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Experiments on Charging of Cold Thermal Energy by Mass Flow Rate of Packed Bed Cryogenic Energy Storage System

Dahui Kwack, Chunsik Lee and Choongsub Yeom*
Plant Eng. Center, Institute for Advanced Engineering, Republic of Korea
*E-mail: dahui3913@iae.re.kr; csyeum@iae.re.kr**

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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 Cryogenic 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. 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, it is necessary to implement multiple CES tanks operation for increasing the capacity of the CES system. Because a large single CES tank system could create significant temperature difference in the heat exchanger, leading to higher exergy loss [2]. The CES system with multiple tanks was developed and the releasing operation experiments of it were conducted in previous study [3,4].

However, in the multiple CES, the temperature distribution differs from that of a single system due to the different inlet conditions of each tank. In this study, three experiments were conducted at different mass flow rates to observe the overall system temperature distribution according to the fluid velocity during charging operation.

2. Methods and Results

The experiments were conducted by using a lab-scale facility with five connected Packed Bed Cryogenic Energy Storages (PBCES) developed in previous study [3,4]. In Sec. 2.1, set-up of the facility was introduced and detailed experimental conditions for each case were explained in Sec. 2.2.

2.1 Detector Model

The structure of PBCES tanks is presented in Fig.1. The flow direction was set from bottom to top for charging. The five RTD sensors, designed with an effective temperature range of -200 to 250 ℃, were installed for each tank. Three RTDs, which are T11 ~ T13, were utilized to monitor the temperature distribution of the packed bed. These sensors were positioned at heights of 190, 380, and 570 mm above the bottom surface of the packed bed. Others were used for measuring inlet and outlet temperature.

The CES tank had an inner diameter of 250 mm, a thickness of 9.3 mm, and a height of 1070 mm. In order to minimize heat loss, an outer tank composed of stainless steel, featuring an inner diameter of 490 mm and a thickness of 9.5 mm, was employed to encapsulate the CES tank. The vacuum insulation level between the two cylinders was maintained at 2 torr.

The packed bed column inside the CES tank 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, yielding values of 2711 kg/m³ and 0.379, respectively. The thermal properties of the pebbles varied with temperature as follows [5]:

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

k is thermal conductivity in $W/(m \cdot K)$, c_p is specific heat in $J/(kg \cdot K)$ and T is temperature in K. These formulas are valid for -160 ~ 40 ℃.

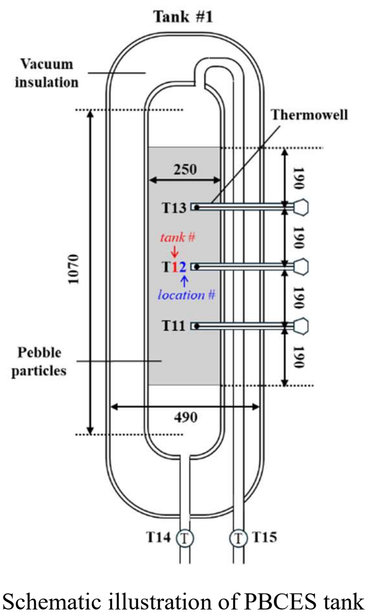

Fig. 1. Schematic illustration of PBCES tank #1.

Fig. 2 shows the entire PBCES system facility, which was set for the charging operation. They were connected by stainless steel pipes, with an internal diameter of 28.4 mm and an outer diameter of 34 mm. The solid line in Fig. 2 was set as flow path for charging. Nitrogen gas was used as the working fluid, and it was vaporized and heated up over -150 °C by electric heater before entering the system. It was passed sequentially from tank #1 to tank #5 through pack beds, transferring cold energy to the pebbles. The flow rate of nitrogen was measured using a thermal mass flow meter with an effective range of -40 to 220 °C.

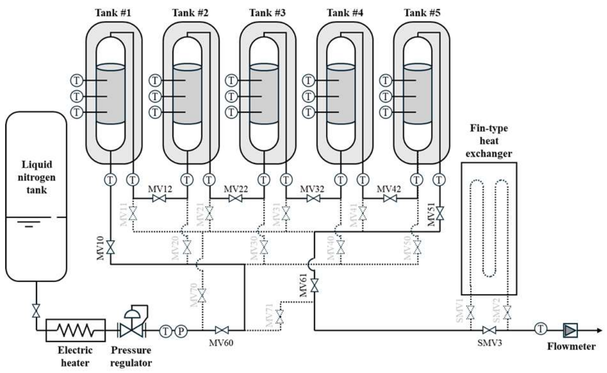

Fig. 2. Multiple PBCES system for charging operation.

2.2 Experimental conditions

The mass flow rate conditions of each experiment case were shown in Table I, with its velocity in packed bed. The maximum mass flow rate was set as 90 kg/h because 100 kg/h was the maximum value that the flow meter could measure. The gauge pressure at the inlet was set to 1 bar, and the target inlet temperature was -150 °C except case 3. In case 3, it was conducted in summer with high room temperature, so that the inlet temperature was just -147 °C. Each experiment was conducted until the outlet temperature of tank 1 converged. The conversion was determined by following equation, where T_{out}^{i} was outlet temperature of tank 1 at that time, and T_{out}^{i-1} was the temperature at 1 minute before.

$$(4)\quad \frac{T_{out}^{i}-T_{out}^{i-1}}{T_{out}^{i}} < 10^{-3} \text{ for 10 min.}$$

Table I. Mass flow rates and velocity in Packed Bed of each case at -150 °C, 1 bar

Case #	Mass flow rate	Velocity in PB
1	90 kg/h	0.484 m/s
2	70 kg/h	0.376 m/s
3	45 kg/h	0.242 m/s

3. Results and Analysis

The results of each experiment were described in Sec. 3.1. And in Sec. 3.2, the temperature distribution changes of each case were compared and analyzed.

3.1. Experiment results

The summarized experiment results were presented in Table II. In order to make the inlet temperature condition, it is required that run the fluid until it reaches -150 °C, and this period is called precooling. The required precooling time of each case was different because of the mass flow rate. Especially, in case 3, the mass flow rate was too small to make the inlet condition, so the target temperature was adjusted to -145 °C. As a result, 30, 60, 120 minutes were required for precooling of 1, 2, and 3 case, respectively. The operation time is the time taken for the outlet temperature of tank 1 to converge, which is including the precooling time. And the charged cold thermal energy in packed bed of each tank was calculated using flowing equation (4), where T_i is averaged temperature of each tank in K, when i minutes until operation time and m is mass of pebble in kg/m^3. The values in Table 2 are the sum of the energy stored in the entire tank.

$$(5)\quad Q_C = \sum_{i=1}^{o.t} c_{p,T_i} \cdot (T_i - T_{i-1}) \cdot m$$

The operating time and stored energy results according to the velocity were also plotted as shown in Fig. 3. The required time for full charge of tank 1 decreases almost linearly as the velocity of fluid increases. However, in the case of charged energy, it can be seen that it increases close to a quadratic function for velocity. That means a flow rate of a certain level or higher is required to store cold heat within a predetermined process time.

Table II. Summarized results of each case.

Case #	Precooling time	Operation time	Charged energy in Packed Bed
1	30 min	160 min	-22,965 kJ
2	60 min	190 min	-18,738 kJ
3	120 min	270 min	-16,939 kJ

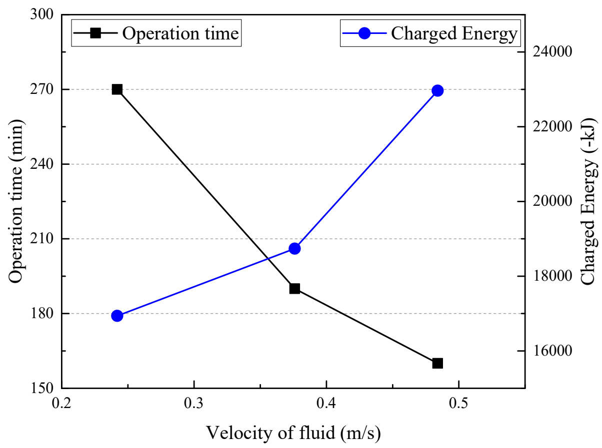

Fig. 3. Operation time and charged energy results according to the velocity of fluid.

3.2. Change of temperature distribution

The changes of temperature distribution during charging operation were shown in Fig. 4. Not only the initial and final temperature distribution, but also the temperature distribution at the end of precooling was also expressed. As shown in Fig. 4, the distribution of case 1 at final was gentle than case 2 and 3. Since the heat transfer rate is theoretically proportional to the square of the fluid velocity, the more active the heat transfer could be occurred with the high velocity. That means that the case 1 could transfer more cold energy to packed bed in same time, so that steeper distribution was expected. However, even its operation time was much shorter than case 3, the distribution of case 1 was the most gradual one. These results show that the temperature distribution in the multiple PBCES is different from the general form of theory.

On the other hand, another conjecture could be presented about this result. The velocity conditions of each case in this study were much small than general cases. It could cause overall low heat transfer rate in these experiments, so that the operation time was more important factor for charging the cold energy to packed bed. In other words, it was not possible to deliver cold energy efficiently to the packed bed at that flow rate level.

This temperature distribution result is very important in determining the exit temperature conditions of the system in process design.

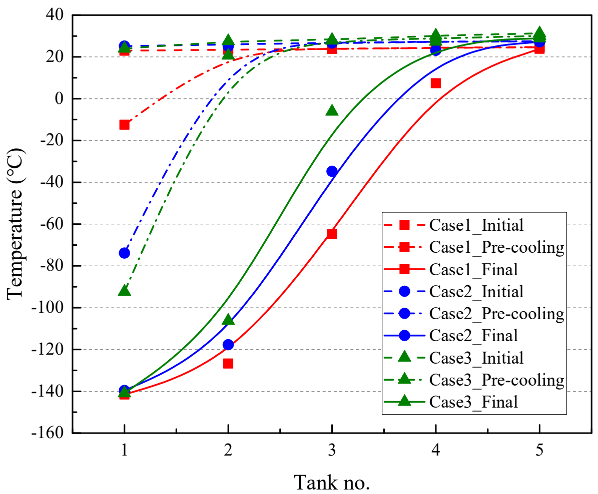

Fig. 4. Changes in temperature distribution of multiple PBCES during charging operation.

4. Conclusion

Charging experiments of multiple PBCES with 3 flow rate conditions were conducted in this study to observe its operation behavior. In the case of operation time and stored cold energy, as expected, the results were inversely and proportional to fluid velocity, respectively. However, the tendency of temperature distribution was different with expect. It was gentler in high velocity condition, so that the exit temperature could be changed before the charging over. This is very important to set the condition of process because the exit temperature of CES must be kept at room temperature, ideally. The distribution result is very important in determining the exit temperature conditions of the system in process design. In order to optimize the LAES process design, it is necessary to set an appropriate CES flow rate considering process time and conditions based on the results of this study.

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REFERENCES

[1] L. Chai, J. Liu, L. Wang, L. Yue, L. Yang, Y. Sheng, H. Chen, and C. Tan, Cryogenic energy storage characteristics of a packed bed at different pressures, Applied Thermal Engineering, Vol. 63, p.439-446, 2014.

[2] Y. Qu, X. Lin, L. Wang, S. Zhang, Y. Bai, Z. Ge, X. Li, and H. Chen, Cryogenic energy storage characteristics in cascaded packed beds, Journal of Energy Storage, Vol. 73, 108867, 2023.

[3] D. Kwack, C. Lee, and C. Yeom, A Comparative Experiments for Efficient Operation of Packed Bed Cold Energy Storage System, Korean Nuclear Society Spring Meeting, Jeju, Korea, May 9-10, 2024.

[4] D. Kwack, C. Lee, and C. Yeom, Experiments on Release of Cold Thermal Energy by Mass Flow Rate of Packed Bed Cryogenic Energy Storage System, Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 24-25, 2024.

[5] H. Tan, Z. Ding, and N. Wen, Numerical study on the thermodynamic performance of a packed bed cryogenic energy storage system, Applied Thermal Engineering, Vol. 214, 118903, 2022.