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Thermodynamic analysis of Liquid air energy storage system integrated to Pressurized water reactor with Consideration of Composition change of Liquefied air after Various cryogenic expansion processes

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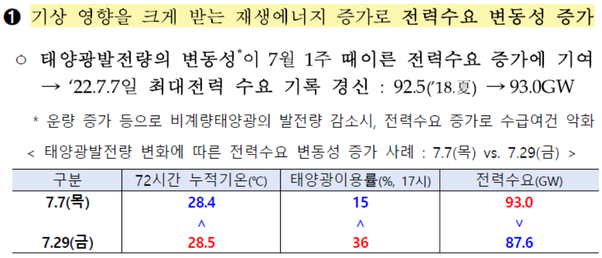
1. Introduction

Various energy policies have been proposed worldwide to reduce carbon emissions. In Korea, for example, the "Renewable Energy 3020 Implementation Plan" aims to increase the share of renewable energy to 30% by 2030 [1]. However, as the proportion of renewables grows, the issue of intermittency arises. The 10th Basic Plan for Long-term Electricity Supply and Demand presents the impact of the increase in renewable energy on power supply and demand [2]. Figure 1 shows one example, illustrating how the increase in renewable energy, which is heavily influenced by weather conditions, leads to increased power demand volatility and provides a case study of this impact. To address this, extensive research has been conducted on pressurized water reactor (PWR) combined with energy storage systems (ESS) [3].


❶ 기상 영향을 크게 받는 재생에너지 증가로 전력수요 변동성 증가

○ 태양광발전량의 변동성*이 7월 1주 때이른 전력수요 증가에 기여
→ '22.7.7일 최대전력 수요 기록 경신 : 92.5('18.夏) → 93.0GW

* 운량 증가 등으로 비계량태양광의 발전량 감소시, 전력수요 증가로 수급여건 악화

< 태양광발전량 변화에 따른 전력수요 변동성 증가 사례 : 7.7(목) vs. 7.29(금) >

구분	72시간 누적기온(℃)	태양광이용률(%, 17시)	전력수요(GW)
7.7(목)	28.4	15	93.0
	∧	∧	∨
7.29(금)	28.5	36	87.6

Fig. 1. Some of the impacts of the increase in renewable energy on power supply and demand [2]

Liquid Air Energy Storage (LAES) is considered a promising ESS due to its high round-trip efficiency (RTE), large energy density, and significant power output, and has therefore been widely studied [4, 5]. Many studies have analyzed and optimized LAES layouts, operational parameters, and their ranges in terms of liquid yield and performance [6]. Liquid yield is a key indicator that determines the flow rate in the discharge process and has thus been the focus of numerous studies. However, changes in air composition have not been thoroughly investigated.

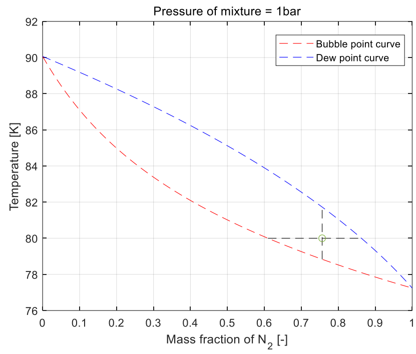


Fig. 2. Boiling temperature curve vs composition of air

Air is a mixture primarily composed of nitrogen and oxygen, and its thermophysical properties vary according to the composition ratio. This also applies to the liquefaction process that involves cryogenic expansion. Previous thermodynamic analyses of LAES generally assume a constant air composition, accounting only for the mass change associated with liquid yield after liquefaction. However, as shown in Fig. 2, the overall composition ratio affects liquefaction temperature, liquid yield, and the composition of each phase. Consequently, not only the liquid yield but also the changes in thermophysical properties due to composition shifts must be considered during the discharge process. Moreover, different operational conditions can lead to varying composition ratios, making further research on this topic necessary.

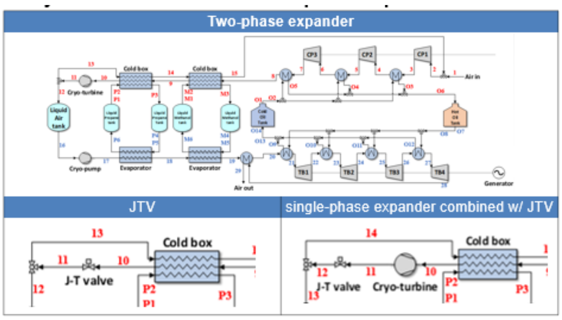


Fig. 3. Layout of various two-phase expansion processes of Linde liquefaction process [7]

The thermodynamic analysis of different two-phase expansion types in the Linde liquefaction process for LAES has been conducted in the previous studies [7].

Figure 3 illustrates the various two-phase expansion methods used in the Linde liquefaction process, including the two-phase expander, Joule-Thomson Valve (JTV), and a combination of a single-phase expander with a JTV. Therefore, the objective of this paper is to compare these different two-phase expansion processes in LAES while accounting for the changes in air composition from a thermodynamic perspective.

Accordingly, this study presents a thermodynamic analysis of a Liquid Air Energy Storage system that accounts for changes in air composition following various cryogenic expansions.

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
(4) All points and processes are at equilibrium.

2.1 System description

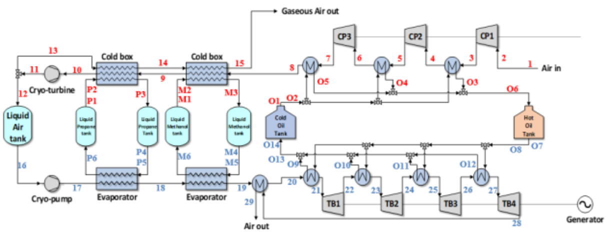


Fig. 4. Layout of LAES in this study

Fig. 4 shows the layout of the LAES to be analyzed in this study. The charging and discharging processes of LAES are described as follows:

The charging process involves creating high-pressure air from external air by compression and cooling when surplus electricity is available. This air is then liquefied through a cold box, and only the liquid air in two-phase air is stored after cryogenic expansion.

The discharging process occurs when there is a power shortage. The liquid air obtained from the charging process is pumped and passed through the cold box to produce high-pressure gaseous air, which is then used to generate electricity through a turbine.

This study focuses on the liquid yield of the air and changes in the composition ratio of the liquid air after various cryogenic expansions.

2.2 Modeling of components & Calculation flow chart

This paper uses the same modeling of components to be used and explained in the previous study [7]. 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. Fig. 5 illustrates the calculation flowchart for the LAES charging process used in this study.

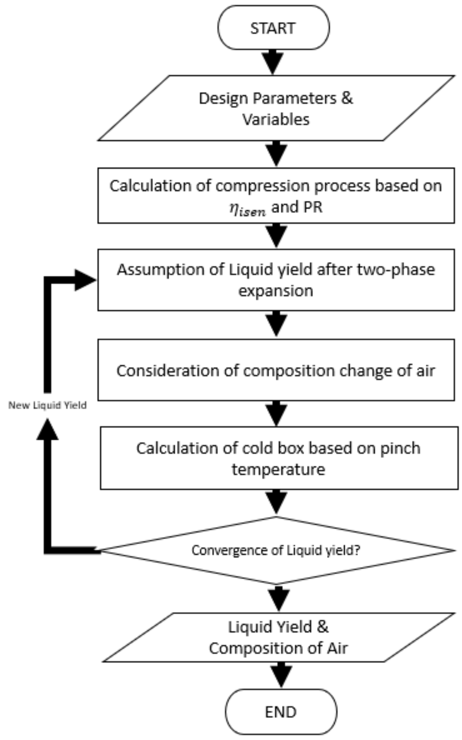


Fig. 5. Flow chart of LAES charging process

2.3 Parameters & Variables

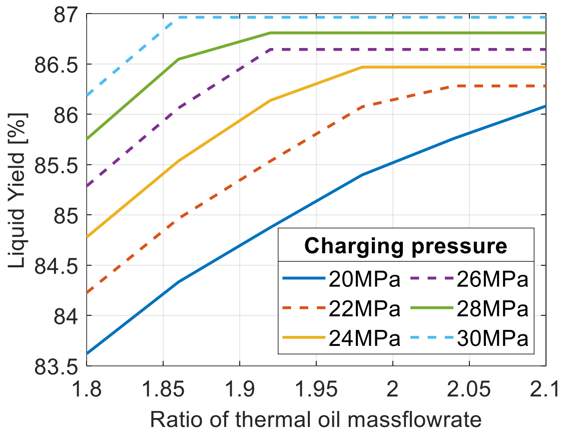
Table I: Parameters and variables of charging process in LAES

Fixed values for cycle design	
Parameters	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
Volumetric fraction of N_2 in air	78%
Volumetric fraction of O_2 in air	21.1%
Volumetric fraction of Ar in air	0.9%
Optimization variables	

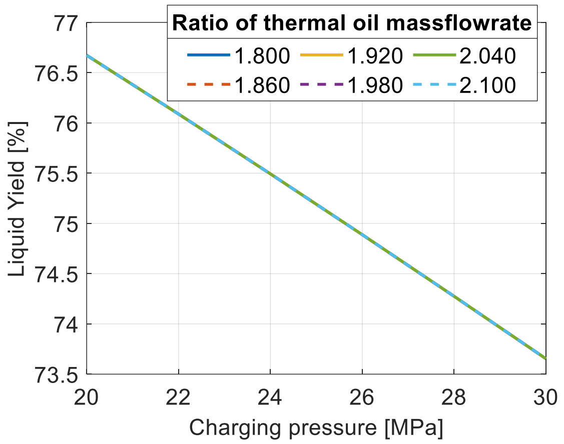
Variables	Ranges
System maximum pressure	20-30MPa
Ratio of thermal oil mass flow rate	1.8-2.1

Table I presents the design conditions and variables used in this study, and the results are obtained based on these conditions.

3. Results and Discussions



(a)



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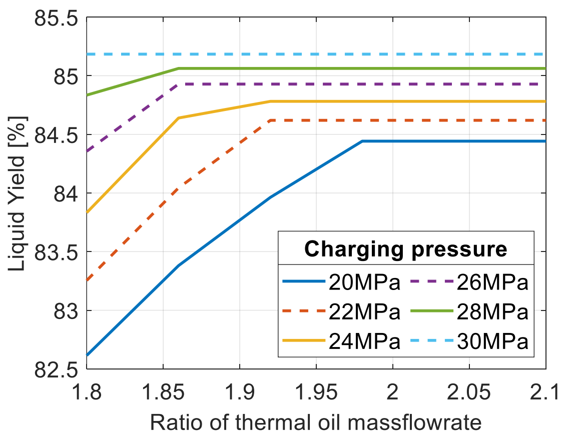


(c)

Fig. 6. Liquid yield trend of two-phase expander (a), JTV (b) and single-phase expander w/ JTV (c)

Fig. 6 illustrates the variation in liquid yield for different two-phase expansion processes as a function of charging pressure and the thermal oil mass flow rate ratio. As depicted in Figures 6(a) and 6(c), the liquid yield increases with charging pressure, which is attributed to the isentropic expansion process. Conversely, Fig. 6(b) demonstrates that the liquid yield of the JTV decreases with increasing pressure. This behavior can be explained by the isenthalpic expansion process, where the rise in pressure leads to an increase in enthalpy, resulting in a reduction in liquid yield. Subsequently, the study will investigate the changes in the composition of liquid air during the cryogenic expansion process.

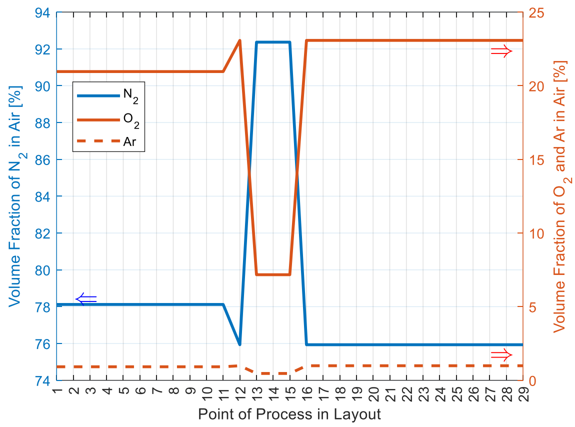
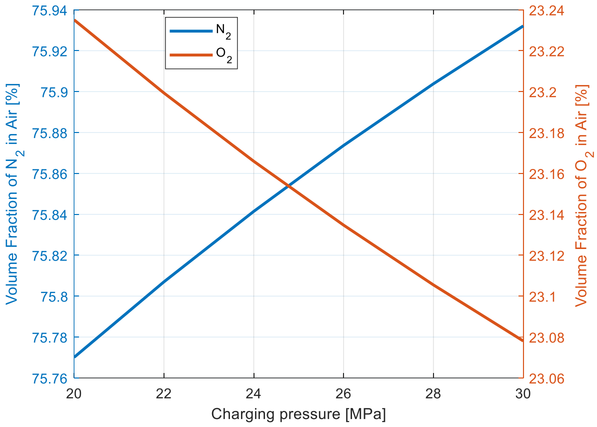
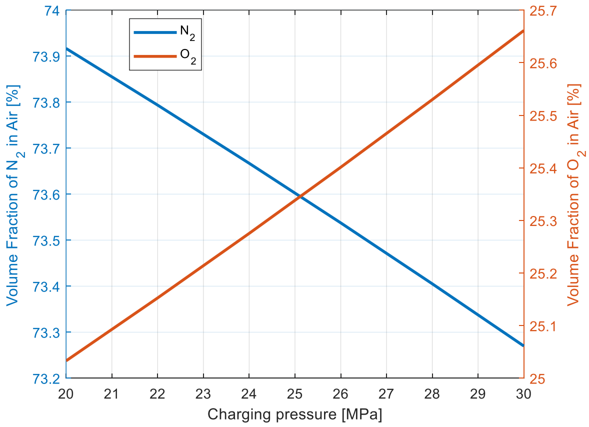


Fig. 7. Composition change of air in the LAES w/ two-phase expander

Figure 7 presents a graph of the air composition at all points of the LAES with two-phase expander proposed in this study, under the condition of maximum efficiency. The air at Point 11, in its two-phase state, is separated into saturated liquid of air at Point 12 and saturated vapor of air at Point 13, and this composition is maintained thereafter. Therefore, by focusing on these points and processes, the phenomenon of interest in this study can be analyzed. The ambient air is composed of 78% nitrogen and 21% oxygen by volume, whereas after the expansion process in this system, the gaseous phase consists of 92.4% nitrogen and 7.2% oxygen, while the liquid phase is composed of 75.9% nitrogen and 23.1% oxygen.



(a)



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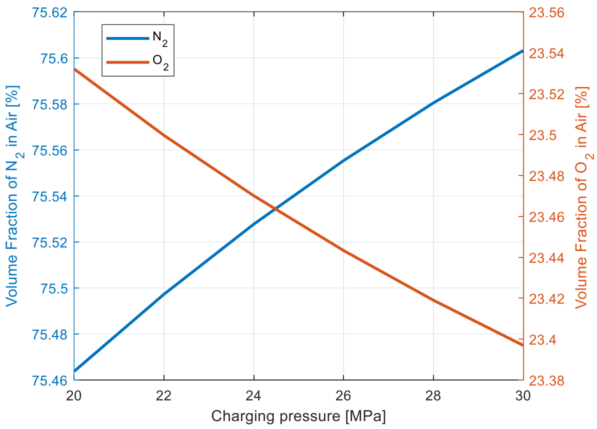

(c)

Fig. 8. Composition change of liquified air vs Charging pressure of LAES w/ two-phase expander (a), JTV (b) and single-phase expander w/ JTV (c)

Fig. 8 illustrates the variations in the volume ratios of oxygen and nitrogen as a function of charging pressure for each expansion process. Fig. 8(a) and (c) present the results for the two-phase expander and single-phase expander with JTV, respectively. As the charging pressure increases, a tendency is observed where the oxygen concentration in the liquid air increases and the nitrogen concentration decreases. In contrast, Fig. 8(b) shows that for the JTV, as the charging pressure increases, the oxygen concentration decreases while the nitrogen concentration increases. This trend is similar to the relationship between liquid yield and charging pressure described earlier. In other words, as the liquid yield increases, the oxygen concentration rises while the nitrogen concentration falls.

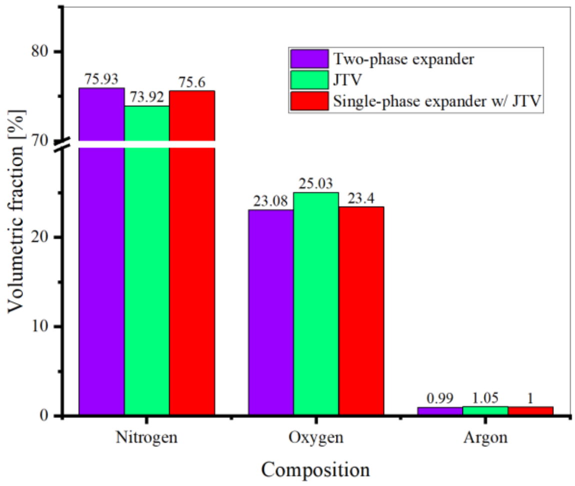

Fig. 9. Composition of liquified air of various two-phase processes

Therefore, it is necessary to compare the composition of liquid air under the conditions that yield the maximum liquid yield for each expansion process. Fig. 9 presents a comparison of the air composition ratios for each expansion process. The two-phase expander and single-phase expander with JTV, which exhibit similar liquefaction rates, show comparable compositions. However, it is evident that the JTV has a distinctly higher oxygen concentration, approximately 2% greater, when compared to the other two processes.

The European Industrial Gases Association (EIGA) recommends that oxygen concentration be kept below 23.5% to prevent toxicity and component degradation [8]. Hence, to meet the criterion of integrity, it is necessary to reduce the oxygen concentration, which implies an objective to increase the liquefaction rate.

4. Summary and Future works

Based on this study, the changes in the composition of liquid air following cryogenic expansion are observed, revealing an increase in the oxygen fraction. Additionally, the composition of the liquid air varied depending on the cryogenic expansion process, which is found to be related to the liquefaction yield and air composition. As the liquefaction yield increased, the oxygen concentration in the liquid air decreased. The JTV, which has the lowest liquefaction yield, was found to produce liquid air with a relatively high oxygen concentration of 25%. To ensure the integrity of the system components, it is necessary to reduce the oxygen concentration.

In this study, the liquid yield and air composition were examined under the assumption of equilibrium state following ideal expansion. However, during rapid ideal expansion processes, metastable liquid exists, which does not vaporize even at temperatures higher than the saturation temperature due to insufficient nucleation sites or an energy barrier that impedes the immediate formation of vapor bubbles. Therefore, further research is needed on a delayed equilibrium model that takes this phenomenon into account.

Considering this, the non-equilibrium model for two-phase expansion of air will also differ, necessitating further investigation.

Acknowledgement

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