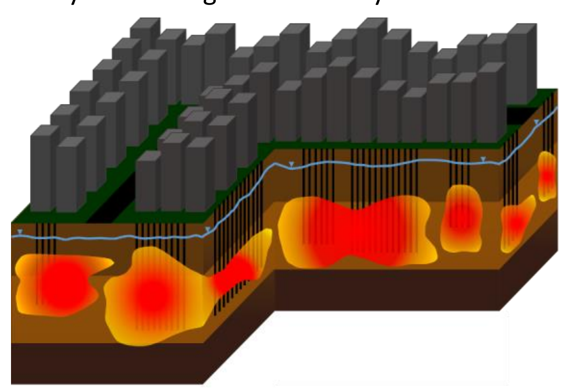

***Fig. 1** Thermal interference in multiple geothermal systems in urban areas*

Cai et al. (2021) assessed numerically the thermal interaction among deep borehole heat exchanger arrays in varying configurations with different number of boreholes. Cai et al. (2021) revealed a temperature drop in of 4.7°C the borehole field after 20 years of operation compared with the performance of a borehole heat exchanger. Cai et al. (2021) demonstrated that the thermal interaction among systems is crucial for understanding the long-term sustainability of the geothermal system. In addition, Perego et al. (2022) developed a three-dimensional numerical model for a pilot case study in Switzerland where simulations were performed to understand the interactions between open and closed-loop geothermal systems. Their findings suggest that with the increasing number of geothermal systems there is the potential of decreasing the systems' efficiency that leads to negative impacts on their sustainability.

Cassina et al. (2022) proposed a framework to design geothermal heat exchangers in urban areas, considering thermal interaction between boreholes to avoid resource overexploitation. However, their approach did not account for the influence of groundwater flow, which can significantly control thermal interference. Attard et al. (2020) introduced the concept of a "thermal protection perimeter", -an area around a geothermal installation where external heat injection alters system performance. The framework enables continuous mapping of geothermal potential while considering thermal interference.

Korhonen et al. (2023) estimated the potential shallow geothermal resources using an infinite borehole field model, considering the thermogeological factors, such as temperature gradient, heat flux, thermal conductivity, heat capacity, formation porosity and bulk density, and advective heat transfer. The results from Korhonen et al. (2023) highlighted that relatively higher groundwater flow velocities enhance geoexchange and system performance. Beyond the technical solutions, Garcia-Gil et al. (2020) emphasized that transitioning from fossil fuel-based energy systems requires scientifically informed policies that requires an adaptive framework for their management and governance, offering a roadmap for policymakers to effectively utilize the underground resource.

Despite the growing importance of thermal interference between individual geothermal systems, and its impact on the long-term performance of the individual geothermal systems, this is often overlooked, especially as the number of geothermal systems continues to increase in urban areas. Limited studies and approaches exist for evaluating thermal interactions between neighboring geothermal systems. To address this issue, we modeled an element-scale borehole field with a 2x2 arrangement of vertical borehole heat exchangers representing two separate geothermal systems situated diagonally from each other (Figure 2). The thermal behavior between the two systems was investigated with a numerical model to understand the key parameters affecting the thermal interference.

2. MATHEMATICAL FORMULATION

To simulate the thermo-hydraulic response of a vertical borehole heat exchanger system during operation, a system of equations describing the heat transfer in pipes, in porous media, and flow in porous media. The governing equation for heat transfer in pipes is based on the conservation of energy and is expressed using equation (1) as follows:

$$\rho_f A_f C_{p,f}\frac{\partial T_f}{\partial t} + \rho_f A_f C_{p,f} v e_t \cdot \nabla T_f = \nabla \cdot \left(A_f k_f T_f\right) + \frac{1}{2} f_d \frac{\rho_f A_f}{d_h}|u|u^2 + Q_{wall} \tag{1}$$

where ρ_f is the fluid density (kg/m^3), A_f is the area of flow (m^2), $C_{p,f}$ is the fluid specific heat (J/kg.K), v is the tangential velocity of flow (m/s), e_t is a unit vector along the pipe tangent, T_f is the fluid temperature (K), k_f is the fluid thermal conductivity (W/m.K), f_d is a friction factor, and Q_{wall} describes the heat exchange through the pipe wall (W). The governing equation describing heat transfer in the porous media is based on the energy balance and is expressed using equation (2) as follows:

$$C_p\frac{\partial T}{\partial t} + \rho_f C_{p,f} u \cdot \nabla T + \nabla \cdot (-k\nabla T) = Q_{wall} \tag{2}$$

where ρ is the porous media density (kg/m^3), C_p is the porous media specific heat (J/kg.K), k is the porous media thermal conductivity (W/m.K), u is the Darcy velocity of flow through the media, and T is the porous media temperature (°C). The governing equation of the fluid flow in the subsurface is based on the mass balance principles described by Darcy's law and is expressed using equations (3) and (4) as follows:

$$\nabla \cdot \left(\rho_f u\right) = 0 \tag{3}$$

$$u = \frac{-K}{\rho_f g}\nabla p + \rho_f g \tag{4}$$

where K is the hydraulic conductivity of the porous media (m/s), g is the gravitational constant (m^2/s), and p is the pore pressure (kPa).

3. NUMERICAL MODEL

A three-dimensional fully coupled thermo-hydraulic model was implemented in COMSOL Multiphysics v5.4, a finite element platform to assess thermal interference among a 2x2 borehole field. The domain comprises of four layers, based on existing studies and borehole log data from the ISGS repository. The physical, thermal, and hydraulic properties are summarized in Table 1.

The domain developed had a length of 80 m, width of 50 m, and a thickness of 150 m (Figure 2). These dimensions were selected to minimize boundary effects. Based on

Table 1. *Material properties of the soil layers*

	Clay and sand	**Glacial till**	**Dolomite**	**Shale**
Thickness *(m)*	6	11.2	104.6	28.2
Density, ρ *(kg/m³)*	1400	1600	2830	2850
Thermal cond., λ *(W/(m.K))*	0.92	1.8	4.5	3.39
Specific heat capacity, C_p *(J/(kg.K))*	1111	978	879	863
Hydraulic cond., k *(m/s)*	1.3x10-6	1.1x10^{-9}	1.0x10^{-12}	2.2x10^{-13}
Porosity, n *(-)*	0.37	0.18	0.10	0.15

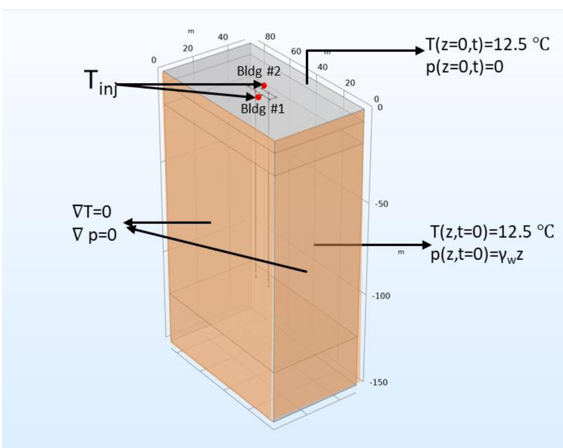

Fig. 2 *Initial and boundary conditions*

hydrogeologic framework for Chicago (Suter et al., 1959), the domain is considered fully saturated much of the year, with a hydrostatic pressure applied throughout the domain as the initial condition. An impermeable boundary condition is applied along the edges of the domain to limit groundwater flow in and out of the? layers. For the initial thermal conditions, a Dirichlet boundary of 12°C is applied throughout the domain (Figure 2) that represents undisturbed ground temperatures in Chicago. The constant injection temperature sourced from two buildings across from each other remained constant at the pipe inlet for 4 weeks. The details of the initial and boundary conditions are shown in Figure 2.

A parametric study to investigate the pipe diameter, velocity, and inlet temperature is conducted. The design and operational parameters varied in the parametric study and the potential scenarios considered are summarized in Table 2.

Table 2. *Input parameters for the parametric study*

Pipe size (D)	T_{inj}	Velocity	Condition
m	°C	m/s	
0.035	30	0.6	Turbulent flow
0.035	40	0.6	Turbulent flow
0.035	50	0.6	Turbulent flow
0.035	30	0.9	Turbulent flow
0.035	40	0.9	Turbulent flow
0.035	50	0.9	Turbulent flow
0.040	30	0.8	Turbulent flow
0.040	40	0.8	Turbulent flow
0.040	50	0.8	Turbulent flow
0.040	30	1.1	Turbulent flow

4. RESULTS AND DISCUSSION

The temporal variation in ground temperature measured at a depth of 1 m below the ground surface in the middle of two borehole heat exchangers was during heat injection at 40 °C is shown in Figures 3 and b. In the selected area of the domain in Figure 3(a), the temperature is expected to increase to over time to 19.4°C, 18.5°C, and 17.7°C, respectively for pipe diameters of 0.035 m, 0.04 m, and 0.05 m. Similarly, on the left side of the selected area, the temperature was predicted is 19°C, 18°C, and 17.2°C, respectively for the same range in pipe diameters (Figure 3b). The expected ground temperature increase linked to using a wider pipe is attributed to an increase in bulk? flow rate which results in decreasing pressure drops and frictional losses when compared to the smaller diameter pipes.

The time series show for outlet temperatures at Buildings 1 and 2 during injection at 40°C are shown in Figures 4(a) and 4(b), respectively. The outlet temperature at Building 1 reaches steady state at 32°C, 34℃, and 35.5℃ for the pipe diameters of 0.035 m, 0.04 m, and 0.05 m, as shown in Figure 4(a). Similar outlet temperatures were predicted for Building 2 as shown in Figure 4(b). This is because of an increase in mass flow rate and decrease in the pressure drop through the pipes.

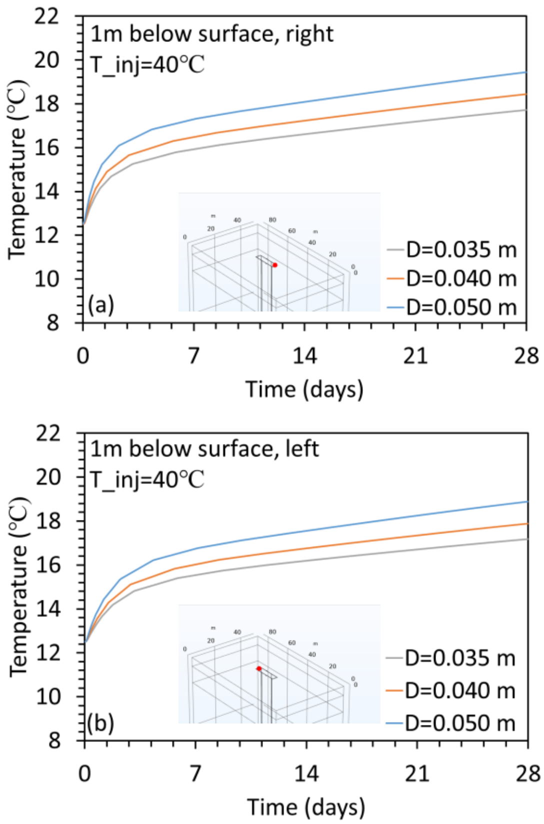

Fig. 3 *Temporal temperature variation at 1 meter below surface for an injection temperature of 40* ℃ *at the (a) right and (b) left of the borehole field*

The horizontal profiles of temperatures in the middle of each soil layer at a depth of 1 m, 12 m, and 60 m, respectively for the pipe diameters of 0.035 m and pipe velocities of 0.6 and 0.9 m/s when the last time step reached at 28 days are shown in Figures 5(a) through 5(f). These results show that in the middle of the first layer, the temperature increases approximately to the values of the injected temperatures near the geothermal pipes, and then decreases to the initial soil temperature in between, as shown in Figures 5(a) and 5(d). In the middle of layers 2 and 3, which are located at depths of 12 and 60 meters below the surface, respectively, the temperature between the geothermal pipes remains relatively constant, indicating an overall ground temperature increase as shown in Figures 5(b), (c), (e), and (f). The temperatures in layer 2 (glacial till) increased less than those in the third layer (dolomite).

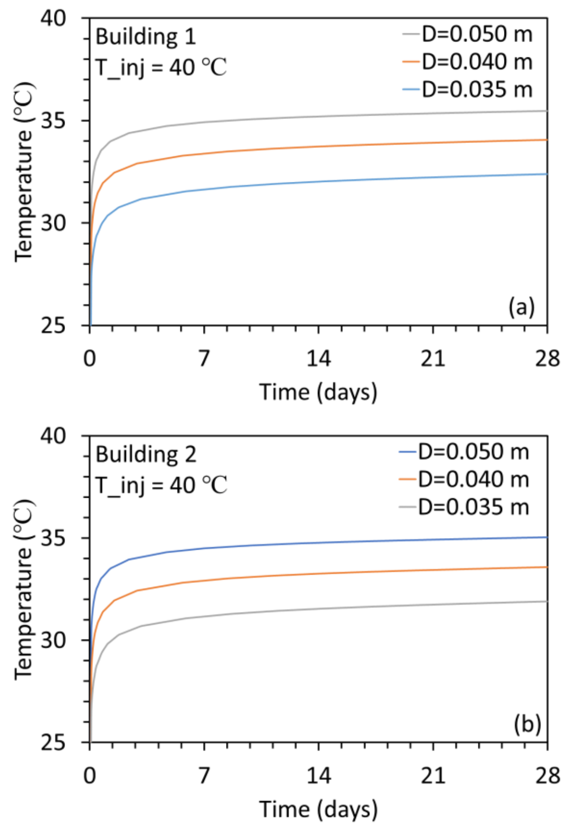

Fig. 4 *Outlet temperatures for an injection temperature of 40* ℃ *at (a) Building 1 and (b) Building 2*

Temperatures rose to 13.5, 14.5, and 15.5°C for the injected temperatures of 30°C, 40°C, and 50°C respectively in the glacial till (Figure 5b), compared to 14°C, 15°C, and 16°C in the dolomite (Figure 5c). This behavior is attributed to the relatively higher thermal conductivity value of the dolomite layer compared to the glacial till, which leads to the faster rates of heat transfer. Moreover, for a pipe velocity of 0.9 m/s, the ground temperature is approximately 0.5 ℃ higher than that for a velocity of 0.6 m/s, indicating a higher heat exchange between the circulated fluid and the ground, as shown in Figure 5(b) and 5(d). Also, the ground temperature increases more as the injected temperature increases as shown in Figures 5(a) through 5(f). The reason for that is relatively higher temperature gradients between the geothermal pipes and the ground.

The thermal plume is defined as the thermally affected area, where the ground temperature deviates from the undisturbed initial temperature. In this scenario, the area around the borehole field impacted during heat injection expands by 2.7, 3.3, and 3.7 m (in both the x and y directions) as the injection temperature increases to 30℃, 40℃, and 50℃, respectively. Delineating the extent of the thermal plume would be an important

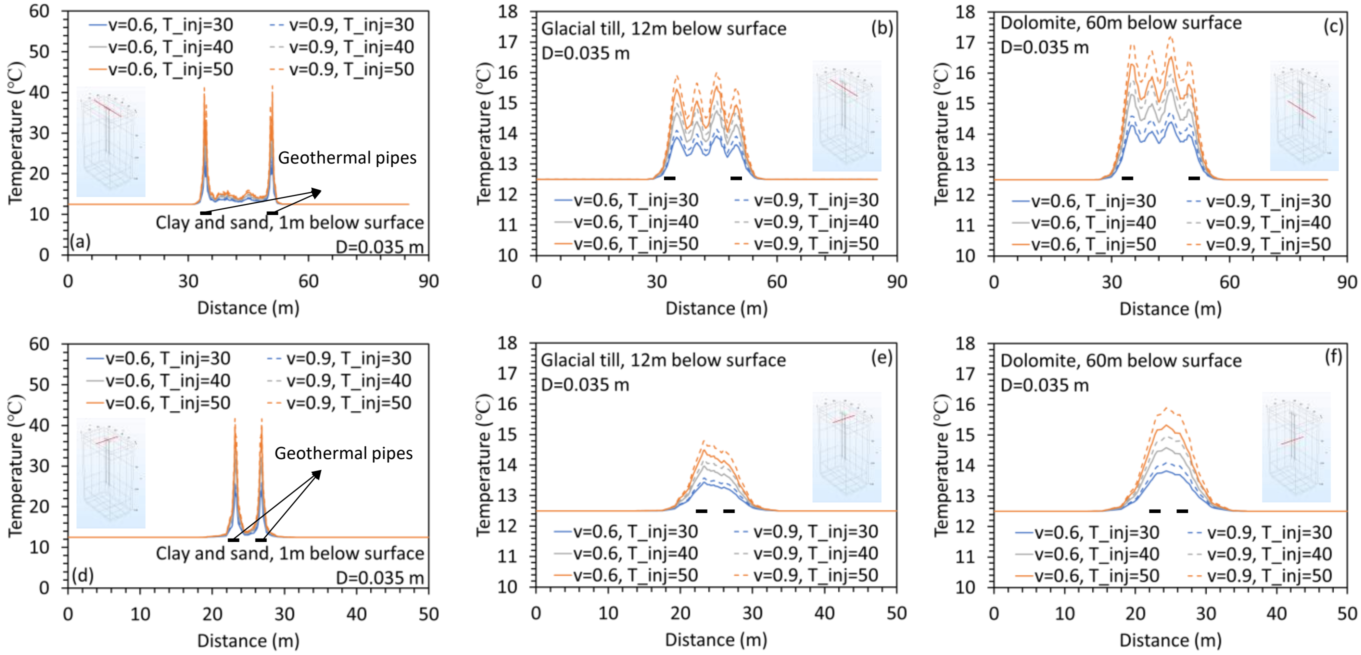

Fig. 5 *Temperature distribution on day 28 for a pipe diameter of 0.035 m and pipe velocities of 0.6 and 0.9 m/s in the x-direction at the middle of (a) layer 1; (b) layer 2; and (c) layer 3 and in the y-direction at the middle of (d) layer 1; (e) layer 2; and (f) layer 3*

consideration when sitting future geothermal systems so that thermal interference could be minimized.

5. CONCLUSIONS

In this paper, an element-scale vertical borehole heat exchanger was used to assess the thermal interactions in a modeled area within the City of Chicago. A three-dimensional coupled thermo-hydraulic 2x2 borehole field is implemented with COMSOL Multiphysics v5.4b and a parametric study was conducted to investigate the effect impacts on the operation under different pipe diameter, flow rate, and injection temperatures. The specific results are as follows:

- The ground temperatures increased to 13.5, 14.5, and 15.5°C for injected temperatures of 30°C, 40°C, and 50°C respectively in the glacial till for the pipe diameter of 0.035 m.
- The ground temperatures were 14, 15, and 16°C for injected temperatures of 30°C, 40°C, and 50°C respectively in the dolomite layer for the pipe diameter of 0.035 m.
- The differences in thermal conductivity values were evident as expected that led to non-uniform temperature profiles.
- The thermal plume reached approximately 2.7, 3.3, and 3.7 m from the boundaries of the borehole field for the injection temperatures of 30°C, 40°C, and 50°C, respectively. As expected, the value increased with higher injection temperatures which can potentially lead to thermal interference.
- The ground temperature increased by approximately 7°C, 6°C, and 5.5°C for pipe diameters of 0.035 m, 0.04 m, and 0.05 m, respectively. Similarly, the outlet temperatures were 32.0°C, 34.0°C, and 35.5°C for pipe diameters of 0.035, 0.04, and 0.05 m. This is attributed to an increase in the mass flow rate and decrease in the pressure drop.

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