Off-design Performance Analysis of Compressed CO_2 Energy Storage System Integrated to a Conventional PWR

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

1. Introduction

The energy production from renewable energy (RE) sources is increasing globally and domestically. Globally, according to the United Nations World Climate Convention, the ratio of RE is expected to increase to reduce greenhouse gas (GHG) emission. In Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE to 20% by 2030 [1]. However, as the proportion of RE increases, major technical challenges also arise.

Solving the intermittency issue of RE is one of the major challenges. Power generation from wind and solar is affected by weather and climate conditions and therefore it cannot always generate power when the demand is high. This issue can be alleviated by load-following operation of a nuclear power plant (NPP). However, it is not economical to control power output of the reactor in an NPP. Energy Storage System (ESS) attached to the power cycle can solve this issue. Among the various ESSs, compressed CO_2 energy storage (CCES) is promising ESS due to high round-trip efficiency (RTE) and simple layout.

CCES integrated to a conventional PWR was studied and analyzed thermodynamically previously. From this reference, its maximum RTE was estimated to be around 62% [2]. However, it doesn't always produce constant work since each time the required power is not same. Thus, it needs to analyze dynamic simulation when it produces different work from on-design. First, the off-design performance analysis in discharging operation mode should be performed as a preliminary study before dynamic simulation. CO_2 after discharging process flows in the low pressure tank (LP tank) due to the closed loop. Hence, the control method should be applied not to affect next charging process.

Therefore, in this paper, the off-design performance analysis of a CCES integrated to a conventional PWR in discharging operation mode is presented. Compared to on-design CCES, the off-design turbine work of CCES are presented in this paper.

2. Thermodynamic modeling

2.1 CCES on-design description

As shown in Figure 1, processes 1-2 and 9-10 are the energy storage process (Charing operation) and the rest of processes are the energy recovery process (Discharging operation).

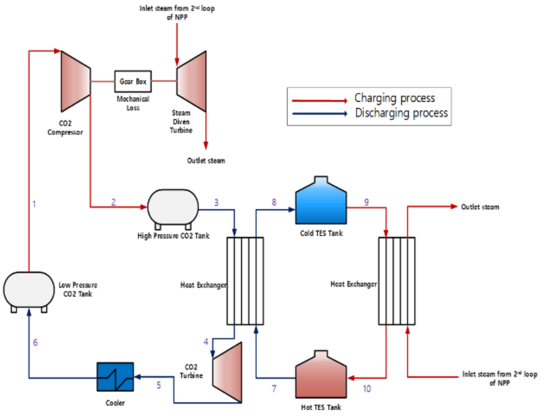


Figure 1. Layout of on-design CCES integrated to PWR steam cycle

2.2. CCES off-design modeling in discharging operation

In this paper, the turbine work produced is evaluated when the mass flow rate of the working fluid, CO_2, are different from the on-design CO_2 mass flow rate during the discharge process. As shown in the figure above, the discharge process uses heat exchangers and turbines. Therefore, CCES off-design analysis requires the conceptual design of heat exchangers and turbine and control strategy.

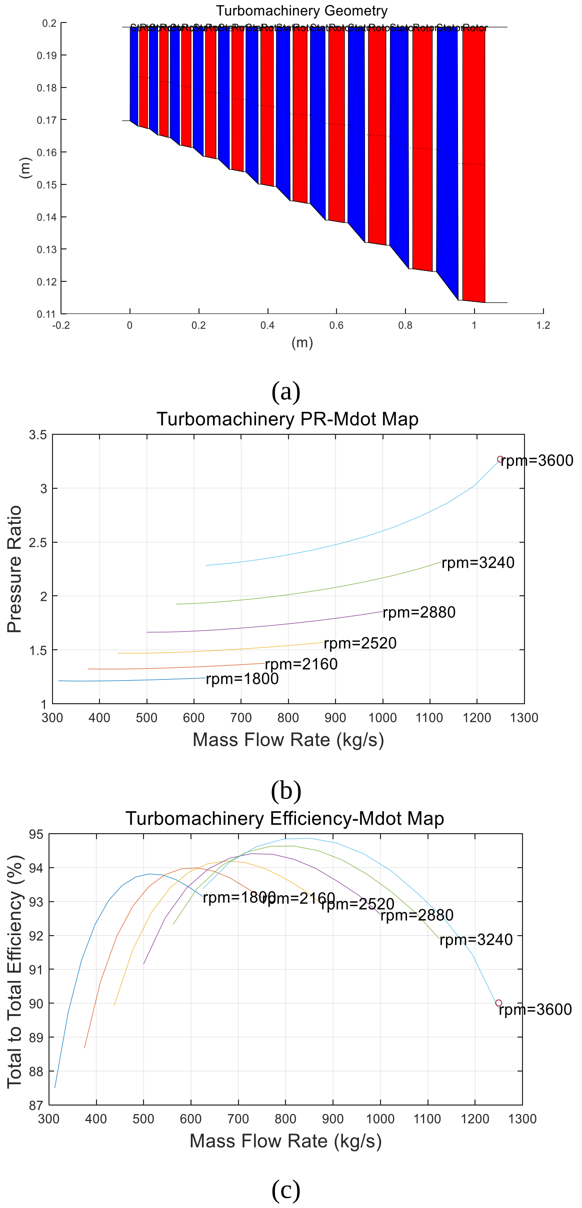
2.2.1 Conceptual design of Turbine

CO_2 turbomachinery can be designed using dimensionless specific velocity (n_s) and diameter (d_s) used in the turbomachinery design with air. KAIST-TMS is a preliminary design code using Balje`s n_s-d_s diagram [3]. Thus, KAIST-TMS predicts efficiency by designing stage number and rotation speed based on single-shaft configuration. Table 1 summarizes KAIST-TMS results. Based on these results, the conceptual design and performance of turbomachinery was analyzed using KAIST-TMD.

Table1. KAIST-TMS results

	Turbine	Unit
Type	axial	
RPM	3600	
Stage	11	
Efficiency	90.01	%

KAIST-TMD is a 1-D mean streamline code developed for the design and performance prediction of turbomachinery. In the preliminary design of the turbomachinery, it is difficult to create a specific shape of the turbomachinery and to predict the performance. To overcome this difficulty, the 1-D mean streamline method is applied. Although the path of fluid in a turbomachinery is 3-D, most of the fluid flows in 1-D path from inlet to outlet. Therefore, it is possible to represent 3-D fluid flow in 1-D using velocity triangles. The conceptual design results for turbine are shown in Figure 2.



(a)

(b)

(c)

Figure 2. Turbine geometry(a), pressure ratio map(b) and efficiency map(c)

2.2.2 Heat exchanger design

KAIST-HXD is used for the heat exchangers design in this paper. PCHE has a form of repeating channels of the same shape and can be evaluated with the representative channel for the whole heat transfer area. KAIST-HXD performs analysis on a unit channel by matching the hot and cold channels one-to-one, then, multiplies the result of unit channel by the total number of PCHE channels [4]. The design results for each heat exchanger (heater and cooler) are summarized in Table 2.

Table2. KAIST-HXD results

	Heater	Cooler
Type	PCHE	PCHE
Length [m]	6.41	1.7
Number of hot channels	240000	100000
Number of cold channels	240000	100000
Diameter of hot channels [mm]	7.5	4.5
Diameter of cold channels [mm]	2.92	15
Fluid of hot channels	HITEC salt	CO_2
Fluid of cold channels	CO_2	Water

2.2.3 Control strategy

During partial load operation, it is expected that the CO_2 after the discharging process will be different from the design point. Under the aforementioned conditions, it is required to control the temperature and pressure of CO_2 before LP tank inlet (Point 6 in Figure 1) to match the design point. Controlled to the pressure by installing a throttle valve between the turbine and the cooler to match the design pressure. In order to maintain the temperature constant, the mass flow rate of water, the coolant of the cooler, is adjusted to control the temperature. In addition, to keep constant TES cold tank, the mass flow rate of HITEC salt is adjusted to control the HITEC temperature (Point 8 in Figure 1).

3. Thermodynamic evaluation and Results

KAIST-QCD is a code for preliminary analysis of cycle performance at off-design conditions. This code also uses REFPROP from NIST and was written in MATLAB. This code performs thermodynamic calculations based on turbomachinery off-design maps, similarity models and the assumption that the cycle is quasi-steady state at the off-design conditions.

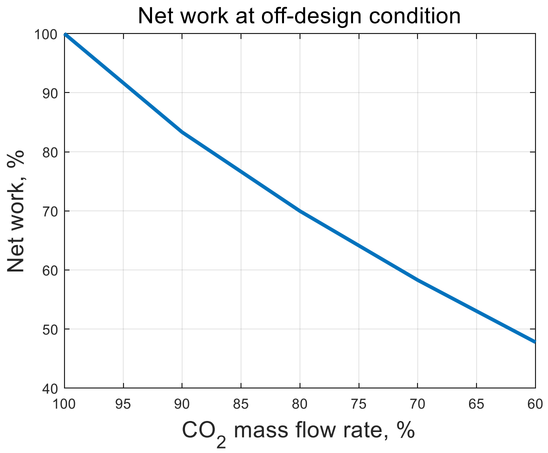


Figure 3. CO_2 mass flow rate vs Net work ratio

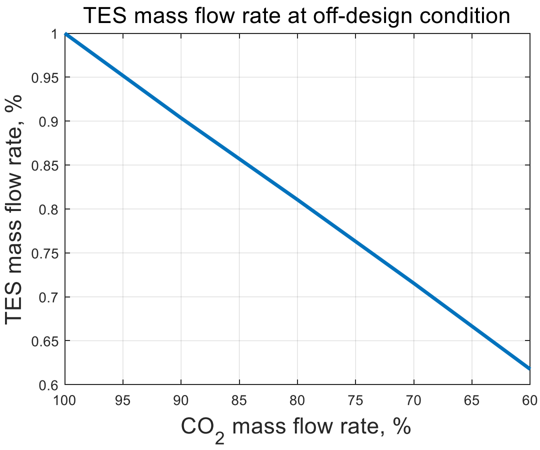


Figure 4. CO_2 mass flow rate vs TES mass flow rate ratio

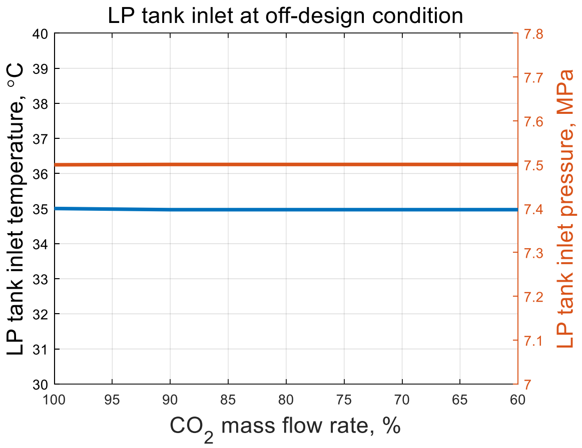


Figure 5. CO_2 mass flow rate vs LP tank inlet T & P

As shown in Figure 3, it has the net work ratio of 48% at the CO_2 mass flow rate of 60%. In other words, when the CO_2 mass flow rate reduces by 40% from the design point, the turbine work produced reduces by 52% from that. That is, it can be seen that the reduction rate of the turbine power generation is higher than the reduction rate of its mass flow rate. As seen in Figure 4, TES mass flow rate decreases by 40% when the flow rate decreases by 38% from the design point. Thus, it can be seen that it approximates the rate of decrease of the TES fluid mass flow rate. Figure 5 shows that the LP tank inlet temperature and pressure remain constant by control strategy even when the CO_2 mass flow rate is changed.

4. Summary and Future works

From the result of the compressed CO_2 energy storage off-design analysis, it is shown that as the CO_2 mass flow rate decreases, the produced turbine work decreases more. Thus, frequent part load operation is not recommended. Then, by control strategy using throttling valve and control of water mass flow rate, LP tank inlet maintain constant form the design point. Thus, it is shown that it doesn't affect to charging process by control method. However, a control method that can improve performance during partial load operation is required such as constant volumetric flow rate method.

In the future, other control methods will be added to further increase the turbine power generation in partial load operation. Finally, based on these results, the transient analysis of CCES will be studied in load-following operation. Further investigation will commence soon regarding dynamic simulation of CCES by adding better control strategy as well.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (2019M2D2A1A02059823)

REFERENCES

[1] 산업통상자원부, 제 9 차 전력수급기본계획(2020~2040), 2020
[2] YongJae Chae et al. “Thermodynamic Study of Compressed CO_2 Energy Storage System Integrated to a Conventional PWR” Transactions of the Korea Nuclear Society Autumn Meeting (2020).
[3] Seong Kuk Cho, Jekyoung Lee, Yongju Jeong, Jeong Ik Lee, Study of non-dimensional number analysis for the conceptual design of S-CO2 compressor, Transactions of the Korean Nuclear Society Autumn Meeting, 2017.
[4] Baik, Seungjoon, et al., Study on CO2-water printed circuit heat exchanger performance operating under various CO2 phases for S-CO2 power cycle application, Applied Thermal Engineering, 2017.