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A study on liquid air energy storage system coupled with liquid hydrogen and LNG regasification process for enhancing round-trip efficiency

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1. Introduction

With increasing variable renewable energy sources, load-following capability is inevitable for conventional power plants, especially for nuclear power plants [1]. Recently developed nuclear power plant, such as APR1400+, is capable of load-following operation but frequent load variations may have adverse effect such as reduced service lifetime and lower capacity factor. In order to increase flexibility of nuclear power plant while minimizing adverse effects, a nuclear power plant with energy storage system is being researched.

A Liquid Air Energy Storage System (LAES) is one of the large-scale Energy Storage Systems (ESSs) and gains attention due to its practical advantages: long lifetime (~30 years), high energy density (~120kWh/m^3), no needs of high-pressure vessel or underground cavern, low operation & management costs [2]. During off-peak hour, energy is stored in the form of liquid air. During peak demand hour, liquid air is evaporated and expanded at air turbine to generate electricity. Heo et al. studied the integration options of LAES with nuclear power plant [3]. The authors showed that LAES has the highest energy density compared to other large scale ESSs. Park et al. studied the thermodynamic performance of LAES mechanically integrated with nuclear steam cycle [4]. The round-trip efficiency of the proposed system is 51% and the Levelized Cost of Electricity (LCOE) is $182.6/MWh, reducing 17% of the standalone's LCOE.

However, the round-trip efficiency of LAES is still lower compared to other energy storage systems. The round-trip efficiency of typical LAES is around 50% [2]. The low efficiency is due to the inefficiency of cold energy recovery in air discharging process. In a typical LAES, the liquid air yield is around 80% which means that useful cold energy is lost during liquefaction process. The loss of cold energy makes less liquid air; therefore, cold energy is not fully recovered during the discharging process. In order to compensate lack of cold energy, the integration with external cold energy source is recently researched [5]. The integration allows to reduce the dependence of cold energy sources, such as methanol and propane in the typical LAES, so that LAES can reach higher discharging pressure during the electricity producing process.

In this study, Liquid Natural Gas (LNG) and liquid hydrogen (LH_2) are proposed as an external cold energy source. LNG and liquid hydrogen are spotlighted as the next-generation eco-friendly fuels. Both fluids exist as liquid form to lower shipping and transportation cost, therefore the regasification process is required to using both fluids in industrial way. By integrating regasification process of LNG and LH_2 to LAES, the cold energy is not only recovered, but also enhances cold energy recovery. High liquid air yield allows high round-trip efficiency which makes more efficient energy storage.

2. Methods

In this section, the proposed system (LAES-LNG-LH_2 system) is described and used thermodynamic equations are presented.

2.1 System description

Fig.1 describes the schematic diagram of LAES-LNG-LH_2 system.

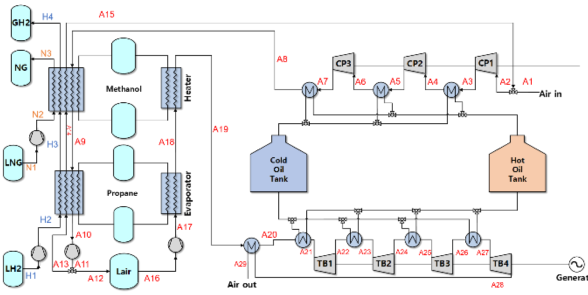

Fig. 1. Schematic diagram of LAES-LNG-LH_2 system

During off-peak hour, when electricity price is low, air is compressed through multi-stage air compressor (A1 to A7). For reducing work consumption of compressor, the compression heat is removed by thermal fluid which therminol VP1 is used in this study. In the typical LAES, compressed air is entered into multi-channel cold box and cooled down to cryogenic temperature by two cryogenic fluid (A8 to A10): methanol and propane. However, in this study, LNG and LH_2 are added for enhancing cold energy recovery. The advantages of integration with regasification process are not only making high liquid air yield but also making high discharging pressure by reducing the amount of cold energy that needs to be recovered at discharging process (A17). It also allows high round-trip efficiency. After cooling process, air is expanded through cryo-turbine and becomes liquid (A10 to A11). Liquid air is stored in cryogenic tank (A12) and gaseous air is recycled for using remaining cold energy in air (A13).

During the peak demand hour, liquid air is pumped by cryo-pump (A16 to A17) and evaporated by methanol and propane to atmospheric temperature (A17 to A19). Then, air is heated by the stored heat in therminol VP1 and expanded through air turbine to generate electricity (A21 to A27).

2.2 Mathematical modelling

For evaluating performance of proposed system, components are modelled by basic thermodynamic equation.

2.2.1 Turbine and Compressor

Turbine and compressor are modelled with isentropic efficiency model. The equation is given by:

$$W_c = \dot{m}(h_{out} - h_{in}) = \frac{\dot{m}(h_{out.isen} - h_{in})}{\eta_{CP}} \quad (1)$$

$$W_T = \dot{m}(h_{in} - h_{out}) = \eta_{TB} * \dot{m}(h_{in} - h_{out.isen}) \quad (2)$$

where W_C and W_T represent the work of air compressor and air turbine, respectively. $\dot{m}$ is mass flow rate, h is specific enthalpy, and η_{isen} is isentropic efficiency of each components.

2.2.2 Heat exchanger

Heat exchanger is modelled with basic heat balance equation. The heat exchanger is assumed as counter-flow heat exchanger and pinch point limitation is applied.

$$Q_{hot} = \dot{m}_{hot}(h_{H_{in}} - h_{H_{out}}) \quad (3)$$

$$h_{C_{out}} = h_{C_{in}} + \frac{Q_{hot}}{\dot{m}_{cold}} \quad (4)$$

$$\textit{Objective function: } min(T_{hot} - T_{cold}) = 5K \quad (5)$$

where Q represents heat transfer rate. h_H and h_C are specific enthalpy of hot side and cold side, respectively. Subscript in and out represent inlet and outlet stream.

2.2.3 Multi-channel cold-box

Multi-channel cold box is the most important component in the proposed system because the liquid air yield and round-trip efficiency are directly affected. Compressed air is cooled down to cryogenic temperature by methanol, propane, recycle air, LNG, and liquid hydrogen (A8 to A10). LNG and liquid hydrogen are evaporated to ambient temperature and cold heat of air is stored in the propane and methanol. For simplifying multi-channel heat exchanger, it is assumed that there is no heat transfer between cold side fluid. Also, the outlet temperature of cold side fluids is predefined. The equation is given by:

$$Q_{hot} = \dot{m}_{hot}(h_{H_{in}} - h_{H_{out}}) = Q_{propane} + Q_{methanol} + Q_{recycle} + Q_{LNG} + Q_{LH_2} \quad (6)$$

Objective function: (7)

$$min\big(min(T_H - T_{propane}), min(T_H - T_{methanool}), min(T_H - T_{LNG}), min(T_H - T_{LO2}), min(T_H - T_{recycle\ air})\big) = 5K$$

where Q represents heat transfer rate. T_{fluid} is temperature profile of each fluids.

2.2.4 Round-trip efficiency

The round-trip efficiency is the most important indicator for storage efficiency of ESS. Generally, the round-trip efficiency is defined as the total electricity generation in the discharging process divided by the power consumption in the charging process. The equation is given by:

$$\eta_{RTE} = \frac{W_{discharging}}{W_{charging}} = \frac{W_{TB} - W_{CRP}}{W_{CP} - W_{CTB} - W_{pump,LNG} - W_{pump,LH_2}} \quad (8)$$

where W_{CP} and W_{TB} represent the work of air compressor and air turbine, respectively. CRP represents cryo-pump and CTB represents cryo-turbine. $W_{pump,LNG}$ and W_{pump,LH_2} represent the work of LNG pump and liquid hydrogen pump, respectively.

Table 1 presents the design parameters for the proposed system.

Table 1. Design parameters

Parameters	Value
Turbine efficiency	92%
Compressor efficiency	85%
Cryo-turbine efficiency	80%
Cryo-pump efficiency	80%
Pinch temperature	5K
Hot side pressure-drop	3% of inlet pressure
Cold side pressure-drop	2% of inlet pressure
LNG inlet temperature	111.15K
LNG inlet pressure	130kPa
LNG outlet pressure	7MPa
LH_2 inlet temperature	15K
LH_2 inlet pressure	300kPa
LH_2 outlet pressure	7MPa
Charging pressure	20MPa
Air mass flow rate	100kg/sec
Thermal oil mass flow rate	200kg/sec
LNG mass flow rate	0.5kg/sec
LH_2 mass flow rate	3.0kg/sec

3. Results

Fig. 2 presents T-s diagram of LAES-LNG-LH_2 system at design point and Table 2 presents the calculated cycle performance and comparison with typical LAES. The round-trip efficiency now becomes 66.5% and liquid air yield increases to 85.3%. the result shows that the round-trip efficiency is dramatically enhanced by adding external cold heat source.

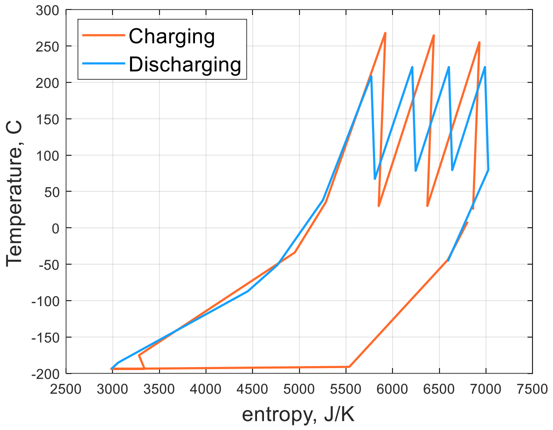

Fig. 2. T-s diagram of proposed system

Table 2. Calculated cycle performance

Parameters	Proposed system	Typical LAES
Turbine work	49.7MW	40.9MW
Compressor work	72.0MW	72.0MW
Cryo-turbine work	1.9MW	1.9MW
Cryo-pump work	2.8MW	1.0MW
Liquid air yield	85.9%	85.0%
Round-trip efficiency	66.9%	56.9%
Discharging pressure	23.1MPa	8.0MPa

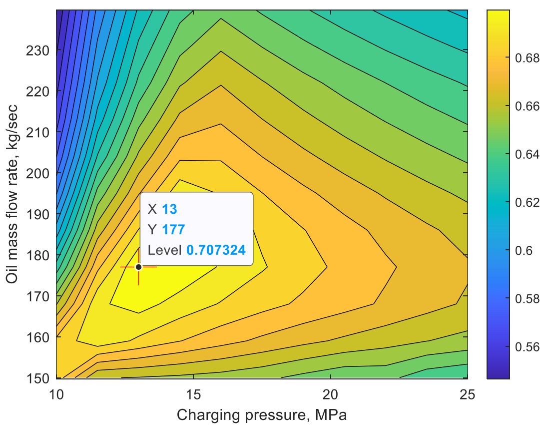

Fig. 3. Sensitivity of round-trip efficiency with charging pressure and oil mass flow rate

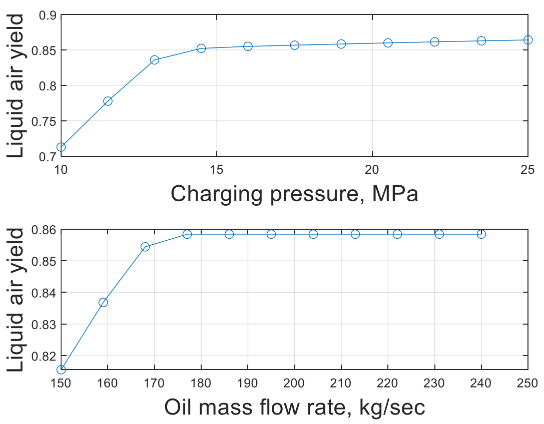

Fig. 4. Sensitivity of liquid air yield with charging pressure and oil mass flow rate

Fig. 3 shows the sensitivity of round-trip efficiency with charging pressure and thermal oil mass flow rate. As charging pressure increases, round-trip efficiency increases sharply and then decreases. In the light of thermal oil mass flow rate, it shows a similar tendency. This is due to the liquid air limitation. Fig. 4 shows the sensitivity of liquid air yield with charging pressure and oil mass flow rate. As both cycle parameters increase, liquid air yield increases but after certain point, there is no further increase. This is because compression work still increases with the charging pressure increase, while the round-trip efficiency reduces due to liquid air limitation. Moreover, increase of oil mass flow rate reduces the temperature of stored compression heat, therefore, turbine inlet temperature reduces after optimum point (A21 to A27). The local maximum round-trip efficiency is 70.7% which is 13.8%p higher than the typical LAES.

4. Conclusions

Load-following operation of a nuclear power plant is becoming important to keep pace with the increase of variable renewable energy source. A recently developed nuclear power plant is capable of load-following operation, but frequent change in power level has adverse effects. In order to enhance flexibility of nuclear power plant, integration of Liquid Air Energy Storage System (LAES) to the nuclear power plant is proposed and researched. One of the challenges in LAES is low efficiency compared to other energy storage systems. To increase the efficiency of LAES, external cold heat source is suggested and in this study Liquid Natural Gas (LNG) and liquid hydrogen are proposed as the external cold heat sources. The performance of LAES-LNG-LH_2 is investigated and it shows that compared to the typical LAES, the suggested LAES-LNG-LH_2 shows great enhancement in round-trip efficiency. By reducing dependency on methanol and propane, LAES can achieve higher discharging pressure. The study showed that the round-trip efficiency is greatly enhanced when coupled with LNG and liquid hydrogen. In the future, the optimization analysis with other cold heat sources will be investigated and compared. Furthermore, the economy of integration will be presented.

5. Acknowledgment

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REFERENCES

[1] Coleman, Justin, Shannon Bragg-Sitton, and Eric Dufek. *An evaluation of energy storage options for nuclear power*. No.

INL/EXT-17-42420-Rev000. Idaho National Lab.(INL), Idaho Falls, ID (United States), 2017.

[2] Borri, Emiliano, et al. "A review on liquid air energy storage: History, state of the art and recent developments." *Renewable and Sustainable Energy Reviews* 137 (2021): 110572.

[3] Heo, Jin Young, et al. "Evaluation of various large-scale energy storage technologies for flexible operation of existing pressurized water reactors." *Nuclear Engineering and Technology* 53.8 (2021): 2427-2444.

[4] Park, Jung Hwan, Jin Young Heo, and Jeong Ik Lee. "Techno-economic study of nuclear integrated liquid air energy storage system." *Energy Conversion and Management* 251 (2022): 114937.

[5] Zhang, Tong, et al. "Thermodynamic analysis of a novel hybrid liquid air energy storage system based on the utilization of LNG cold energy." *Energy* 155 (2018): 641-650.