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Thermodynamic analysis of Claude liquefaction process for Liquid Air Energy Storage System Integrated to Pressurized Water Reactor

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1. Introduction

In South Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE to 20% by 2030 due to decrease of greenhouse gas emission [1]. However, as the proportion of variable RE (VRE) increases, major technical challenges also arise.

Power generation from VRE has an intermittency problem because it is affected by the weather and environment. Thus, the intermittency issue of VRE has to be solved. This issue can be addressed by load-following operation of a nuclear power plant (NPP). However, it is not economical to control power output of the reactor in an NPP. A reliable energy storage system coupled with the NPP can solve this issue. Liquid air energy storage system (LAES) is one of the most attractive energy storage systems (ESS) due to high round-trip efficiency (RTE), high energy density, great power rating and sufficient capacity [2].

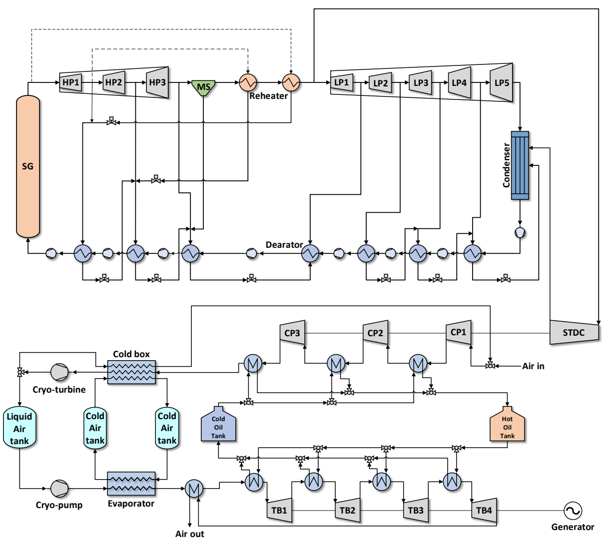


Fig. 1. Layout of LAES integrated into steam cycle of PWR [3]

J.H. Park [3] performed the techno-economic analysis of LAES integrated to the steam cycle of PWR. The new layout and the concept of mechanical integration between LAES and PWR were suggested as shown in Fig. 1. In the previous work, the feasibility of LAES integrated to PWR was discussed.

A liquefaction process is one of the most major issues to design LAES since LAES should have the liquid air as energy storage material. Many types of LAES can exist depending on the various types of two-phase expansion and liquefaction processes. From the literature survey, three types of expansion processes in the liquefaction process were first identified: 2-phase expander [6, 7], Joule-Thomson valve (J-T valve) [8, 9], and single-phase expander combined with J-T valve [10]. In addition, there are various liquefaction cycles for LAES such as Linde cycle, Claude cycle, Kapitza cycle and Heylandt cycle.

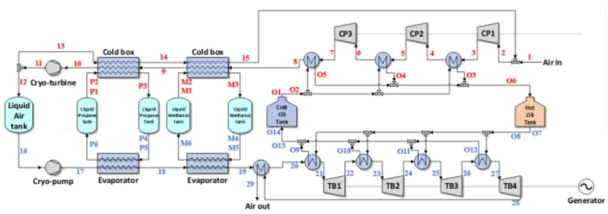


Fig. 2. Layout of LAES Linde w/ two-phase expander [8]

The two-phase expansion of Linde liquefaction process in LAES was studied and analyzed thermodynamically previously as shown in Fig. 2 [8]. From the previous study, its maximum RTE was estimated to be around 49%. This refence used Linde cycle that is the simplest liquefaction cycle of LAES. There are other liquefaction cycles such as Claude cycle and Kapitza cycle, thus, other liquefaction processes of LAES need to be analyzed thermodynamically to identify the best liquefaction process.

This paper aims to compare with various two-phase expansion processes of Claude cycle instead of using Linde cycle. Therefore, in this paper, a thermodynamic analysis of different expansion processes in Claude cycle for a LAES system integrated to a conventional pressurized water reactor (PWR) is presented. The comparison of various expansion processes was performed in terms of RTE of LAES.

2. Thermodynamic modeling

Assumptions used for the modeling are as follows:

(1) Water, nitrogen, and oxygen tanks have the same temperature and pressure.
(2) There is no pressure drop in the pipelines.
(3) There are no changes in potential and kinetic energies

2.1 System description

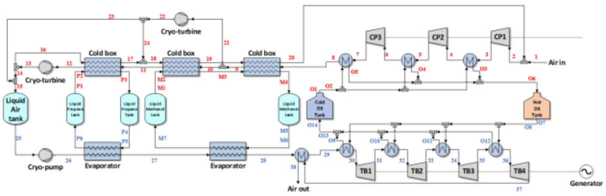


Fig. 3. Layout of LAES Claude w/ two-phase expander

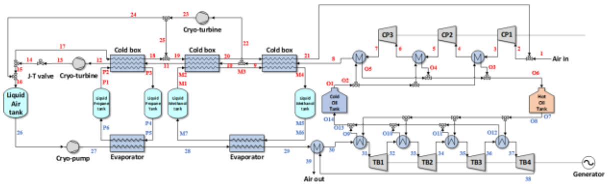


Fig. 4. Layout of LAES Claude w/ single-phase expander combined w/ JTV

The layouts of LAES using Claude cycle with a 2-phase expander, and a single-phase expander combined with a J-T valve are shown in Figs. 3, and 4, respectively. Compared with Linde cycle, Claude cycle has a bypass process in liquefaction process. As shown in Fig. 3, Claude cycle has additional stream to bypass air from the hot side outlet of the first heat exchanger to the cold side inlet of the second heat exchanger via cryo-expander. It is expected to have the best performance at lower maximum pressure compared to Linde cycle. In addition, in this paper, the case to use only J-T valve is not considered unlike the previous study since it cannot be conducted without additional components to control the mass flowrate of propane and methanol.

2.2 System performance criterion

Round-trip efficiency (RTE) is the ratio of energy stored over energy retrieved from storage. The most important criterion for evaluating the performance of energy storage system (ESS) is RTE. RTE can be defined differently for different ESS since the opportunity of energy produced can differ depending on the ESS concept. LAES is integrated to a PWR via steam turbine driven compressor (STDC). In other words, the generated work of steam turbine is the same as the consumed work of air compressor. Thus, in this study, RTE is defined as LAES produced total work per work loss in the steam cycle of PWR.

$$\eta_{\mathrm{RT}} = \frac{\dot{\mathrm{E}}_{\mathrm{discharging}}}{\dot{\mathrm{E}}_{\mathrm{charging}}} = \frac{\dot{W}_{TB,dis} - \dot{W}_{Pump,dis}}{\dot{W}_{NPP,loss}} \quad (1)$$

2.3 Modeling of components

This paper uses the same modeling of components to be used and explained in the previous study [8]. For turbomachinery, thermodynamic properties of its outlet are obtained to use its isentropic efficiency. However, in the case of cryo-pump, the inlet is the liquid air at atmospheric pressure and the outlet is determined by the highest possible inlet temperature of the evaporator without pinch problem. It is why the discharging pressure is much lower than the charging pressure.

For heat exchangers, these properties of both inlet and outlet are calculated to consider pressure drop ratio, energy balance, and minimum pinch temperature. In this paper, the minimum pinch temperature in heat exchangers is assumed to be 5K. As explained in this reference, it cannot be designed since the liquid air is impossible to be compressed through cryo-pump in discharging process due to minimum pinch problem [8].

2.4 Parameters & Variables

In this paper, the design parameters and variables of LAES with Claude cycle are shown in TABLE I. These values of the design parameters and variables are based on the previous study [3, 8]. Compared to Linde cycle, it has two additional variables: temperature and fraction of bypass air. To design and choose the bypass point in a liquefaction process, the temperature of bypass air is considered to be the same as the temperature at the bypass point.

Table I: Parameters and variables of LAES w/ Claude cycle

Fixed values for cycle design	
Variables	Values
Compressor efficiency	85%
Turbine efficiency	90%
Cryo-expander efficiency	80%
Cryo-pump efficiency	80%
Pressure drop	3%
Pinch of HX	5K
Minimum propane temperature	93K
Maximum propane temperature	214K
Minimum methanol temperature	214K
Maximum methanol temperature	288K
Temperature of Ambient Air	298K
Pressure of Ambient Air	101kPa
Optimization variables	
Variables	Ranges
System maximum (charging) pressure	18-32MPa
Ratio of thermal oil mass flow rate	1.8-2.1
Temperature of bypassed air	270-300K
Fraction of bypassed air	0.01-0.05

3. Results and Discussions

3.1 Results of two-phase expander

Figures 5 depicts the variation in round trip efficiency of two-phase expander with respect to charging pressure and thermal oil mass flow rate ratio. For the two-phase expander, the results suggest that the maximum RTE of

48.5% is obtained at a charging pressure of 24 MPa and a ratio of thermal oil mass flow rate of 1.920. In addition, it shows that the optimization point (charging pressure) varies as the ratio of thermal oil mass flow rate changes.

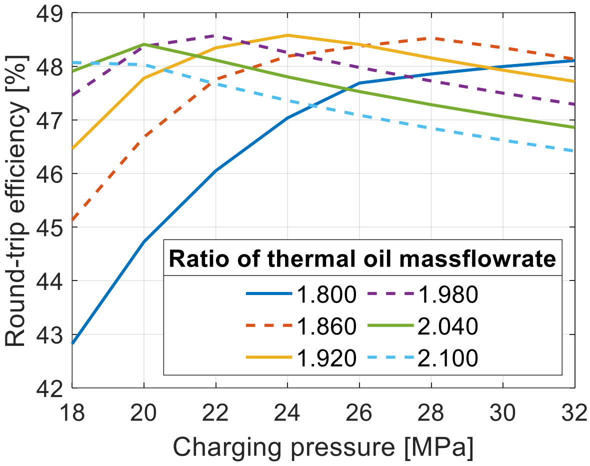
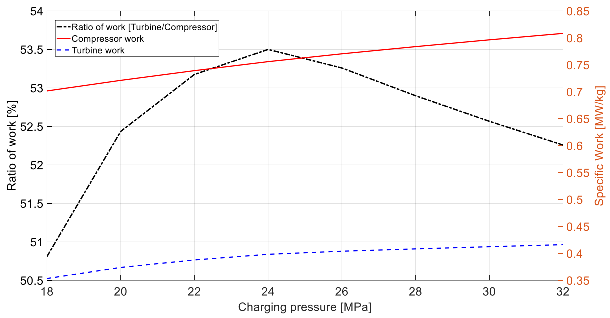
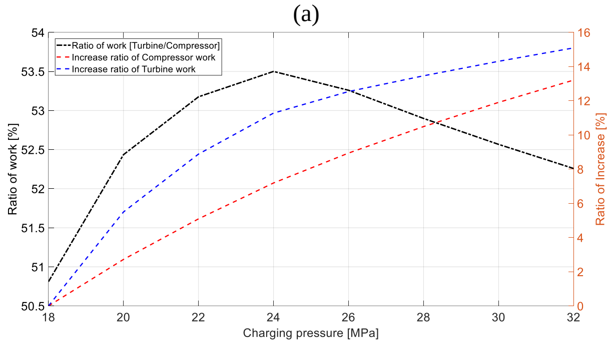


Fig. 5. RTE vs Charging pressure (Legend: Ratio of thermal oil mass flow rate) of LAES w/ 2-phase expander (Bypass temperature and fraction: 300K and 0.01)



(a)



(b)

Fig. 6. Ratio of work and Specific work (a) and Ratio of increase (b) vs Charging pressure (Legend: Ratio of work, compressor and turbine work) of LAES w/ 2-phase expander

Fig. 6 shows the variation of compressor work, turbine work, and the ratio of turbine and compressor work at different changing pressures. Both turbine work and compressor work increase with increasing charging pressure. RTE increases either by increasing the turbine work or by decreasing the compressor work, or both.

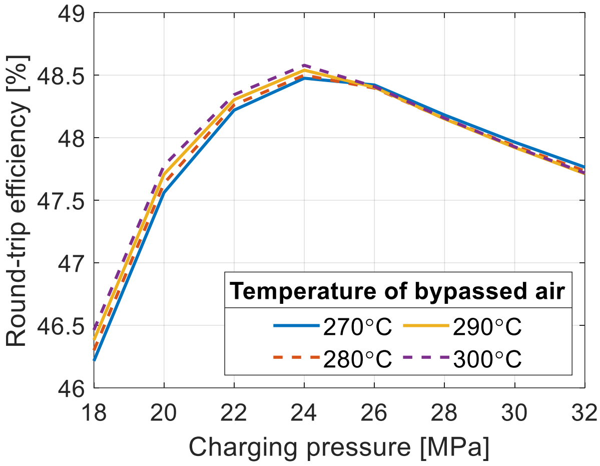
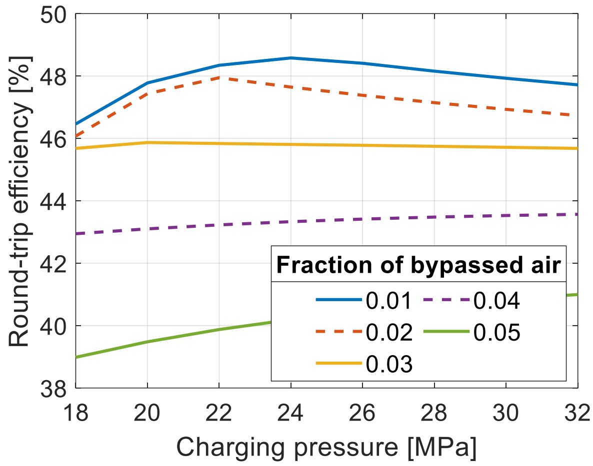
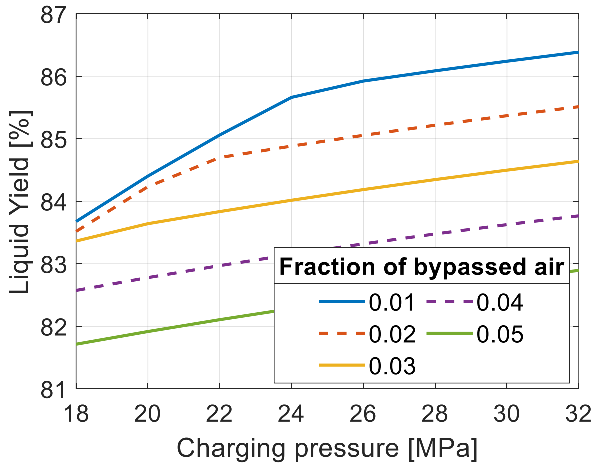


Fig. 7. RTE vs Charging pressure (Legend: Bypass temperature) of LAES w/ 2-phase expander (Bypass fraction and ratio of thermal oil mass flow rate: 0.01 and 1.92)

Fig. 7 shows the variation of RTE with the charging pressure and the temperature of bypass air. RTE seems to be insensitive to the temperature of bypass air unlike charging pressure and the ratio of thermal oil mass flow rate. Thus, the sensitivity of RTE to the temperature of bypass air is not further analyzed.



(a)

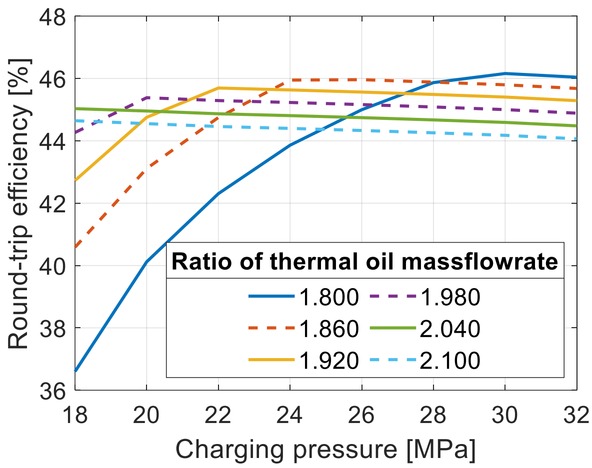


(b)

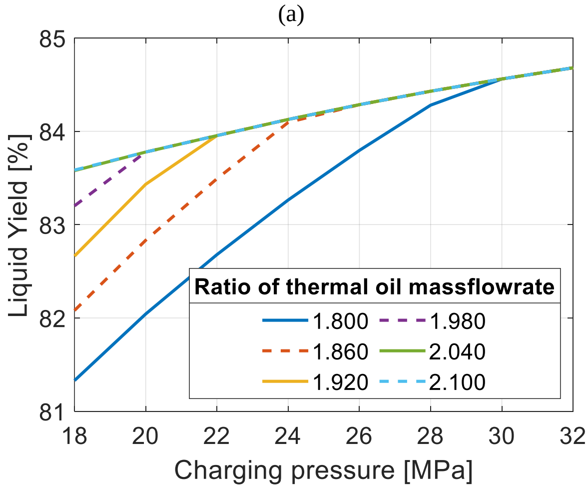
Fig. 8. RTE (a) and Liquid yeild (b) vs Charging pressure (Legend: Bypass fraction) of LAES w/ 2-phase expander
(Bypass temperature and ratio of thermal oil mass flow rate: 300K and 1.92)

Fig. 8 (a) and (b) show the variation of RTE and liquid yield with respect to the charging pressure and the fraction of bypass air, respectively. Ths fraction of bypassed air appears to have a large effect on both RTE and liquid yield. As the fraction of bypass air increases, both decreases. In other words, in case of Claude cycle, more bypass fraction is not preferred for better performance of LAES since the outlet of cryo-expander for bypass air has less liquid air fraction.

3.2 Results of single-phase expander w/ J-T valve



(a)



(b)

Fig. 9. RTE (a) and Liquid yield (b) vs Charging pressure (Legend: Ratio of thermal oil mass flow rate) of LAES w/ single-phase expander w/ J-T valve
(Bypass temperature and fraction: 270K and 0.01)

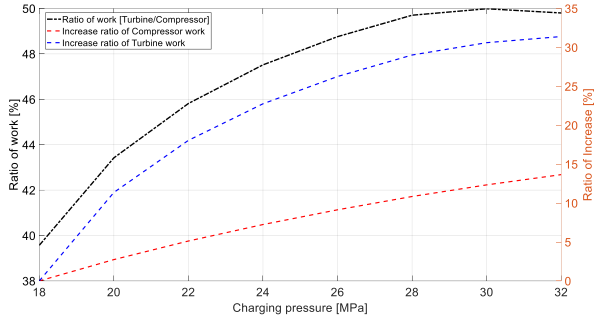


Fig. 10. Ratio of work and Ratio of increase vs Charging pressure (Legend: Ratio of work, compressor and turbine work) of LAES w/ single-phase expander w/ J-T valve

Fig. 9 (a) and (b) depict the variation of RTE and the liquid yield of single-phase expander with J-T valve with respect to the charging pressure and the ratio of thermal oil mass flow rate, respectively. In Fig. 9 (a), the RTE increases as charging pressure increases until the maximum point, which is in contrast with Fig. 5. As shown in Fig. 9 (b), liquid yield increases as charging pressure increases, but the slope of graph becomes gradual. In other words, the work of turbine is changed by the liquid yield of air due to the working fluid of turbine. Fig. 10 shows the variation of compressor work, turbine work, and the ratio of turbine and compressor work at different changing pressures. The trend of turbine work in Fig. 10 follows the liquid air yield with respect to the change of charging pressure.

4. Summary and Future works

In this study, LAES systems using different expansion processes in Claude liquefaction process are analyzed and compared: two-phase expander and single-phase expander with J-T valve. Two-phase expander shows the highest RTE due to the largest liquid yield and the highest pressure in cryo-pump outlet. The maximum RTE is 48.58% and the optimal RTE conditions are different from the maximum liquid yield conditions due to different rates of turbine work and compressor work increase. Compared with the previous study for Linde liquefaction process, the highest RTE of Claude is about 0.8% less than that of Linde, and the charging pressure of Claude is also lower than that of Linde by 3MPa.

As future works, various liquefaction processes of LAES will be further investigated for different layout to identify the layout and processes with the best performance. Other liquefaction processes to be investigated include Kapitza cycle and Heylandt cycle with bypassing and merging points.

Acknowledgement

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