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Thermal Storage Performance of a Dual-Purpose Underground Thermal Battery for Shaping the Electric Demand of Buildings

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ABSTRACT

A dual-purpose underground thermal battery (DPUTB) integrates a ground heat exchanger with underground thermal energy storage. It can be installed in shallow boreholes (less than 6 m deep) and thus is less expensive than the conventional ground heat exchangers. The thermal energy storage can be used to shave or shift the electric load for meeting the thermal demands of a building. The charging and discharging performance of a lab-scale DPUTB were tested. The test results show that the DPUTB can be fully charged within 4 h and can provide 34 W cooling continuously for 2.5 h with a supply water temperature below 14°C. A small amount of phase-change material significantly increased the thermal storage capacity.

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

1. INTRODUCTION

The continuously increasing demand for electricity in the world stresses the existing electric grids and increases fossil fuel consumption and greenhouse gas emissions. Electricity generation from renewable energy (such as wind, solar, and geothermal) reduces fossil fuel consumption and associated carbon emissions [1]. However, the penetration of renewable energy to electric grids is constrained because of the mismatch between the intermittent renewable power generation and the fluctuating electric demand [2,3].

A promising method to address this challenge is to integrate thermal energy storage (TES) on the demand side of the electric grids. The peak electric demand in buildings can be shifted or leveled by integrating TES systems, thereby improving the reliability and resilience of the electric grids and increasing the use of renewable energy [4]. Geothermal heat pumps are proven to more efficiently cool or heat a building than other heating and cooling technologies. However, applications of geothermal heat pumps are hindered by the high cost of installing the ground heat exchanger. The commonly used vertical bore ground heat exchangers are usually installed in deep vertical bores (deeper than 60 m), which are expensive to drill.

To reduce the cost and increase the value of geothermal heat pump systems, a dual-purpose underground thermal battery (DPUTB) was invented at the US Department of Energy’s Oak Ridge National Laboratory [3]. The DPUTB innovatively integrates a ground heat exchanger with underground TES. The DPUTB is designed to be installed in a shallow vertical bore (less than 6 m deep), which is much shallower than the vertical bores required for installing the conventional vertical bore ground heat exchangers; therefore, the

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installation cost can be largely reduced. To increase TES capacity and improve the heat transfer performance of the TES, encapsulated phase-change materials (PCMs) are used in the TES. Thermal storage performance of the DPUTB in the charging and discharging processes was experimentally investigated.

2. EXPERIMENTAL APPARATUS OF A DPUTB

The schematic of the lab-scale DPUTB and the experimental apparatus are depicted in Figure 1, and Figure 2 is a photo of the actual experimental apparatus.

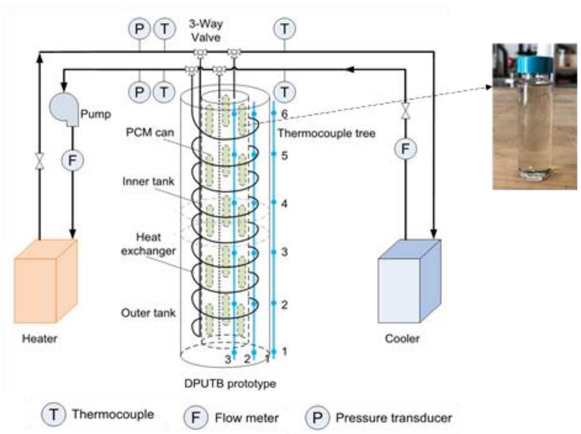


Figure 1. Schematic of an experimental apparatus for characterizing performance of a lab-scale DPUTB.

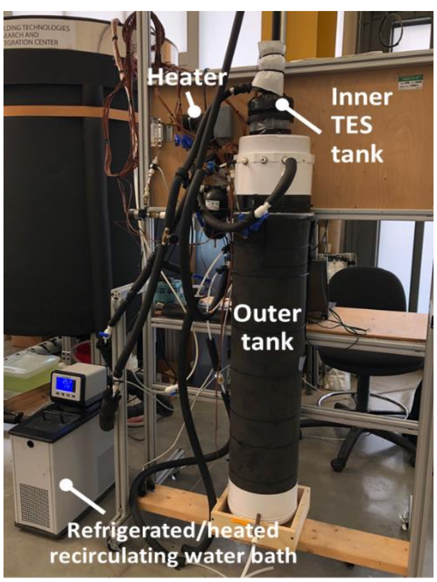


Figure 2. Photo of the experimental apparatus for characterizing performance of a lab-scale DPUTB.

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). Both tanks are made with PVC. A total of 27 glass cans (each with a volume of 40 ml) were evenly placed in the inner tank as shown in Figure 1. These cans are filled with a customized PCM made with zinc chloride and other additives. The PCM has a melting temperature of 9°C and its heat of fusion is 70.7 kJ/kg, which was measured through a differential scanning calorimetry test. A long tube was immersed in the inner tank from the top to the bottom to feed cold water during the charging process. The replaced water flows out from the top of the inner tank. During the discharging process, warm water is supplied from the top and the replaced water flows out from the inner tank through the long tube.

The discharge rate of the inner tank (Q_d) is calculated with Eq. (1). The water flow direction entering/exiting the inner tank is changed by switching the three-way valves shown in Figure 1.

$$Q_d = m_w c_p (T\_in - T\_out) \tag{1}$$

where m_w is the water flow rate entering/exiting the inner tank during discharging, 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) is filled with water and a helical heat exchanger made with copper is immersed in the water. The helical heat exchanger is coupled with a heater, representing the condenser of a ground source heat pump, and exchanges heat with the water in the annulus, which then transfers heat to the ambient or the ground formation surrounding the DPUTB. To reduce heat loss from the inner tank, a rubber foam with a thickness of 6 mm, which has an R-value of 1, is adhered to the exterior surface of the inner tank. Water in the annulus recovers energy losses from the inner tank, which improves the operational efficiency of the ground source heat pump.

A heater, which is controlled by a transformer, provides the required constant heat input to either the inner tank or the annulus of the DPUTB at a predefined schedule to emulate heat rejection load. A refrigerated recirculating water bath provides chilled water at a constant temperature to the inner tank at a predefined schedule to emulate cooling input. The heat rejection load can also be emulated by supplying warm water maintained at a constant temperature by the water bath.

A thermocouple tree with five thermocouples was inserted into the inner tank to measure the temperature profile of the inner tank along with its height. Another two thermocouple trees were placed in the annulus and on the external surface of the outer tank, respectively, to measure the vertical temperature profiles as shown in Figure 1. The flow rates of the chilled water and warm water were measured with two identical flowmeters (Model FTB601B-T, 0.1-2 l/min, ±1%). The inlet and outlet water temperatures at the inner and outer tank were measured with T-type thermocouples. The data acquisition system recorded the measurements at 1-min intervals.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The thermal storage performance of the inner tank is crucial to the overall performance of the DPUTB. The charging and discharging performance of the inner tank were characterized using the experimental apparatus. The outer tank was not filled with water during the initial tests and the inner tank was exposed to a controlled indoor environment.

At the beginning of the charging test, the inner tank was filled with 20°C water. Chilled water at a temperature of 3.5°C and a flow rate of 0.11 LPM flowed into the inner tank from the water bath. Figure 3 shows the measured temperature of the inner tank during a 4-h charging test. T_in and T_out are the inlet and outlet water temperatures of the inner tank, respectively. T_1 through T_5 are the five thermocouples evenly distributed on the thermocouple tree from the bottom to the top.

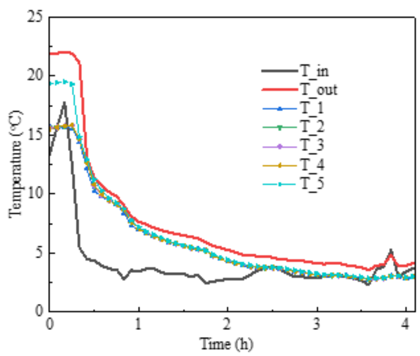
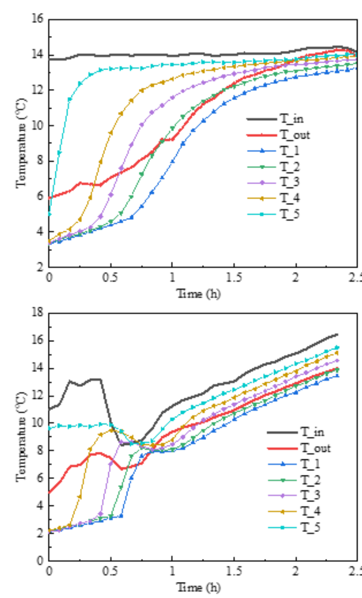


Figure 3. Inner tank temperature during the charging test.

Figure 3 shows the water temperature in the inner tank (T_1 through T_5) rapidly became uniform after the first 15 min and is equilibrium to the inlet temperature at the end of the charging process. Ideally, warm water in the tank would be displaced from the bottom to the top by the cold water during the charging process so that the cooling input can all be stored in the tank. In this case, the temperature will stratify along with the height of the tank at the early time of the charging process. However, Figure 3 does not show any significant difference between the measurements of the five thermocouples except in the first 15 min of the test, likely because of the heat transfer from the uninsulated tube immersed in the inner tank. The temperature difference between the cold water in the tube and the surrounding water introduced a natural convection movement in the tank, which resulted in the mixing of water and a uniform water temperature. The mixing of water will result in some cooling input being released with the water flowing from the tank. An insulated tube may help reduce the heat loss and thus increase the charge rate.

The discharging tests were conducted in two methods: one is to inject water at a constant temperature (14°C) to the inner tank, and the other is to supply a constant heat flux (28 W) to the inner tank. The inner tank temperature change during the two discharging tests is shown in Figure 4. The results indicate that temperature stratification occurred in both tests. As warmer water flowed from the top of the inner tank, it gradually displaced the stored cold water and melted the PCMs, which resulted in the temperature stratification. With the first discharging method, the discharge process lasted for about 1.5 h before the outlet temperature rose to 12°C, whereas in the second method, the outlet temperature took 1.75 h to reach 12°C.



(a)

(b)

Figure 4. Inner tank temperature during discharging tests in different discharging methods: (a) with a constant inlet water temperature; and (b) with a constant heat flux.

Figure 5 shows the discharge rate of the two discharging methods during 2.5 h of discharging tests. The discharge rate of the constant inlet temperature method was 60 W at the beginning while it decreased and gradually approached zero at the end of the discharge process. The reason for the gradual decrease of the discharge rate is the temperature difference between the inlet and outlet water temperatures became gradually smaller as the water in the inner tank was heated and displaced with the warm water flowing in from the top of the inner tank. The measured discharge rate of the constant heat flux method was around 34 W when the flow became stable. It is higher than the power input of the electric resistance heater because of the transient heat transfer process and the displacement of the cold water stored in the inner tank. Furthermore, heat from the circulation pump and the ambient air was also transferred in the inner tank with the water flow and through the inner tank wall. The fluctuation of the discharge rate at the beginning was due to changes in the water flow rate, which was manually adjusted at the beginning of the test.

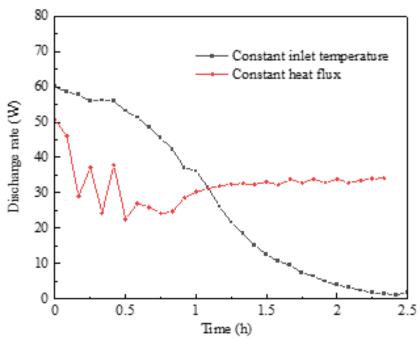


Figure 5. Discharge rate resulting from two discharging methods.

As shown in Figure 5, the discharge rate resulting from the constant inlet temperature was higher at the early time of the discharging process than that with the constant heat flux, but it approached zero at the end of the discharge process. The outlet water temperature was around 14°C at the end of the 2.5-h discharge process in both tests. However, the cumulative cooling output in the first test (with constant inlet temperature) was 251.5 kJ, which is lower than the 280.7 kJ cooling output in the second test (with constant heat flux). As shown in Figure 4, when the outlet temperature reached 14°C in the first test, most of the inner tank had a cooler temperature than in the second test. In contrast, the outlet temperature was near the lowest temperature in the inner tank in the second test. These results indicate that discharging the inner tank with a constant heat flux can make full use of the stored energy because the inlet water temperature increased with the increase of outlet temperature and thus kept a substantial temperature difference between the water and the PCM in the inner tank.

The energy storage capacity of the inner tank was 72.5% higher than that of a sensible thermal storage that has the same volume as the inner tank when the average tank temperature rise is 5°C. The PCM only occupied 12% of the inner tank volume. To further increase the energy storage capacity of the inner tank, the latent heat and/or volume of the PCMs need to be increased.

4. CONCLUSIONS

This study experimentally investigated the thermal storage performance of a DPUTB in the charging and discharging processes. The results of the charging tests show that the temperature in the inner tank rapidly became uniform after the first 15 min and finally reached equilibrium with the inlet temperature.

The 2.5 h of discharging tests were conducted in two methods: constant inlet water temperature (14°C) and constant heat flux (28 W). The results show that temperature stratification occurred in both tests. The discharge rate of the first method was 60 W at the beginning but gradually decreased to zero. The discharge rate of the second method was around 34 W. Although the PCM only occupied 12% volume of the inner tank, the energy storage capacity of the inner tank was increased by 72.5% compared with sensible thermal storage with the same volume for the same 5°C change in the average tank water temperature. Higher PCM volume and/or new PCMs with higher latent heat can further increase the thermal storage capacity.

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