A Sensitivity Study of Isothermal Thermo-Electric Energy Storage System

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1. Introduction

Due to concerns in the renewable energy intermittency issue, interests in the application of EES (Electrical Energy Storage) systems are increasing worldwide. For a variety of reasons, including changes in the power regulatory environment, continued reliance on industry, commerce and home and power quality, EES will become more important. Thus, growth in EES systems will be the growth of renewable energy for a major energy source [1].

In accordance with this situation, EES has to become more effective, efficient and economically competitive systems. This means that high energy density should be obtained from design of the energy storage system. Accordingly, this paper proposes an isothermal TEES (thermo-electric energy system) that stores electricity as heat. Moreover, a TEES with high power density is selected, and designed while optimizing the round-trip efficiency.

The TEES system is different from other ESSs (energy storage systems) in that the charging and discharging cycles are operated separately. This difference can raise the possibility that the discharging period can be adjusted by increasing the charging amount. Furthermore, TEES can become a large scale EES when it is coupled with a nuclear power plant. It can further assist nuclear power plant’s flexible operation. In this paper, an isothermal thermo-electric energy storage (TEES) is investigated. The sensitivity of system’s performance is studied with the assumed component performances to understand and optimize the processes better.

2. Methods

2.1 Isothermal TEES systems model

The TEES system has a charging cycle and a discharging cycle. The thermodynamic cycle of TEES is not completely reversible ('reversible' refers to a thermodynamic cycle that can operate in both clockwise and counterclockwise directions). The concept of isothermal TEES has been proposed to maximize expansion work. An isothermal expansion with good heat transfer to the hot storage is necessary. The charging cycle and the discharging cycle are connected with the hot storage (TES: thermal energy storage), in which the heat of the charging cycle is stored in the TES and then received by the discharging cycle later on.

The charging cycle of TEES system is composed of isothermal compressor (C1), isentropic expander (E2), hot storage (hot water tank and cold water tank), heat exchanger (HX) and ice storage. And the composition of the discharge cycle of the TEES system is isothermal expander (E2), isentropic pump (C2), hot storage, heat exchanger, and ice storage.

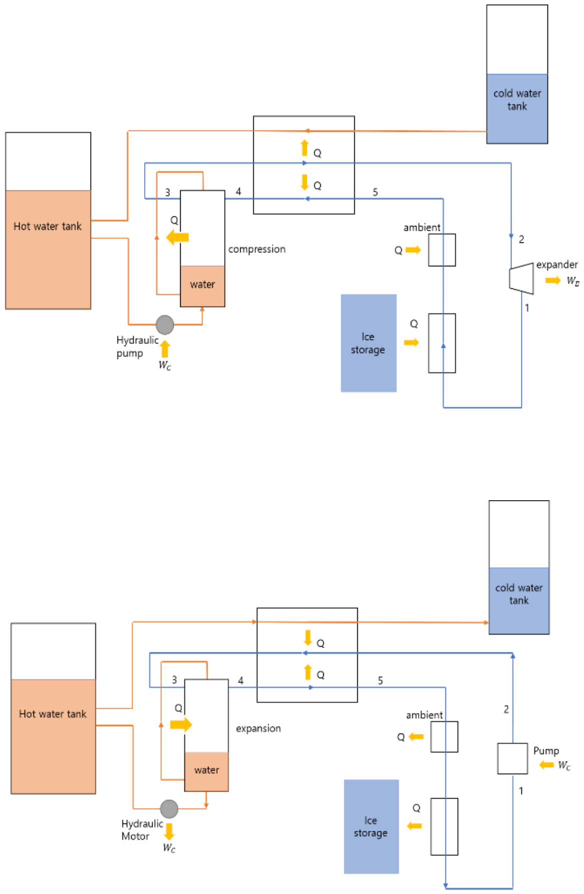

Fig 1. Isothermal TEES system, charging (up) and discharging (down)

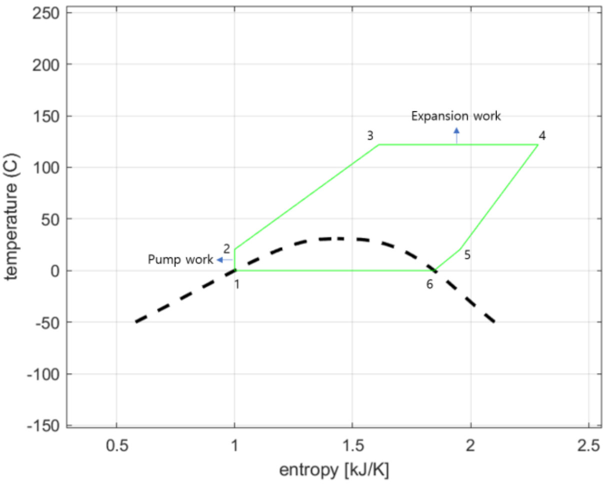

Fig 2. Cycle of isothermal TEES system with co2 during discharging mode.

2.2 Performance of TEES System

The performance of TEES can be expressed with round-trip efficiency (RTE) and power density.

2.2.1 Round-trip efficiency of TEES system

The definition of RTE of the TEES system is basically the ratio of the electric output power during discharge mode to the electric input power during charging mode. The power of expansion and compression in each mode for working fluid is calculated using an isentropic efficiency.

$$\text{RTE} = \frac{w_{discharging}}{w_{charging}} = \frac{w_{E2} - w_{C2}}{w_{C1} - w_{E1}} \quad (1)$$

An isentropic efficiency is defined as:

$$\mu_{comp} = \frac{w_{comp,i}}{w_{comp}} \quad (2)$$

$$\mu_{expander} = \frac{w_{expander}}{w_{expaner,i}} \quad (3)$$

To define round-trip efficiency of isothermal TEES rather than round-trip efficiency of isentropic TEES system, we add the concept of back work ratio (r_{bw}).

$$r_{bw,charging} = \frac{w_{E1,i}}{w_{C1,i}} \quad (4)$$

Similar to the back work ratio of charging cycle, the back work ratio of discharging cycle is also the ratio of the ideal work of the expander and the ideal work of the compressor. However, unlike the back work ratio of charging cycle, the work of the expander is at the denominator for discharging cycle.
Finally, RTE for isothermal TEES system is defined as:

$$\eta_{RT} = \frac{\eta_{C1}}{\eta_{C2}} \; \frac{\eta_{C2}\eta_{E2} - r_{bw2}}{1 - \eta_{C1}\eta_{E1} - r_{bw1}} \frac{w_{E2,i}}{w_{C1,i}} \quad (5)$$

Because TEES system is not perfectly reversible, the round-trip efficiency of the TEES system can be degraded due to the exergy loss of system. Due to the minimum temperature difference required for heat transfer to/from the heat storage, the hot and cold temperature difference of the heat engine is slightly smaller than that of the heat pump. The exergy losses occurring in the turbomachinery have a greater impact on round-trip efficiency compared to the exergy losses in the heat exchangers with the good thermally matched TEES system. Thus, if the exergy losses are neglected in the heat exchanger, the back work ratio of charging mode and discharging mode is equal and then, the maximum round- trip efficiency can be obtained as:

$$\eta_{RT,max} = \frac{\eta_{C1}}{\eta_{C2}} \; \frac{\eta_{C2}\eta_{E2} - r_{bw}}{1 - \eta_{C1}\eta_{E1} - r_{bw}} \quad (6)$$

The maximum round-trip efficiency in equation (6) shows that the back work ratio is important to increase the round-trip efficiency.

2.2.2 Power density of the TEES system

The power density of the TEES system can be defined as the ratio of work during the discharging mode to the hot and cold tanks. Determining discharging work and heat storage volume (V : volume) are as follows:

$$(power\ density) = \frac{W_{discharging} \times discharging\ period}{V_{hot\ tank} + V_{cold\ tank}}$$

$$= \frac{w_{E2} - w_{C2}}{V_{hot\ tank} + V_{cold\ tank}} \quad (7)$$

3. Results and Discussions

Assumptions used for the modeling are as follows

1) There is no pressure drop in the pipelines.
2) There are no changes in potential and kinetic energies.
3) The volume and pressure of the hot tank are determined from the tank temperature at which the water quality is zero, and the temperature and volume of the cold tank are determined with respect to the exchange of heat in the heat exchanger during the discharge cycle and the water quality is zero.
4) The minimum pressure is determined from the isentropic components' inlet temperatures (charging : isentropic expander inlet temperature / discharging : isentropic pump inlet temperature) and quality of working fluid is 0.

Table 1. Design parameters of TEES

parameters	Value	Unit
Isentropic efficiency of turbine	85	%
Isentropic efficiency of compressor	85	%
Isothermal efficiency of turbine	88	%
Isothermal efficiency of compressor	86	%
Mass flow rate ratio ($CO_2 : water$)	1:0.3	

Table 2. Variable of parameters of TEES

parameters	Value	Unit
Maximum pressure	16	MPa
Isentropic components inlet temperature	-50	℃
Hot water tank temperature	122	℃

3.1 Sensitivities of TEES

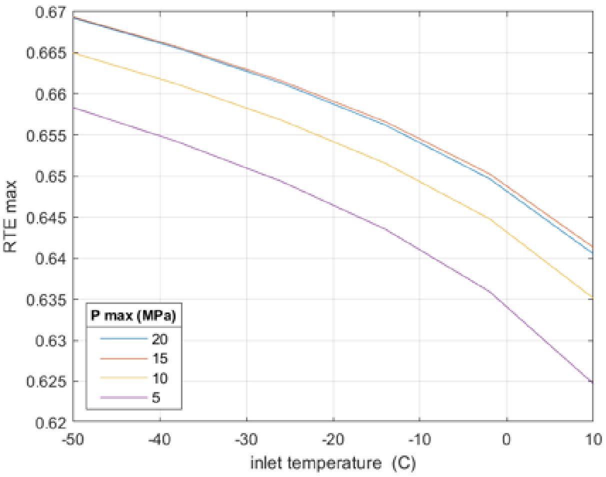

Fig 3. Sensitivity of inlet temperature of isentropic components and maximum pressure – RTE max

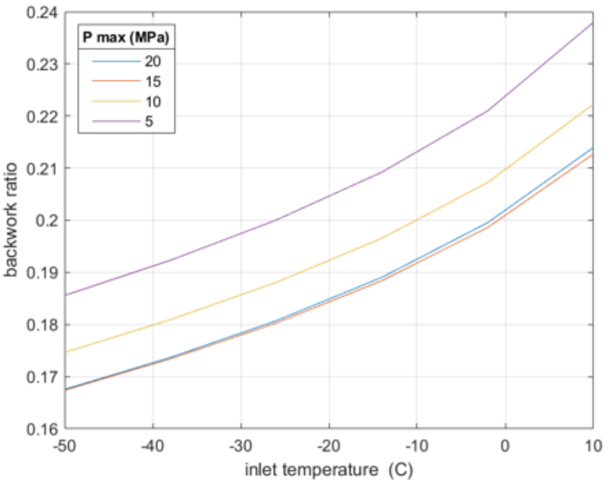

Fig 4. Sensitivity of inlet temperature of isentropic components and maximum pressure – simplified back work ratio

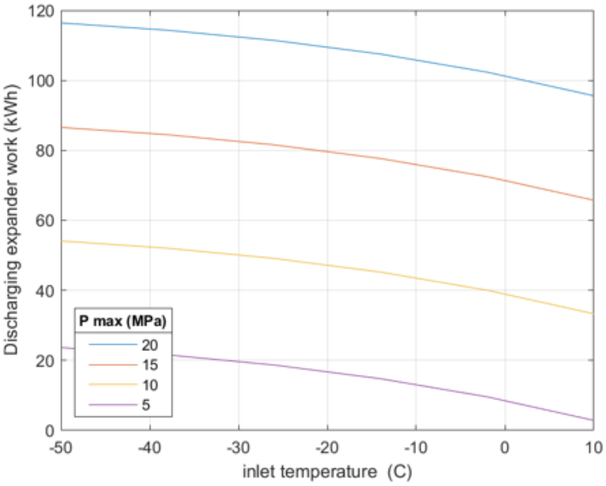

Fig 5. Sensitivity of inlet temperature of isentropic components and maximum pressure – Discharging expander work (discharging period : 5hr)

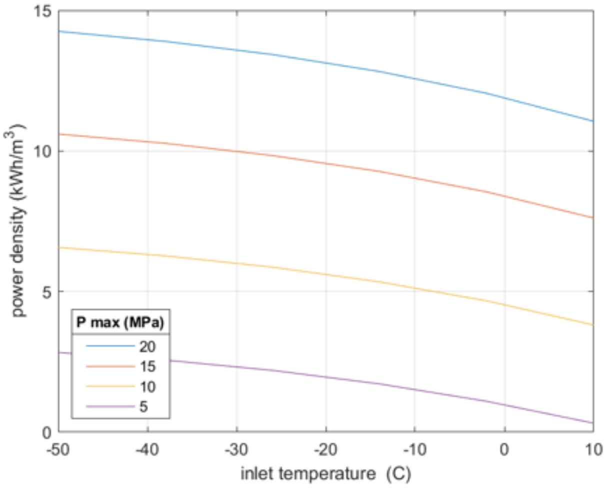

Fig 6. Sensitivity of inlet temperature of isentropic components and maximum pressure – power density (discharging period : 5hr)

The lower the inlet temperature of isentropic components, the higher the RTE and power density become. As the changing maximum pressure increases, the RTE tends to increase and the power density tends to decrease. The round-trip efficiency is dominated by the back work ratio and the power density is dominated by the isothermal expansion during the discharging mode. This is because, as the ratio of maximum pressure and minimum pressure rapidly increase, the increase rate of the work of isentropic compression becomes larger than the increase rate of the work of the isothermal expansion during discharging mode. In addition, since the back work ratio, which is the ratio of isothermal expansion and isentropic compression, is reversed, maximum RTE is very sensitive to back work ratio.

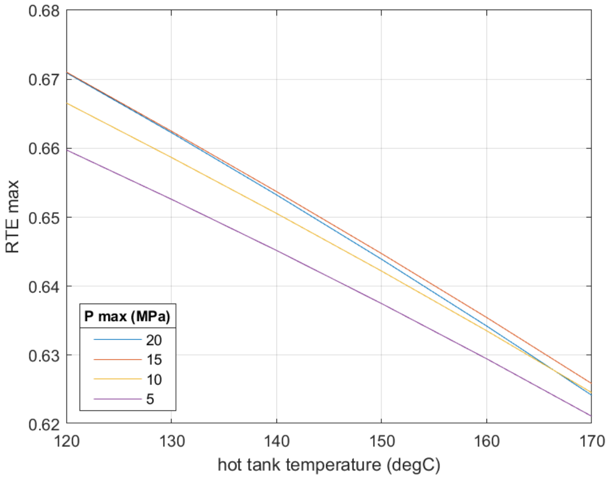

Fig 7. Sensitivity of hot tank temperature and maximum pressure – RTE max

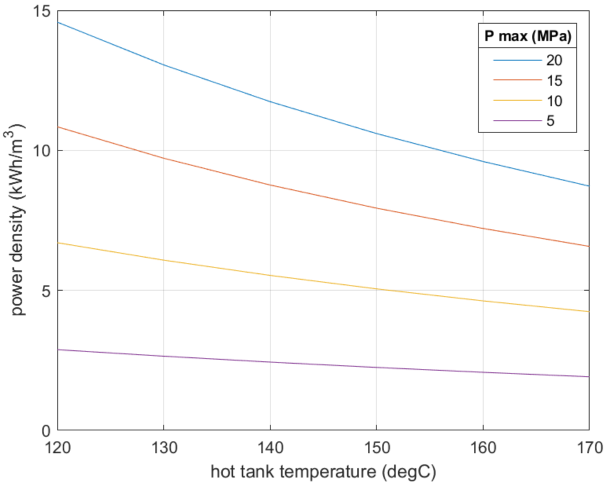

Fig 8. Sensitivity of hot tank temperature and maximum pressure – power density

The higher the temperature of the hot water tank is, the RTE and the power density are lower. The reason is as the hot tank temperature increases, the temperature at which isothermal expansion occurs increases and the work of isothermal expansion becomes smaller. Moreover, the reversal of pressure is due to the reversal of the work ratio of the isothermal expansion and isentropic compression. Therefore, it is observed that the maximum round-trip efficiency and power density are more sensitive to pressure than to the isentropic components' inlet temperature. Therefore, the maximum round-trip efficiency and the power density of the isothermal TEES were checked in the proposed the system to be 0.664 and 16.82kWh/m^3, respectively, when isentropic components' inlet temperature is -50℃ and the maximum pressure is 25 MPa.

4. Conclusions

The TEES proposed in this paper is able to transfer heat directly to the thermal energy storage, so unlike the isentropic TEES system, it is possible to maximize the isothermal expansion work, thereby increasing the round-trip efficiency with a low back work ratio. However, since the charging mode and the discharging mode were designed to work with the same pressure ratio, the increase rate of the work of components doing isentropic work at high pressure ratios exceeded the isothermal work. Here, if the pressure ratio of the isothermal expansion in the discharge mode is appropriately increased rather than the pressure ratio of the isothermal compression in the charging mode, it is expected that the thermal energy due to the internal dissipation of the isothermal compression/expansion will recover higher power. Therefore, a more effective the isothermal TEES system can be developed from this sensitive study in the future.

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