Thermodynamic analysis of mechanically integrated liquid air energy storage system with nuclear power plant

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1. Introduction

From the Paris Agreement in 2015, both developed and developing countries are obliged to reduce their Green House Gas (GHG) emission [1]. Renewable Energy (RE) is consistently recognized as a major mean of coping with climate change. Due to rapid increase in share of electricity generation from RE, conventional power plants such as coal and Nuclear Power Plants (NPP) are led to reduce their electricity generation at certain time of year, month or day [2]. Especially, a nuclear power plant has a limitation to follow varying demands rapidly due to reduced service lifetime of safety important components which impacts economy of an NPP.

In order to overcome this problem, integration of an Energy Storage System (ESS) to the NPP has been suggested and researched as one of the solutions for grid stabilization [3]. Among various ESSs, the Liquid Air Energy Storage System (LAES) has high potential to store grid scale energy. LAES is a mature technology for storing air in liquid form by multiple compression and liquefaction processes. LAES has many advantages such as less geographical constraint for installation, eco-friendly power source and considerably high-power density.

However, the compressor work of LAES becomes very large to store nuclear power plant scale energy. The grid-scale compressor is still being developed (highest value is 100MWe by Siemens), therefore, Steam Turbine-Driven-Compressor (STDC) is selected to replace motor compressor. The integration of NPP and LAES is established with STDC. When electricity price is low or there is excess energy, steam is bypassed before Low Pressure Turbine (LPT) and operating steam turbine to store mechanical energy. According to Lee et al. [4], the integration of the secondary side of NPP and STDC showed that LAES can be one of the possible options to efficiently store energy.

The purpose of this study is to calculate round-trip efficiency and energy density with detail modeling of integrated LAES. By modeling LAES with NPP, the round-trip efficiency is optimized and optimization point will be suggested. Cycle performance is calculated by an in-house code built in MATLAB environment (KAIST-CCD).

2. Methodology

2.1 Layout of secondary side of NPP

In order to evaluate thermodynamic performance of LAES, the secondary side of NPP should be modeled first. A conventional NPP layout is utilized with some modifications to reflect real conditions [5]. Cycle parameters such as SG thermal power, steam mass flow rate is referenced from the prior research [4] and listed below.

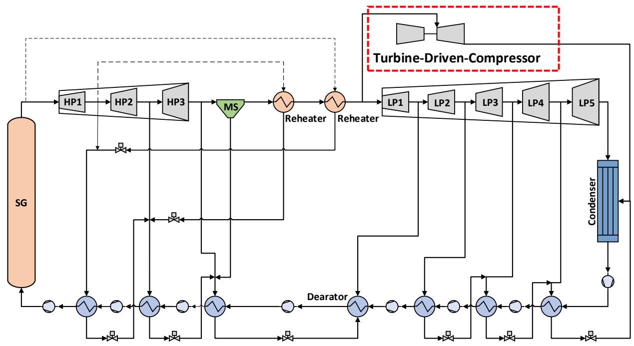


Fig. 1. Configuration of NPP secondary side with Steam Turbine-Driven-Compressor

Table 1: On-design cycle parameters

Cycle parameters	value
SG thermal power	$3985MW_{th}$
Steam mass flow rate	2250.6kg/s
SG inlet temperature	232℃
SG outlet pressure	6632.7kPa
SG outlet temperature	282.2℃
Condenser pressure	5.07kPa
Condenser temperature	33℃

2.2 Layout of Liquid Air Energy Storage System

Fig. 2 shows schematic diagram of a conventional LAES. There are five operating processes through charging to discharging processes; Compression, Liquefaction, Storage, Evaporation, and Expansion. When steam is bypassed from NPP to the STDC, mechanical work is generated and transferred to air compressors. Air is compressed by multi-stage air compressor and compression heat is stored in thermal oil tanks. High pressure-low temperature air is expanded by cryo-turbine to liquefy air at around 90K and 102kPa. After air is liquified, liquid air is stored into liquid air

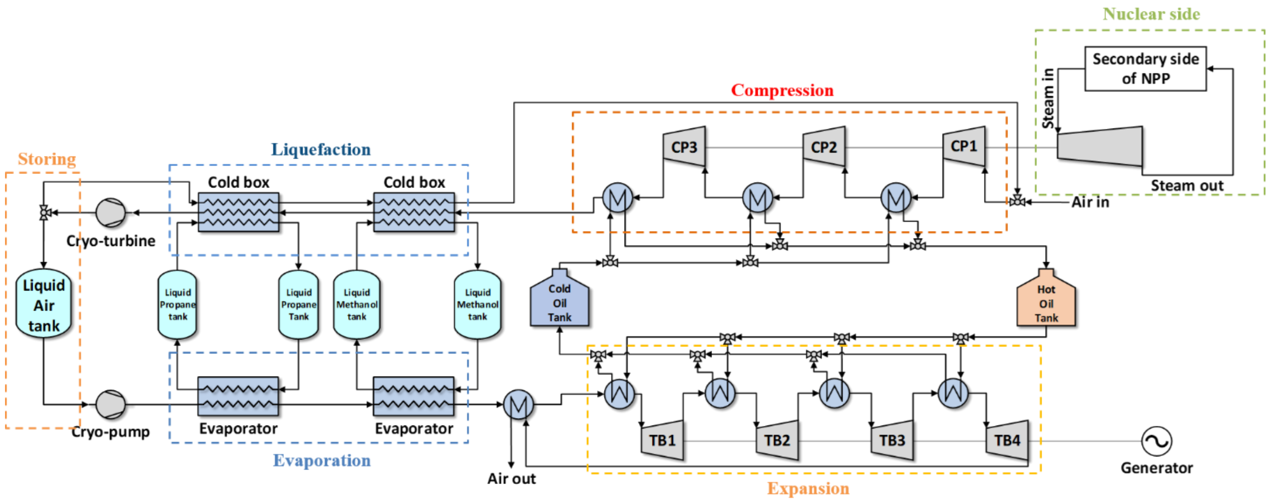


Fig. 2. Schematic diagram of LAES integrated with STDC

tank and gaseous air is recycled to use low temperature heat.

When electricity demand is increasing, stored liquid air is pumped by cryo-pump and evaporated. Evaporated air is heated by thermal oil and expanded to generate electricity.

2.3 Modeling of Liquid Air Energy Storage System

2.3.1 Compressor

At the charging process, ambient air is compressed to a high pressure by the multi-stage air compressor. The air outlet enthalpy at each stage is:

$$h_{i+1} = h_i + \frac{h_{isen} - h_i}{\eta_{comp}} \quad (eq.1)$$

Where h_i is specific enthalpy at each stage and η_{comp} is the isentropic efficiency of the air compressor.

2.3.2 Turbine

At the discharging process, pressurized air is expanded to ambient pressure by the multi-stage air turbine. The air outlet enthalpy at each stage is:

$$h_{i+1} = h_i - \eta_{turb}(h_i - h_{isen}) \quad (eq.2)$$

Where h_i is specific enthalpy at each stage and η_{turb} is the isentropic efficiency of the air turbine.

2.3.3 Pump

At the discharging process, liquid air is pumped to high pressure. The air outlet enthalpy at cryo-pump is:

$$h_{i+1} = h_i + \frac{h_{isen} - h_i}{\eta_{pump}} \quad (eq.3)$$

Where h_i is specific enthalpy at each stage and η_{pump} is the isentropic efficiency of the cryo-pump.

2.3.3 Air-Oil HX

Outlet enthalpy of air and oil are calculated based on energy conservation and pinch point limitation.

$$h_{H.out} = h_{H.in} - \frac{m_C}{m_H}(h_{C.out} - h_{C.in}) \ (eq.4)$$

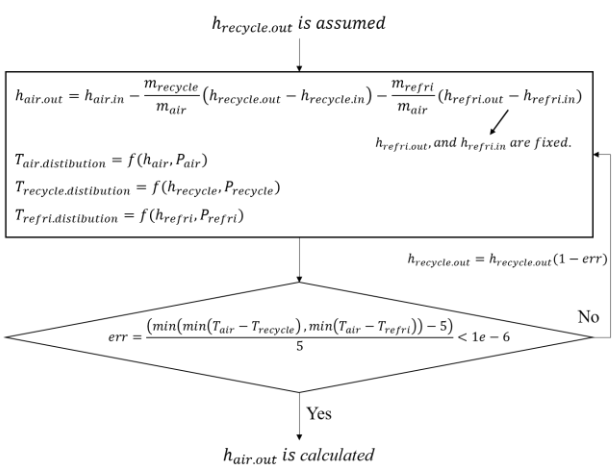
$$min(T_H - T_C) = 5K \quad (eq.5)$$

Where m_i is mass flow rate and T is temperature distribution in HX. H and C mean hot and cold side.

2.3.4 Cold box

Cold box is composed of three streams: Compressed air, refrigerator, and recycled air.

To analyze inner temperature distribution, it is assumed that there is no heat exchange between refrigerator and recycled air. From the assumption, energy conservation and pinch point limitation, outlet enthalpy of air is calculated.



2.3.5 Round-trip efficiency

Round-trip efficiency is one of the most important indicators which shows how efficiently energy is saved. Round-trip efficiency is defined as follow:

$$\boldsymbol{\eta_{RT}} = \frac{\boldsymbol{W_{discharging}}}{\boldsymbol{W_{charging}}} \ (\boldsymbol{eq.6})$$

Where $\boldsymbol{W_{charging}}$ *is charging work and* $\boldsymbol{W_{discharging}}$ *is discharging work.*

In the above equation, charging work is fixed as decreased power of NPP and discharging work is net generated work by LAES. Therefore, above equation is replaced as follow:

$$\boldsymbol{\eta_{RT}} = \frac{\boldsymbol{W_{discharging}}}{\boldsymbol{W_{charging}}} = \frac{\boldsymbol{Y * m_{air} * \Delta h_{turb}}}{\boldsymbol{W_{NPP}}} \ (\boldsymbol{eq.7})$$

Where Y is liquid air yield, $\boldsymbol{m_{air}}$ *is air mass flow rate,* $\boldsymbol{\Delta h_{turb}}$ *is specific work of turbine, and* $\boldsymbol{W_{NPP}}$ *is decreased power of NPP.*

Round-trip efficiency of LAES is optimized by following cycle conditions.

Table 2. Cycle parameters of LAES

Parameters	Value
Maximum pressure	Optimized
Oil mass flow rate	Optimized
Pressure drop	1%
Pinch point	5K
Turbine efficiency	90%
Compressor efficiency	85%
Cryo-turbine efficiency	85%
Cryo-pump efficiency	85%
Mechanical loss	2%

3. Result

3.1 Off-design results of secondary side of NPP

From the off-design analysis of the secondary side of NPP, work of STDC is calculated.

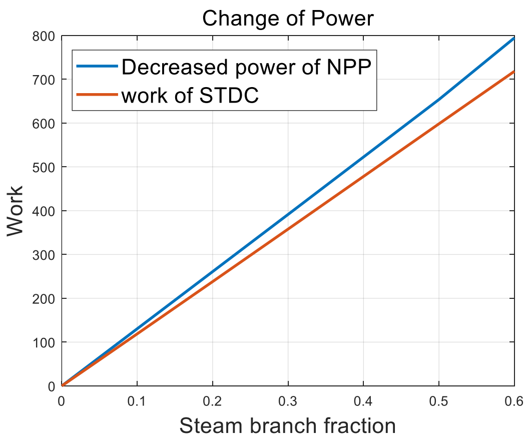


Fig. 3. Decreased power of NPP and work of STDC

As steam branch fraction is increased, power of NPP is linearly decreased. Decreased power of NPP is transformed into work of STDC. STDC work is used at compressor work calculation. With some mechanical loss, following equation is used to calculate compressor work.

$$W_{compressor} = W_{STDC} * \eta_{mech.loss}$$

Where $W_{compressor}$ *is compressor work,* W_{STDC} *is STDC work, and* $\eta_{mech.loss}$ *is mechanical loss.*

3.2 Optimization results of LAES

From the off-design results of NPP, round-trip efficiency of LAES is calculated.

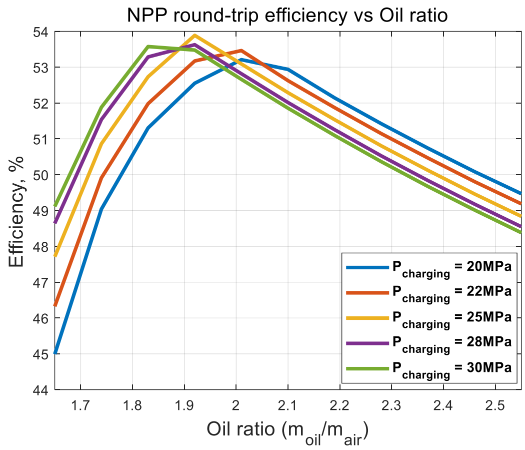


Fig. 4. Round-trip efficiency of LAES with oil ratio

Fig. 4 shows the change of round-trip efficiency with oil mass flow ratio and maximum charging pressure. As oil ratio increases, round-trip efficiency is increased until reaching the local maximum. This is because liquid air yield is limited.

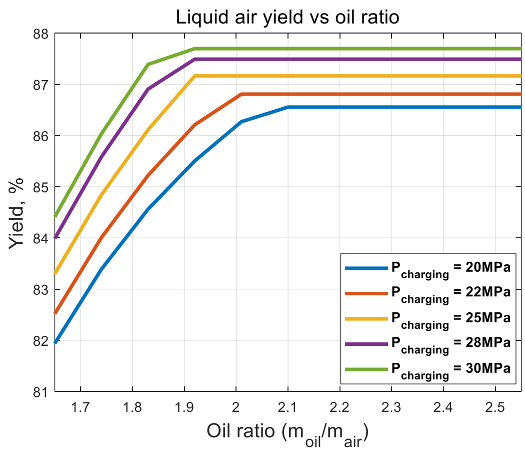


Fig. 5. Liquid air yield of LAES with oil ratio

As seen in Fig. 5, liquid air yield is increased until certain value and becomes constant. This is because the pinch point of Cold box is located at the end of the hot side. If the mass flow rate of oil is increased until certain value, the pinch point of air-oil HX is located at the end of the hot side. This means that the outlet temperature of the cold box is no longer decreased leading to liquid air yield limitation.

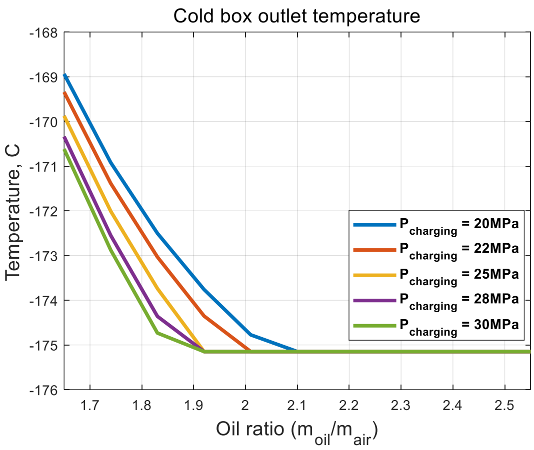


Fig. 6. Cold box outlet temperature

As seen in Fig. 6, Cold box outlet temperature is reached to local minimum at optimum oil mass flow rate. It means that increasing oil mass flow rate over the optimal point cannot affect liquid air yield making round-trip efficiency decreased. For the same reason, the optimum for maximum pressure exists.

Summary of optimized parameters and performance of LAES is given below;

Table. 3 Optimized parameters

Parameters	Value
Maximum pressure	25MPa
Oil mass flow ratio	1.92
Round-trip efficiency	53.9%
Energy density	123.5kWh/m^3
Air mass flow rate	Vary by steam mass flow rate
Liquid air yield	87.1%

4. Conclusions

Thermodynamic performance of mechanically integrated LAES with NPP is evaluated. To evaluate performance of LAES, off-design performance of NPP is evaluated first. As steam branch fraction increases, power of NPP is linearly decreased. Decreased power of NPP is transformed into mechanical power of STDC. With some mechanical loss, STDC work is used for air compression. From the results of off-design analysis, thermodynamic performance of LAES is evaluated. As oil mass flow ratio increases, round-trip efficiency is increased until the local maximum point. After the maximum, the round-trip efficiency is decreased. This is because liquid air yield is limited. At the optimum point, the pinch point is located at the end of the hot side of the cold box. After the optimum point, the hot side outlet temperature no longer decreases. That is why optimum charging pressure and oil ratio values exist. From the pinch point analysis and thermodynamic analysis, performance of LAES is optimized when work of STDC is given. The maximum round-trip efficiency is 53.9% when the maximum pressure is 25MPa and oil mass flow ratio is 1.92. This result shows that mechanically integrated LAES with NPP is possible and can become a competitive option to efficiently storing energy. In the future, economic feasibility of the integrated LAES will be assessed. Off-design performance of LAES will be also evaluated to demonstrate the feasibility of the concept.

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