Preliminary Performance Analysis of the Power Conversion System for the Thermal Energy Storage System Integrated Nuclear Power Plant

Seunghwan Oh, Jeong Ik Lee *
Nuclear & Quantum Engr. Dept. KAIST
Corresponding author: jeongiklee@kaist.ac.kr

1. Introduction

Concerns about global environment issues, such as greenhouse effect and fine dust air pollution, have led to growing interest in low-carbon energy sources. South Korea also announced that it will increase the proportion of renewable energy generation to 20% by 2030 through the 3020-implementation plan. More than 95% of new renewable energy generation facilities are solar (63%) and wind (34%). Solar and wind are representative intermittent energy sources. Because of the problem of intermittency, it is difficult to match power supply and demand and oversupply problem will be prominent as the proportion of renewable energy generation increases. Therefore, the expansion of renewable energy should be developed safely and efficiently while keeping nuclear power as a power source to stabilize the grid. This may require load following operation abilities of a nuclear power plant. Thus, a nuclear power plant integrated with thermal energy storage system (TES) that can follow power supply and demand fluctuations without directly changing the core power was suggested for flexible nuclear power plant operation [1].

TES integrated nuclear power plant is a system that stores heat in the TES by dividing a part of the mass flow rate of the secondary side (Rx2) when oversupply occurs. When additional power is needed, thermal energy is supplied from TES to produce additional power through a dedicated TES power conversion system (PCS). In this study, the overall performances of this system, such as charging process and discharging process, are analyzed.

2. Methods and Results

2.1 Thermal energy storage efficiency

Energy storage efficiency is simply defined as the ratio of electrical energy output to electrical energy input [2]. It is also called round-trip efficiency. In the case of TES, the input is a thermal energy input. Therefore, in this case, it is expressed as the ratio of electric power when used directly without storing the thermal energy and electric power when used after storing the thermal energy. In this study, since the mass flow rate diverges in front of the low pressure (LP) turbine for load following operation, it is expressed as follows. W_{LP}, W_{pcs} are the power that the LP turbine does not produce by storing heat and the power produced from stored heat using pcs, respectively.

$$\eta = \frac{W_{pcs}}{W_{LP}}$$

2.2 Rx2-TES-PCS cycle modeling

2.2.1 Rx2-TES heat exchange with one heat exchanger

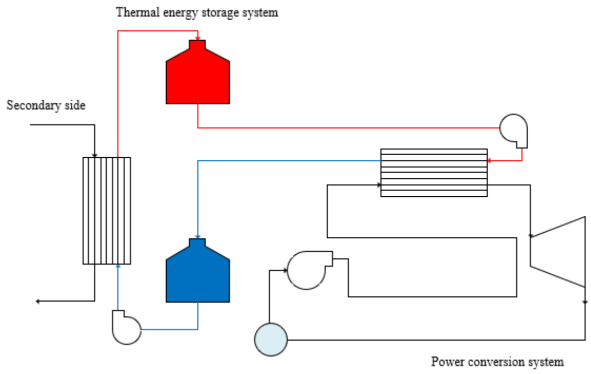

Fig. 1. Rx2-TES-PCS simple cycle

Table. 1. Rx2-TES-PCS cycle conditions

Secondary side	Fluid	Water
	Inlet temperature [°C]	251.5
	Outlet temperature [°C]	194.9
	Pressure [MPa]	1.4
	Mass flow rate [kg/s]	453.6
TES	Fluid	HITEC salt
	Cold tank temperature [°C]	145
	Charging time / Discharging time	1
Power conversion system	Fluid	CO_2
	Maximum pressure [MPa]	20
	Pump inlet temperature [°C]	30
	Turbine efficiency	0.9
	Pump efficiency	0.8
	Heat exchanger effectiveness	0.92

Fig. 1 shows the Rx2-TES-PCS simple cycle. The heat exchange between the secondary side and TES is a charging process and the heat exchange between TES and PCS is a discharging process. In this study, the heat exchange is calculated by effectiveness so that physically impossible outlet temperature can be calculated. For example, pinch temperature difference is below 0°C. Therefore, the pinch temperature difference is always larger than 0°C by decreasing the heat exchanger effectiveness or increasing the mass flow rate. Rx2-TES-PCS cycle condition is in Table. 1. In this study, the mass flow rate for branching to TES is 20%, and the charging time and discharging time is same. Also, trans-critical CO_2 cycle is used for PCS. Since the melting temperature of HITEC salt, which is thermal energy storing fluid in this study, is 142°C, the cold tank temperature is set to 145°C. Values other than Table. 1 are calculated to meet the specified conditions.

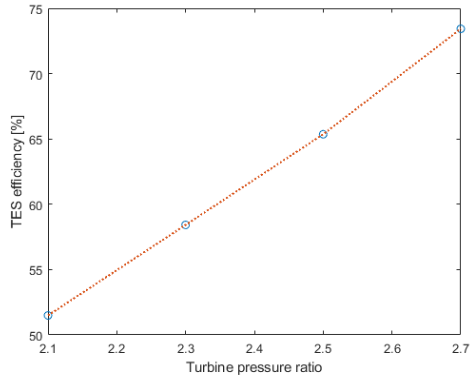

Fig. 2. Turbine pressure ratio of the TES attached power conversion system vs. TES efficiency

Analyzing the cycle in Fig. 1 based on Table. 1, the temperature of the hot tank is 198.67°C, maximum TES efficiency is 73.43%. Fig. 2 shows the TES efficiency according to the turbine pressure ratio of the TES attached power conversion system. From the pressure ratio 2.8, the pump inlet condition is in a 2-phase state.

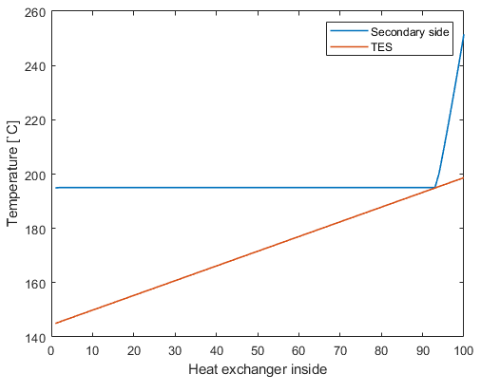

Fig. 3. Temperature profile inside heat exchanger

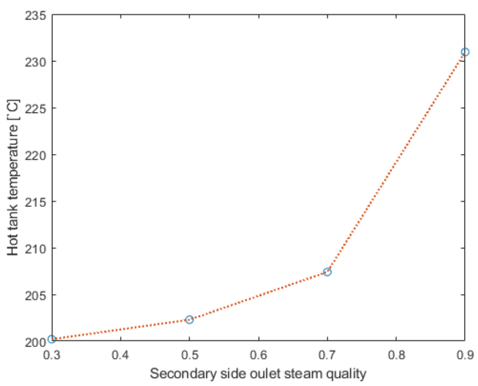

Fig. 4. Secondary side outlet steam quality vs. Hot tank temperature

Fig. 3 shows the secondary side temperature profile and TES heat transfer fluid (HTF) temperature profile. Since there is a phase change section, a pinch occurs inside the heat exchanger. Thus, there is a big difference the hot tank temperature and secondary side inlet temperature. In general, high turbine inlet temperatures have high cycle efficiencies. Fig. 4 shows the hot tank temperature according to the secondary side outlet steam quality. Increasing the secondary side outlet steam quality in order to increase the temperature of the hot tank increases the amount of unused heat. Therefore, to reduce the amount of heat discarded, a Rx2-TES-PCS cycle layout in Fig. 5 can be considered.

2.2.2 Rx2-TES heat exchange with two heat exchangers

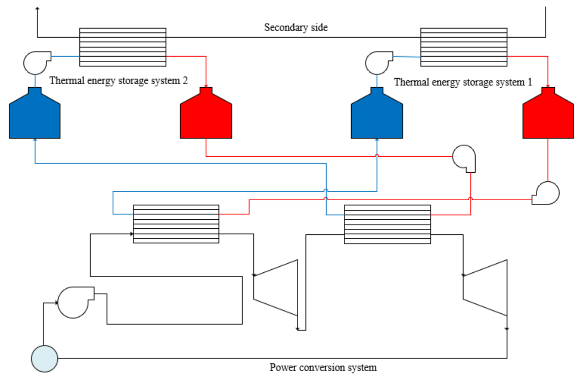

Fig. 5 Rx2-TES-PCS reheat cycle

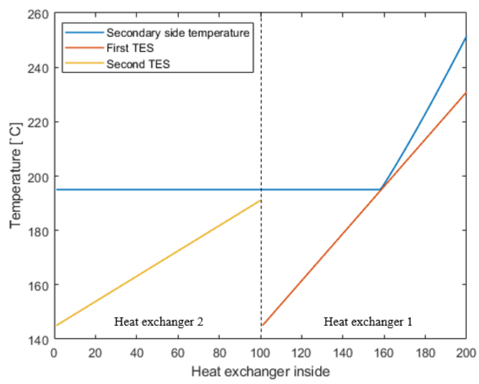

Fig. 6. Temperature profile inside 2 heat exchangers (First heat exchanger steam outlet quality is 0.9)

Rx2-TES-PCS reheat cycle uses 2 hot tanks and 2 cold tanks. Both cold tanks have the same temperature. The first turbine pressure ratio is limited since the first turbine outlet temperature is lower than the cold tank temperature. Fig. 6 shows an example of the temperature profile in the two heat exchangers in Fig.5. More heat can be used by adding additional heat exchanger.

Fig. 7 shows the secondary side first and second heat exchanger outlet steam qualities according to the first hot tank temperature. If the secondary side first heat exchanger outlet steam quality is low, the difference from the second heat exchanger outlet steam quality is large. Since a large amount of HTF is required for first steam-TES heat exchanger for low outlet steam quality, relatively large amount of heat can be drawn from the secondary side in the second heat exchanger.

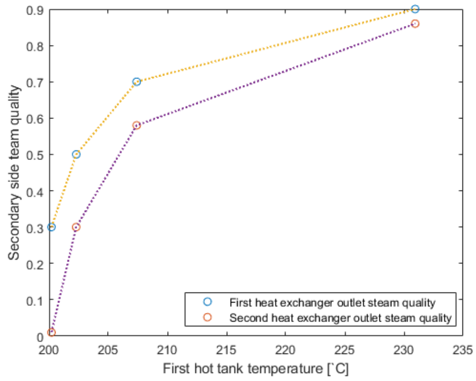

Fig. 7. First and second heat exchanger outlet steam qualities vs. First hot tank temperature

Figs. 8, 9 and 10 show the PCS efficiency, the PCS mass flow rate and the TES efficiency according to the secondary side first heat exchanger outlet quality, respectively. Although high secondary side first heat exchanger outlet steam quality has high PCS efficiency, it has low TES efficiency since it produces low power because of low mass flow rate. For the same reason, it is better to use one heat exchanger to produce power at lower temperatures than to use two heat exchangers to increase the temperature.

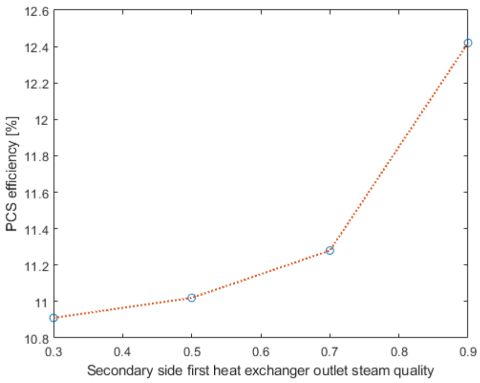

Fig. 8. Secondary side first heat exchanger outlet steam quality vs. PCS efficiency

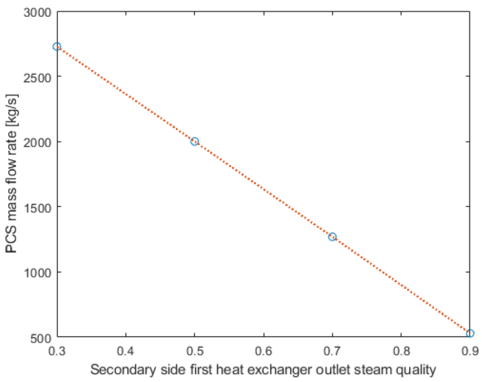

Fig. 9. Secondary side first heat exchanger outlet steam quality vs. PCS mass flow rate

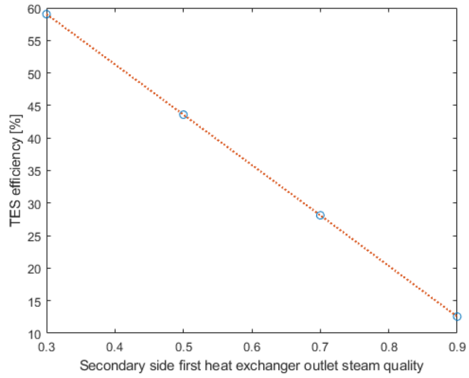

Fig. 10. Secondary side first heat exchanger outlet steam quality vs. TES efficiency

3. Conclusions

In this study, the overall system performances are analyzed with respect to hot tank temperature and TES efficiency, etc. Because of the inner pinch problem in the heat exchanger, the temperature of HTF cannot increase sufficiently. Thus, the cycle layout using two heat exchangers is considered to increase hot tank temperature. However, small amount of PCS mass flow rate is required for high hot tank temperature so that power produced by PCS becomes small. This causes a reduction in TES efficiency despite the increase in PCS efficiency. As a result, using one heat exchanger is more efficient than using two heat exchangers. In other words, increasing the hot tank temperature while reducing the mass flow rate is inefficient. In actual heat exchange with steam, the hot tank temperature may be lower than the results of this study so that TES efficiency may be lower.

CO_2 is first used as PCS working fluid to analyze overall system performance. However, the cycle efficiency using CO_2 is low at this operation temperature. CO_2+R-32 mixture fluid or CO_2+Toluene mixture fluid are considered potential candidates for efficiency improvement in the temperature below 300°C [1]. Thus, these fluids will be discussed for improving PCS efficiency and TES efficiency with several cycle layouts.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (NRF-2019M2D2A1A02059823).

REFERENCES

[1] Seungjoon Baik, Study on CO_2 based Mixture Power Cycle for Flexible Operation of Nuclear Power Plant, Ph.D. Dissertation, 2018.
[2] Sameer Hammer, Johannes L. Van Niekerk, Thermodynamic modelling of thermal energy storage systems, Energy Procedia 93 (2016) 25-30.