Preliminary thermodynamic analysis of LAES integrated nuclear power plant

Jung Hwan Park[a], Seung Hwan Oh[a], Young Jae Choi[a], Jin Young Heo[a], Jeong Ik Lee[a]*

[a]Department of Nuclear and Quantum Engineering N7-1 KAIST 291 Daehak-ro, Yuseong-gu,
Daejeon, Republic of Korea 305-338, junghwanpark@kaist.ac.kr
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Due to rapid increase in share of electricity generation from renewable energy sources, conventional power plants such as coal and nuclear power plants are led to reduce their electricity generation at certain time of year, month or day [1]. Especially, a nuclear power plant has limitation to follow this trend due to reduced service lifetime of safety important components in the nuclear power plant (NPP) which reduces economy substantially.

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 peak shaving, load leveling, price arbitrage and stabilizing [2]. There are several ESS models such as thermal energy storage system, compressed air energy storage system and liquid air energy storage system. Among various ESSs, the Liquid Air Energy Storage System (LAES) has high potential to store grid scale energy. LAES is mature technology for storing air in liquid form by multiple compression and liquefaction processes. Therefore, LAES has many advantages such as less geographical constraint for installation, eco-friendly power source and considerably high-power density.

In this paper, integration of NPP and LAES is established by operating Steam Turbine-Driven-Compressor. Excess energy in the steam of NPP is used to operate Turbine-Driven-Compressor and transformed into compression energy of air. To minimize impact on the primary side, steam is bypassed before Low Pressure Turbine (LPT) and fed in to condenser after being expanded to condenser pressure. Therefore, in order to evaluate feasibility of the suggested integration, thermodynamic analysis of secondary side of the NPP should be preceded.

The purpose of this research is to find out how steam bypassing affects several important factors such as steam generator inlet temperature and turbine power change to identify feasibility of integration. By applying a steam turbine off-design model [4], variation in steam turbine power is presented and steam turbine control strategy is suggested for minimizing change on the secondary side. Cycle performance is calculated by an in-house code built in *MATLAB* environment (KAIST-CCD).

2. Methodology

2.1 On-design Model

In order to evaluate thermodynamic performance of the secondary side of NPP, a conventional NPP layout is utilized with modifications to reflect real conditions [3]. Secondary side consists of High-Pressure Turbine (HPT), Low-Pressure Turbine (LPT), 2 Reheaters, 6 Feedwater Heaters, 1 Deaerator, 1 Moisture separator, 1 Condenser and 8 Feedwater Pumps [3]. In order to heat up feedwater, there are 7 steam extraction lines in total; 3 from the HPT and 4 from the LPT. To maintain high quality of steam for turbine blade integrity, moisture separator is located after the HPT. Other cycle parameters such as SG thermal power, steam mass flow rate is referenced from the prior research [5] and listed below.

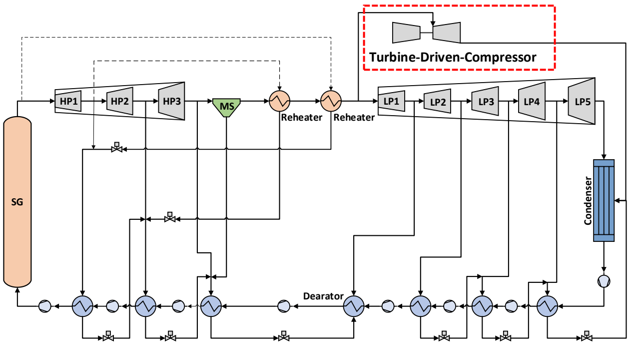

Fig. 1. Configuration of NPP secondary side with Steam Turbine-Driven-Compressor

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 Off-design model

Because steam is branched before the LPT, only the LPT is operating at off-design conditions while the HPT is operating at on-design conditions. To evaluate off-design performance of the LPT, turbine off-design model is implemented in the code. According to Lee et al. [4], if volumetric flowrate is maintained at each turbine inlet, turbine pressure ratio and efficiency show design value regardless of load variation because other coefficients are treated as constant (*eq. 1*).

$$Q = c_d a A\sqrt{\frac{2}{\gamma-1}[(\frac{P_2}{P_1})^{\frac{2}{\gamma}} - (\frac{P_2}{P_1})^{\frac{\gamma+1}{\gamma}}]} \qquad (eq.\ 1)$$

where Q is volumetric flow rate, c_d is flow coefficient, A is flow area, γ is specific heat ratio, $P_{1,2}$ are inlet, outlet pressure.

Therefore, if the volumetric flow rate is kept constant by using throttling valve located before the LPT and controlling steam extraction at each turbine stage, the efficiency and pressure ratio are maintained as in their designed value.

$$\frac{\dot{m}_{on,i}}{\rho_{on,i}} = \frac{\dot{m}_{off,i}}{\rho_{off,i}} \qquad (eq.\ 2)$$

Therefore, to maintain volumetric flow rate at each stage inlet, steam extraction fraction is calculated with an iterative method. To calculate extraction mass flow rate, quality of the extracted steam (h_{ex}) is assumed as the same with the on-design quality.

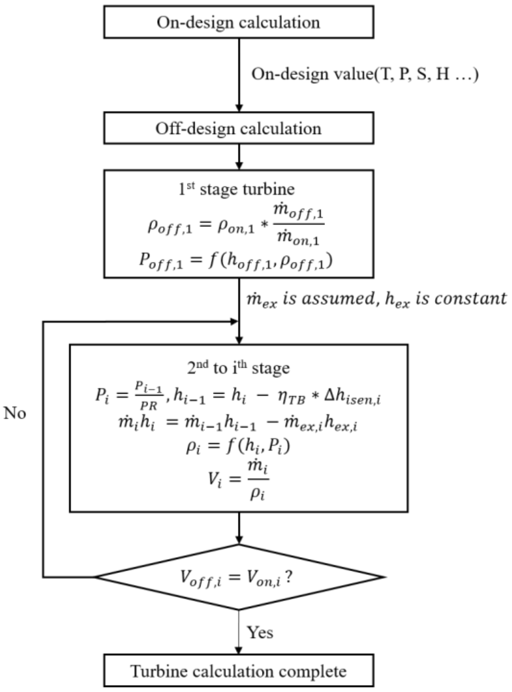

Fig. 2. Flow chart of off-design turbine calculation

3. Results

3.1 On-design model results

HPT, LPT and Feedwater pump work are calculated and listed in the table.

Table 2: On-design cycle performance

Cycle parameters	Value
SG thermal power	3985MW$_{th}$
Steam mass flow rate	2250.6kg/s
SG inlet temperature	232℃
HPT turbine work	464.7MW$_{th}$
LPT turbine work	1016.5MW$_{th}$
Feedwater pump work	22.5MW$_{th}$
Cycle net work	1400.4MW$_e$
Cycle net efficiency	35.1%

3.2 Off-design model results

Change of power and SG inlet temperature is calculated as steam branch fraction increases.

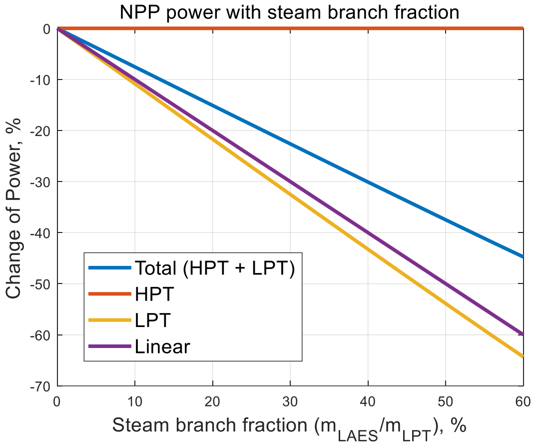

Fig. 3. Change of Power with steam branch fraction

As the steam branch fraction increases, the LPT work is linearly decreased because pressure ratio and turbine efficiency are maintained as their design values.

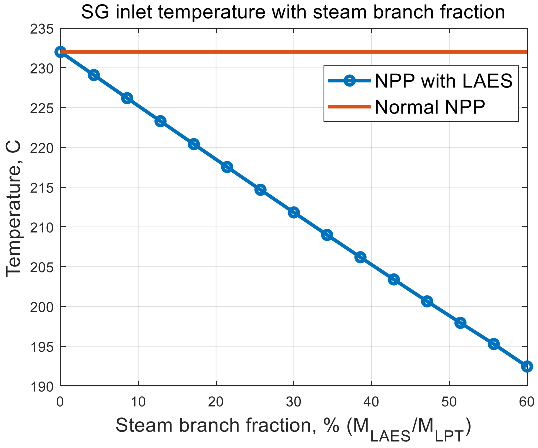

Fig. 4. SG inlet temperature with steam branch fraction

However, as steam branch fraction is increased, SG inlet temperature is linearly decreased.

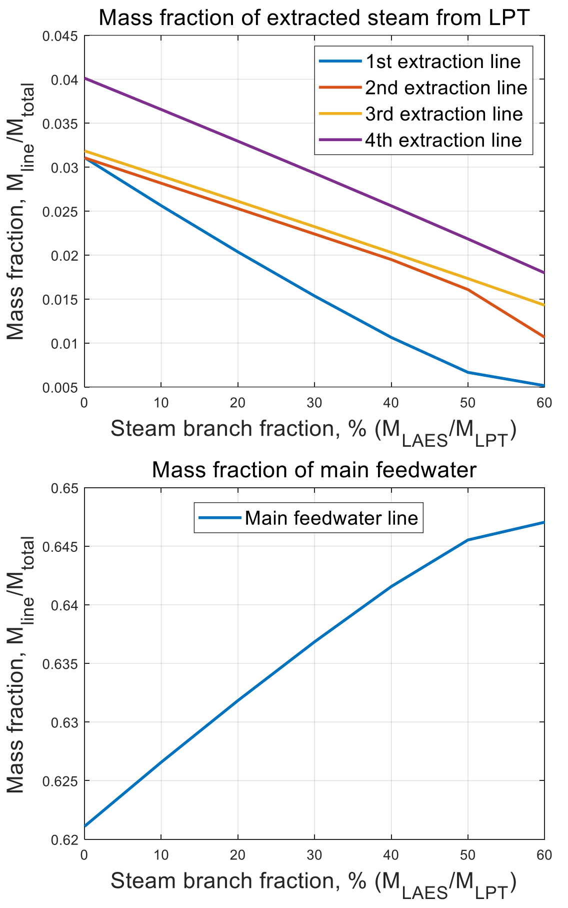

Fig. 5. (a) Mass fraction of extracted steam from LPT, (b) Mass fraction of main feedwater

This is because, As shown in Fig. 5, the mass fraction of extracted steam from LPT is decreased while mass fraction of main feedwater is increased. The reason for the decrease of extracted steam is because quality of steam at the LPT inlet is increased due to throttling process. Therefore, there is no need to extract steam as same as amount of on-design extraction.

Extracted steam from LPT has a purpose to maintain quality in the turbine, but at the same time, it is also used to heat the main feedwater. Therefore, decrease of extracted steam and increase of mass flow rate of main feedwater makes SG inlet temperature decreased.

In order to maintain SG inlet temperature at the design value (~232℃), another control strategy is needed.

The control strategy is to increase the steam extraction fraction after the HPT (before moisture separator). The reason is that when steam is extracted after HPT, it is possible to maintain SG inlet temperature while minimizing the impact on HPT. Controlled steam extraction fraction and calculated SG inlet temperature are shown below.

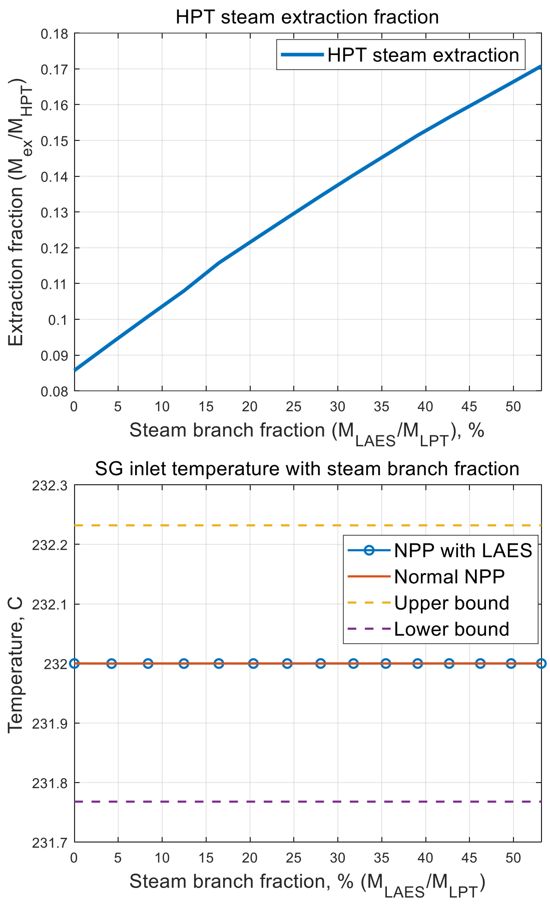

Fig. 6. (a) HPT steam extraction fraction, (b) SG inlet temperature with branch fraction

Fig. 6 (b) shows that SG inlet temperature can be maintained by changing the steam extraction fraction at HPT. Meanwhile, LPT inlet mass flow rate is changed to maintain the SG inlet temperature, the turbine work should be changed. The corrected turbine work is calculated and given in the below figure.

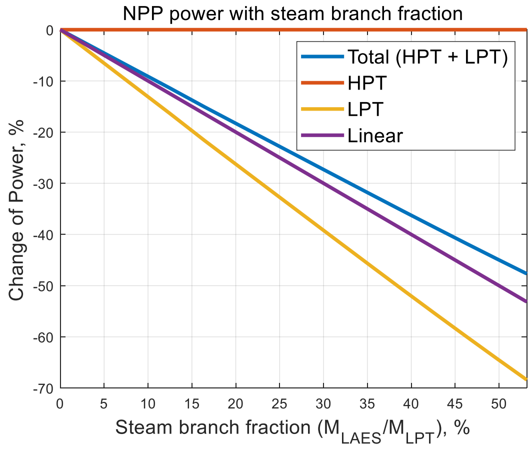

Fig. 7. Corrected change of power with steam branch fraction

The turbine work is decreased more than before controlling HPT steam extraction because the LPT inlet mass flow rate is decreased to adjust the SG inlet temperature. If 10% of LPT inlet mass flow rate is branched to the Steam Turbine-Driven-Compressor for LAES, the secondary side total power is decreased by 9%.

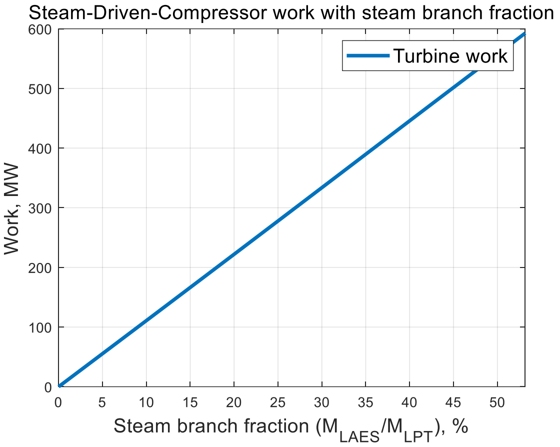

Fig. 8. Transferred work to LAES steam turbine

The Steam Turbine-Driven-Compressor work is calculated. Fig. 8 shows linear increase of Steam Turbine-Driven-Compressor work.

4. Conclusions

Thermodynamic performance of the newly proposed LAES integrated nuclear power plant is presented in this paper. To evaluate its feasibility, secondary side of the NPP is modeled with modifications and the off-design steam turbine model is implemented in the code. As the steam branch fraction increases to the Steam Turbine-Driven-Compressor, the SG inlet temperature is linearly decreased because mass flow rate of main feedwater line is increased and the LPT steam extraction for heating feedwater is decreased. This result may cause serious problem on the primary side. Therefore, a new control mechanism is suggested to maintain the SG inlet temperature. To increase feedwater temperature, steam extraction fraction at the HPT (before moisture separator) is controlled. Change of steam extraction fraction shows that the SG inlet temperature is maintained as well. These results show that the integration of LAES and NPP is possible while minimizing the changes in primary side. In the future, an off-design model of feedwater heater, reheater and feedwater pump will be also implemented to evaluate detail performance of the integrated cycle. Moreover, thermodynamic analysis of mechanically integrated LAES will be performed to demonstrate the feasibility of the concept.

5. Acknowledgement

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