A Comparative Experiments for Efficient Operation of Packed Bed Cold Energy Storage System

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1. Introduction

Liquid Air Energy Storage system (LAES) has been noted to efficiently operate renewable energy systems or power plants such as nuclear power plant because of its high energy density and eco-friendly characteristics [1]. The Cold Energy Storage (CES) is the most key component that improves the round-trip efficiency of LAES by exchanging cold energy between the liquefaction process for energy storage and the evaporation process for power generation.

The functional characteristic of CES that it can be used in cold energy as well as electrical power could extend application range of SMR for load-following operation. When cold energy is required in a power concentrated area such as a data center, not only the power but also the cold heat for cooling can be supplied. It allows for direct utilization of its cold energy released during the power generation process, thereby promoting higher efficiency and broader utilization.

In order to achieve the commercialization of LAES and increase the capacity of the CES system, it is necessary to implement multiple CES tanks operation. Because a large single CES tank system could create significant temperature difference in the heat exchanger, leading to higher exergy loss [2]. This study was aimed to experimentally identify the efficient charging method of cold energy for multiple CES tanks, which is packed bed type using pebbles.

2. Experiment

The experiment was conducted using a lab-scale facility with five connected Packed Bed Cold Energy Storages (PBCED). In Sec. 2.1, the design of a single PBCES and the medium of packed bed was introduced. In Sec. 2.2, detailed information about the facility and the two types of operation methods, serial and parallel, were explained.

2.1. Packed bed cold energy storage

The CES cylinder was made of stainless steel and had an inner diameter of 250 mm, a thickness of 9.3 mm, and a height of 1070 mm, as shown in Fig. 1. Three RTD sensors, designed with an effective temperature range of -200 to 250 ℃, were utilized to monitor the temperature distribution of the packed bed. These sensors were encased in thermowells, 1/2 inch in inner diameter, and positioned at heights of 190, 380, and 570 mm above the bottom surface of the packed bed. In order to minimize heat loss, an outer cylinder composed of stainless steel, featuring an inner diameter of 489 mm and a thickness of 9.5 mm, was employed to encapsulate the CES cylinder. The vacuum insulation level between the two cylinders was maintained at 2 torr.

The packed bed column inside the CES cylinder had a height of 760 mm. Granite pebbles, ranging in size from 8 to 12 mm, were utilized as the medium. The density and porosity of the pebbles were determined through a simple test using a basket and water, yielding values of 2711 kg/m³ and 0.379, respectively. The thermal properties of the pebbles varied with temperature as follows [3]:

(1) $k = -8.43 \times 10^{-3} \cdot T + 4.869$
(2) $c_p = 2.09 \cdot T + 287.1$

k is thermal conductivity in $W/(m \cdot K)$, c_p is specific heat in $J/(kg \cdot K)$.

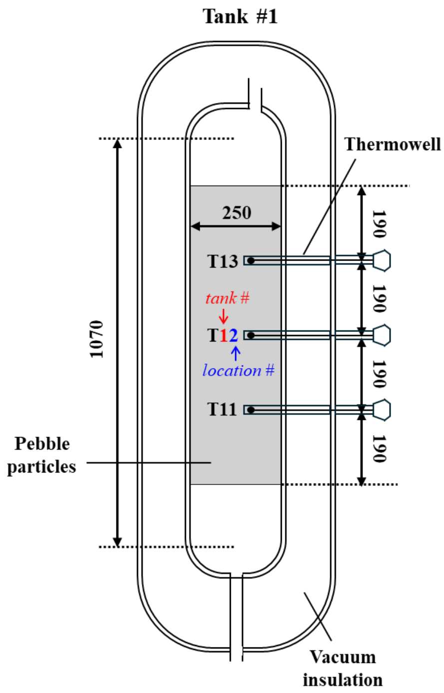

Fig. 1. Schematic illustration of packed bed cold energy storage tank #1.

2.2. Experimental setup

Two operational methods, serial and parallel, were employed to store cold energy in the 5 PBCES. In this study, two cold storage experiments were conducted using cryogenic nitrogen gas as the working fluid, implementing both the serial and parallel operation methods. The objective of the experiments was to charge cold energy into three tanks instead of five, owing to time constraints at the experimental site. The detailed experimental system and each method were explained in Sec. 2.2.1 and 2.2.2.

2.2.1. Serial operation.

Fig. 2 shows the experimental system, with a focus on the serial operation. All pipes were made of stainless steel, with an internal diameter of 28.4 mm and an outer diameter of 34 mm. Liquid nitrogen was withdrawn from its reservoir and heated up to -165℃ for phase change via an electric heater. In the serial operation, the vaporized nitrogen solely enters the bottom of the first tank (#1) and traverse through the packed bed, transferring cold energy to the pebbles. The gas from tank #1 then proceeds into the subsequent tanks (#2 to #4), and ultimately exits through the outlet of the last tank (#5). To dissipate the cold nitrogen to ambient temperature, a fin-type heat exchanger was employed. The flow rate of nitrogen was measured using a thermal mass flow meter with an effective range of -40 to 220 ℃. Due to the large differential pressure induced by the fin-type heat exchanger, the system pressure was adjusted to approximately 5 bar to achieve the targeted flow rate of 60 kg/hr.

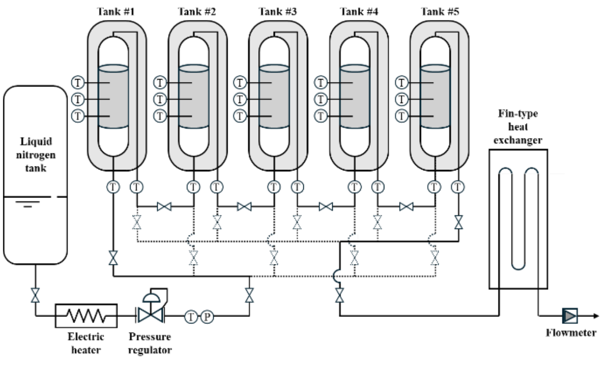

Fig. 2. Cascaded experimental system of packed bed cold energy storage for serial operation.

2.2.2. Parallel operation.

Fig. 3 shows the experimental system, with a focus on the parallel operation. The process preceding the packed bed is same as in the serial operation. However, in parallel operation, the vaporized gas branches off and simultaneously enters tanks #1 to #3. The branched gases traverse through each packed bed and combine after the tanks. Since our system lacks a flow distribution device, the flow rates of each tank are variable and indeterminate. To prevent unnecessary cold flow, a tank that is deemed fully charged is closed to halt the flow of nitrogen gas into that tank. All other conditions remain consistent with those of the serial operation.

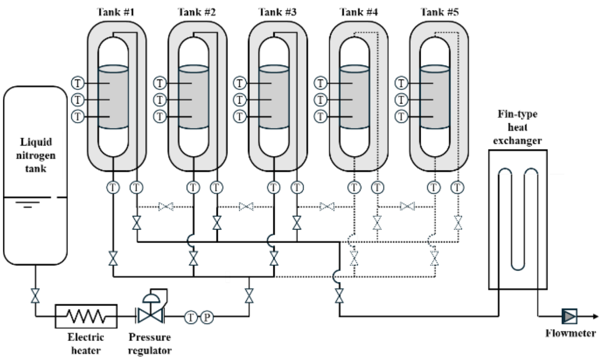

Fig. 3. Connected experimental system of packed bed cold energy storage for parallel operation.

3. Results

In each experiment, cold charging was conducted for 350 minutes. The temperature distribution results were compared in Section 3.1. In Section 3.2, the charged cold amounts of each tank were calculated and compared for both operations.

3.1. Transient temperature in axial direction

Fig. 4 and Fig. 5 show the axial temperature distribution of serial and parallel operations, respectively. In both results, the inlet temperature is indicated as -150°C. However, it should be noted that the temperature sensor installed in the pipe was not inserted inside it, resulting in the actual temperatures at the inlet and outlet being approximately 10°C lower than the displayed data. It was determined that the charging process was completed when the three internal temperatures converged.

In serial operation, tanks #4 and #5 are connected to mitigate the temperature gradient from the fin-type heat exchanger. TK4 and TK5 represent the average temperature of #4 and #5 tanks, respectively. The charging process was completed from #1 tank to #3 tank, with each tank requiring 150, 250, and over 350 minutes, respectively. Fig. 4. also demonstrates the characteristic that the converged temperature increases as it progresses towards the rear end tank.

In parallel operation, the charging process was completed in the order of #3, #1, and #2 tanks. The required times for each tank were 270, 300, and over 350 minutes, respectively. It took longer to charge the first tank compared to serial operation, but the total time required to charge all three tanks was similar. In parallel operation, the converged temperatures of each tank were the same, but this temperature was higher than the converged temperature of the second tank in serial operation.

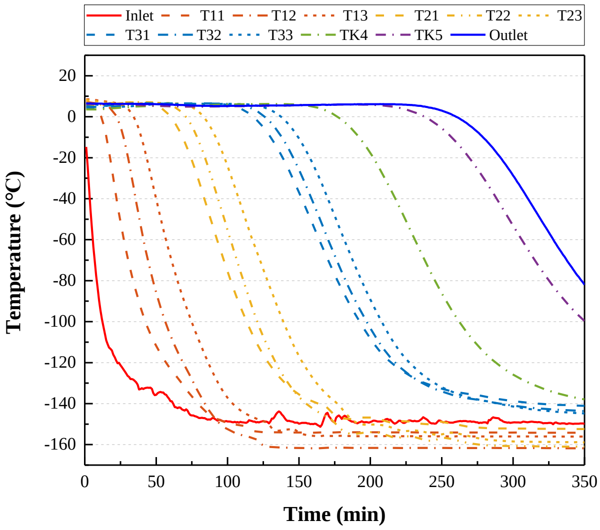

Fig. 4. Transient axial temperature distribution of serial operation.

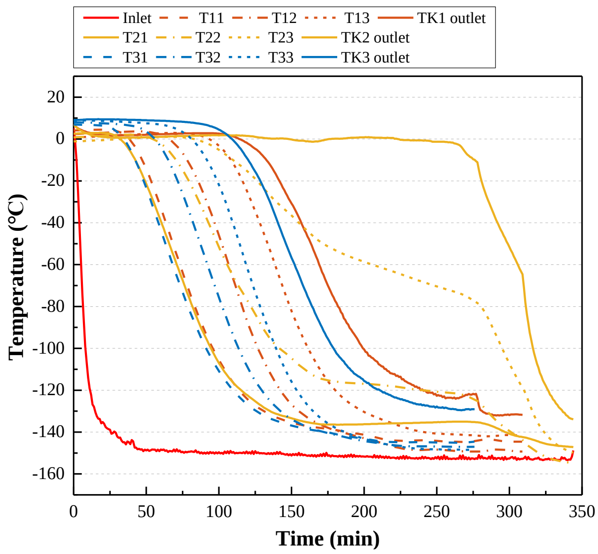

Fig. 5. Transient axial temperature distribution of parallel operation.

3.2. Cold thermal storage

The charged cold thermal energy in packed bed of each tank was calculated using flowing equation (3), where T_i is temperature in K, when i minutes and m is mass of pebble in kg/m^3.

$$(3) \quad Q_C = \sum_{i=1}^{350} c_{p,T_i} \cdot (T_i - T_{i-1}) \cdot m$$

The calculation results are presented in Table I. As anticipated, the total amount of charged cold thermal energy in serial operation was greater than in parallel operation. However, it is worth noting that the energy imbalance between tanks was also larger in serial operation. In particular, the amount of cold thermal energy charged in the last tank (#3) in serial operation was smaller compared to the parallel case.

Table. I. Charged cold thermal energy calculation results.

Operation:	Serial [kJ]	Parallel [kJ]
Tank #1	-7,250	-6,518
Tank #2	-7,182	-6,616
Tank #3	-6,637	-6,870

4. Conclusion

The two experimental results indicate that serial operation is more effective in charging a greater amount of cold energy in PBCES than parallel operation. However, serial operation also presents an energy imbalance issue between tanks. Conversely, this issue did not arise in the parallel case, possibly because the action of closing the fully charged tank was not implemented in serial operation. To address this, a combination of the two methods is proposed to achieve a fully charged PBCES while avoiding energy imbalance problems. As a result, it is suggested to use serial operation with the practice of closing tanks in order to achieve an efficient PBCES charging operation.

ACKNOWLEDGE

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