

Geothermal Heat Pump System Showcase: Short-Term Validation of Borehole Heat Exchanger Performance from Field Data to Numerical Modeling

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ABSTRACT

Since 2011, a geothermal heat pump (GHP) system has been operating to provide space heating and cooling for the Solar Radiation and Research Laboratory (SRRL) building at the National Laboratory of the Rockies (NLR) in Golden, Colorado. The system consists of 23 vertical boreholes, each extending to a depth of 300 ft (91 m), connected to 11 water-to-air heat pump units and four circulation pumps. Between fiscal years 2023 and 2025, additional power meters and temperature sensors were retrofitted to support detailed system performance assessment and model development. This study presents preliminary monitoring results and the development of an initial numerical model of the borehole heat exchanger field. The model incorporated site-specific geometry, ground thermal properties derived from thermal response tests, and ambient temperatures, and simulated system behavior over a representative operating day in September 2025. Model predictions of outlet temperatures were compared against corresponding field measurements. Results showed that modeling initialized with a simplified linear subsurface temperature gradient presents systematic discrepancies in outlet temperature, whereas incorporating depth-informed borehole temperature measurements for initialization yields substantially improved agreement with observations. The findings highlight the sensitivity of short-term predictive modeling to the representation of initial subsurface thermal conditions and underscore the value of high-resolution field measurements for model calibration and validation. These preliminary results inform ongoing efforts to extend the modeling framework to longer time horizons and to refine monitoring and modeling strategies that support the design and operational optimization of GHP systems in research and commercial buildings.

1. INTRODUCTION

Geothermal heat pump (GHP) systems coupled with borehole heat exchangers (BHEs) have been extensively deployed as an energy-efficient solution for space heating and cooling across a range of building scales (Oh and Beckers 2023). By leveraging relatively stable subsurface temperatures, GHP systems can achieve higher coefficients of performance (COPs) than conventional air-source heat pump systems (De Swardt and Meyer 2001; Spitler et al. 2017). At the system level, the thermal performance of BHEs is dependent on various factors, including borehole geometry, ground thermal properties, and time-varying building loads (Gultekin et al. 2016; Tang and Nowamooz 2019). These factors are typically represented during system design using simplified assumptions and semi-analytical or numerical formulations to estimate ground thermal response under prescribed loading conditions (e.g., Spitler 2000; Mitchell et al. 2023). Once deployed, however, GHP systems operate under dynamic conditions that may deviate from those assumed at the design stage due to changes in building usage, equipment operation, seasonal load imbalance, and cumulative thermal interactions within the borehole field. Consequently, understanding in-situ system behavior under realistic operating conditions remains a key challenge for accurately representing GHP system performance beyond the design stage.

Previous studies have evaluated BHE performance using a range of experimental and modeling approaches, including thermal response tests (TRTs) (Esen and Inalli 2009; Lee 2011), long-term monitoring of system operations (García-Céspedes et al. 2020; Liu et al. 2020), and numerical simulations at both the borehole and system levels (Biglarian et al. 2017; Oh et al. 2025). Long-term monitoring has provided valuable insights into seasonal and multi-year ground temperature evolution, while short-term tests are commonly used to estimate effective ground thermal properties for design purposes. Modeling approaches, ranging from analytical line-source formulations to detailed finite-element or finite-volume methods, have been widely applied to simulate heat transfer within boreholes and surrounding ground. However, discrepancies between modeled results and measured performance are frequently reported (e.g., Beier et al. 2018), particularly under operating conditions involving variable flow rates or time-varying thermal loads, for which simplified modeling assumptions can lead to temperature deviations of several degrees especially at early times. In addition to modeling limitations, a key challenge in field-to-model validation lies in the availability, spatial distribution, and temporal resolution of measurements. In many installed GHP systems, temperature, flow rate, and power measurements are insufficiently distributed or sampled to enable robust comparison with numerical predictions (e.g., limited temperature measurements at varying depths and locations). Moreover, sensor placement and data acquisition strategies are often not designed with model validation as a primary objective, which can constrain the identification and attribution of uncertainty sources. High-resolution, detailed monitoring of operational systems thus presents a practical opportunity to improve field-to-model evaluation under realistic operating conditions.

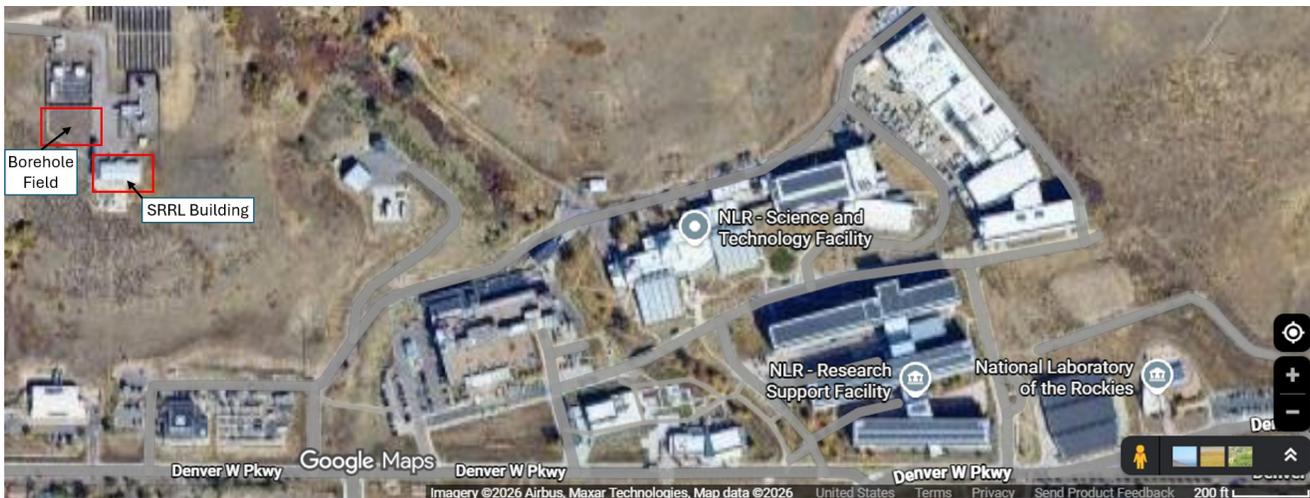
This study presents preliminary measurements from an operational GHP system at the National Laboratory of the Rockies (NLR) and examines the short-term predictive capability of a numerical model for the borehole field using site-specific inputs. The modeling framework incorporated borehole geometry, ground thermal properties estimated from TRTs, ambient conditions, and time-varying injection flow rates and temperatures obtained from field measurements. The analysis focused on a representative one-day operating

period, during which field measurements of inlet temperatures, flow rates, and depth-varying borehole temperatures were used as inputs, while modeling results were compared with measured outlet temperatures. Rather than addressing long-term system performance or lifetime ground thermal behavior, this work emphasizes evaluation of model fidelity at short time scales and identification of factors influencing agreement between simulated and observed responses. Specifically, this study aims to: (1) verify the quality and consistency of field measurements to support reliable model initialization; (2) develop and calibrate an initial numerical representation of the system using measured, site-specific inputs; and (3) assess agreement between modeled and measured outlet temperatures over the selected operating period. The results are intended to inform future extensions of the modeling effort to longer time horizons and to guide refinements in both modeling assumptions and monitoring strategies.

2. SYSTEM DESCRIPTION AND FIELD MEASUREMENTS

2.1. Site and System Overview

This study utilizes an operational GHP system at the SRRL facility, located at the NLR in Golden, Colorado (Figures 1(a) and (b)), as a case study for numerical model developments and field-to-model comparison. The SRRL building, totaling 4,200 ft² (\approx 390 m²), houses laboratories and facilities for metrology, optics, radiometer calibration, and outdoor performance testing, with an additional 1,896 ft² (\approx 176 m²) added to provide space for researchers (Anderson, 2010). Several laboratory processes, particularly in the optics lab, generate significant internal heat, resulting in a peak cooling load of approximately 116 kBTU/h (\approx 34 kW) and a peak heating load of 50 kBTU/h (\approx 15 kW). The building operates 24 hours/day, 7 days/week, making consistent heating and cooling essential for maintaining stable indoor conditions and reliable operation of sensitive instruments.



(a)



(b)

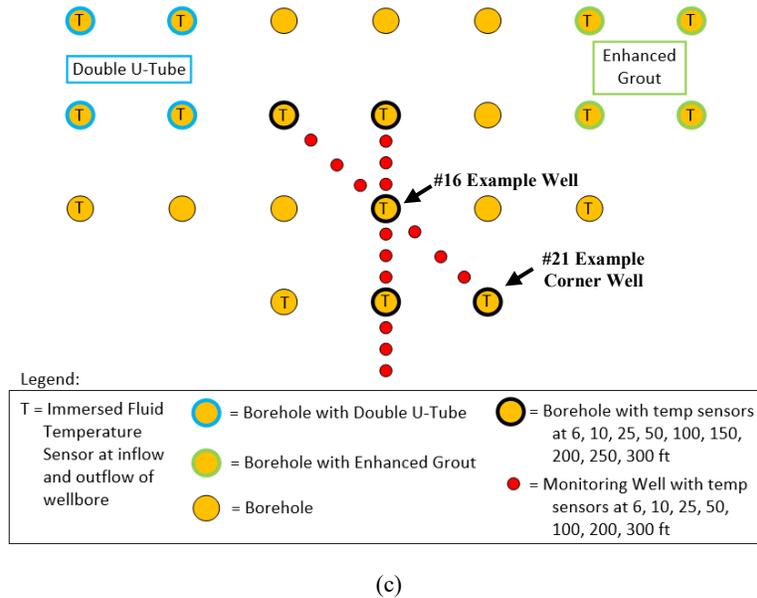


Figure 1. System overview: (a) location of the Solar Radiation and Research Laboratory (SRRL) building in the NLR campus in Golden, Colorado, (b) Solar Radiation and Research Laboratory (SRRL) building where 11 heat pump units supply space conditioning (Anderson 2010), and (c) borehole field layout with boreholes #16 and #21 highlighted as examples (Anderson 2010).

The borehole field consists of 23 vertical wells with a diameter of 6 in. (15 cm), each approximately 300 ft (91 m) deep (Figure 1(c)), arranged in a regular grid with nominal spacing of approximately 30 ft (9 m), and connected to 11 distributed water-to-air heat pump units through individual supply and return circuits. Both single and double U-tube configurations are present within the borehole field, and the circulating fluid is a propylene glycol-water mixture. Thermal energy is exchanged between the building and the subsurface via the heat pump units, which extract or reject heat in response to building heating and cooling demands. The system, commissioned in 2011, continues to serve the space heating and cooling requirements of the SRRL building, with loads monitored continuously through a recently upgraded instrumentation system (fiscal years 2023–2025) to provide the boundary conditions and validation data required for evaluating numerical model performance under realistic operating conditions.

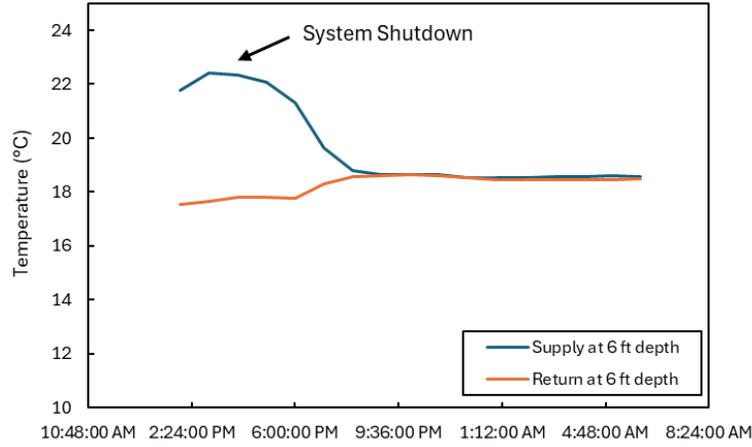
2.2. Instrumentation and Measurement Overview

The SRRL GHP system was instrumented with both surface and subsurface sensors to capture loop dynamics and subsurface thermal behavior. Surface instrumentation includes 33 temperature sensors monitoring bulk ground- and building-loop headers as well as individual borehole loops, 31 flow meters for the bulk and individual loops, and 17 electric power meters for heat pumps, circulation pumps, and the building’s heat recovery system. Subsurface sensors (Figure 1(c)) comprise 45 downhole temperature sensors mounted directly on U-tube pipe surfaces in five boreholes, 40 immersed sensors near the tops of 16 boreholes, and 105 multi-depth sensors in 15 monitoring wells. These sensors cover a range of configurations, including single and double U-tubes with standard or thermally enhanced grouting. Monitoring wells (diameter = 4.5 in. (11 cm), depth = 300 ft (91 m)) are located both within and outside the borehole field and provide additional depth-resolved validation points. Table 1 summarizes the sensor types, locations, and configurations.

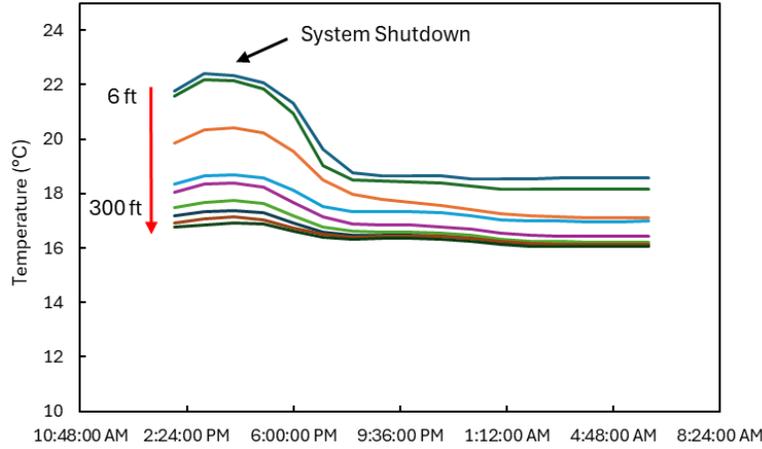
Table 1. Summary of temperature sensors in the SRRL GHP system

Sensor type	No. of boreholes/wells	Depth range (ft)	Tube type / grouting
Downhole	5 boreholes	6–300	Single U-tube, standard
Immersed	16 boreholes	Top only	Single/double U-tube, standard/enhanced
Monitoring	15 wells	6–300	N/A

During a 16-hour system shutdown and recovery period in November 2025, when the GHP system was not operating, sensor data were cross-checked and aligned for the quality check. Across the borehole field, most sensors showed convergent readings within a few hours, indicating stable post-shutdown behavior and reliable depth-resolved temperature measurements. Some sensors, particularly those immersed in counter-flow positions, were damaged and excluded from analysis. The corner borehole (e.g., #21 in Figure 1(c)) recovered more rapidly and recorded slightly lower temperatures than other locations, reflecting its distinct thermal boundary conditions. Borehole #16, located near the center of the field (Figure 1(c)), is shown as a representative example of the observed temperature dynamics used for data quality checks and model initialization (Figure 2). Overall, temperature profiles presented coherent spatial patterns, with near-linear vertical gradients within the borehole array and deviations near the field edges due to boundary effects. These observations established confidence in the quality of the measurements, informed the selection of representative boreholes, and supported the development of initialization strategies for subsequent numerical modeling.



(a)



(b)

Figure 2. Temperature distribution for borehole #16 before and after system shutdown on November 2, 2025: (a) supply and return temperatures at 6 ft depth and (b) temperature variations along the borehole from 6 ft to 300 ft depth over time

3. NUMERICAL MODELING AND VALIDATION RESULTS

3.1. Model Settings

The borehole field was modeled using COMSOL Multiphysics (version 6.3), applying a coupled heat transfer framework that accounts for transient heat conduction in the surrounding ground and convective–conductive heat transfer within the U-tube heat exchangers. Fluid flow in the piping was assumed to be single-phase, incompressible, and characterized by constant thermophysical properties. Heat transfer in the circulating fluid was governed by the energy balance equation:

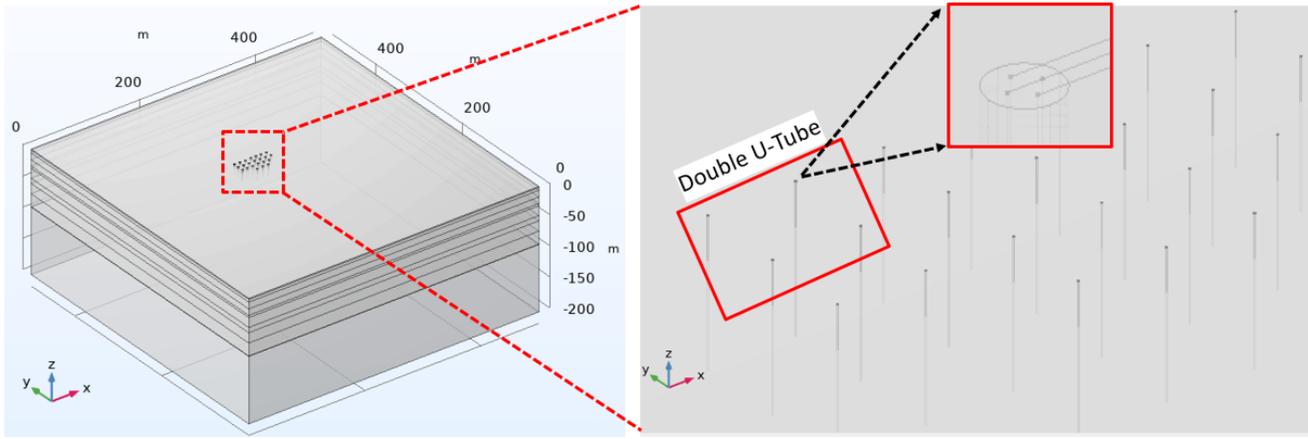
$$\rho A C_p \left(\frac{\partial T}{\partial t} + u \right) \cdot \nabla T = \nabla \cdot A \lambda \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q + Q_{wall} + Q_p \quad (1)$$

where ρ = density (kg/m^3); A = pipe cross section area (m^2); C_p = specific heat capacity at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$); T = absolute temperature (K); u = velocity vector of translational motion (m/s); λ = thermal conductivity of the piping material and soil layers ($\text{W}/\text{m}\cdot\text{K}$); f_D = the Darcy friction factor as function of the Reynolds number, surface roughness, and hydraulic diameter; d_h = hydraulic diameter; Q = general heat source (W/m); Q_{wall} = external heat exchange through the pipe wall. Q_p = an optimal term where the pressure drop is considerable and the fluid is compressible, assumed as zero in this study. Frictional heat dissipation was evaluated using the Churchill friction model, with a surface roughness of 0.0015 mm representative of high-density polyethylene (HDPE) pipes. Heat transfer in the surrounding ground was modeled using the transient heat conduction equation:

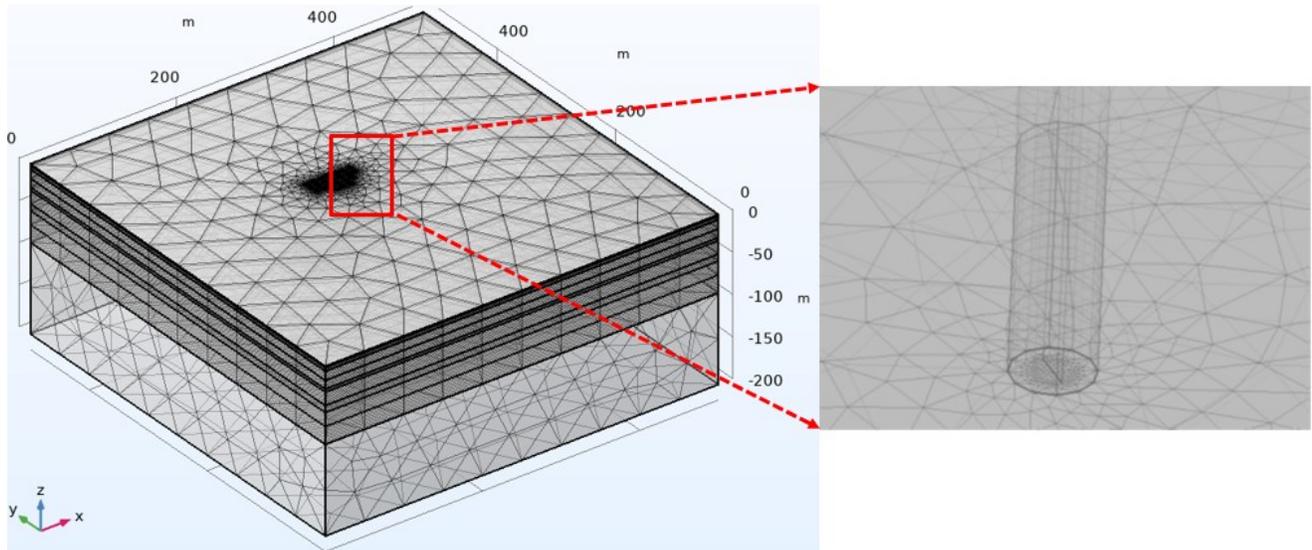
$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \cdot u \cdot \nabla T + \nabla \cdot q = Q \quad (2)$$

where q = conductive heat flux (W/m^2). The model geometry followed the SRRL borehole field configuration (Figure 3(a)), consisting of 23 vertical boreholes with depths of 91 m (300 ft) incorporating both single and double U-tube configurations with standard or thermally

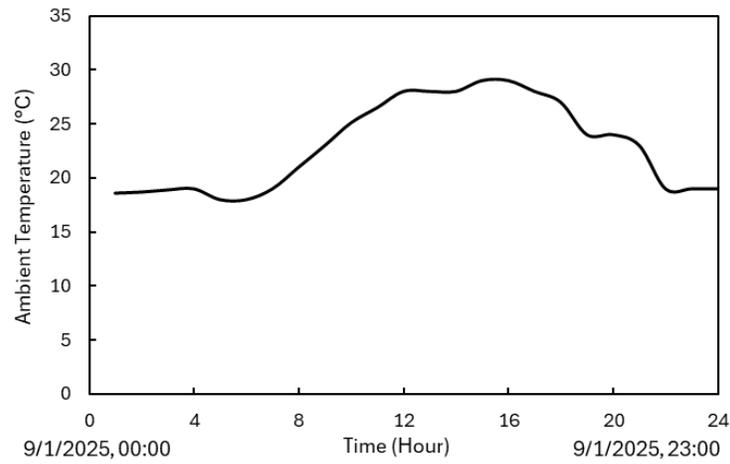
enhanced grouting. The borehole field was embedded in a three-dimensional domain sized to minimize boundary effects. Subsurface thermal and physical properties were derived from site-specific borehole logs comprising 34 layers and aggregated into nine representative layers, each assumed homogeneous to reduce computational cost (Table 2). The computational domain was discretized using anisotropic swept meshes, with unstructured tetrahedral elements applied at the ground surface and bedrock layer (Figure 3(b)). An iterative mesh refinement procedure was applied, starting from coarse meshes that produced unrealistic temperature distributions. Swept and anisotropic meshes were then applied near the boreholes to better capture steep temperature gradients. The final mesh produced physically realistic results in good agreement with field measurements, suggesting reasonable grid-independence of the numerical solution. Boundary conditions and model inputs were prescribed using field measurements from a representative operating day on September 1, 2025, during which the system showed continuous operation with stable flow rates and injection temperatures. Time-varying ambient temperature was applied at the ground surface (Figure 3(c)). Measured inlet temperatures were imposed as Dirichlet thermal boundary conditions at the piping inlets, while measured flow rates were applied as inlet mass-flow boundary conditions governing advective heat transport in the pipes (Figure 3(d)). Two initialization strategies were evaluated for the subsurface temperature distribution. In the first case, the initial temperature distribution was defined using a linear geothermal gradient of $25\text{ }^{\circ}\text{C}/\text{km}$ combined with the average annual surface temperature, an approach commonly adopted in the literature for numerical modeling of borehole heat exchangers (e.g., Oh et al. 2025). In the second case, the initial subsurface temperature profile was refined using depth-resolved temperature measurements from borehole #16, providing a measurement-based representation of the pre-existing thermal state of the borehole field (Figure 3(e)).



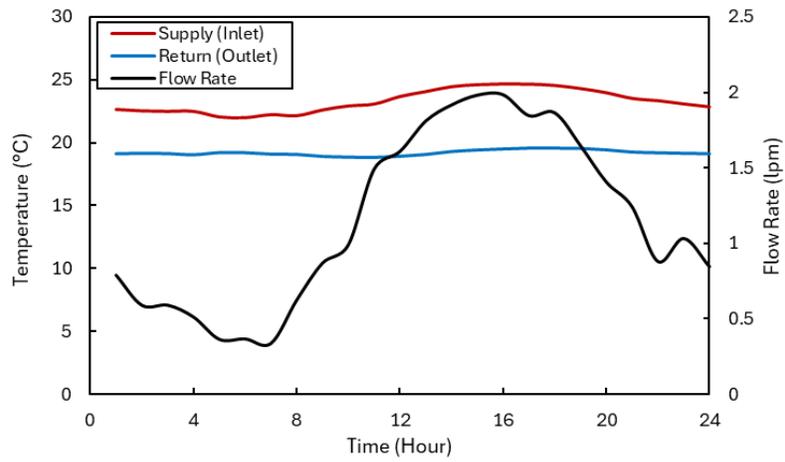
(a)



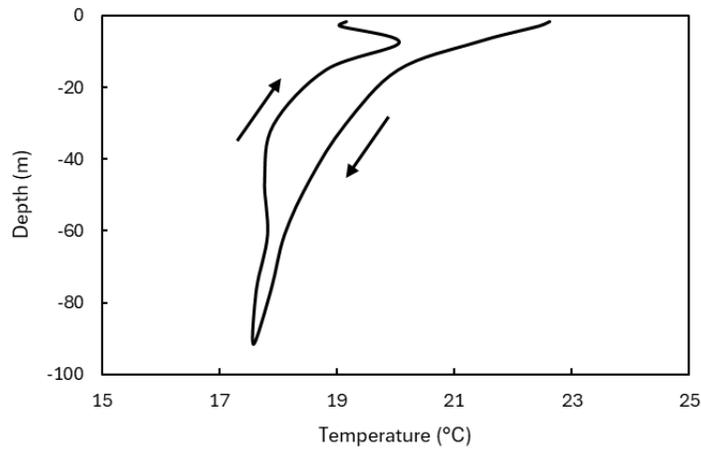
(b)



(c)



(d)



(e)

Figure 3. Numerical model settings: (a) model geometry, (b) mesh settings, (c) ambient temperature assigned on top surface, (d) supply temperatures and flow rates (modeling inputs), and (e) subsurface temperature distribution at depths on September 1, 2025, at 00:00 AM

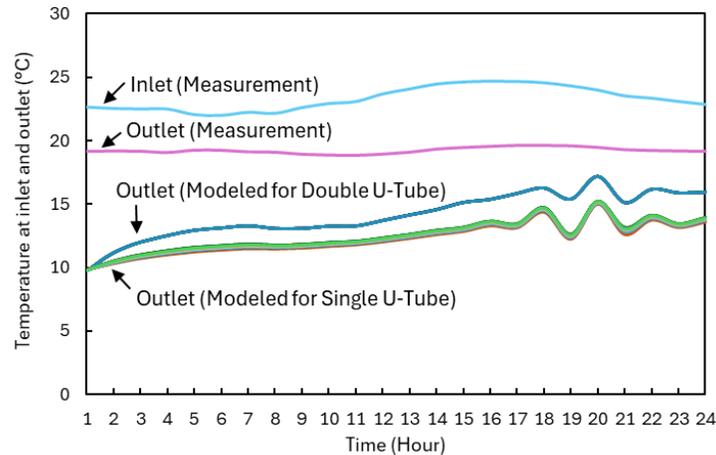
Table 2. Material properties for the nine ground layers in numerical modeling

Layer	Depth (m)	Depth (ft)	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)	USCS ¹	Soil or Bedrock type
0	1.8	6	0.8	950	SP	Backfill
1	4.4	14.5	1.523	873.4	SP-SM	Shoshonite (Basalt) Bedrock
2	15.2	50	0.759	1062.4	SP-SM/CL/ML	Sandstone to siltstone
3	25.6	84	0.724	1456.4	SM/ML	Sandstone/claystone
4	29.3	96	1.128	997.7	SC	Very clayey sandstone
5	45.1	148	0.951	1472.2	SM	Sandstone
6	53.5	175.5	0.672	1098.0	SM	Sandstone/siltstone
7	70.1	230	0.993	1197.9	SM	Sandstone/siltstone
8	91.4	300	0.803	1159.7	SM	Siltstone

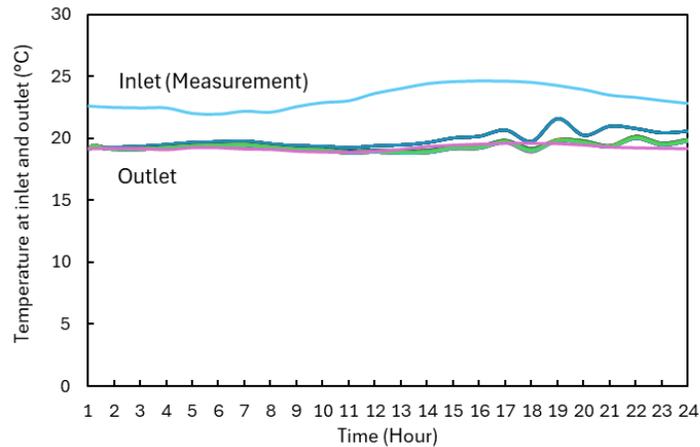
¹Note: United soil classification system (USCS) classifies soils based on grain size, gradation, plasticity, and liquid limit (ASTM D2487): SP = poorly graded sand, SP-SM = poorly graded sand with silt, CL = lean clay (low plasticity), ML = silt (low plasticity), SM = silty sand, SC = clayey sand.

3.2. Modeling Results and Validations

Modeled borehole outlet temperatures were compared with field measurements to evaluate the short-term predictive capability of the numerical model. Figure 4 compares measured outlet temperatures (pink line) with model predictions for a representative operating day in September under two subsurface temperature initialization strategies. Field measurements show that outlet temperatures were consistently about 3.5 °C lower than inlet temperatures during the selected period, indicating cooling-mode operation in which heat was rejected to the ground. This behavior is consistent with expected system operation, and the measured outlet temperature of approximately 19 °C implies that the effective subsurface temperature during operation was substantially higher than the subsurface temperature prescribed by a simplified initialization based on an average annual surface temperature of 9.8°C and a 25°C/km geothermal gradient. When the subsurface temperature field was initialized using this linear gradient (Figure 4(a)), the model systematically underpredicted borehole outlet temperatures throughout the simulation period. Although outlet temperatures in double U-tube boreholes were approximately 2°C higher than those in single U-tube boreholes due to cumulative thermal interaction associated with fluid circulation through two pipes at approximately 23 °C, the modeled temperatures initially reflected the unrealistically cold subsurface conditions and increased only gradually as heat was transferred from the circulating fluid to the surrounding ground. Even after this transient adjustment, the modeled outlet temperatures remained well below the measured values. These discrepancies occurred despite the use of measured inlet temperatures and flow rates as boundary conditions, demonstrating that inaccuracies in the representation of subsurface thermal conditions can dominate short-term simulation outcomes. The results highlight potential limitations of applying idealized or design-stage geothermal gradients especially for short-term operational modeling.



(a)



(b)

Figure 4. Numerical modeling results under two subsurface temperature initialization strategies: (a) initialized using a linear subsurface temperature gradient and (b) initialized using depth-resolved temperature measurements from borehole #16.

Figure 4(b) shows the modeled outlet temperatures when the subsurface temperature field was initialized using depth-resolved measurements from borehole #16 (Figure 3(e)). With this initialization, the modeled outlet temperatures closely matched the measured values throughout the simulation period, capturing both the absolute magnitude (approximately 19°C) and temporal evolution of the outlet temperature. Discrepancies were generally within $\pm 0.2^\circ\text{C}$ for most of the simulation period, with larger deviations confined to a limited time window (approximately hours 17–24). Quantitative comparison indicated mean absolute errors of approximately 0.23–0.26°C for single U-tube boreholes and 0.69–0.70°C for double U-tube boreholes, with the latter primarily influenced by localized transient discrepancies. Similarly, the corresponding mean bias errors were approximately 0.04–0.15°C for single U-tube boreholes and 0.7–0.77°C for double U-tube boreholes, indicating a slight overestimation by the model. While identical inlet temperatures and flow rates were prescribed in both modeling cases, the improved agreement can be directly attributed to a realistic representation of the initial subsurface thermal state. By starting the simulation with a temperature profile that reflects operational ground conditions, the model correctly resolved heat exchange between the circulating fluid and the borehole without devoting a significant portion of the simulation to warming the surrounding ground. These results demonstrate that short-term prediction of borehole outlet temperatures is highly sensitive to the initial subsurface temperature distribution and emphasize the value of depth-informed field measurements for model initialization and validation.

4. CONCLUSIONS AND FUTURE WORK

This study presented a preliminary evaluation of a borehole field for a GHP system at the NLR. The system consists of 23 vertical boreholes supplying 11 water-to-air heat pump units, monitored with an array of surface and subsurface sensors. Sensor data quality was verified through cross-checking and a controlled no-operation recovery period, demonstrating consistent and reliable depth-resolved measurements suitable for model calibration. Numerical modeling of the borehole field captured the dominant thermal processes governing short-term system response. Model predictions were highly sensitive to the representation of the initial subsurface temperature distribution. Initializing the model with a simplified linear geothermal gradient systematically underpredicted outlet temperatures, whereas depth-resolved borehole measurements provided accurate representation of the subsurface state, leading to close agreement with field observations. When initialized using measured subsurface temperatures, modeled outlet temperatures agreed with measurements within $\pm 0.2^\circ\text{C}$ for most of the simulation period, with mean absolute errors on the order of 0.2–0.7°C depending on borehole configuration. These results emphasize the strong sensitivity of short-term model predictions to the initial subsurface temperature distribution and demonstrate the value of depth-resolved temperature measurements for model calibration and validation in this study. Future work will extend the modeling framework to evaluate long-term borehole thermal behavior, optimize system operation, and perform a comprehensive analysis of system performance from the borehole field to the heat pumps. Incorporating seasonal and multi-year dynamics, alongside enhanced monitoring strategies, will support improved design guidance, operational optimization, and validation of numerical models for commercial and research-scale GHP applications.

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