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Experimental Study on Charging and Discharging Performance of a Dual-Purpose Underground Thermal Battery

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ABSTRACT

A dual-purpose underground thermal battery (DPUTB) was proposed for Grid-interactive Efficient Buildings. It integrates underground thermal energy storage with a shallow-buried ground heat exchanger (less than 6 m deep). The charging and discharging performance of a lab-scale DPUTB were experimentally investigated. The test results show that the lab-scale (1:125 in volume) DPUTB can provide 34 W cooling continuously for 3.7 h with a supply water temperature below 14°C. The water temperature rise of the inner tank was slowed down during the discharging process due to the phase change of the phase change material (PCM). Thermal storage capacity was increased by 156% using the PCM that only occupied 19% volume of the inner tank. The heat lost from the inner tank was recovered in the outer tank and led to the efficiency improvement of a ground source heat pump.

Keywords: Ground heat exchanger, demand response, phase-change material, thermal storage, underground thermal battery

1. INTRODUCTION

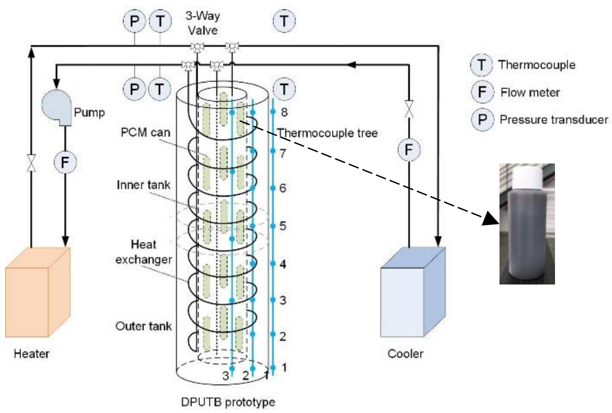
Renewable energy (such as wind, solar, and geothermal) can reduce fossil fuel consumption and associated carbon emissions and alleviate the stresses of electric grids [1,2]. However, the penetration of renewable energy is constrained by the mismatch between the intermittent renewable energy supply and the fluctuating demand [3,4]. Thermal energy storage (TES) is a suitable method to address this challenge [5]. The reliability and resilience of the electric grids can be improved by shifting or leveling the peak electric demand in buildings using TES systems [6]. Furthermore, the usage of renewable energy can also be increased. Geothermal heat pumps are proven to be more efficient than other heating and cooling technologies applied to buildings. However, applications of geothermal heat pumps are hindered by the high cost of drilling vertical bores (deeper than 60 m) for installing vertical bore ground heat exchangers [7].

A dual-purpose underground thermal battery (DPUTB) was invented at the US Department of Energy's Oak Ridge National Laboratory [4]. The DPUTB innovatively integrates a ground heat exchanger with underground TES. It is designed 1) to reduce the installation cost by being installed in a shallow vertical bore (less than 6 m deep) compared with conventional vertical bore ground heat exchangers (usually 60 m deep) and 2) to provide higher grid flexibility by integarting underground TES. By using encapsulated phase-change materials (PCMs), the TES capacity can be increased.

This study experimentally investigated the charging and discharging performance of a lab-scale DPUTB that uses a customized PCM in the inner tank to add latent heat storage while the outer tank is filled with water.

2. EXPERIMENTAL APPARATUS OF A DPUTB

Figure 1 shows the schematic and the photo of a lab-scale DPUTB, which has a 1:125 volume ratio to a full-size DPUTB, and the experimental apparatus.



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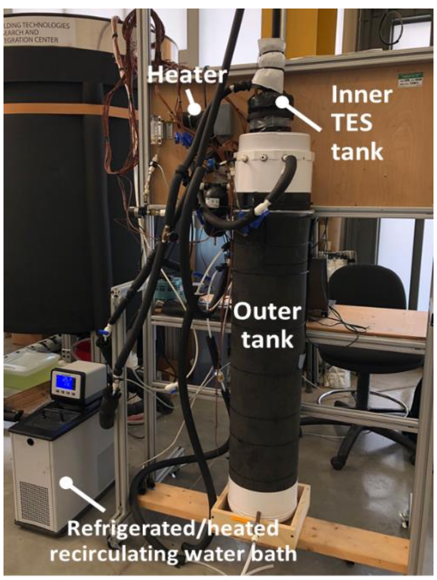

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Figure 1. An experimental apparatus for characterizing the performance of a lab-scale DPUTB: (a) schematic and (b) photo.

The DPUTB consists of an inner tank (Φ 9.7 cm × 1.2 m) and an outer tank (Φ 20.3 cm × 1.2 m). A total of 27 plastic cans (each with a volume of 63 ml) were evenly placed in the inner tank. These cans are filled with a customized salt hydrate PCM made with calcium chloride and other additives. The thermal properties of this PCM were measured through a differential scanning calorimetry (DSC) test using a tiny sample and a thermal bath using an encapsulated sampe in a plastic can (a volume of 63 ml), respectively. As shown in Figure 2, its heat of fusion is 118 kJ/kg. The thermal bath test results showed that the temperature range during the phase change is from 6°C to 12°C. During the charging test, cold water from a recirculating refrigerated water bath was supplied to the bottom of the inner tank through a plastic tube immersed in the inner tank, and water leaving from an opening on the top of the inner tank returned to the water bath. During the discharging test, warm water was spread from the top, and the displaced water flowed out of the inner tank through the immersed plastic tube.

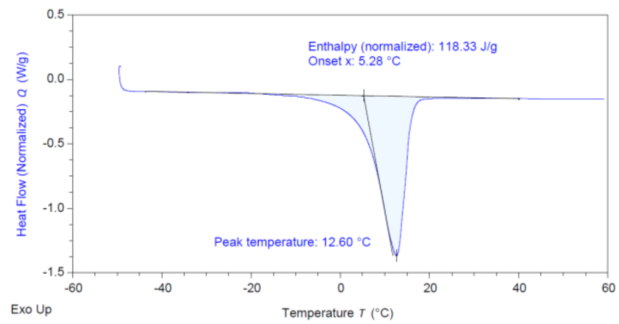


Figure 2. PCM characterization result using DSC.

The charge and discharge rate of the inner tank ($\dot{Q}_c$ and $\dot{Q}_d$) are calculated with Eqs. (1) and (2).

$$\dot{Q}_c = \dot{m}_w c_p (T\_out - T\_in) \quad (1)$$
$$\dot{Q}_d = \dot{m}_w c_p (T\_in - T\_out) \quad (2)$$

where $\dot{m}_w$ is the water flow rate entering/exiting the inner tank, c_p is the specific heat of water, *T_in* and *T_out* are the inlet and outlet temperatures of the inner tank, respectively.

The annulus of the DPUTB (i.e., space between the inner and outer tanks) was filled with water, in which a helical heat exchanger was immersed. The helical heat exchanger was connected with an electric heater, emulating the condenser of a ground source heat pump, and exchanged heat with the water in the annulus. The water flow direction entering/exiting the inner tank and the outer tank was changed by switching the three-way valves, as shown in Figure 1.

Hot water to either the inner tank or the annulus of the DPUTB was provided by a heater with the required constant heat input to emulate heat rejection load. A refrigerated recirculating water bath provided chilled water at a constant temperature to the inner tank to emulate cooling input. As shown in Figure 1, a thermocouple tree with five thermocouples was installed in the inner tank to measure the vertical temperature profile.

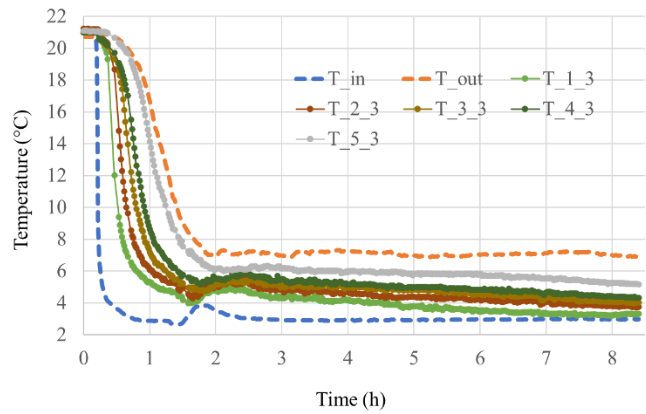
Another two thermocouple trees were placed in the annulus and on the external surface of the outer tank, respectively, to measure their vertical temperature profiles. More details about this experimental apparatus and the data acquisition system specifications are provided in a previous publication [8].

3. EXPERIMENTAL RESULTS AND DISCUSSION

The thermal storage (charging) and discharging performance of the inner tank are crucial to the overall performance of the DPUTB. They were characterized through lab tests, and they are presented below.

The inner tank and outer tank were filled with 21°C water at the beginning of the charging test. Chilled water (3°C, 0.12 liter per minute) from the water bath flowed into the inner tank. Figure 3 shows the measured temperature of the inner tank during an 8-h charging test and a 7-h discharging test. T_in and T_out are the inlet and outlet water temperatures of the inner tank, respectively. T_1_3 through T_5_3 are the five temperature measurement points evenly distributed from the bottom to the inner tank, and T_1_2 through T_8_2 are the eight temperature measurement points evenly distributed from the bottom to the top of the outer tank.

During the charging test, warm water (at room temperature) in the tank was displaced from the bottom to the top by the cold water. Therefore, the temperature of the water near the bottom (T_1_3) first reduced, then the water temperature decreased successively from the bottom to the top (T_2_3 through T_5_3). It took around two hours to reach stable water temperature in the inner tank. When the inner tank temperature reduced to 6°C, the PCM started to freeze. A thermal stratification with about 2°C temperature difference between top and bottom was observed at the end of the 8-hour fully charging process.



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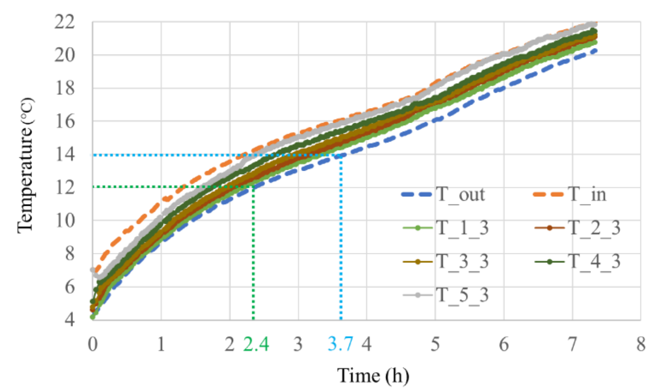

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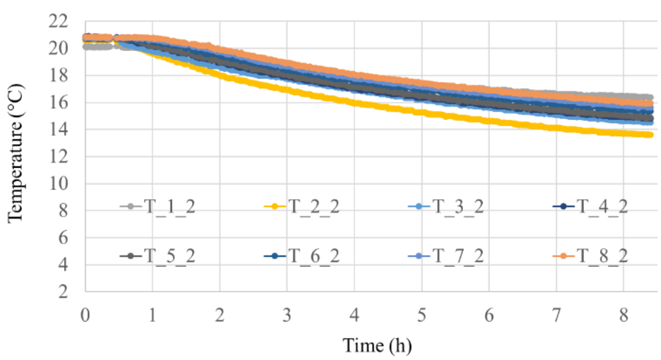
Figure 3. Inner tank temperature during charging test (a) and discharging test (b).

The discharging test was conducted by supplying a constant heat flux (34 W) to the inner tank. The stored cold water (around 4°C at the beginning) was gradually replaced with the warmer water flowed from the top of the inner tank, which kept the thermal stratification in the tank, as shown in Figure 3. When the water temperature in the tank rose, the PCMs went through three heat transfer processes. First is the sensible heat transfer between the PCMs and the water, resulting in PCM temperature rising. When the temperature rose to about 6°C, the PCMs started melting, and it absorbed more heat from the surrounding water so that the outlet water temperature rise was slowed down until all the PCMs were melted. After that, there was only sensible heat transfer between the PCMs and the water, which can be seen from the change in the slope of the outlet temperature rise at the 5th hour. The discharging process lasted for about 3.7 h before the outlet temperature rose to 14°C (or about 2.4 h before the outlet temperature rose to 12°C). It took around 5 hours to reach 16°C before all the PCMs were melted. It implies that if the PCM was melted faster, the inner tank could have supplied water cooler than 12°C for a longer period.

Figure 4 shows the outer tank temperature during the charging and discharging tests. The outer tank has 2°C of thermal stratification for the reason that there is no heat rejection load from outside of the DPUTB to the outer tank through the helical heat exchanger. If the outer tank works as the heat sink through the helical heat exchanger, the thermal stratification in the outer tank would be eliminated. The average outer tank temperature was reduced from 21°C to 16°C during the charging test, which was due to the cooling loss from the inner tank. The water in the outer tank had a slight temperature rise during the discharging test. As the water temperature of the outer tank was below 18°C at the end of the discharging process, it can be used as a heat sink of a ground source heat pump to provide space cooling efficiently.



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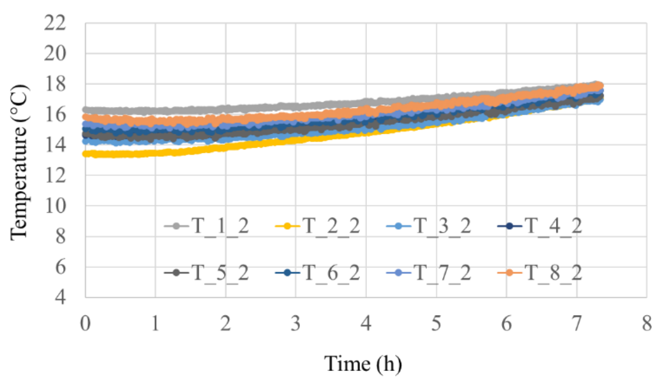

(b)

Figure 4. Outer tank temperature during (a) charging test and (b) discharging test.

Figure 5 depicts the heat transfer rates during the charging and discharging tests. The heat transfer rate of the first hour in the charging test was high because the water in the inner tank, which was at room temperature at the beginning, was replaced with the cold water from the refrigerated water bath. The heat transfer rate reached and stayed around 34W during both the charging and discharging tests.

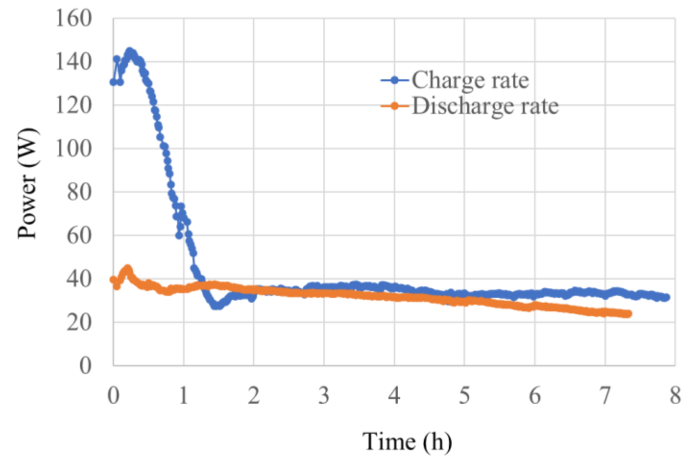

Figure 5. Heat transfer rate during the charging and discharging tests.

Figure 6 compares the outlet water temperature of the inner tank during the discharging tests of two cases under the same operating conditions (when there is no water filled in the outer tank). Case 1 is the discharging test that used PCMs, occupying 19% volume of the inner tank, to provide additional latent cooling storage capability. Case 2 only used water in the inner tank for sensible thermal storage. It shows that the outlet water temperature of Case 1 was higher than that of Case 2 at the beginning. That's because the specific heat capacity of the PCM is lower than that of water. When the outlet water temperature rose to 10°C and above, the outlet water temperature of Case 1 began to be lower than that of Case 2, it indicates the phase change in the PCM took effect and slowed down the temperature rise in the inner tank. A low and long-lasting outlet water temperature from the DPUTB indicates larger thermal storage capacity and better discharging performance. The energy storage capacity of the inner tank with PCMs in it was 156% higher than that with water only when the average tank water temperature raised 6°C.

For improving the thermal storage and discharging performance of the DPUTB, the following methods are recommended: 1) enhancing thermal conductivities of PCM materials, using new PCMs with lower melting temperature and higher latent heat, 2) improving heat transfer between PCM and water, and 3) increasing the volume of PCM in the inner tank if it is cost effective.

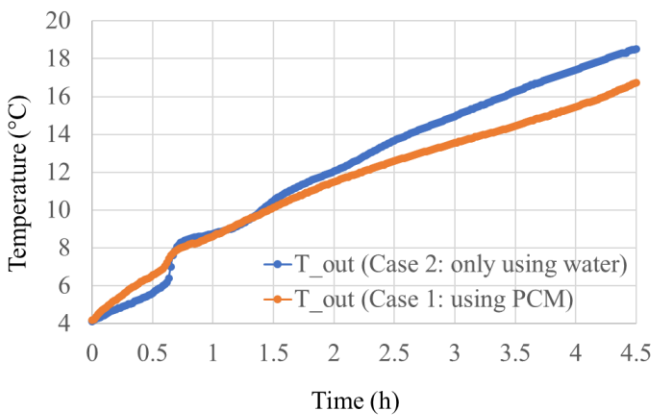

Figure 6. Comparison of outlet water temperature during discharging tests.

4. CONCLUSIONS

This study experimentally investigated the charging and discharging performance of a lab-scale DPUTB, which has the inner tank containing the bottles filled with calcium chloride-based PCM. The charging test has shown thermal stratification along the vertical direction of the inner tank. The cooling energy lost from the inner tank was recovered and stored in the outer tank. The cooler water in the outer tank can improve the efficiency of a ground source heat pump. The results also showed that the melting of PCM slowed down the temperature rise of the inner tank water so that the inner tank provided cooler than 14 °C water (effective for space cooling) for a longer period than using only water in the inner tank. Although the PCM only occupied 19% volume of the inner tank, the energy storage capacity of the inner tank was increased by 156% compared with chilled water storage with the same volume for the same temperature change of 6 degrees. Increasing PCM's volume and/or latent heat capacity and improving heat transfer between the PCM and water can help achieve better thermal storage and discharging performance.

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