Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-27, 2017

Development of Control Strategy of S-CO_2 Recompression Brayton Cycle for SFR Application based on Adjoint Method

Seongmin Son [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST)*
373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Korea
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

The Supercritical CO_2 power cycle (S-CO_2 cycle) is the power cycle that works with supercritical state CO_2 as a working fluid. CO_2 shows abrupt change of material properties near the critical point. The S-CO_2 cycle utilizes these non-linear properties at compression stage. The S-CO_2 cycle has high efficiency due to the reduced compression work. Because of the low expansion ratio and specific volume, the S-CO_2 cycle has advantages of reducing size of components compared to other gas cycles. Furthermore, unlike steam, CO_2 does not react violently with sodium. Considering these strengths, there are attempts to apply S-CO_2 cycles to the secondary side of the sodium-cooled fast reactor (SFR). [1]

While designing S-CO_2 cycle, an engineer should confirm every parameter during the steady state operation, such as component performances, system boundary conditions, and so on. However, in real condition, it is impossible to maintain the operation as perfectly the same as the design condition. For example, if the power of the reactor needs to be increased as the demand of electricity rises, thermal input as well as the turbine load of the S-CO_2 cycle will be change. If cooler outlet temperature vary due to the climate changes, the S-CO_2 cycle will be change, too. At off-design operating conditions, optimal operating condition will vary.

According to the previous research of Ahn (2016) [2], it is possible to improve the cycle thermal efficiency of the S-CO_2 power cycle by controlling turbomachine rpms under off-design conditions. Ahn showed maximum 9% point improvement of the cycle thermal efficiency for the SFR applications even without optimization. Therefore, to operate the power system efficiently, it is important to build an optimal control strategy for the S-CO_2 cycle. In these days, many researchers apply the Genetic Algorithm [3] or the Artificial Neural Network [4] to optimize the S-CO_2 power cycle steady state design. Unfortunately, analyzing the S-CO_2 cycle at the off-design operating conditions requires more computational cost than solving a steady state design problem. It is because of the increase in the design variables and in the need of iterative calculation. Therefore, it is hard to attempt traditional stochastic global optimization methodologies to build the optimal control strategy.

In this paper, the authors propose a method to quickly optimize S-CO_2 cycle off-design control strategy using the adjoint method [5] for SFR applications. Throttling, mass flow bypass, total inventory and turbomachine rpm changes are considered. Target cycle layout is the S-CO_2 recompression Brayton cycle layout with a single shaft. Both of the thermal power-changing scenario (Part-load scenario) and heat sink temperature-changing scenario for SFR operation are selected as the problem.

2. Methodology

2.1 S-CO_2 Recompression Brayton cycle for SFR

The S-CO_2 Recompression Brayton cycle is a highly efficient cycle with relatively small components. In this research, the authors assume that all turbomachines share rpm from the single shaft. Throttling, mass flow bypass, total CO_2 inventory and turbomachine rpm changes are considered.

The cycle layout of S-CO_2 recompression Brayton cycle is shown in Figure 1.

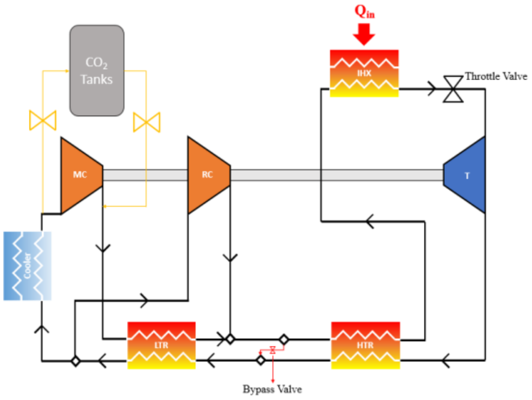

Figure 1. S-CO_2 Recompression Brayton Cycle

At the steady state, cycle design conditions for SFR are shown in Table 1.

Table 1. Cycle design parameters

Layout	Recompression Brayton	
System Maximum Pressure	20	MPa
Turbine Inlet Temperature	505	ºC
Cooler Outlet Temperature	31.3	ºC
Turbine Efficiency	90	%
Compressor Efficiency	80	%
Recuperator Effectiveness	95	%
HTR hot side pressure drop	60	kPa
HTR cold side pressure drop	30	kPa
LTR hot side pressure drop	40	kPa
LTR cold side pressure drop	20	kPa
Precooler pressure drop	20	kPa
Heater pressure drop	50	kPa
Turbine pressure ratio	Optimized	
Main Compressor Split	Optimized	

2.2 Adjoint Method

Adjoint method is the way to calculate the sensitivity by solving a dual problem, without calculating every perturbation of design parameters. In the previous study, Son et al., [6] introduced the way to apply adjoint method to S-CO$_2$ power cycle. According to Son et al., 1st order sensitivity (Jacobian) and 2nd order sensitivity (Hessian) can be calculated as Equation (1) and (2).

Design Parameters:

$$\boldsymbol{p} = (p_1, p_2, \ldots\ldots, p_N)^T$$

Dependent Variables:

$$\boldsymbol{x} = (x_1, x_2, \ldots\ldots, x_M)^T$$

Problem:

$$\boldsymbol{f}(\boldsymbol{x},\boldsymbol{p}) = \big(f_1(\boldsymbol{x},\boldsymbol{p}), f_2(\boldsymbol{x},\boldsymbol{p}), \ldots, f_M(\boldsymbol{x},\boldsymbol{p})\big)^T = (0,0,\ldots,0)^T$$

Jacobian:

$$\frac{dg}{d\boldsymbol{p}} = g_{\boldsymbol{p}} + g_{\boldsymbol{x}}\boldsymbol{x}_{\boldsymbol{p}} = g_{\boldsymbol{p}} - g_{\boldsymbol{x}}\big(\boldsymbol{f}_{\boldsymbol{x}}^{-1}\boldsymbol{f}_{\boldsymbol{p}}\big) = g_{\boldsymbol{p}} - (g_{\boldsymbol{x}}\boldsymbol{f}_{\boldsymbol{x}}^{-1})\boldsymbol{f}_{\boldsymbol{p}}$$
$$= g_{\boldsymbol{p}} - \lambda^T \boldsymbol{f}_{\boldsymbol{p}} \ldots (1)$$
$$when \quad \boldsymbol{f}_{\boldsymbol{x}}^{\boldsymbol{T}}\lambda = g_{\boldsymbol{x}}^T$$

Hessian:

$$\boldsymbol{H} = g_{\boldsymbol{pp}} - {\lambda_1}^T \boldsymbol{f}_{\boldsymbol{p}} - \boldsymbol{f}_{\boldsymbol{p}}^{\boldsymbol{T}}\lambda_1 - {\lambda_3}^T \boldsymbol{f}_{\boldsymbol{p}}$$
$$+\left(\begin{array}{c} -\lambda_0^T\left\{\begin{array}{c} \dfrac{\partial}{\partial p_1}(\boldsymbol{f}_{\boldsymbol{p}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{p}}}{\partial x_i}\dfrac{dx_i}{dp_1} \\ + \left[\dfrac{\partial}{\partial p_1}(\boldsymbol{f}_{\boldsymbol{x}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{x}}}{\partial x_i}\dfrac{dx_i}{dp_1}\right](-\boldsymbol{f}_{\boldsymbol{x}}^{-1}\boldsymbol{f}_{\boldsymbol{p}}) \end{array}\right\} \\ -\lambda_0^T\left\{\begin{array}{c} \dfrac{\partial}{\partial p_2}(\boldsymbol{f}_{\boldsymbol{p}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{p}}}{\partial x_i}\dfrac{dx_i}{dp_2} \\ + \left[\dfrac{\partial}{\partial p_2}(\boldsymbol{f}_{\boldsymbol{x}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{x}}}{\partial x_i}\dfrac{dx_i}{dp_2}\right](-\boldsymbol{f}_{\boldsymbol{x}}^{-1}\boldsymbol{f}_{\boldsymbol{p}}) \end{array}\right\} \\ \vdots \\ -\lambda_0^T\left\{\begin{array}{c} \dfrac{\partial}{\partial p_N}(\boldsymbol{f}_{\boldsymbol{p}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{p}}}{\partial x_i}\dfrac{dx_i}{dp_N} \\ + \left[\dfrac{\partial}{\partial p_N}(\boldsymbol{f}_{\boldsymbol{x}}) + \displaystyle\sum_i \dfrac{\partial \boldsymbol{f}_{\boldsymbol{x}}}{\partial x_i}\dfrac{dx_i}{dp_N}\right](-\boldsymbol{f}_{\boldsymbol{x}}^{-1}\boldsymbol{f}_{\boldsymbol{p}}) \end{array}\right\} \end{array}\right) \ldots (2)$$

2.3 Quasi-steady state analysis

There are two methodologies for the cycle off-design performance analysis: Transient analysis and Quasi-steady state analysis. In the mathematical viewpoint, transient analysis is the method that considers time derivative terms to solve the system of differential equations. It is suitable to analyze the events with sudden changes, such as start-up scenario, accident, and so on. However, it requires a lot of computational resource to solve the non-linear system of differential equation numerically. The quasi-steady state analysis is the way to analysis off-design scenario under assumption of slow transient. In this case, time derivative terms can be ignored, so the computational cost requirement decreases. This methodology cannot analyze fast events, but it is suitable for applying to the scenario with slow transient behavior.

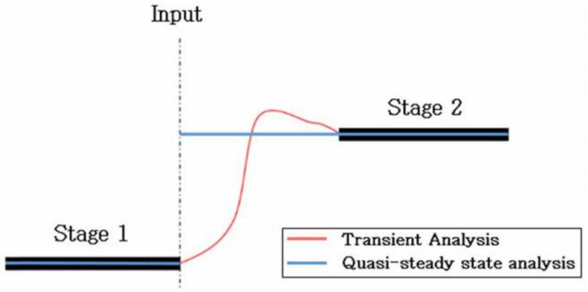

Figure 2. Schematic diagram of transient analysis and quasi-steady state analysis

Since both the part-load problem and heat sink temperature-changing problem can be treated slow transition when the operating is pre-scheduled or to respond to the seasonal variation of the heat sink temperature, the authors adopt the quasi-steady state analysis in this problem. In house KAIST-TMD [7] and KAIST-HXD [8] codes are used to evaluate the off-design performance of turbomachines and heat exchanger.

Figure 3. shows the Quasi-steady state performances along the heat sink temperature differences. the result of the Fig 3 is only considering the inventory as the control parameter. The blue line is the result of the constant maximum pressure assumption (as 20 MPa, which as same as design condition) and the red line is the result with optimal inventory.

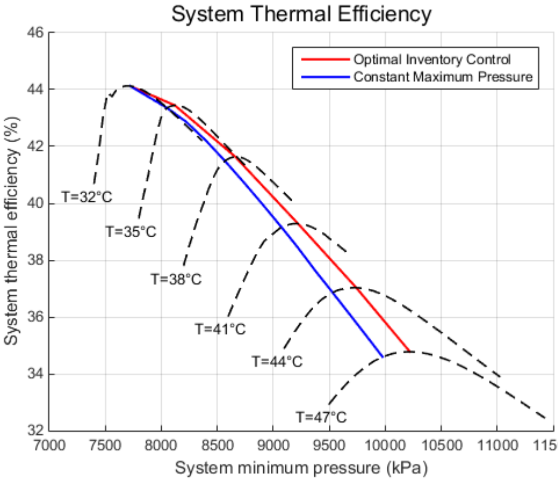

Figure 3. Influence on the control strategy for heat sink temperature-changing scenario

According to the Figure 3, considerable enhancement of the cycle efficiency is shown by the optimal inventory control strategy. The authors will present at the conference presentation both of the results with more control parameters and the result of the part-load problem case.

3. Summary and Conclusions

This study suggests the adjoint method to build an optimal control strategy for the thermal power-changing scenario of SFR. The considered cycle layout is S-CO_2 recompression Brayton cycle, which is highly efficient cycle layout composed of relatively less number of components. Turbomachines are assumed to be synchronized with a single shaft. Control variables are chosen to be throttling, bypass, inventory and rpm of turbomachines. Quasi-steady state analysis is adopted to the methodology to analyze off-design performances. The part-load scenario and the heat sink temperature-changing scenario are considered. For the quasi-steady state analysis, in-house turbomachines and heat exchanger off-design performance analysis codes, KAIST-TMD and KAIST-HXD, are used. Optimal control strategy that can achieve highest cycle efficiency with control under off-design scenario can be expected to be built.

REFERENCES

[1] Ahn, Yoonhan, Seong Jun Bae, Minseok Kim, Seong Kuk Cho, Seungjoon Baik, Jeong Ik Lee, and Jae Eun Cha. "Review of supercritical CO 2 power cycle technology and current status of research and development." Nuclear Engineering and Technology 47, no. 6 (2015): 647-661.
[2] Y. Ahn, Study of innovative Brayton cycle design and transient analysis for Sodium-cooled fast reactor application, Ph.D. Dissertation, 2016
[3] Fraser, Alex S. "Simulation of genetic systems by automatic digital computers I. Introduction." Australian Journal of Biological Sciences 10.4 (1957): 484-491.
[4] McCulloch, Warren S., and Walter Pitts. "A logical calculus of the ideas immanent in nervous activity." The bulletin of mathematical biophysics 5.4 (1943): 115-133.
[5] Y. Cao, S. Li, L. Petzold, and R. Serban, “Adjoint sensitivity analysis for differential algebraic equations: The adjoint DAE system and its numerical solution,” SIAM J. Sci. Comput., vol. 24, no. 3, pp. 1076–1089, 2003
[6] Seongmin Son, Jeong Ik Lee, "Application of Adjoint Sensitivity Analysis Method to Supercritical CO2 Power Cycle Optimization", Under Review
[7] Cho, Seong Kuk, et al. "S-CO2 Turbine Design for Decay Heat Removal System of Sodium Cooled Fast Reactor." ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition. American Society of Mechanical Engineers, 2016.
[8] Ahn, Yoonhan, Jekyoung Leea, Hwa-Yong Junga, and Jeong Ik Leea. "Preliminary design study of S-CO2 power conversion system for PG-SFR." system 1, no. 2 (2013): 3.