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

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Introduction

▣ From the Paris Agreement in 2015, Renewable Energy (RE) has been rapidly increased because of its recognition as a major mean of coping with climate change.

▣ Due to rapid increase of RE, conventional power plants such as coal and Nuclear Power Plant (NPP) are led to reduce their electricity generation at certain time of year, month, and day.

▣ However, NPP has a limitation to follow varying demands rapidly due to reduced service lifetime of safety components which impacts economy of an NPP. To overcome this problem, Energy Storage System (ESS) is suggested as one of the solutions for grid stabilization.

▣ Among various ESSs, LAES has high potential to store grid scale energy. LAES is mature technology for storing air in liquid form and has less geographical constraint for installation, eco-friendly power source and considerably high energy density.

▣ The integration between NPP and LAES is established by Steam Turbine-Driven-Compressor (STDC) which transfer high pressure steam energy into air compressor energy. When electricity price is low, steam is bypassed from NPP and operating STDC to generate mechanical work.

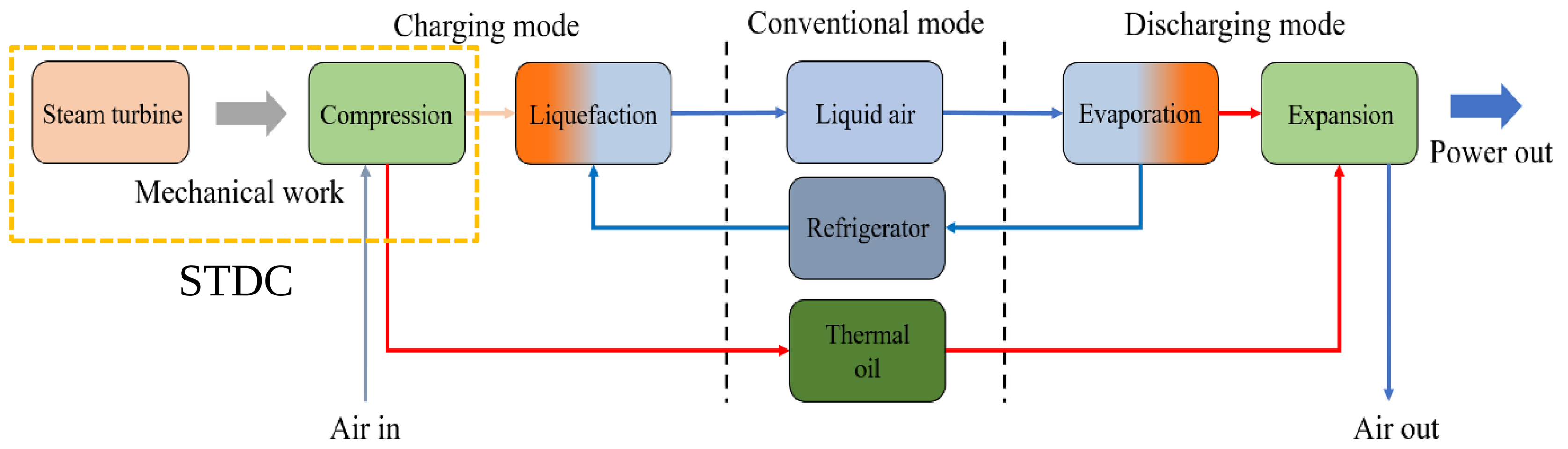

Fig. 1. Diagram of mechanically integrated LAES system with NPP

▣ Therefore, to evaluate performance and possibility of integrated system, thermodynamic analysis is essential not independent system but integration system.

▣ The purpose of this study is to evaluate thermodynamic performance of integration system such as round-trip efficiency and energy density. For the evaluation of suggested system, round-trip efficiency is optimized and optimization value of round-trip efficiency and energy density are represented.

▣ Cycle performance is calculated by an in-house code built in MATLAB environment called KAIST-CCD which calculates performance of closed cycle.

Methodology

1. Modeling of secondary side of NPP

▣ In order to evaluate integration system, the secondary side of NPP is modeled first. A conventional NPP layout is utilized with some modification to reflect real conditions.

▣ Cycle parameters such as SG thermal power and steam mass flow rate are referenced from the prior research. Refenced values are given at table 1.

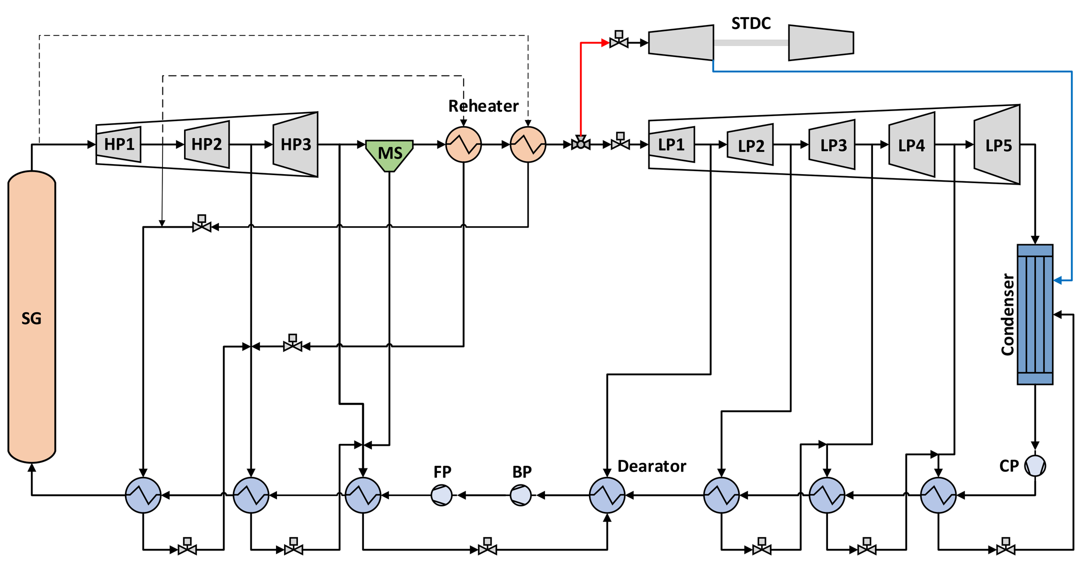

Fig. 2. Configuration of secondary of NPP with STDC

Table 1. Reference value of NPP

Cycle parameter	Value
SG thermal power	3985MWth
Steam mass flow rate	2250.6kg/sec
SG inlet temperature	232°C
SG outlet pressure	6632.7kPa
SG outlet temperature	282.2°C
Condenser pressure	5.07kPa
Condenser temperature	33°C

2. Modeling of liquid air energy storage system

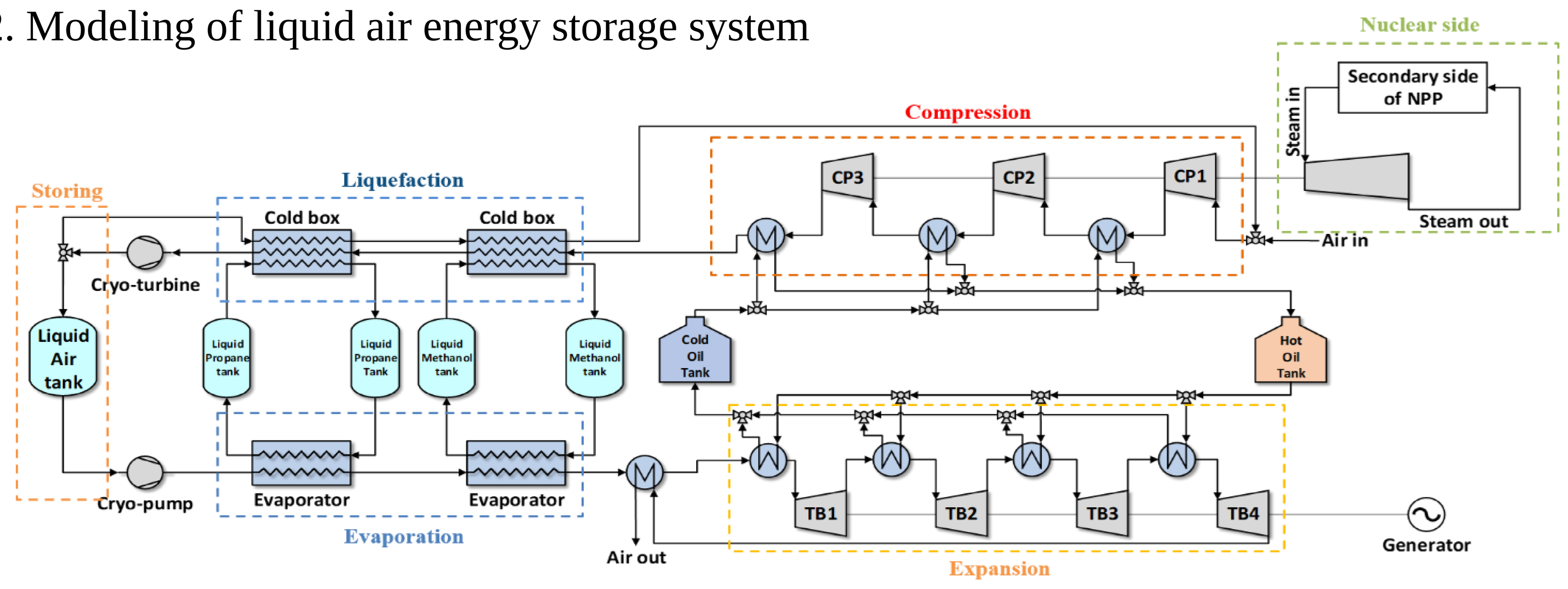

Fig. 3. Configuration of liquid air energy storage system with STDC

▣ Because work of air compressor is mainly defined by work of steam turbine from NPP, the capacity of LAES belongs to NPP.

▣ Therefore, from the results of cycle analysis of NPP, round-trip efficiency of integrated LAES is defined as below.

$$\eta_{RT} = \frac{E_{discharging}}{E_{charging}} = \frac{W_{net\ of\ LAES} * t_{discharging}}{W_{loss\ of\ NPP} * t_{charging}} \qquad (eq.\ 1)$$

where η_{RT} is round-trip efficiency, E is energy, W is work of system and t is storing or discharging time of ESS.

▣ Work loss of NPP is calculated by modeling of secondary side with STDC.

▣ Net work of LAES is optimized with two variables : maximum charging pressure (P_{max}) and thermal oil mass flow rate (m_{oil}/m_{air}). Used parameters are given below:

Table 2. On-design cycle parameters of LAES

Variable	Charging Pressure	oil Mass flow rate	Pressure drop	Pinch point	Turbine Efficiency	Compressor Efficiency	Cryo-pump Efficiency	Cryo-turbine efficiency
Value	Optimized	Optimized	1%	5K	90%	85%	85%	85%

Results

▣ From the modeling of secondary side of NPP, on-design and off-design performance are calculated.

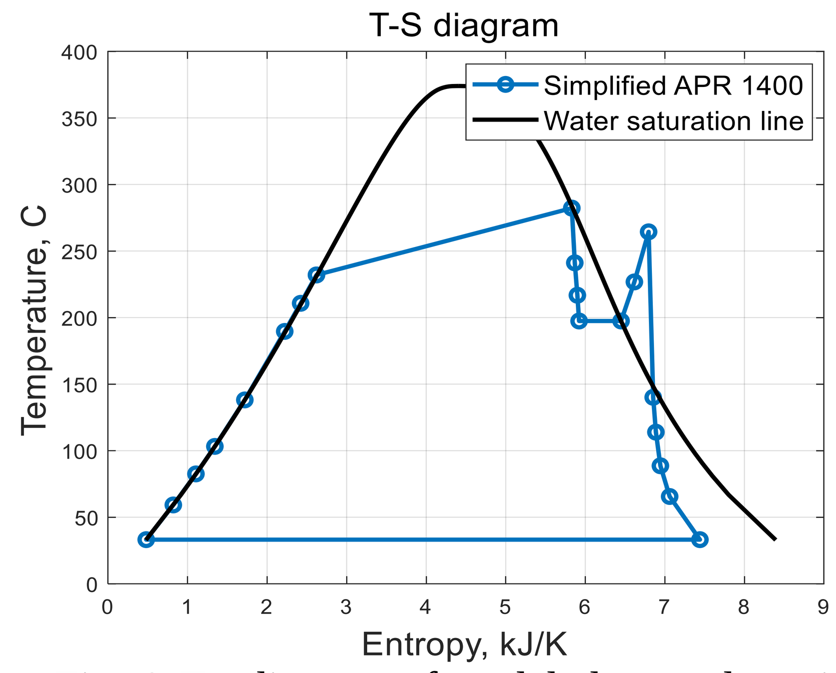

Fig. 4. T-s diagram of modeled secondary side

Table 3. Design results of secondary side

Properties	Reference value	Design value
SG thermal power	4000MWth	3985MWth
Net electricity	1425MWe	1403.6MWe
Steam mass flow rate	2250.6kg/s	2250.6kg/s
SG inlet Temperature	232.2°C	232°C
Cycle net efficiency	35.6%	35.2%
Condenser Pressure	5.08kPa	5.08kPa

▣ Because of modification and simplification, there is some difference between reference value and design results. However, the error is much low, this model is selected to use for further research.

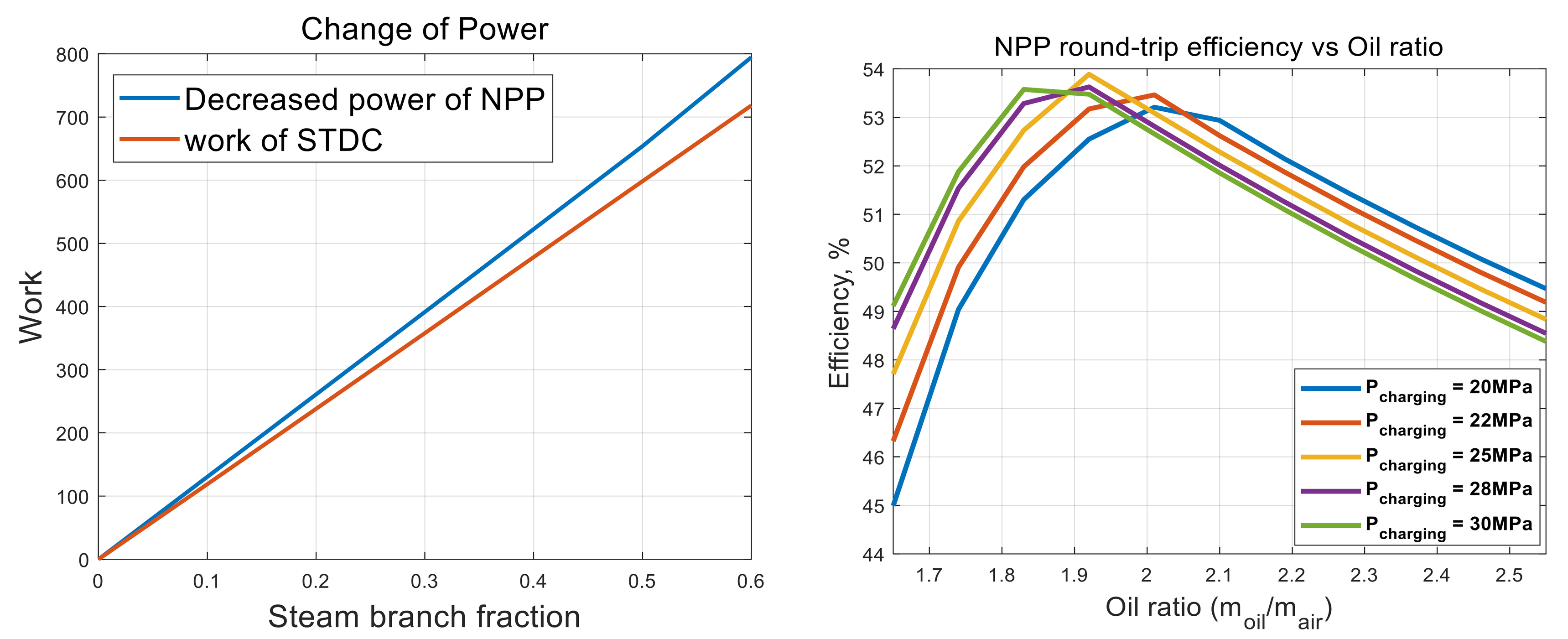

Fig. 5. Decreased power of NPP (left) and round-trip efficiency of LAES (right)

▣ For calculating round-trip efficiency of nuclear integrated LAES, decreased power of NPP and work of STDC are calculated with steam branch fraction.

▣ As steam branched to STDC, power of NPP is linearly decreased but more than that of STDC. This is because of off-design consideration on the LPT which is represented previous work.

▣ Fig. 5 shows the change of round-trip efficiency with oil mass flow rate and maximum charging pressure. As oil mass flow ratio increases, round-trip efficiency is increased until reaching the local maximum. This is because that liquid air yield is limited by pinch point at heat exchanger.

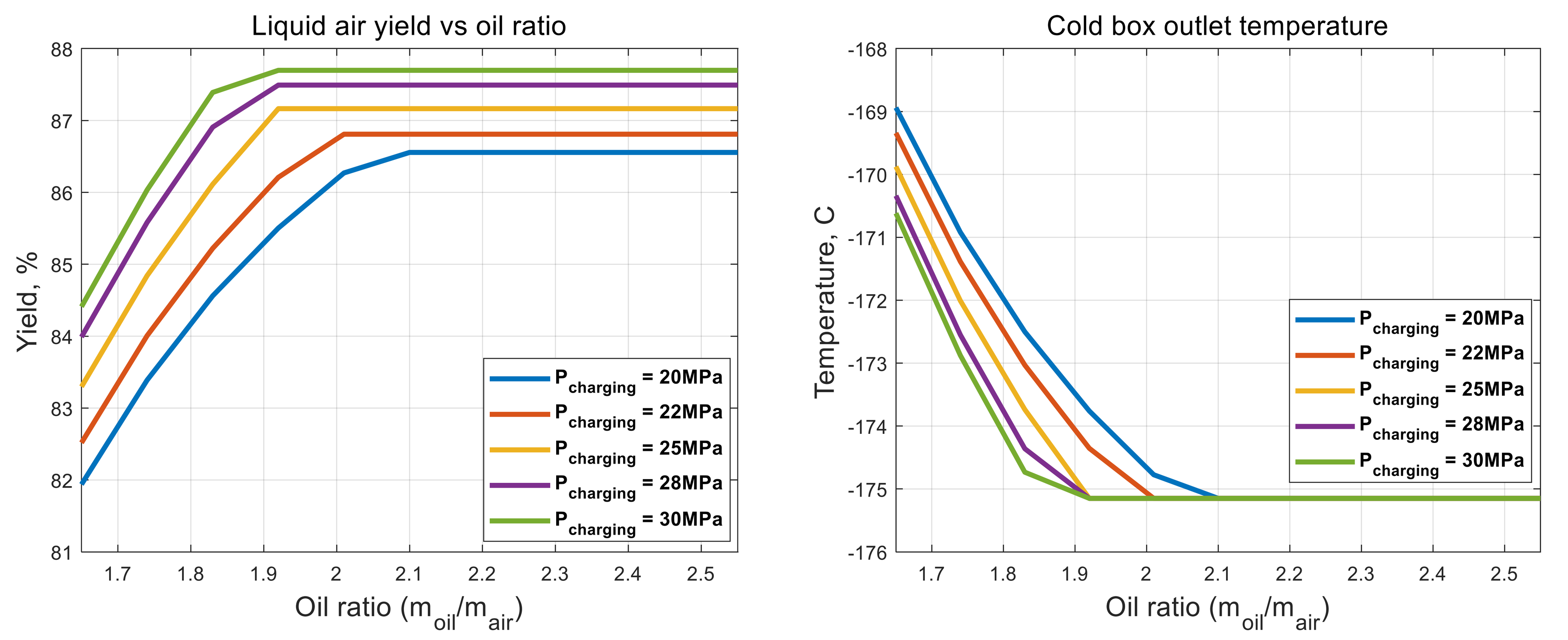

Fig. 6. Liquid air yield with oil ratio (left) and cold box outlet temperature (right)

▣ As seen in figure 6, liquid air yield is increased until certain value and got constant value (left figure). This is because cold box outlet temperature reaches to cold side inlet temperature leading to no additional cooling.

▣ From thermodynamic analysis of LAES, optimized performance and variable are listed below table :

Table 4. Optimization results of LAES with NPP

Parameter	Value
Maximum charging pressure	25MPa
Oil mass flow ratio	1.92
Round-trip efficiency	53.9%
Energy density	123.5kWh/m³
Liquid air yield	87.1%

Conclusions

▣ Thermodynamic analysis of mechanically integrated liquid air energy storage system with NPP is conducted with optimization.

▣ Round-trip efficiency of integration LAES is maximized when charging pressure is 25MPa and oil mass flow ratio is 1.92.

▣ Because of pinch temperature at cold box, there is no effect on round-trip efficiency with increase of charging pressure and oil mass flow rate.

▣ From the analysis, round-trip efficiency of integration system is shown as 53.9% and energy density is shown as 123.5kWh/m³.

▣ This results show that nuclear integrated LAES can be a promising options to efficiently storing energy.

▣ In the future, economic analysis and off-design analysis of integrated LAES will be also evaluated to demonstrate the overall feasibility of suggested concept.

Acknowledgement

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