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Field Test and Thermal Performance Comparison of a Novel Underground Thermal Battery with a Single U-tube Borehole Heat Exchanger for Geothermal Heat Pump Application

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ABSTRACT

Geothermal Heat Pumps (GHP) are a proven technology to electrify and decarbonize space heating and cooling by utilizing the thermally consistent underground as a heat sink or source. However, the high drilling costs of conventional borehole heat exchangers (BHEs) associated with GHP systems and subsurface heterogeneity have been two major challenges to their widespread adoption. In this paper, we present results from a field-scale pilot of an Underground Thermal Battery (UTB) as a potential alternative to a conventional BHE. To benchmark the UTB performance, a side-by-side field test was conducted to compare the UTB with a conventional BHE installed at the same site. The UTB was installed in a 7.01-meter-deep borehole having a diameter of 0.9 meter, whereas the conventional BHE (with single U-tube loop) is in a borehole with 36.6-meter depth and 0.15-meter diameter. Both are integrated into a GHP system to meet the thermal energy demands of office space at the Illinois Energy Farm on the University of Illinois Urbana-Champaign campus. The system's performance is compared in terms of heat transfer rate, outlet temperatures, and contributions to the overall thermal power of the GHP system under varying thermal demands and in different heat pump operation modes: heating only, cooling only, and hybrid (alternative, diurnal heating and cooling). Results to date indicate that the UTB delivers a more consistent response under during a time period of varying thermal demands. Its operational performance is better during short-term with higher thermal demands, while the conventional BHE performs better under continuous, long-term thermal demands.

1. INTRODUCTION

The adoption of geothermal heat pumps (GHPs) offers numerous advantages. Nationwide deployment of GHPs in the US could reduce annual CO_2 emissions by 7,351 million metric tons, saving consumers $19 billion annually in their heating costs projected out to 2050, further reducing the need for installing additional electricity transmission lines by 33%, while creating jobs and improving public health [1]. However, the higher upfront cost of installing GHP systems remains a significant barrier to their widespread adoption [2]. The primary contributor to this cost is drilling of borehole heat exchangers (BHE), which usually accounts for over 50% of the total system installation cost[3]. To make the technology more affordable, further research is needed to identify alternative heat exchange technologies and develop lower cost drilling methods.

Past research to develop alternative heat exchangers, beyond the conventional U-tube design, including coaxial, spiral , horizontal loop configurations [4] [5] [6], U-tube loops with spacers and grooves [7], as well as helical U-tubes and W-tubes [8] designs, among others. One promising technological development that combines the design of a helical U-tube design with a thermal storage unit is an Underground Thermal Battery (UTB), a new shallowly-buried heat exchanger developed at the Oak Ridge National Laboratory (ORNL) over the past few years. The UTB is a dual-purpose system that can function both as a heat exchanger and a thermal energy storage device. Past research on the UTB has focused on various aspects, including lab-scale prototype development and thermal performance assessment [9], numerical model creation and validation [10], development of a new g-function [11], performance evaluation during charging and discharging cycles [12], and its effect on building electric demand [13].

The next step in the commercialization of the UTB is the current field testing at the Illinois Energy Farm on the University of Illinois Urbana-Champaign campus. The UTB is a component of a larger geothermal system, which includes a GHP and three other conventional borehole heat exchangers which was commissioned in May 2024. The geothermal system replaces a 3-ton conventional air conditioning and propane heating system for roughly half of the conditioned space. The remaining half of the space remains connected to the original heating and cooling system. Altogether, the GHP system includes three conventional BHEs connected in parallel, and the UTB. A data acquisition system has been set up at the site with remote monitoring capabilities. The GHP system is implemented to provide a side-by-side comparison between the UTB with conventional BHEs under identical geological and thermal conditions. For this study, performance is compared between the UTB and one of the three conventional BHEs (single U-tube). The other two conventional BHEs are not in the scope of this study although they do have other scientific purposes.

2. SYSTEM SCHEMATICS AND WORKING PRINCIPLE

As shown in Figure 1 (d), the UTB and a conventional BHE are installed adjacent to each other, with a 54.9 m (180 feet) distance between them. Both are connected to a GHP that supplies heating or cooling to approximately half of the office space. The UTB has a depth of 7.01m (23 feet) and a diameter of 0.91 m (3 feet), while the BHE has a depth of 36.6 m (120 feet) and a diameter of 0.15 m (0.5 feet) (Figure 1b).

The conventional BHE, also referred as borehole W1 in this study, has a single U-tube. One leg of the U-tube serves as the inlet, while the other functions as the outlet. The UTB features a tank design with a helical pipe attached to the interior wall of the tank (Figure 1c). The inner helical -pipe spirals from the top to the bottom of the tank and back to the top through a straight pipe. The tank is designed to be versatile, allowing the fluid inside it to be easily replaced with other mediums. For the current study, the tank is filled with fresh water. The glycol circulates through the helical pipe, exchanging heat with the water inside the tank, which in turn exchanges heat with the surrounding ground. To monitor temperature stratification within the UTB, two thermocouple trees are installed. Each tree contains 10 thermocouples evenly spaced along the vertical axis, providing detailed measurements of temperature variation within the tank. The materials used in these two heat exchangers differ based on their designs. The helical pipe in the UTB is made of flexible blue cross-linked polyethylene (PEX) while the U-tube in the BHEs is made of high-density polyethylene (HDPE).

A mixture of water and propylene glycol (70-30% ratio) circulates through a hydronic loop connecting the UTB and the BHEs to the GHP. The flow rate of heat transfer fluid in the UTB and BHE can be individually controlled (either remotely or manually). The inlet and outlet temperatures from the GHP system, as well as the flow rate of each BHE are measured continuously every minute, and the values are averaged over 15-minute intervals.

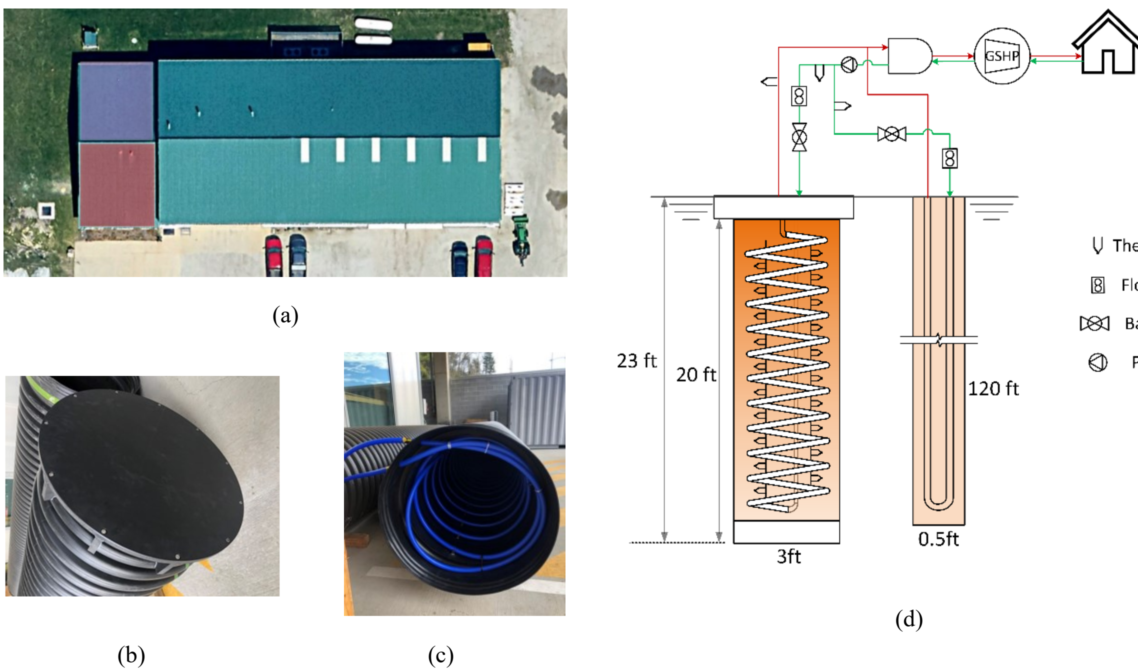


Figure 1: (left) Field-test site satellite view (a), blue shaded region is served by GHP and red shaded region is served by conventional heating-cooling system, UTB tank with bottom attached on a corrugated HDPE pipe (b), PEX attached on the interior wall of the UTB (c), and schematics of the field test experiment (right).

The W1 BHE and UTB are designed to have an equal heat exchange surface areas of 35 square meters in contact with the surrounding ground to ensure an equal comparison between the two. The GHP system was commissioned in May 2024, and periodic testing was conducted for the first month. This study presents results from the first seven months of operation (June 2024 to December 2024). During this time, while the inlet temperature to W1 and UTB remained identical, the mass flow rate was intentionally varied to evaluate its impact on the performance.

3. GOVERNING EQUATIONS

The thermal power output from both the boreholes is calculated using Equation (1), where T_{in} and T_{out} are the measured inlet and outlet temperatures of the BHE (°C), $\dot{m}$ is the measured mass flow rate (kg/s), and Cp is the specific heat capacity of the glycol, assumed constant as 4186 J/Kg-K.

$$\dot{Q} = \dot{m}C_p(T_{in} - T_{out}) \tag{1}$$

The rate at which the thermal energy is contributed from each BHE is calculated using Equation (2). This contribution is expressed as a percentage of the total thermal power provided by the BHE and UTB at a given instant. In Equation (2), the thermal power contribution is represented as $\dot{Q}_{th}contribution$ (%). The thermal power transferred from an individual BHE is represented by $\dot{Q}_{delivered\ by\ W1\ or\ UTB}$ (watts) and the total thermal power transferred W1 and the UTB is given by $\dot{Q}_{\ delivered\ total}$(watts).

$$\dot{Q}_{th}contribution\ (\%) = \frac{\dot{Q}_{delivered\ by\ W1\ or\ UTB}}{\dot{Q}_{\ delivered\ total}} \times 100 \tag{2}$$

The daily heating and cooling percentage are calculated as the ratio of time the GHP system operates in heating or cooling mode for a specific day. This is determined using Equation (3).

$$Daily\ heating\ vs\ cooling\ (\%) = \frac{Total\ duration\ of\ heating\ or\ cooling}{Total\ duration\ of\ systme\ operation} \times 100 \tag{3}$$

4. RESULTS

The results from June to December 2024, are presented during which the GHP system is operated automatically to maintain the room temperature at its setpoint. The GHP was switched into heating mode when the room temperature fell below 20.6°C (69°F) and into cooling mode when the room temperature rose above 23.3°C (74°F). To analyze the data according to the operation mode, the time period was subdivided into cooling mode (from June 7 to October 25) when the GHP system was exclusively used for cooling, hybrid mode (from October 26 to November 14) when the system operated in both heating and cooling modes, and heating mode (from November 15 to December 31) when the heating was the primary use.

4.1 Cooling mode

During cooling mode, two scenarios are analyzed: identical flow rates and variable flow rates. The flow rate was kept equal through both the UTB and W1 during the first scenario, while flow rates in the UTB and W1 were intentionally varied between during the second scenario. Running an equal flow rate would help to determine the baseline thermal performance under same operating conditions, while allowing variable flows would help us study the correlation between flow rates and the thermal performance.

4.1.1 Different flow rates

For this comparison, the thermal power output or total heat transfer rate from the UTB and the conventional W1 is used as the primary comparison parameter. It was observed that altering the flow rate significantly impacted the inlet temperature to the BHEs. This phenomena occurs because changes in flow rate directly impacts the heat transfer rate and thermal power extracted from the BHE, which is reflected in the outlet temperatures. Since the BHEs and the GHP operate in a closed-loop circuit, variations in the outlet temperature of the BHEs also affects the temperature of the glycol exiting the GHP and returning to the BHEs. We also determined that the output thermal power from the BHEs is strongly correlated with both flow rate and inlet temperature. Because these two parameters are not mutually exclusive, the results are normalized in terms of thermal power output per unit flow rate. Figure 2 shows this comparison, along with the trendline between these two parameters. Seven different mass flow rate and inlet temperature scenarios were investigated. Figure 3 presents the ratio of the mass flow rates between W1 and UTB for these scenarios.

On average, the normalized thermal power output is higher for W1 than UTB. However, the ratio of thermal power output between W1 and UTB decreases as the inlet temperature increases to the BHEs. For instance, data periods 3 and 7 had similar flow rate ratios, but the inlet temperature at data point 7 was 26.8°C compared to 20.7°C at data point 3. The output thermal energy ratio between W1 and UTB was 4.4 at data point 3, while it was only 1.4 at data point 7. During data period 6, the normalized thermal power output from both UTB and W1 was the same, due to a higher W1 flow rate compared to UTB (flow rate ratio of 2.12). There are other data period where W1 flow rate is higher (exceeding a ratio of 2.0), such as data period 4 and 5, however, during these periods, the inlet temperature to the boreholes was lower compared to data period 6.

From these two plots, it can be concluded that although W1 generally outperforms UTB, higher inlet temperatures favor the performance of the UTB. A higher inlet temperature at the same flow rate indicates higher thermal loads. Given the thermal buffer of the UTB, it performs better with higher thermal loads, especially for shorter operating periods.

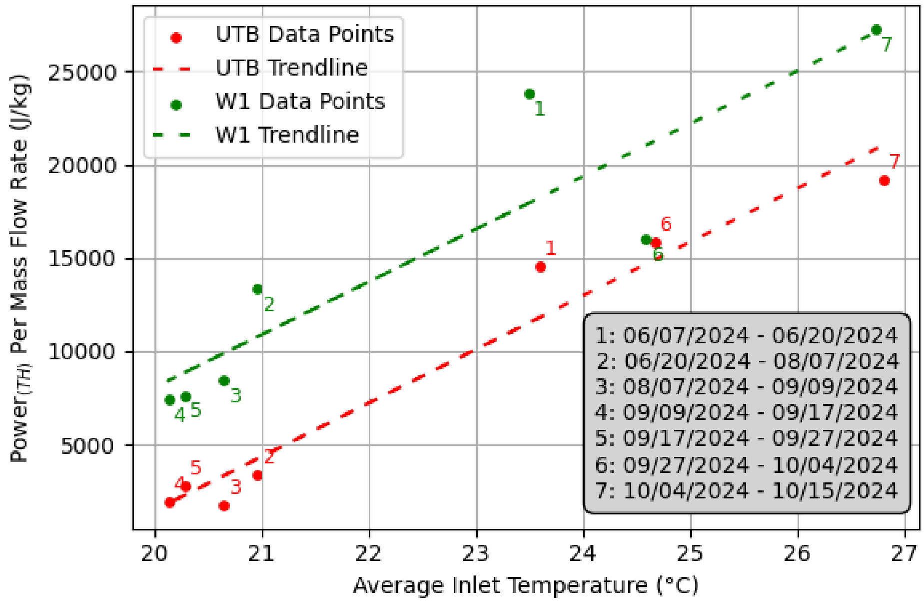


Figure 2: Thermal power per unit flow rate *vs.* inlet temperature. The trendlines show correlation.

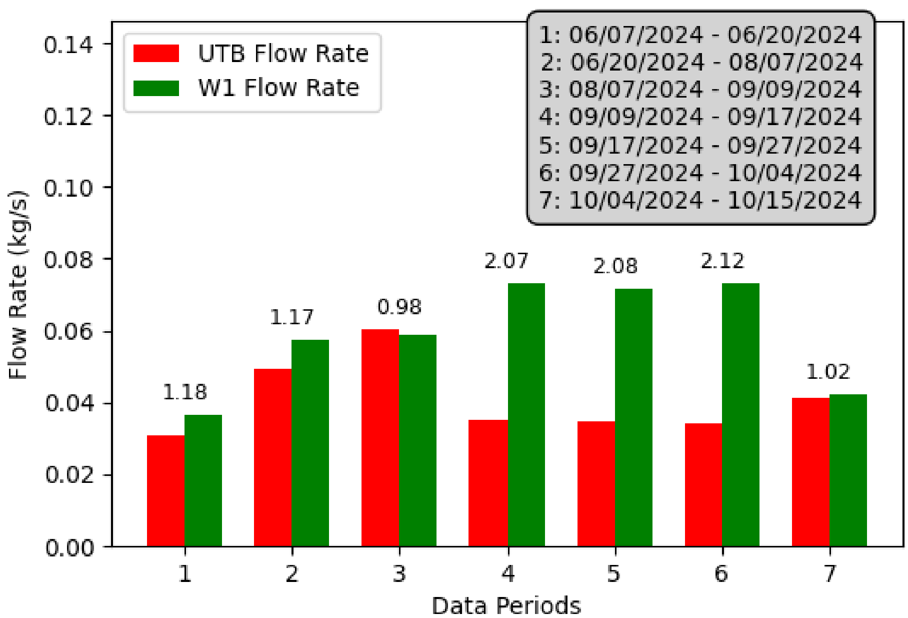


Figure 3: Flow rate comparison between UTB and W1 for all scenarios.

4.1.2 Outlet temperature fluctuation

When the inlet temperatures at both W1 and UTB are identical, it is also valuable to examine the outlet temperatures and their fluctuations under the dynamic thermal energy demands of the office space. In Figure 4 the outlet temperatures from UTB and W1 is compared for data period 6 of Figure 3. The clusters of data points in Figure 4 represent the inlet and output temperatures over the course of a day. It was observed that the outlet temperature from the UTB was relatively stable and exhibited a smaller range of variation compared to W1. This suggests that UTB can perform better under fluctuating and peak thermal energy demands. In general, a similar trend was observed for all data periods shown in Figure 3, with the difference in outlet temperature range decreasing for the scenarios with comparable flow rates and longer time periods.

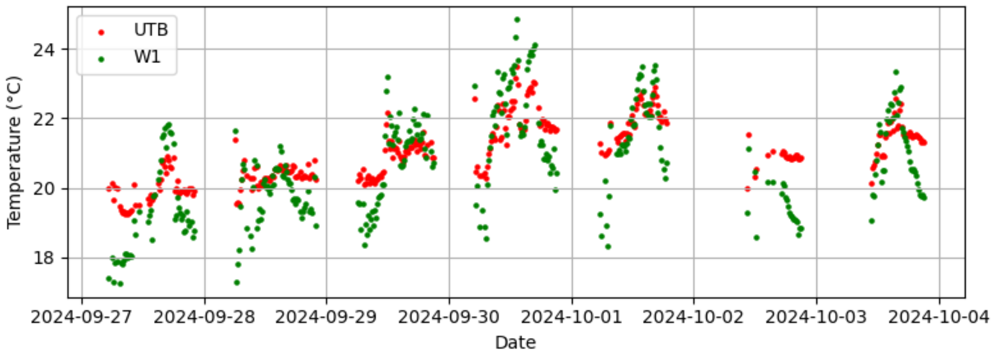


Figure 4: Comparison of outlet temperatures for the W1 BHE and UTB.

<ins>4.1.3 Equivalent flow rates</ins>

For this comparison, identical flow rates were maintained between October 4 and 15, 2024. The results of the testing, including flow rates, outlet temperatures, thermal energy transfer, and instantaneous thermal power contribution are shown in Figure 5. The instantaneous thermal power contribution, $\dot{Q}_{th}contribution$ (%), indicates the percentage of thermal power (heat conduction into the ground) contributed by W1 and the UTB that sum to 100%. As shown, the outlet temperature from W1 is lower than that from the UTB, which is also reflected in thermal power output and the percentage contributions. That data presented in Figure 5(c) shows that UTB has relatively better performance during and after increasing the thermal energy loads. This is due to the ability of UTB to provide a buffer of thermal energy that slows the change in outlet temperature, which is observed by the narrowing difference between outlet temperature of these heat exchangers. The average instantaneous thermal power contribution during this period was 58.8% for W1 and 41.2% for the UTB.

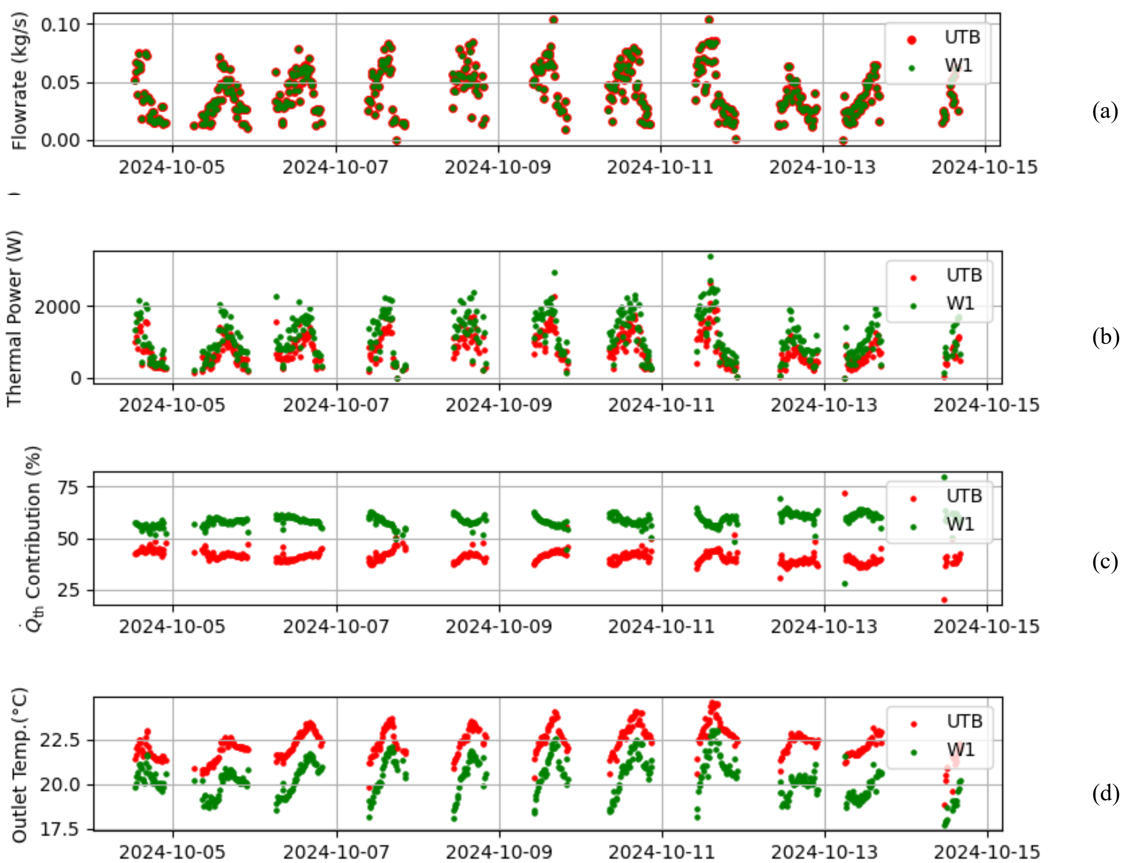


Figure 5: Comparison of identical flow rates with graphs of (a) flow rate, (b) thermal power output, (c) thermal power contribution, and (d) outlet temperature.

4.2 Hybrid mode

From October 26 to November 21 in 2024, alternating periods of heating and cooling was experienced each day. During this period, the GHP provided heating in the early mornings and late evenings, while cooling was required during the daytime hours when the ambient temperature rose. Furthermore, in few other days, either heating or cooling occurred for more than 90% of day. Data for these days were not included under hybrid operational mode. In Figure 6(a), the proportions of the days when heating or cooling occurred are shown. In Figures 6(b), (c) and (d), the fraction of thermal energy output contributed by each W1 and the UTB are shown. As shown in the Figure 6(a), the cooling demand was dominant during the first several days, while proportion of heating gradually increased during the period. The percentage contribution of each heat exchanger in meeting thermal demand of the building during hybrid mode in shown in Figure 6(b).

Both W1 and the UTB contributed significantly during this time period, although UTB performed marginally better than W1. In the early several days, when the cooling demand was dominant, W1 outperformed the UTB, however, as the time progressed and heating became more prevalent, the UTB started to perform better. Overall, the thermal energy contributions during this test were 51% from the UTB and 49% from W1. To better understand the heating and cooling patterns, further insights are presented in Figure 6(c) and Figure 6(d). In Figure 6(c), the thermal energy contributions during the cooling mode are shown, whereas in Figure 6(d) the contributions during heating are shown. For cooling mode, W1 initially performed better, but the benefits gradually diminished over time, with the UTB eventually outperforming the W1 by the end of the testing. For the heating mode, the UTB outperformed W1 consistently, although the difference in performance diminished over time.

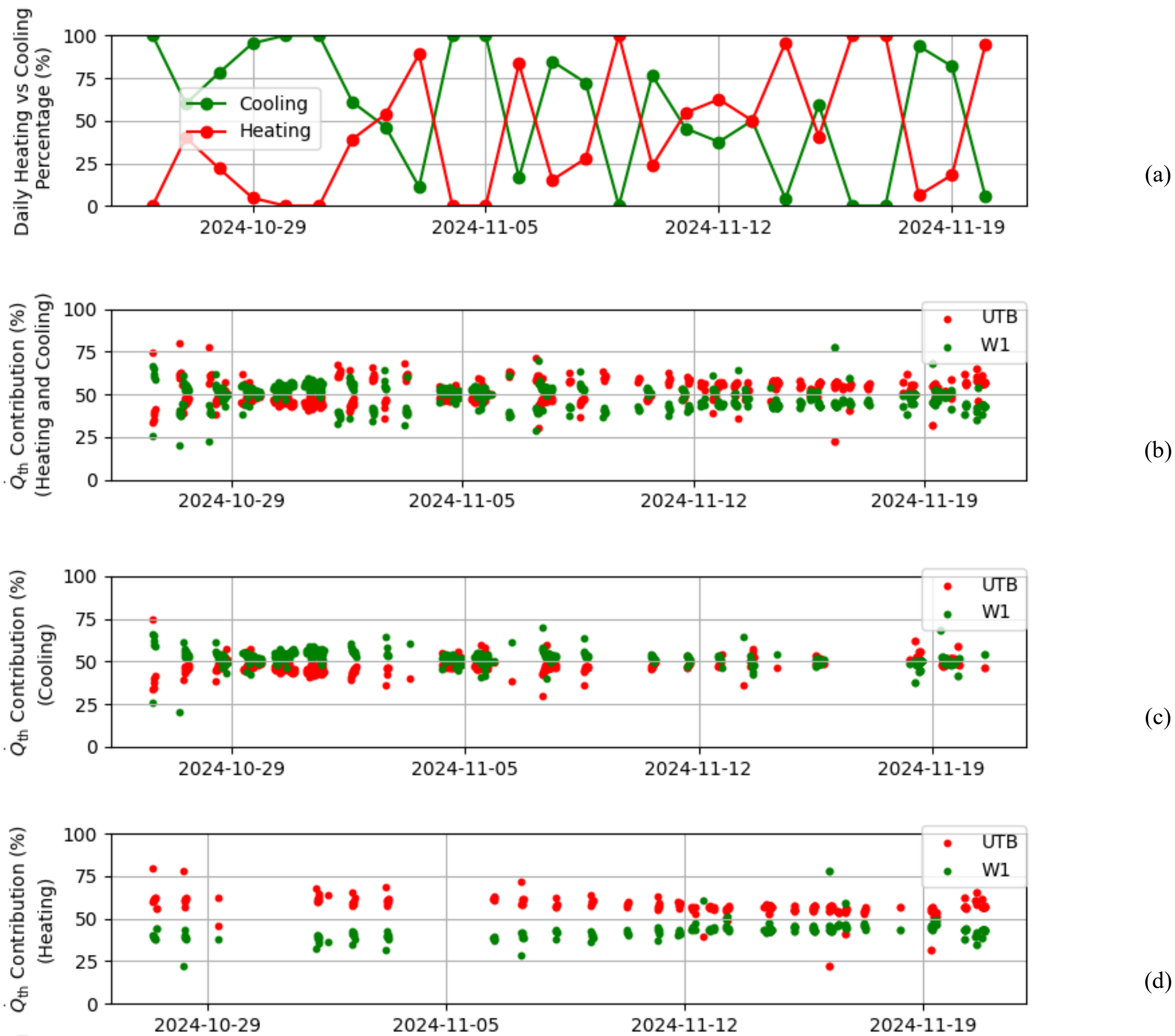
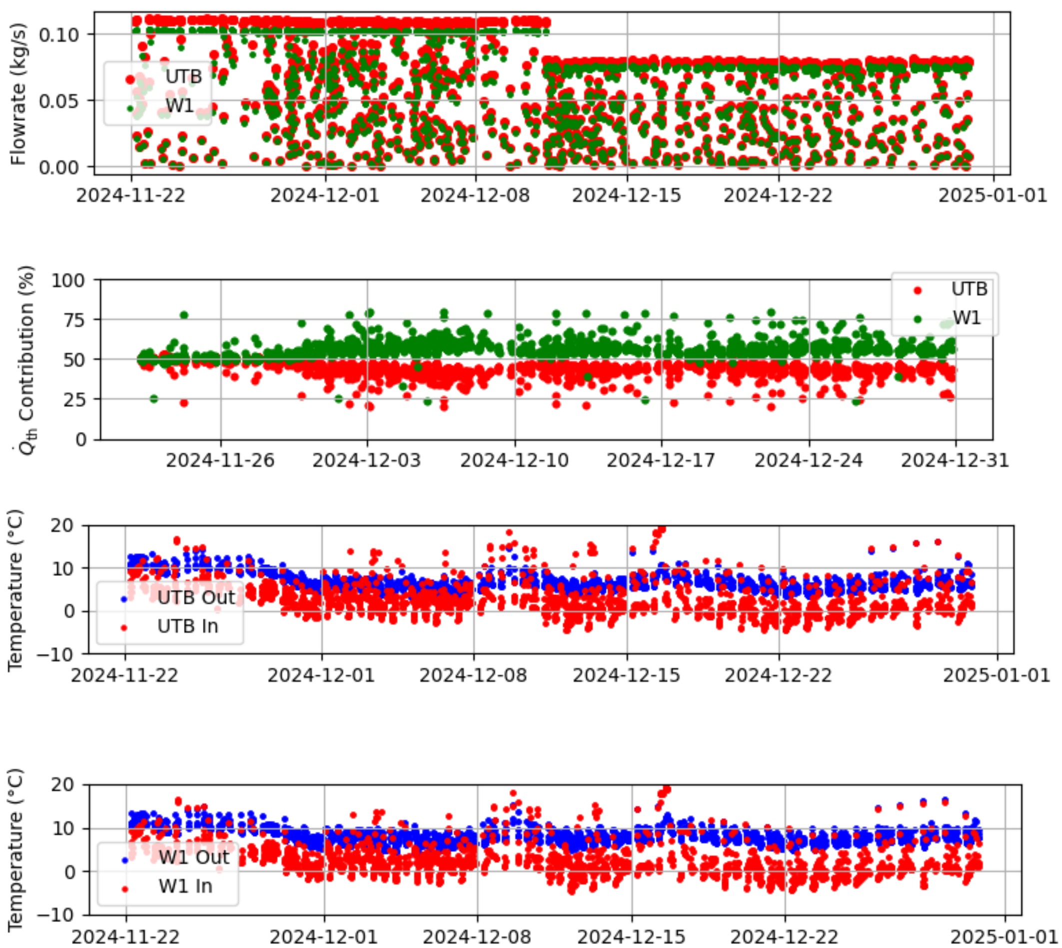


Figure 6. Daily distribution of heating and cooling load (a), and performance comparison during hybrid testing (b), (c), (d).

4.3 Heating mode

After November 22, 2024, the ambient air temperature dropped increasing heating demand in the office space. The results for the heating mode are shown in Figure 7. During this time period, the flow rate was similar in both the W1 BHE and the UTB, as shown in Figure 7(a), with only a slightly higher flow rate observed in the UTB. Although, we intended to maintain identical flow rates, this discrepancy occurred due to issues with the instrumentation. The thermal power contributions from W1 and UTB are presented in Figure 7(b), and the inlet and outlet temperatures at the two heat exchangers is shown in Figures 7(c) and 7(d). During the first several days of the heating season, the thermal performance of W1 and the UTB was similar. However, as heating became dominant and thermal energy was continuously drawn from the ground, W1 demonstrated better performance than the UTB. We also determined that the UTB performance recovered after a short break or less frequent operation on December 10 and December 17. On average, 55.5% of the heating demand was provided by W1, while 44.5% was supplied by the UTB.



(a)

(b)

(c)

(d)

Figure 7: Performance comparison during heating season. Shown are the (a) flow rates, (b) thermal power contributions, (c) UTB inlet and outlet temperatures, and (d) W1 inlet and outlet temperatures.

5. DISCUSSIONS

To better understand the results of this study, it is useful to examine the temperature difference between the glycol entering the BHEs and the average temperature of the W1 borehole (for W1) and UTB tank water (for UTB). This temperature difference impacts the temperature changes of the water glycol mixture being circulated through BHEs. The undisturbed ground temperature, average UTB tank water temperature, and W1 entering fluid temperature are compared in Figure 8. UTB has a water buffer between the heat exchange loop and the ground, while W1 is in direct contact with the ground. During initial days of cooling period, W1 borehole temperature is close to the undisturbed ground temperature and the average UTB tank temperature is closer to ambient temperature. The deltaT between the ground and heat exchangers that drives the heat transfer process is greater for W1 than UTB. However, during the hybrid period, the average UTB temperature is higher than the ground, which leads to a better performance for the UTB that results from a higher heat transfer rate, especially during the heating operation during hybrid mode. During the winter heating season, the average UTB tank water temperature would fall below the average W1 inlet temperature and hence BHE performs better.

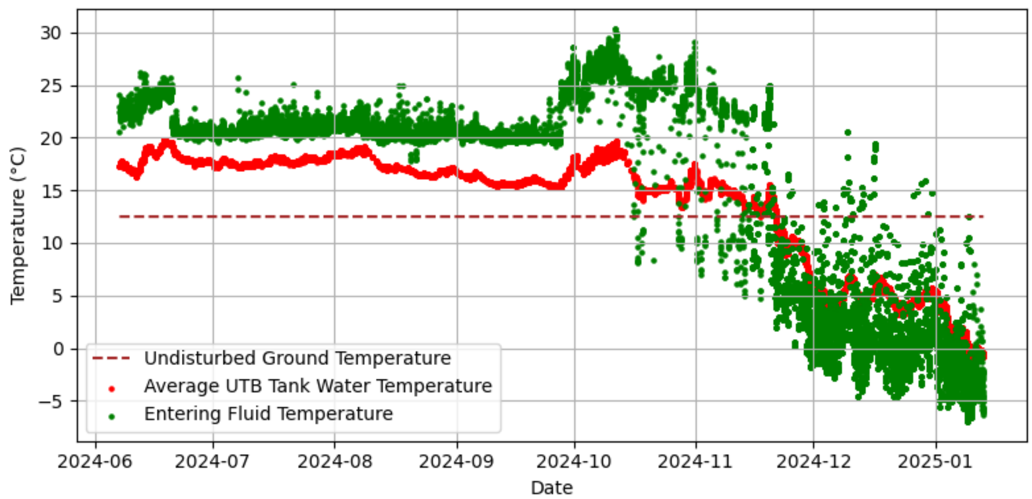


Figure 8: Comparison of initial ground temperature, average UTB temperature, and inlet temperatures at W1 during the testing period.

To better assess the deltaT between the air and the ground, the evolution of average UTB tank water temperature and the daily ambient air temperature is shown in Figure 9. Although the average UTB tank water temperature is lower than the ambient temperature in the summer and higher than the ambient temperature in the winter, it is directly influenced by the ambient temperature with only a small lag time. The depth range of W1 is greater than that of the UTB, the BHE temperatures are less sensitive to the seasonal temperature changes leading to a longer lag time. This delay contributes to better performance of W1 during prolonged heating seasons.

As the ambient air temperatures drop well below freezing beyond December 2024, the next phase of our work will focus on the performance of UTB under phase changes i.e., freezing of water in the UTB. It is also important to note that at the start of the upcoming summer cycle, the UTB temperature could be lower than average W1 borehole temperature, and therefore the performance of the UTB will be different from the performance during this summer cooling season.

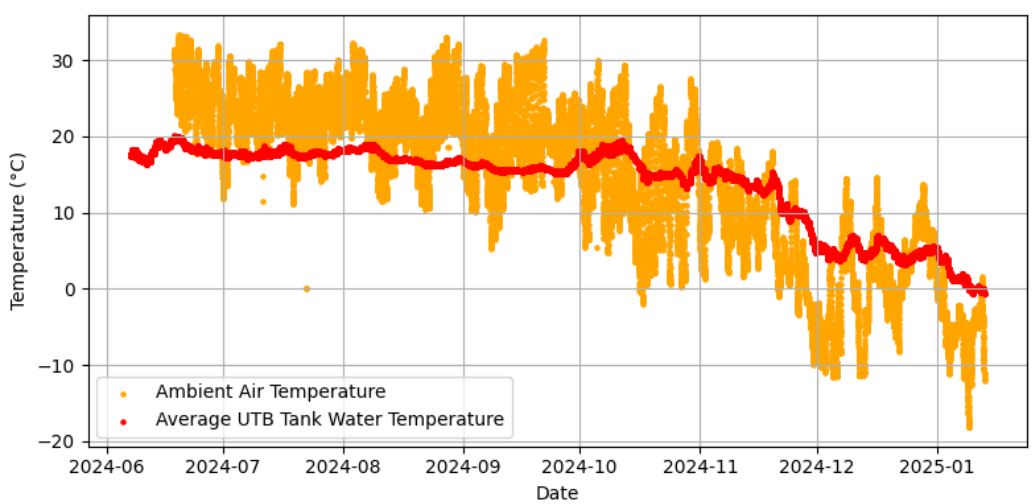


Figure 9: Comparison of the ambient air temperature with the average temperature of water in the UTB.

6. CONCLUSIONS

This study presents a comparative analysis of heat exchangers designed for GHP applications: a conventional U-tube BHE (W1) and a novel UTB. Thermal performance was evaluated during three operational modes: cooling mode, hybrid mode, and a heating mode. Results indicate that the conventional BHE outperforms UTB during long periods when the thermal energy demand is constant, such as in the cooling and heating seasons. However, during the shoulder season (hybrid mode), when the building has short-term thermal energy loads for heating or cooling, UTB performs better. Results also revealed that UTB can deliver a stable outlet temperature compared to W1 during peak load demands. A combination of a UTB and a conventional BHE could provide optimal thermal performance compared to using either two BHEs or two UTBs. This can be achieved with proper control strategies to utilize the UTB to handle peak thermal demands and BHEs to handle base thermal demands.

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