RESEARCH CONFERENCE ARTICLE

HIGH-RESOLUTION MONITORING AND SIMULATION OF TEMPERATURES IN A BOREHOLE HEAT EXCHANGER FIELD OVER MULTIPLE YEARS

BHEs

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INTRODUCTION

Efficient and sustainable use of shallow geothermal energy for heating and cooling depends largely on understanding how borehole heat exchangers (BHEs) interact with the subsurface. These, embedded in the subsurface, serve as conduits for the extraction or injection of thermal energy from or into the ground via a ground source heat pump (GSHP). A thorough understanding of the temperature variation within a field of BHEs is key to improving system efficiency and extending the operational lifespan.

While numerous shallow geothermal systems are in operation worldwide, only a few are equipped with detailed monitoring systems. As a result, the availability of long-term performance data for GSHPs is limited. Existing studies involving high-resolution subsurface temperature data often focus on short-term measurements intended for site evaluation or to estimate thermal properties of the subsurface domain. This is in contrast to the operation time of BHEs, which is foreseen to be several decades. Furthermore, predicting long-term changes in subsurface temperature is particularly difficult due to the complex and often uncertain influence of geological, climatic, and operational factors.

A BHE field, consisting of three BHEs and one observation borehole, has been monitored over six years using distributed temperature sensing (DTS) and other equipment that records operational data. Subsurface temperatures have been captured, providing a detailed view of the ground's thermal behavior. This data enables a spatial analysis of temperature dynamics during operation and supports validation of predictive numerical models as presented in this study.

SITE & BHE SYSTEM CHARACTERISTICS

The monitored BHE field is situated in Lausen, near Basel, Switzerland, at an elevation of 345 meters (1132 feet) above sea level. The site lies on a horst structure within the Table Jura region, a geological formation approximately one kilometer (0.6 mile) wide. The subsurface profile (Figure 1) begins with a six-meter (19.7 feet) thick Quaternary layer composed of clay and limestone debris, followed by 65 meters (213 feet) of Opalinus Clay. The uppermost 12 meters (39 feet) of this layer are heavily weathered and exhibit a high density of fractures. In this zone, hydraulic testing during the exploration phase revealed hydraulic conductivities between 10^{-6} and 10^{-5} m s^{-1}. Groundwater flow is limited to this weathering zone. Below this layer, the sequence continues with the Staffelegg Formation (Lias, Jurassic) from 71 to 105 meters (233 to 344 feet), followed by the Klettgau Formation (Keuper, Triassic) down to a depth of 147 meters (482 feet). The geological characterization was based on core drilling, while the resulting borehole has been subsequently used as an observation well for the nearby BHE system.

To provide heating and passive cooling for two multi-family homes, the BHE system was installed in 2015. This array is used for House A and includes three double-U tube BHEs (A1–A3), each reaching a depth of 146 meters (479 feet), as well as the observation borehole (OB) as described above. The BHEs are connected via a central distribution shaft to a GSHP with a heating capacity of 24.6 kW (7 tons). For regeneration, the system is operated in a passive, free cooling mode in summer. The OB contains a non-operational BHE used solely for monitoring purposes (see Figure 1 and Table 1 for system layout and specifications).

Before commissioning, the site underwent extensive geological, hydrogeological, and geophysical investigations. Understanding the thermal behavior of the subsurface is essential for evaluating the impact of BHE operations, so both standard and enhanced thermal response tests (TRT and ETRT) were conducted. The ETRT revealed thermal conductivities ranging from 2 to 3 W m^{-1} K^{-1} (1.2 to 1.7 btu/h ft^{-1} $°F^{-1}$), depending on the rock composition.

The spatial and temporal temperature evolution of the BHE array has been monitored by DTS during the operation. For this purpose, BHEs A1–A3 and OB are equipped with a fiber optic cable with a length of 1,300 m (4265 feet), which is laid in a loop from the ground level along the outer wall to the bottom of the BHE tubes. The spatial and temporal resolutions were set to one meter and 20 minutes, respectively. The ground temperatures have been measured since the start of operation in March 2016 and are ongoing to date.

Figure 1

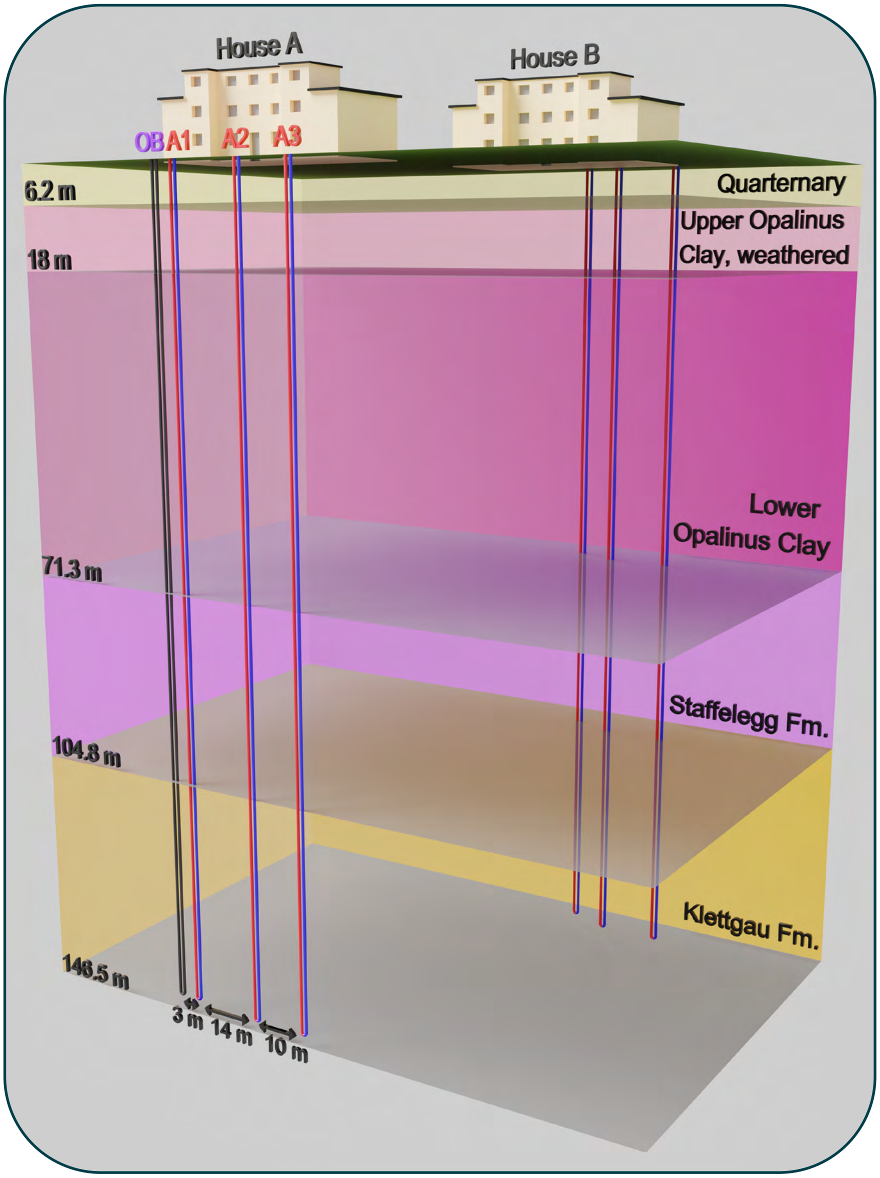


Table 1

	BHEs A1−A3	OB
Depth	146 m	146 m
Borehole diameter	127 mm	146 mm
BHE type	Double U-tube	Single U-tube
Diameter / Wall thickness / Shank-space	40 / 3.7 / 45 mm	40 / 3.7 / 45 mm
Grout material	Thermally enhanced, $\lambda < 2.0$ W m^{-1} K^{-1}	Thermally enhanced, $\lambda < 2.0$ W m^{-1} K^{-1}
Heat carrier fluid	Ethylene glycol-based	Water

To monitor system performance, heat meters and data loggers are used to measure the amount of extracted/injected thermal energy as well as the inlet and outlet temperatures of the heat carrier fluid at 30-minute intervals. Ambient air temperature is recorded at five-minute intervals.

NUMERICAL MODEL SETUP

To identify the key factors influencing thermal changes at the site, a numerical model was developed using COMSOL Multiphysics® to simulate heat transfer within the BHE system. This three-dimensional model spatially resolves the characteristic geometry of the tube. Heat extraction and free cooling are implemented by simulating the laminar flow of the heat carrier fluid through the U-tubes.

The model domain is divided into subdomains that correspond to the major geological layers based on the lithostratigraphic data. A volumetric heat capacity of 2.26 MJ m^{-3} K^{-1} (3.91 Btu ft^{-1} °F^{-1}) and the thermal conductivity profile obtained from the ETRT are assigned accordingly. The initial temperature distribution throughout the domain is set based on the daily average temperature profile recorded at the OB on April 1, 2016.

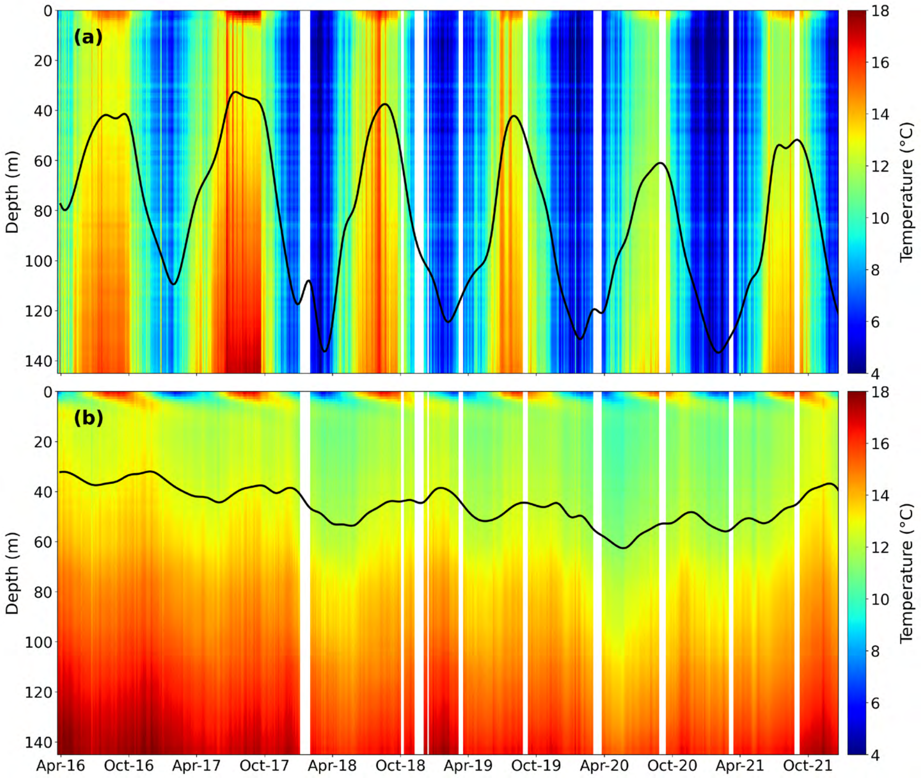
Monthly average flow rates and inlet temperatures of the heat carrier fluid are used as input data for the BHE field operation. Ambient air temperature, averaged monthly, is applied as the boundary condition at the ground surface.

MEASURED HIGH-RESOLUTION TEMPERATURE DATA

The DTS data reveal gradual thermal changes in the BHE field over the operational period. Figure 2 shows the daily averaged temperature evolution for BHE A1 and OB from late March 2016 to December 2021. BHEs A2 and A3 show very similar temperature patterns to A1. Heating periods appear as blueish colors, while vertical red lines represent free cooling phases (see Figure 2a). After the heating season, ground temperatures recover quickly each year, reaching similar levels at the beginning of summer as in the first operational year. The depth-averaged temperatures show a cooling trend of about 0.55 to 0.56 °C (0.99 to 1.01 °F) per year.

For BHE A1, monthly depth-averaged temperatures in winter typically range between 5 and 7 °C (41 and 45 °F), while summer temperatures fall between 12 and 15 °C (54 and 59 °F) (Figure

Figure 2



2a). Even though no free cooling operation in summer 2020 resulted in limited regeneration, subsurface temperatures were not significantly lower in the following winter. This suggests that regeneration was low in previous years as well, accounting for only 1 to 5% of the energy extracted from the ground.

Due to thermal interference from the neighboring BHEs, A2, located at the center of the array, experienced a slightly stronger cooling effect, partly due to thermal interference from neighboring BHEs. However, monthly averaged temperatures have stabilized around 5 °C (41 °F) during the last three winters, indicating that the system is appropriately dimensioned.

Since OB is not connected to the heating system, its temperature changes are much lower compared to the active BHEs (Figure 2b). Seasonal effects are noticeable down to about 8.5 meters (28 feet) depth. A cooling trend of 0.3 to 0.4 °C (0.5 to 0.7 °F) per year can also be observed in the OB, which is due to the cold plume spreading from BHE A1, located only 3 meters away (10 feet).

SIMULATION RESULTS

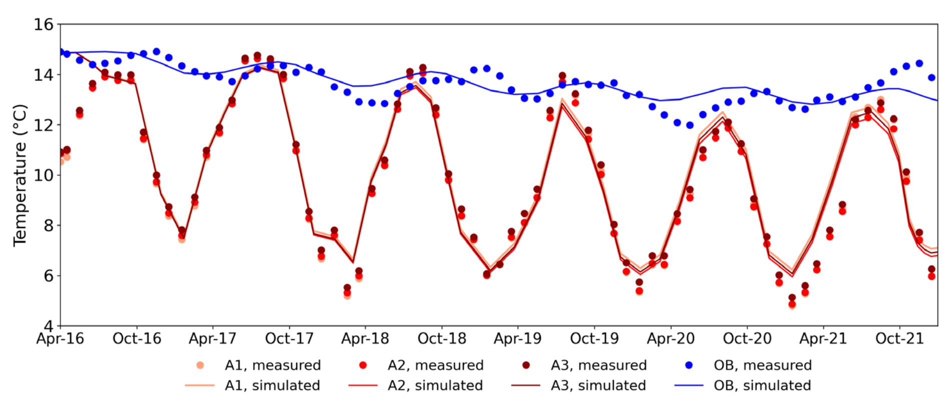
The simulation results for monthly depth-averaged temperatures from April 2016 to December 2021 are presented in Figure 3. In general, the measured temperatures exhibit larger peaks compared to the simulated temperatures. This difference is largely because the model uses monthly averaged data, smoothing out short-term peaks. Similarly, monthly averages of inlet temperature and flow rate do not capture the real operational conditions of GSHPs. Thus, to enhance model accuracy, increasing the temporal resolution of the input data is recommended.

For the BHEs, simulation results show good agreement with the measured data, particularly given the high variability in the recorded temperatures. Further, the simulation captures the thermal interference observed between the BHEs, with BHE A2 showing a slightly stronger cooling trend than A1 and A3, consistent with the monitoring data (Figure 3).

For OB, the model does not fully reproduce the observed temporal temperature variations (Figure 3), and the measured temperatures tend to lag behind the simulated values. Nonetheless, the general cooling trend observed in the measurements is well represented by the model.

CONCLUSION

In this study, six years of high-resolution temperature data from a monitored BHE field, collected by DTS, are combined with a 3D numerical simulation. While the long-term monitoring shows a cooling trend of about 0.55 to 0.56 °C (0.99 to 1.01 °F) per year at the BHEs, winter temperatures have stabilized after three years of operation, indicating the system is properly sized. However, free cooling contributes only a small amount to ground regeneration. The double U-tube numerical model closely matches the temperature trends observed in the BHEs. Although the model captures the long-term cooling trend in the nearby observation borehole, it cannot fully replicate the observed thermal variability. Together, the study proves that long-term monitoring and detailed modeling provide valuable insights that can help improve the design, operation, and performance forecasting of geothermal systems.



ACKNOWLEDGEMENTS

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REFERENCES

This article is a shorter version of the paper with the same title and authors published in the proceedings of the IGSHPA Research Conference Montréal, May 28-30, 2024 (https://doi.org/10.22488/okstate.24.000019).

Figure Captions

Figure 1: 3D view of the spatial layout of the BHEs and their surrounding geological setting. OB: observation borehole, A1–A3: monitored BHEs.

Figure 2: Subsurface daily-averaged temperatures measured in the ring space of (a) the borehole heat exchangers A1, and (b) the observation borehole. The black line indicates the monthly depth-averaged temperature.

Figure 3: Comparison of the depth-averaged measured temperatures with the simulated temperatures along the borehole heat exchangers A1, A2, A3, and the observation borehole (OB).

Table Heading

Table 1: Data on the BHE installation and observation borehole.