Experiments on Release 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**

***Keywords : Liquid Air Energy Storage, Cold Energy Storage, Packed Bed, Cascaded Packed beds**

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. 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]. The CES system with multiple tanks was developed and the charging operation experiments of it were conducted in previous study [3,4].

In case of releasing operation, the output temperature and the maintenance time of low temperature are critical for the liquified process of LAES. In this study, the releasing operation experiments with 3 mass flow rate conditions were carried out to observe the difference of releasing temperature, thermal movement of the system, and maintenance time.

2. Experiments

The experiment was conducted by using a lab-scale facility with five connected Packed Bed Cold 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. Set-up of the facility

The structure of PBCES tanks is presented in Fig.1. The flow direction was set from T14 to T15 for charging, and it was reversed for releasing operation. 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 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. 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) $c_p = 2.09 \cdot T + 287.1$

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 ℃.

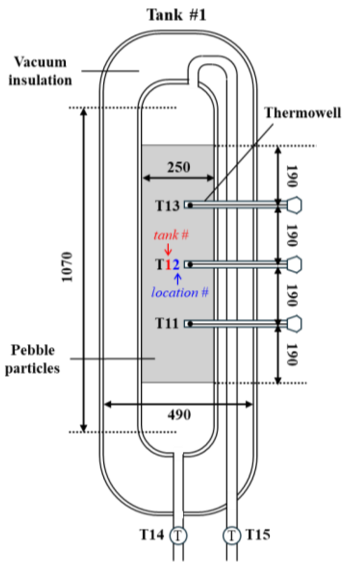

Fig. 1. Schematic illustration of PBCES tank #1.

Fig. 2 shows the entire PBCES system facility, which was set for the releasing operation. #1 and #2 tanks are main cold storages, and the others are buffer tanks. 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 releasing. Nitrogen gas was used as the working fluid, and it was vaporized and heated up over 15 ℃ by electric heater before entering the system. It was passed sequentially from tank #5 to tank #1 through pack beds, transferring cold energy to the pebbles. 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 ℃.

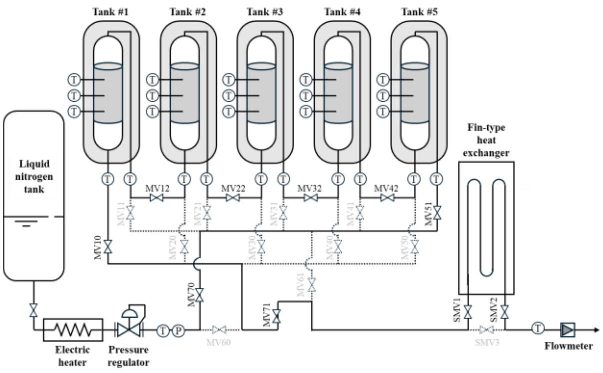

Fig. 2. Experimental system of PBCES for releasing operation.

2.2. Experiment conditions

The mass flow rate conditions of each experiment case were shown in Table. I. They were set 1/5, 1/3, and 1/2 of charging condition, respectively. Due to the large differential pressure induced by the fin-type heat exchanger, the system pressure was adjusted to 1.6, 2.0, and 2.4 bar to achieve the targeted flow rate in case 1, 2, and 3, respectively. The 45 kg/h was the maximum mass flow rate that could be achieved under 2.5 bar system pressure. The releasing were conducted for 5000 s.

Before releasing operation, the cold energy charging operations were conducted with 90 kg/h for 3hrs to make the initial condition of releasing. MV 60 and 61 were used for charging instead of MV70, 71. Cryogenic nitrogen gas was also used as the working fluid after being heated to -150 ℃.

The temperature after charging of each case were presented in Table. II. Even the initial conditions of each charging were different due to the time constraints at the experimental site, the temperature gradient after charging were similar except case 2. Unlike the other cases were conducted in July, the case 2 was conducted in May, so that the heat loss was smaller than others. Nevertheless, the temperatures of main storage tanks, TK1 and TK2, were set to almost same level in all cases.

Table. I. Mass flow rates in charging and releasing operations of each case.

Case #	Charging	Releasing
1	90 kg/h	18 kg/h
2		30 kg/h
3		45 kg/h

Table. II. The averaged tank temperature [℃] before and after charging operation of each case.

Case #		TK1	TK2	TK3	TK4	TK5
1	Initial temp.	-4.5	17.6	18.0	20.0	23.8
	After Temp.	-142	-133	-93.4	-30.3	15.3
2	Initial temp.	11.6	20.9	22.1	22.6	24.3
	After Temp.	-141	-133	-108	-55.2	5.67
3	Initial temp.	22.9	23.4	23.8	24.4	24.7
	After Temp.	-142	-132	-91.5	-22.9	22.3

3. Results

The amounts of cold energies before and after releasing operation were described in Sec. 3.1. And in Sec. 3.2, the temperature distribution changes of each case were compared and analyzed. The tendencies of releasing temperature were explained in Sec. 3.3.

3.1. Charged and released cold energies.

The charged and released cold thermal energy in packed bed of each tank was calculated using flowing equation (3), where T_i is averaged temperature of each tank 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 calculated energies of each case were presented in Table. III. The charged cold energy of case 2 was little bit larger than others, because the cool weather allows small heat loss than other cases. However, the release energies of each cases show well the increasing tendency with mass flow rate.

Table. III. Charged and released energies of each case.

Case #	Charged Energy	Released Energy
1	-21,367 kJ	4,026 kJ
2	-24,768 kJ	5,166 kJ
3	-22,429 kJ	6,675 kJ

3.2. Temperature changes of each releasing operation

Finding out the temperature distribution changes of the PBCES system is important in establishing its cold energy utilization other than the LAES liquefaction process. In Fig. 4, the thermal movement of entire system, which are temperature distributions before and after releasing, were shown. Although the starting conditions were not the same in each case, the temperature gradient in case 3 was changed most rapidly as expected. The distributions of case 1 and case 2 look similar at end time, but the temperature of case 2 was already lower at the starting time.

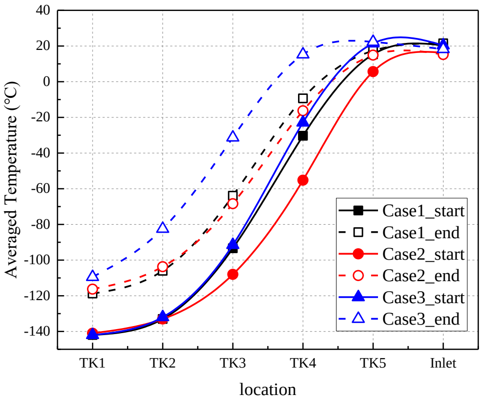

Fig. 3. Temperature distribution of entire system at starting and end time of releasing.

3.3. Tendency of releasing temperature.

In order to stably supply the cold to the LAES liquefaction process, it is required to release cold for as long as possible below the target temperature. The outlet temperatures of each case were shown in Fig. 4 to compare the tendency. In case 1, the lowest outlet temperature was -121 °C even the averaged TK1 temperature was -142 °C. It is because the fluid velocity with that mass flow was not enough to transfer the heat to packed bed. The velocities of nitrogen gas at -100 °C in each case were calculated and shown in Table. IV. The velocity is proportional to the mass flow rate, and it is the most important factor in determining its heat transfer rate.

However, the difference between lowest temperatures of case 2 and 3 was only 3 °C, which was not different as much as case 1 and 2. That means over 45 kg/h, the heat transfer rate will not be changed as much as between case 2 and 3. On the other hand, the case 1 with small mass flow rate maintained a constant temperature for a long period of time than other cases. The maintained time with temperature in lowest value + 5 °C were 4000, 3000, and 1700 seconds in each case.

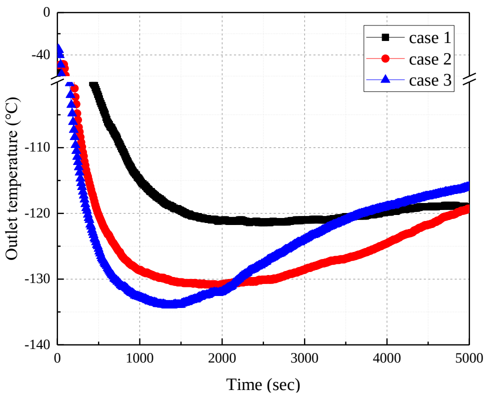

Fig. 4. Transient outlet temperature of each case.

Table. IV. Calculated nitrogen gas velocities in packed bed of each case at -100 °C.

Case #	Mass flow rate	Velocity
1	18 kg/h	0.068 m/s
2	30 kg/h	0.114 m/s
3	45 kg/h	0.171 m/s

4. Conclusion

Through the releasing experiments in this study, it was figured out that enough fluid velocity, more than 0.171 m/s, is required to release the fluid with charged temperature in PBCES system. However, the smaller mass flow rate with low velocity was good for maintaining a constant releasing temperature. The maintenance for a long period is important in liquified process in LAES, because the process operation time is mostly more than 3 times of the evaporation process. And the gentle temperature distribution is beneficial in terms of system stability. In conclusion, the mass flow rate should be set with considering not only the target releasing temperature, but also the process operation time in entire LAES system.

ACKNOWLEDGE

This work was supported by the 'Development of liquid air energy storage (LAES) and utilization system' project of the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (RS-2022-00143652).

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, A Comparative Experiments for Efficient Operation of Packed Bed Cold Energy Storage System, Korean Nuclear Society Spring Meeting Jeju, Korea, May 9-10, 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.