Development of an Underground Thermal Battery for Enabling Ground Source Heat Pump Applications and Shaping Electric Demand of Buildings

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An innovative underground thermal battery (UTB) can provide not only a stable heat sink or heat source for efficient heat pump operation, but also a thermal energy storage to overcome the mismatch between intermittent renewable power supply and fluctuating thermal demands of a building. This article introduces the recent developments of the UTB, including concept design, lab tests, and modeling. Initial results indicate that the UTB has a potential to enable both efficient air-conditioning and active demand side management without sacrificing the desired comfort condition and convenience in the building.

Introduction

Ground source heat pump (GSHP) is an energy efficient technology for space heating, space cooling, and water heating. It is estimated that 6 trillion Megajoules of primary energy can be saved per year in the United States by retrofitting the existing heating and cooling systems with GSHPs due to their high efficiency (Liu et al. 2019a). GSHP systems utilize a ground heat exchanger (GHE) to extract heat from the ground in winter or reject heat to the ground in summer. The vertical bore ground heat exchanger (VBGHE) is the most commonly used GHE in the United States due to its reliability and small footprint. However, the high installation cost of the VBGHE, which accounts for more than 30% of the total installation cost of a GSHP system (NYSERDA 2017), limits a broader adoption of GSHPs in the United States. Previous efforts to reduce the cost of VBGHE have mostly focused on improving heat transfer inside the borehole. However, the small diameter of the borehole (< 0.15 m) restricts the potential for performance improvement and cost reduction. A recent study (Liu et al. 2018) concluded that the cost reduction potential of improving borehole heat transfer is less than 30% and dependent on the ground thermal conductivity. New GHE designs that can more drastically reduce the installation cost of the GHE are highly desirable for broader adoption of GSHPs in the United States.

On the other hand, the stability of the electric grid has been a growing concern in recent years as the intermittent renewable power generation causes large swings in the demand of the electric grid. The "duck curve" phenomenon, as shown in Figure 1, reflects the mismatch between the intermittent renewable power supply and

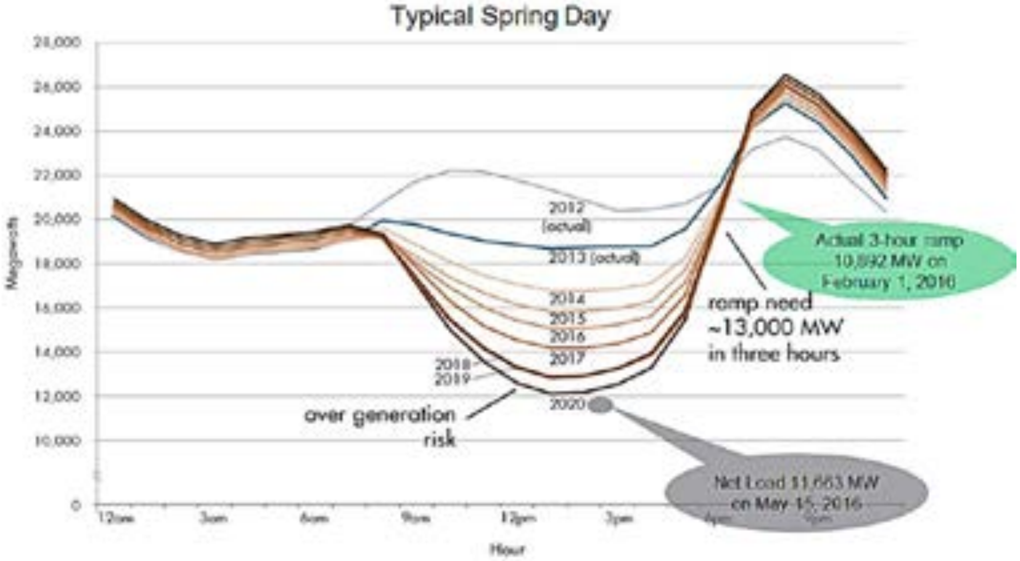


Fig. 1: "Duck Curve" of electricity demand due to intermittent renewable power. Reproduced with permission from California ISO (CAISO 2013).

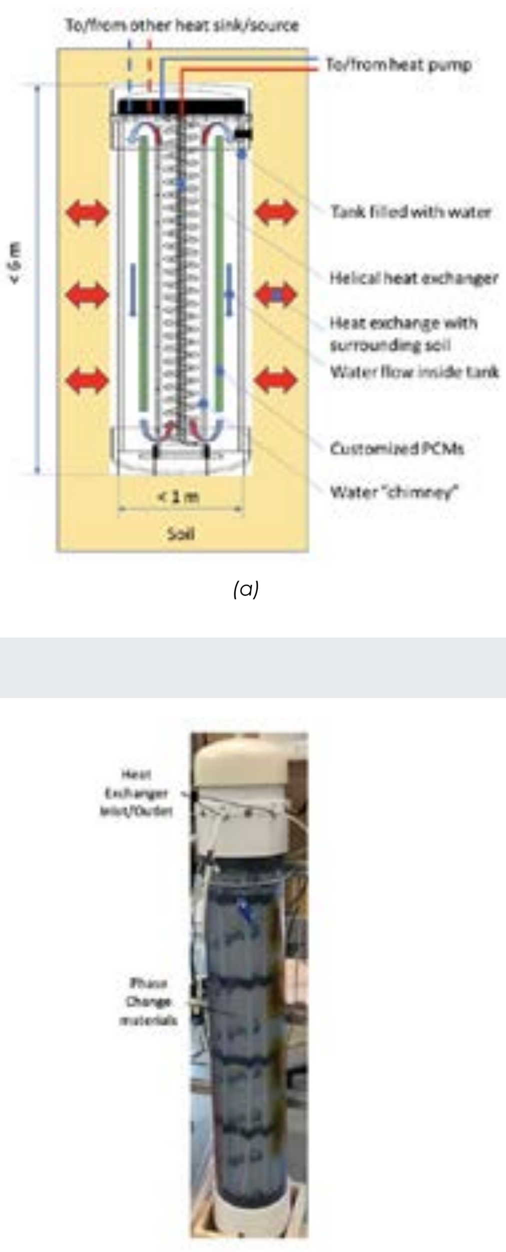
the demand of the grid. The rapid ramp-up and large fluctuations in the electricity demand significantly challenge the operation of the electric grid. Furthermore, the excess of renewable power generation has to be curtailed, resulting in limited use of renewable power (NREL 2015). Measures to reduce the "duck curve" effect can significantly improve the stability and cost-effectiveness of the electric grid (Klein et al. 2016).

Because approximately 40% of electricity consumed in buildings is for thermal demands, including space heating, space cooling, and water heating (IEA 2018), thermal storage could be an effective method to solve the mismatch between the intermittent renewable power supply and the fluctuating building electric demand.

An innovative low-cost underground thermal battery (UTB) has been invented to provide not only a stable heat sink or heat source for efficient heat pump operation, but also a thermal energy storage to overcome the mismatch between the intermittent renewable power supply and building's thermal demands. This article introduces the recent developments of the UTB, including concept design, lab tests, and modeling.

UTB as a low-cost ground heat exchanger

Figure 2(a) is the prototype of the UTB designed as a low-cost GHE. It is a tank filled with water and buried in the shallow subsurface of the ground. There is a helical heat exchanger immersed in the center and panels of a customized phase-change material (PCM) suspended in the water to increase the thermal storage capacity of the UTB. A full-scale UTB has a diameter of 1 m, and a depth of 6 m, so that it can be installed by using auger drill rigs with a lower cost than the installation of small diameter but deep boreholes used for conventional VBGHE. A 1:5 small-scale prototype of the UTB was built, and tested to characterize its performance, as show in Figure 2(b). The dimensions of a full-scale UTB, the small-scale UTB, and a conventional VBGHE are listed in Table 1.



(a)

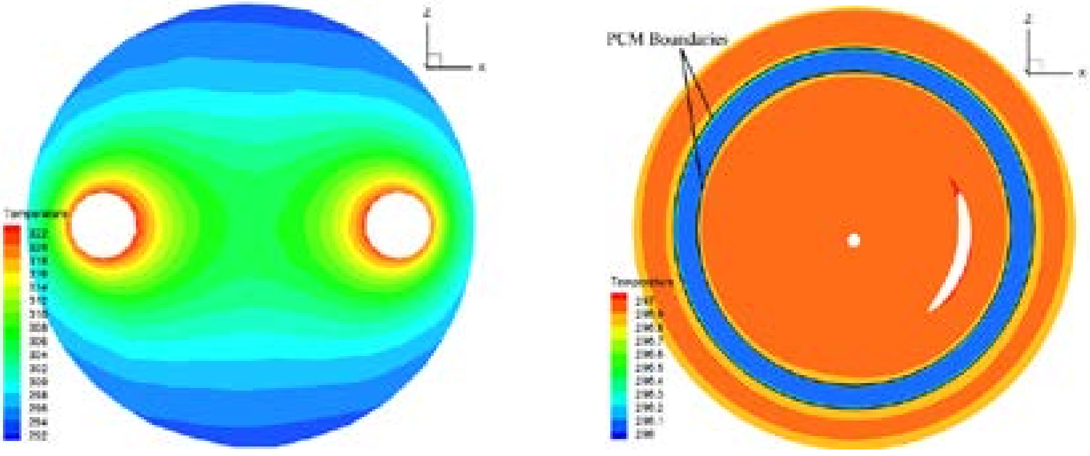
(b)

Fig. 2: The first UTB prototype: (a) schematic design; and (b) a small-scale prototype for lab testing.

Table 1. Dimensions of conventional VBGHE, a full-scale UTB, and a small-scale UTB

Dimension	VBGHE borehole	Full-scale UTB	Small-scale UTB
Depth (m)	61	6	1.2
Diameter (m)	0.15	1	0.2
Volume (m^3)	1.08	5.49	0.04
Surface Area (m^2)	28.8	22.3	0.9
Surface area to volume ratio	26.7	4.1	20.3

Both a detailed 3D numerical model (Zhang et al. 2019) and a 1D numerical model (Warner et al. 2019) were developed for evaluating the short- and long-term performance of the UTB. The numerical models have been validated against the experimental data from the



(a)

(b)

Fig. 3: The 3D model predicted temperature distributions in the horizontal cross-section at the middle of the borehole after 6 hours of 4 kW heat rejection: (a) with conventional vertical bore ground heat exchanger; and (b) with underground thermal battery (filled with water and PCM).

small-scale UTB prototype. Figure 3 shows the comparison, predicted by the 3D simulation, between the temperature responses of a full-scale UTB and a conventional VBGHE after applying a constant heat input (4 kW) for 6 hours. Conventional VBGHEs exchange heat between the heat carrier fluid and the surrounding solid material (i.e., grout and soil) through conduction heat transfer. There is a significant temperature difference between the heat carrier fluid and the surrounding soil, as indicated by the significantly different colors surrounding the heat carrier fluid and the borehole wall. In contrast, the heat rejected to, or extracted from, the UTB causes natural convection within the tank, resulting in a well-mixed tank water temperature, as indicated by the uniform orange color in the UTB. The large thermal capacity of the UTB keeps its leaving fluid temperature much lower than that of the conventional VBGHE.

Figure 4 shows the measured leaving fluid temperature resulting from three different fillings in the tank of the small-scale prototype—water only (UTB baseline), both water and PCM (UTB with PCM), and dry sand only (to emulate a basket heat exchanger). It is clear that the leaving fluid temperature of the basket heat exchanger rose much faster than the other two configurations in response to the same heat input (75W, equivalent to 9.375 kW heat input to a full-scale UTB). It is because the basket heat exchanger transfers heat solely through conduction, which results in a large temperature gradient between the fluid in the heat exchanger and the

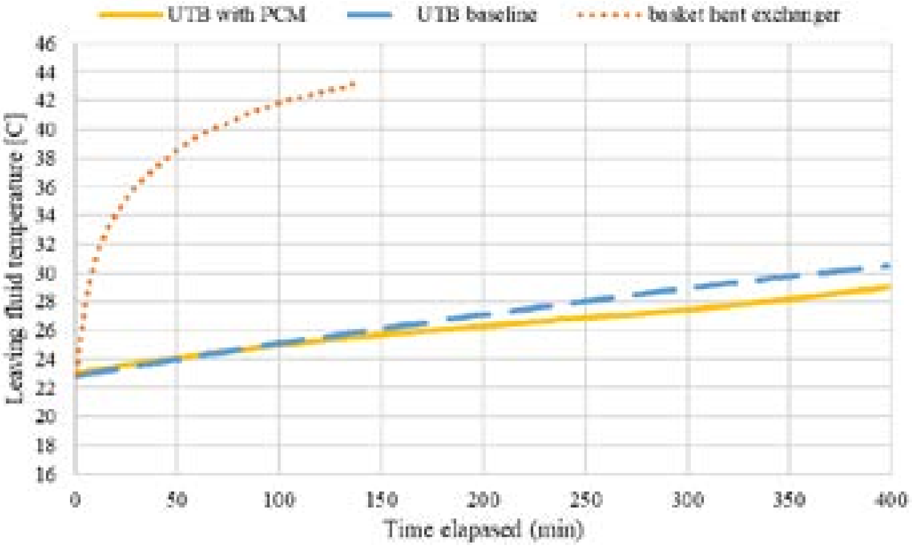


Fig. 4: Measured leaving fluid temperatures resulting from three different fillings in the tank of a small-scale prototype in response to a 75 W constant heat input.

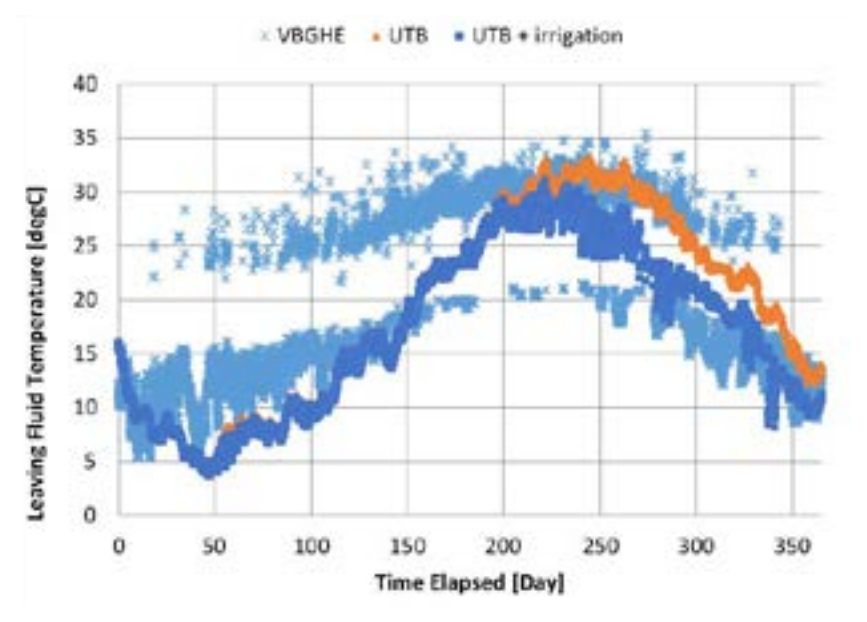


Fig. 5: Comparison of leaving fluid temperature of a conventional VBGHE and two UTBs.

surrounding sand. In contrast, although water has a low thermal conductivity similar to the sand, the natural convection of water inside the UTB makes the tank water well mixed (i.e., the large thermal capacity of the entire tank of water is utilized), resulting in a slow temperature increase. The melting process of PCM further slows down the temperature rise.

Figure 5 depicts the 1D model predicted leaving fluid temperature from two UTBs (with 0.8 m diameter and 6 m depth) and a conventional VBGHE (installed in a borehole 61 m deep and with 0.15 m diameter) during a full year of operation of a residential GSHP system in Knoxville, Tennessee. As shown in Figure 5, UTB avoids the wide daily swings in the leaving fluid temperature seen from the VBGHE. However, the smaller ratio of the surface area to volume of UTB limits the amount and rate of heat exchange with the surrounding soil, compared to the VBGHE. As a result, the tank water temperature keeps increasing during the summer and the annual maximum leaving fluid temperature of the UTB is slightly lower than that of the VBGHE. Simulation results indicate that using the two UTBs to replace a VBGHE can result in about 2% operating cost savings of the GSHP system at locations with high ground thermal conductivity (> 2.67 W/m-K). Figure 5 also shows that the leaving fluid temperature of the UTB can be lowered in the summer by integrating it with a lawn irrigation system of the house conditioned by the GSHP system, further improving the heat pump performance. In this case, the warm water in the UTB is flushed out regularly to irrigate the lawn, and the cold city water refills the UTB to restore its cooling capacity. Notably, no additional water consumption is required besides what would have been used by the existing irrigation. A preliminary cost analysis indicates that the installed cost of the two UTBs could be 39% lower than that of the VBGHE if casing is not needed for drilling the large diameter shallow boreholes (Warner et al. 2019).

Dual-Functional UTB for Load Shifting

The UTB is further developed to enable thermal energy storage in addition to ground heat exchange (Liu et al. 2019b). Figure 6 is the second prototype of the UTB with dual functions (patent pending). It consists of a small enclosed inner tank within the original water tank. The inner tank is wrapped with a blanket filled with customized PCMs, which act as both an insulator (due to the low thermal conductivity of the PCM) and an energy storage medium. A heat exchanger is submerged in the inner tank, and another heat exchanger is installed in the annulus. This design allows for storing chilled water or ice in the inner tank which can provide direct cooling to eliminate the electricity consumption of the heat pump during the peak hours of the electric grid. The annulus of the UTB is used as a ground heat exchanger.

By integrating the second prototype UTB with a dual-source heat pump, which has both a water-cooled and an air-cooled condenser, multiple operation modes can be utilized based on the renewable power supply and building thermal demand, as depicted in Figure 7. During the off-peak hours (for example, late evening or early morning), or when there is an overproduction of renewable power (for example, early afternoon), the heat pump runs at its full capacity with the air-cooled condenser to provide space cooling and in the meantime make chilled water or ice in the inner tank (Mode 1). During the peak hours, or the ramping up period of the electricity demand in the late afternoon, the stored chilled water or ice is used to provide direct cooling to the building, and the heat pump is turned off (Mode 2). Once the ice is melted, and the inner tank water temperature is above the temperature threshold for providing direct cooling, the heat pump is turned on to provide space cooling using the water-cooled condenser and reject heat to the annulus of the UTB (Mode 3). Because water in the annulus is cooled by both the surrounding soil and the in-

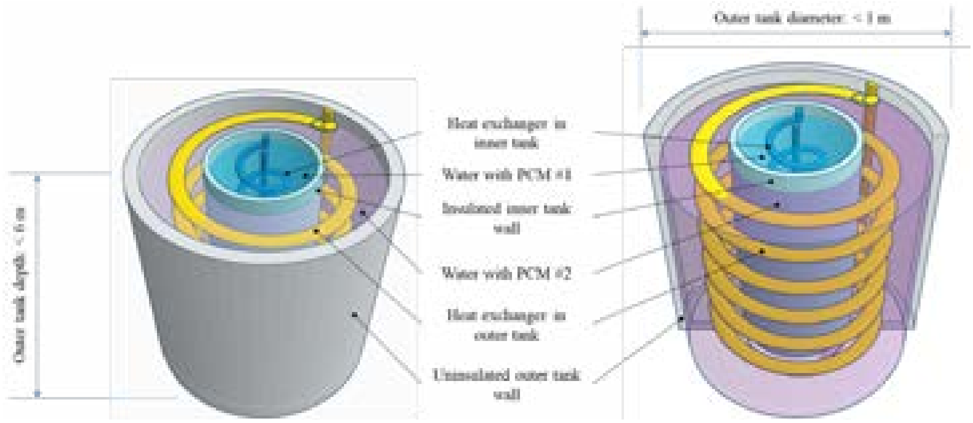
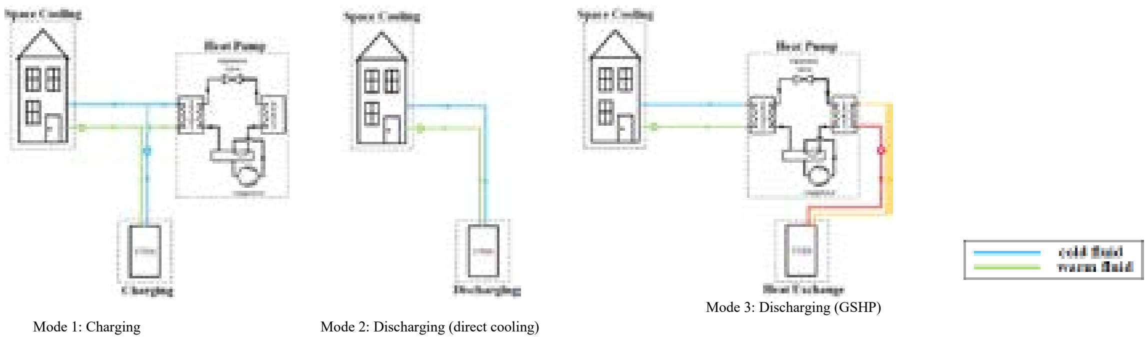


Fig. 6: Schematic of the second prototype of UTB.



Mode 1: Charging

Mode 2: Discharging (direct cooling)

Mode 3: Discharging (GSHP)

Fig. 7: Multiple operation modes of the dual function underground thermal battery for cooling operation.

ner tank, the heat pump can run efficiently, and thus the power consumption is low. The cooling-storage (Mode 1) and heat rejection (Modes 2 and 3) modes alternate daily so that the PCM in the UTB cycles more often between freezing and melting. It thus makes the PCM more effective in mitigating the rapid change of the leaving fluid temperature of the UTB.

A 1:5 small-scale prototype of the dual function UTB was also built and tested. Figure 8 shows the temperature response of a 14-hour test of the prototype when it was installed in a lab space with controlled ambient temperature. It can be seen from Figure 8 that the water in the inner tank can be cooled down from 17 °C to 3 °C during the 6-hour charging period (Mode 1) while the water in the annulus was above 13 °C. During the direct cooling period (Mode 2), a constant heat input (35 W, equivalent to 4.375 kW cooling load for a full-scale UTB) was rejected to the inner tank, the leaving water temperature from the heat exchanger in the inner tank (HX1) increased from 3 °C to 16 °C in two hours. The direct cooling can be prolonged at lower temperature by increasing the thermal storage capacity of the inner tank (e.g., making ice or adding PCM). After 2 hours of direct cooling operation, the UTB was run as a ground heat exchanger (through HX2 in the annulus of the UTB) and the 35 W heat input cycled on and off in 15-minute intervals to simulate the GSHP operation in part-load conditions. The leaving fluid temperature of the UTB is maintained below 20 °C for about 6 hours, which enables the GSHP to run at a high efficiency.

The primary advantage of the dual function UTB over conventional thermal energy storage technologies (e.g., ice storage) is that the hybrid nature of the design allows for shaping the electricity demand profile while satisfying the building's thermal load (both for heating and cooling) efficiently. Because the UTB is buried in the ground, it not only eliminates the need for insulation and building floorspace, but also makes use of the ground as a heat sink or heat source for efficient operation of the heat pump. Furthermore, integrating thermal energy storage and ground heat exchanger into one device is less expensive than using multiple individual components for the same purpose.

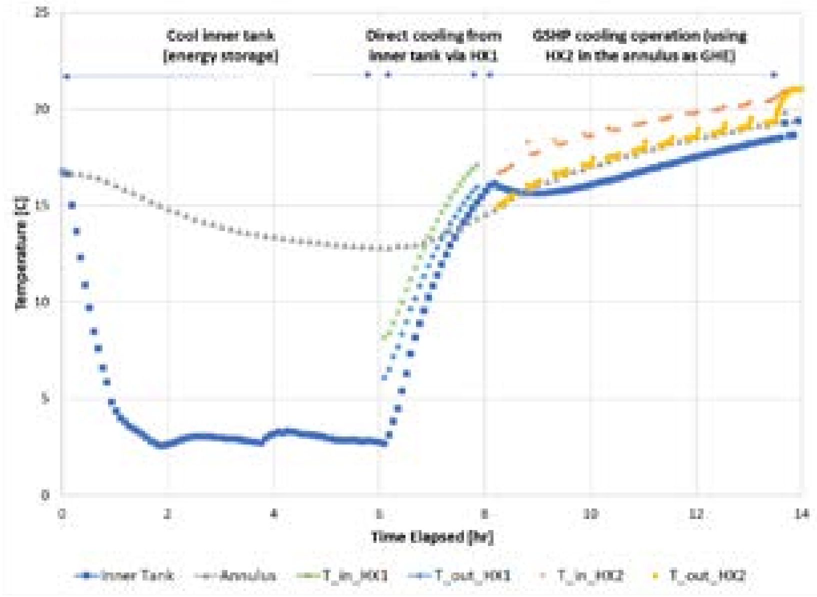


Fig. 8: Lab test results for a 14-hour operation of a dual-function UTB.

Conclusions

A new design of ground heat exchangers, the underground thermal battery (UTB), was developed. Lab tests and computer simulation results indicated that the UTB could achieve the same performance as the conventional VBGHE. A preliminary cost analysis indicates that, for achieving the similar annual performance, the installed cost of the UTB could be 39% lower than that of the conventional VBGHE. Further development of UTB enables active thermal energy storage so that it can be used to overcome the mismatch between the intermittent renewable power supply and fluctuating building thermal demands. It provides a new solution for both efficient air-conditioning and active demand side management without sacrificing the desired comfort condition and convenience in the building.

Acknowledgement

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