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Comparison of Linde and Claude Liquefaction Processes for Liquid Air Energy Storage System Integrated to Pressurized Water Reactor

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1. Introduction

The share of renewable energy (RE) is increasing significantly around the world to address climate change. In South Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE to 20% by 2030 [1]. However, as the proportion of variable RE (VRE) increases, major technical challenges also arise.

Power generation from VRE is mostly affected by weather and climate conditions and therefore it cannot always generate constant power output. This irregularity in electricity production can result in an inability to meet peak electricity demand, known as intermittency. Thus, solving the intermittency issue of VRE is one of the major challenges.

The conventional power plants need to respond to demand in such a scenario. The majority of electricity generated in South Korea is produced through thermal and nuclear power. Of these, nuclear power is a particularly suitable option for reducing carbon emissions. Thus, this issue can be addressed by the load-following operation of a nuclear power plant (NPP). However, in contrast to controlling the power output of the reactor in the NPP directly, a reliable energy storage system (ESS) coupled with the NPP can be an economically favorable option. Liquid air energy storage systems (LAES) are among the most promising ESS due to high round-trip efficiency (RTE), high energy density, great power rating, and sufficient capacity [2, 3].

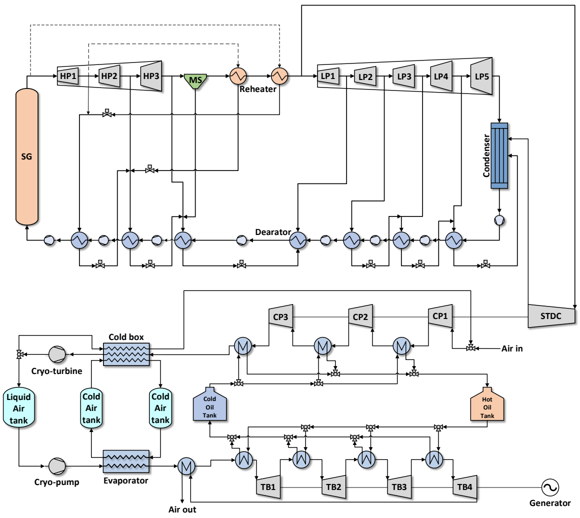


Fig. 1. Layout of LAES integrated to steam cycle of PWR [4]

J.H. Park [4] studied techno-economic analysis of LAES integrated to steam cycle of pressurized water reactor (PWR). The new layout and concept of mechanical integration between LAES and PWR were suggested as shown in Fig. 1.

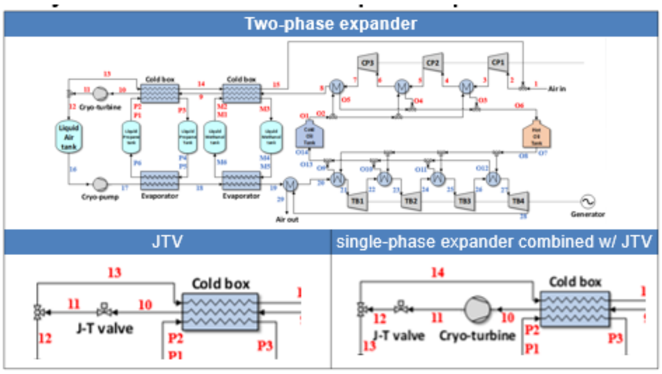


Fig. 2. Layout of various two-phase expansion processes of Linde liquefaction process [5]

The liquefaction process is one of the most critical issues in designing LAES, as liquid air is required as the energy storage material. The liquefied air from this process generates electricity through an air turbine. In other words, the flow rate of the working fluid during the discharge process is determined by this process. The two-phase expansion in the Linde and Claude liquefaction processes within LAES has been previously studied and analyzed thermodynamically [5, 6]. Fig. 2 shows various two-phase expansion processes in the Linde liquefaction process: two-phase expander, Joule-Thomson Valve (JTV), and single-phase expander combined with JTV. Hence, this paper aims to thermodynamically compare various liquefaction and two-phase expansion processes in LAES.

Table I: Results of various expansion processes [5]

	2-phase expander	Single-phase expander w/ JTV	JTV
Liquid Yield [%]	87.61	85.64	76.38
Round-trip Efficiency [%]	49.25	47.37	38.93

Table I presents the outcomes of previous research [5]. As shown in Table I, round trip efficiency (RTE), a critical parameter for LAES, exhibits a correlation with liquid yield. As previously mentioned, the mass flow rate of air during the discharge process depends on the liquefaction process, which ultimately determines the liquid yield in LAES.

Therefore, in this paper, a preliminary comparison of various liquefaction processes and cryo-expansion processes for an LAES system integrated with a conventional PWR in terms of liquid yield is presented.

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

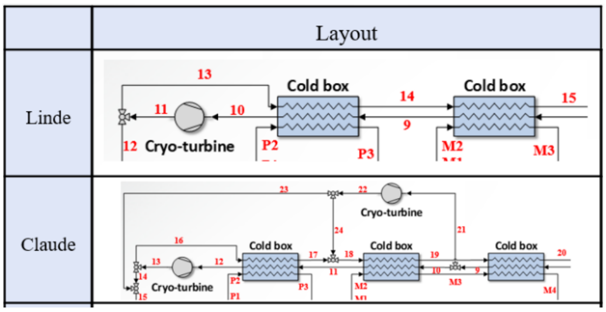


Fig. 3. Layout of various liquefaction processes in LAES

As depicted in Figure 3, two types of two-phase expansions are first identified. The application of two-phase expansion processes applies to all liquefaction processes discussed in this paper.

In the Claude liquefaction process, some of the hot air from the middle of the first cold box is diverted and mixed with the cold gaseous air located between the two cold boxes, unlike the Linde liquefaction process. This merging occurs after the air has been expanded through the cryo-expander.

2.2 System performance criterion

RTE is defined as the ratio of energy stored to energy retrieved from storage. The most important criterion for evaluating the performance of an ESS is RTE. However, in this paper, liquid yield is used as the performance criterion for the liquefaction process in LAES, as previously explained. The liquid yield, which is the mass flow rate of the working fluid during the discharge process, depends on the type of liquefaction process and the conditions of LAES. As shown in Table I, liquid yield has a dominant effect on RTE. Consequently, this paper uses liquid yield instead of RTE as the preliminary performance criterion in the liquefaction process.

$$\text{Liquid Yield} = \mathrm{f}(\mathrm{p}, \mathrm{h}, \dot{m}) = \left(\frac{h_{real} - h_{p_{sat},liq}}{h_{p_{sat},vap} - h_{p_{sat},liq}}\right) * \frac{\dot{m}_{real}}{\dot{m}_{int}}$$

2.3 Modeling of components

This paper uses the same modeling of components to be used and explained in the previous study [5]. For turbomachinery, thermodynamic properties of its outlet are obtained to use its isentropic efficiency. 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 (HX) is assumed to be 5K.

2.4 Parameters & Variables

In this paper, the design parameters and variables of LAES with various liquefaction processes are shown in TABLE II. These values of the design parameters and variables are based on the previous study [4, 5, 6].

The Linde liquefaction process has two variables: system maximum pressure and the ratio of thermal oil mass flow rate. Compared to the Linde liquefaction process, the Claude process has two additional variables: temperature and the fraction of bypass air. When designing and selecting the bypass point in a liquefaction process, the temperature of the bypass air is assumed to be the same as the temperature at the bypass point.

Table II: Parameters and variables of charging process in LAES w/ various liquefaction processes

Fixed values for cycle design

Variables	Values
Compressor efficiency	85%
Cryo-expander 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

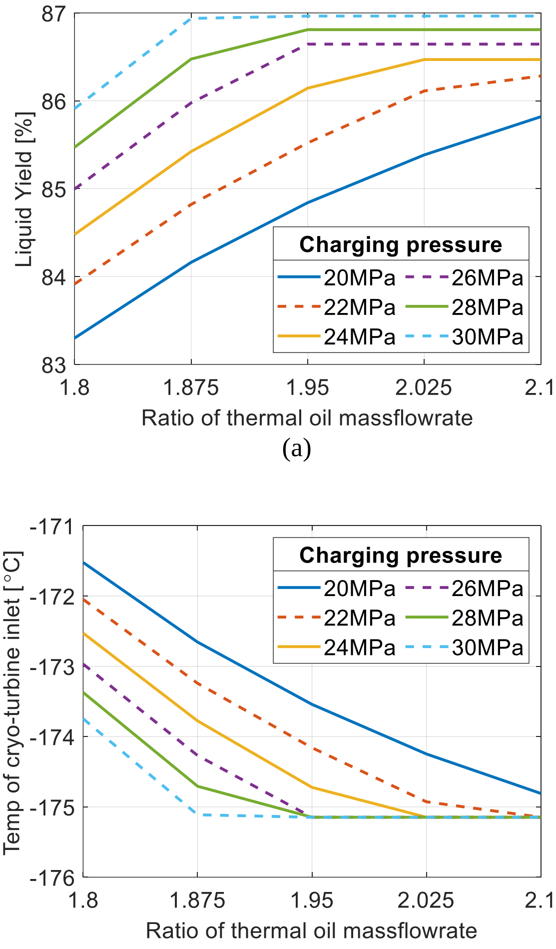
Optimization variables

Liquefaction process		Variables	Ranges
Claude	Linde	Maximum (Charging) pressure [MPa]	20~30
		Ratio of thermal oil mass flow rate [-]	1.8~2.1
		Fraction of bypassed air [%]	1~5
		Temperature of bypassed air [K]	270~300

3. Results and Discussions

3.1 Results of Linde liquefaction process

Fig. 4 depicts the variation in liquid yield and the temperature at the cryo-expander inlet of the Linde process with a 2-phase expander as a function of charging pressure and the thermal oil mass flow rate ratio, respectively. In Fig. 4(a), the liquid yield increases with increasing charging pressure due to the isentropic expansion process. Specifically, at the same temperature, the point at higher pressure has lower entropy than the point at lower pressure, resulting in lower enthalpy through isentropic expansion. In other words, this leads to lower flow quality and higher liquid yield. Then, the liquid yield increases up to a certain point with an increase in the thermal oil mass flow rate ratio. As illustrated in Fig. 4(b), the temperature at the cryo-expander inlet increases with the thermal oil mass flow rate ratio and then converges to a certain temperature due to the pinch condition of the cold box. The process achieves its highest liquid yield of 86.96%.



(a)

(b)

Fig. 4. Liquid yield (a) and Temperature of cryo-expander inlet (b) vs Ratio of thermal oil massflowrate (Legend: Charging pressure) of Linde w/ 2-phase expander

Fig. 5 shows the trends in liquid yield for the Linde process with a single-phase expander and JTV as a function of charging pressure and the thermal oil mass flow rate ratio. Compared to the Linde process with a 2-phase expander, it exhibits similar trends and achieves a maximum liquid yield of 85.18%.

Fig. 6 illustrates the change in liquid yield for the Linde process with JTV as charging pressure and the ratio of thermal oil mass flow rate vary. As shown in Fig. 6, it exhibits a single decreasing trend with increasing charging pressure, unlike the other 2-phase expansion processes, due to the isenthalpic expansion process. In other words, at the same temperature, the point at higher pressure has higher enthalpy than the point at lower pressure, resulting in higher enthalpy after the isenthalpic expansion process. Consequently, this leads to higher flow quality and lower liquid yield. The process achieves a maximum liquid yield of 76.67%.

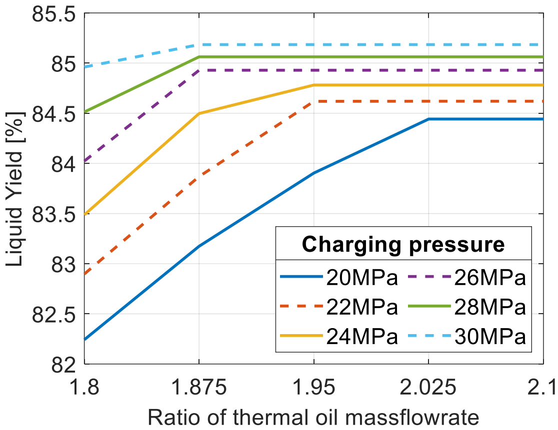


Fig. 5. Liquid yield vs Ratio of thermal oil massflowrate (Legend: Charging pressure) of Linde w/ single-phase expander w/ JTV

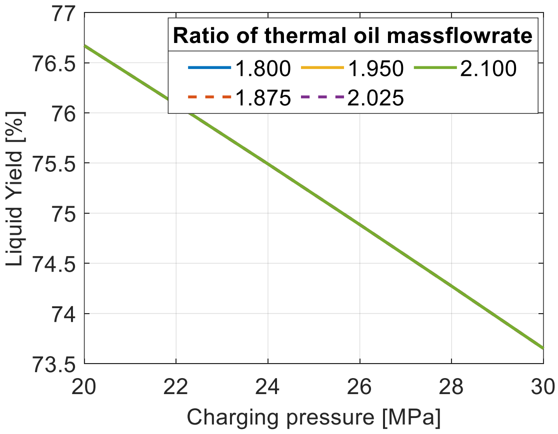


Fig. 6. Liquid yield vs Charging pressure (Legend: Ratio of thermal oil massflowrate) of Linde w/ JTV

3.2 Results of Claude liquefaction process

Figs. 7, 8, and 9 show the variation in liquid yield for the Claude process with a 2-phase expander, as a function of charging pressure, the ratio of thermal oil mass flow rate, and the fraction and temperature of bypassed air. In Fig. 7, compared to the Linde process, the Claude process exhibits a similar trend but achieves a lower maximum liquid yield of 86.28%. As illustrated in Fig. 8, the liquid yield decreases as the fraction of bypassed air increases because the mass flow rate of the inlet in the 2-phase expansion process decreases. Fig. 9 shows that the temperature of the bypassed air has little effect on liquid yield.

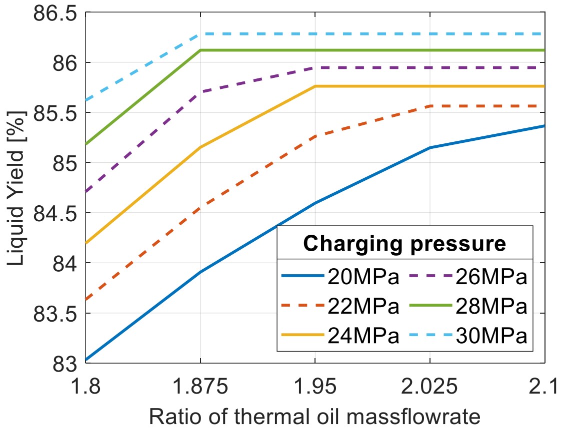


Fig. 7. Liquid yield vs Ratio of thermal oil massflowrate (Legend: Charging pressure) of Claude w/ 2-phase expander

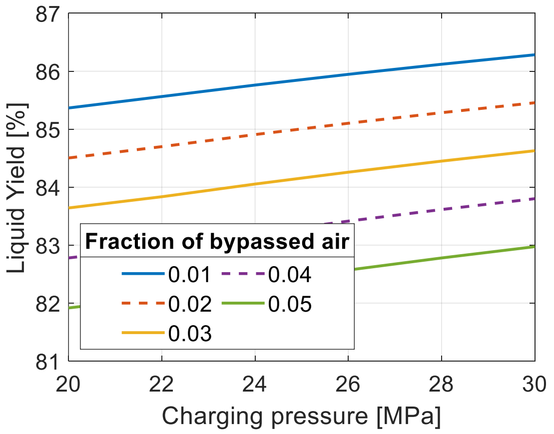


Fig. 8. Liquid yield vs Ratio of thermal oil massflowrate (Legend: Fraction of bupassed air) of Claude w/ 2-phase expander

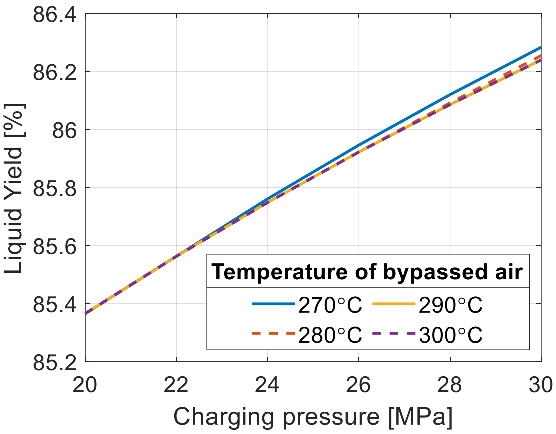


Fig. 9. Liquid yield vs Ratio of thermal oil massflowrate (Legend: Temperature of bupassed air) of Claude w/ 2-phase expander

Fig. 10 and 11 depict the results of Claude process with single-phase expander with JTV and with only JTV, respectively. These processes achieve a maximum liquid yield of 84.56% and 76.30%, respectively.

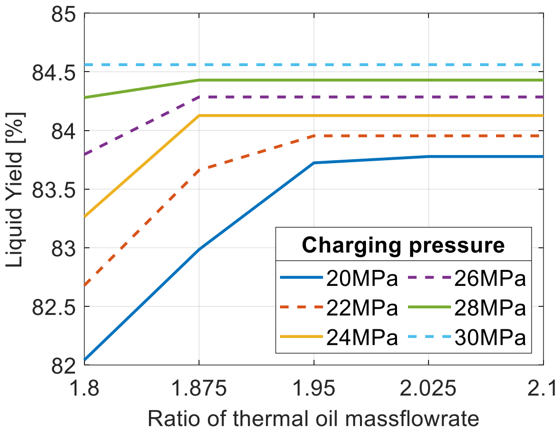


Fig. 10. Liquid yield vs Ratio of thermal oil massflowrate (Legend: Charging pressure) of Claude w/ single-phase expander w/ JTV

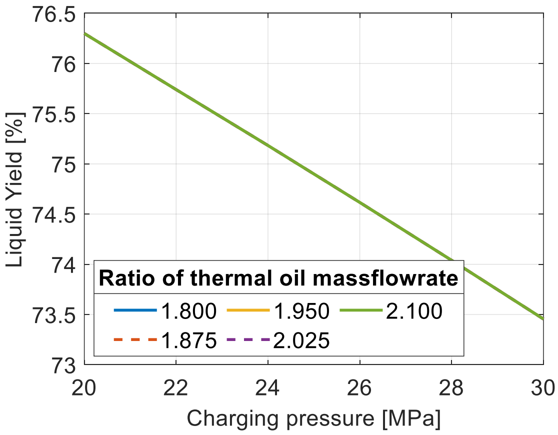


Fig. 11. Liquid yield vs Charging pressure (Legend: Ratio of thermal oil massflowrate) of Claude w/ JTV

The maximum liquid yields of two liquefaction processes with all 2-phase expansion processes are summarized in TABLE III.

Table III: Liquid yields of two liquefaction processes

Liquid Yield [%]	**2-phase expander**	**Single-phase expander w/ JTV**	**JTV**
Linde	86.96	85.18	76.67
Claude	86.28	84.56	76.30

4. Summary and Future works

In this study, different liquefaction processes incorporating various 2-phase expansion methods within LAES are analyzed and compared. The analysis reveals that the Linde liquefaction process with a 2-phase expander in LAES achieves the highest liquid yield of 86.96%. An increased fraction of bypassed air in the cold box results in a lower liquid yield, while the temperature of the bypassed air has minimal impact on the yield. In summary, the 2-phase expander produces a higher liquid yield when both the inlet and outlet pressures are higher due to the isentropic expansion process. Conversely, the JTV process yields a higher liquid yield with lower inlet and higher outlet pressures, driven by the isenthalpic expansion process.

The primary objective of this paper is to conduct a preliminary comparison of selected liquefaction processes during the charge phase of LAES, focusing solely on liquid yield. However, future studies should also consider the discharge process using RTE. Further research will explore different layouts and processes within LAES to determine the configurations that offer the best performance. Additionally, experimental setups will be necessary to compare the types of 2-phase expansion processes in relation to liquid yield.

Acknowledgement

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