Experimental Evaluation of a Linear Quadratic Controller for S-CO_2 Cycle

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1. Introduction

More than 80% of all international trade is carried out over the sea, and this volume of shipping is rising yearly. The problem is international marine transport relies heavily on fossil fuels, generating 1.2 gigatons of CO_2 equivalent in 2020. This is responsible for approximately 3% of worldwide greenhouse gas emissions. By 2050, the resulting greenhouse gases are expected to be responsible for up to 17% of all global carbon dioxide emissions. Consequently, the goal of the International Maritime Organization's (IMO) greenhouse gas (GHG) standards is to lower the carbon intensity of global shipping [1]. These regulations will oblige container ships to switch fuel to non-carbon-based fuel.

Small modular reactors (SMR) are being advocated for marine propulsion as environmental concerns drive the need for innovative marine propulsion systems. The design goals of SMR are simple, compact, efficient, and safe, and these goals are appropriate for marine propulsion. The KAIST Micro Modular Reactor (KAIST-MMR), which is one of the SMRs, have been proposed for use in maritime propulsion systems.

The KAIST-MMR is a transportable, completely modularized 10 MWe class reactor for microgrid power generation. It was designed with a 20-year refueling cycle in mind, and the S-CO_2 Bryton cycle was chosen as the power conversion system [2]. The design concept of combining an S-CO_2 cycle and a reactor core into a single module allows the KAIST-MMR to have a size and mass appropriate for ship propulsion. The previous studies have shown that the KAIST-MMR is a reasonable choice to satisfy the propulsion requirements for a 1,000 TEU container ship [3].

The S-CO_2 system must be able to meet the power maneuvering requirements of marine propulsion in order to be used as a marine propulsion system. The load-following operation of S-CO_2 systems for ship propulsion has previously been widely studied. The challenge is that the turbine exhaust temperature, core power, and mass flow all change during the load-following operation.

The S-CO_2 Brayton cycle has a precooler that rejects heat to environment after work is produced, and it also determines the inlet condition of compressor. The heat rejection process occurs near the critical point. The changes in the inlet condition of compressor significantly impact the thermodynamic properties of the gas, and affect the compression process. Moreover, the surge line of the compressor changes as the inlet condition changes, which can substantially influence the safety of the compressor operation [4]. Unanticipated behavior may occur if the compressor inlet conditions enter the liquid-vapor dome of the T-S diagram [5].

Therefore, the fine control of the S-CO_2 compressor inlet conditions is required to keep the compressor operation reliably and efficiently. The use of LQ controllers has been proposed for the control of S-CO_2 precoolers. The LQ controller is a controller that minimizes a cost function for a given system by representing the system dynamics linearly and the cost as a quadratic equation [6]. LQ controllers have been proposed for the control of S-CO_2 precoolers because they offer several advantages, including stable system control, fewer tuning variables, and optimal control without additional tuning.

However, the previous studies only presented the feasibility of LQ controllers using MARS-KS codes, but did not provide experimental verification [7]. In this study, the experimental verification of the LQ controller is conducted using the autonomous Brayton cycle test loop (ABC test loop) constructed at KAIST. The system dynamics of precooler system obtained by simulation using MARS-KS code. The designed LQ controller using system dynamics was experimentally tested.

2. Methods and Results

This section describes the design and experimental validations of LQ controllers. The following section includes system identification, controller design, the implementation and experimentation of the LQ controller, and evaluation results.

2.1 LQ Controller Design Using MARS-KS

Based on the working mechanism of the precooler, the mechanism of the precooler system that uses the water flow control valve to change the CO_2 outlet temperature can be divided into four steps. First, the water control valve opening fraction changes. Second, the water flow rate changes according to the valve opening fraction. Third, the amount of heat removed by the water from the CO_2 changes due to the change in water mass flow rate. Therefore, the overall system diagram in Figure 1 can be divided into three parts as shown in Figure 2. That is, the dynamics G between the opening fraction of the water valve and the CO_2 outlet temperature shown in Figure 1 is represented by the combination of dynamics G_0, G_1, G_2 in Figure 2.

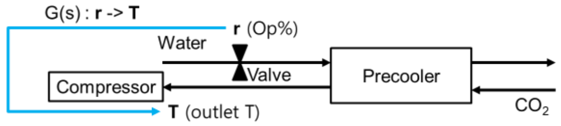

Fig. 1 System diagram of precooler system

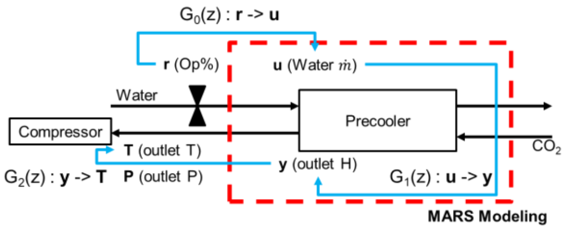

Fig. 2 Modified system diagram of precooler system

The previous research has shown that the dynamics between water flow rate and S-CO_2 outlet enthalpy in S-CO_2 pre-coolers can be modeled by identifying system dynamics at on-design [8]. During off-design operating conditions, the system dynamics is obtained by multiplying the on-design dynamics by a lumped correction factor, C_f. Therefore, to determine the system dynamics of a printed circuit heat exchanger (PCHE) type pre-cooler in the ABC test loop, the precooler was modeled with the MARS-KS code as shown in Figure 3.

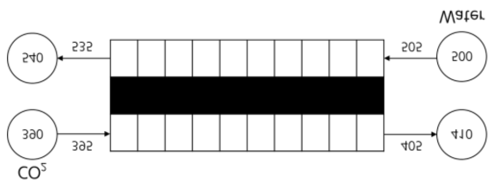

Fig. 3 Node structure of precooler system

To identify the system dynamics, the step signal was applied to the precooler system as an input and the output was measured in the system modeled with the MARS-KS code. To make the input signal a unit step and the output signal start at 0, the normalization was performed as shown in Equation 1.

$$u(k) = \frac{u_0(k)}{u_{0,min}} - 1$$
$$y(k) = 1 - \frac{y_0(k)}{y_{0,max}} \cdots (1)$$

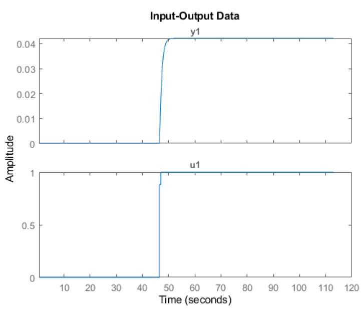

Fig. 4 System response for a unit step input

The normalized system I/O data was measured with the MARS-KS code, as shown in Figure 4. The transfer function $\tilde{G}(z)$ is approximated with Equation (2) using the least squares method on the data shown in Figure 4.

$$\frac{\mathcal{Z}\{y(k)\}}{\mathcal{Z}\{u(k)\}} = \frac{Y(z)}{U(z)} = \tilde{G}(z)$$
$$= C_f \frac{0.01989\,z + 0.004617}{z^2 - 0.3074\,z - 0.1112} \cdots (2)$$

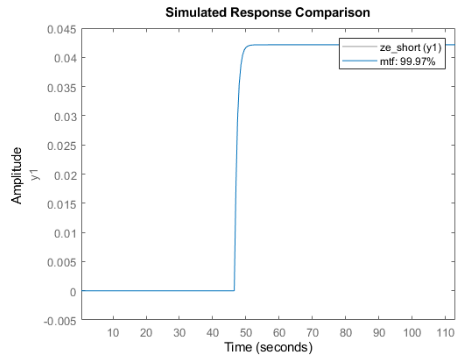

Fig. 5 System response comparison for a unit step input

Figure 5 is a graph comparing the system response calculated with MARS-KS simulation to the system response calculated using the transfer function to validate the transfer function in Equation 2. This shows that Equation 2 simulates the dynamics of the system well.

The state space realization of Equation 2 is given as Equation 3, using the observable canonical form

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}u(k) \\ \quad y(k) = \boldsymbol{C}\boldsymbol{x}(k) + Du(k) \end{cases} \cdots (3)$$

where,

$$\begin{cases} \boldsymbol{A} = \begin{bmatrix} -0.3433 & 1 \\ 0.05896 & 0 \end{bmatrix} \\ \boldsymbol{B} = \begin{bmatrix} 0.02004 \\ 0.001064 \end{bmatrix} C_f \\ \boldsymbol{C} = \begin{bmatrix} 1 & 0 \end{bmatrix} \\ D = 0 \end{cases}$$

The optimal LQ controller gains **K** that minimizes the performance index calculated by solving the Riccati equation [9]. As the precooler system is working on a discrete time domain, the discrete-time algebraic Riccati equation and the state space of the system of Equation 3 are used to calculate the optimal gain **K**.

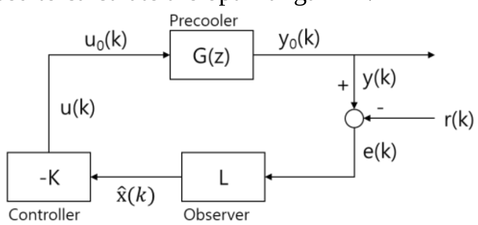

Fig. 6 LQ controller with full-state observer [7]

Let the value of $\mathbf{B}$ and gain $\mathbf{K}$ at the design point as $\mathbf{B_0}$ and $\mathbf{K_0}$ respectively, then the LQ controller with full state observer, shown in Figure 6, for an S-CO_2 precooler system that works on arbitrary CO_2 inlet condition by using appropriate C_f in the case of $\mathbf{R} = \mathbf{0}$ is calculated with Equation 4.

$$\mathbf{B} = C_f\mathbf{B_0} = C_f\begin{bmatrix}0.01989\\0.004617\end{bmatrix}$$
$$\mathbf{K} = C_f^{-1}\mathbf{K_0} = C_f^{-1}[15.449 \quad 50.265] \cdots (4)$$

By using the full state observer, the observed state $\hat{\mathbf{x}}$ of precooler system with LQ controller is given as Equation 5.

$$\hat{\mathbf{x}}(k+1) = \begin{bmatrix}-0.3074 & 0\\-0.07133 & -0.2321\end{bmatrix}\hat{\mathbf{x}}(k) - \begin{bmatrix}0.3074\\0.1112\end{bmatrix}e(k) \cdots (5)$$

where the control law of the LQ controller is

$$\mathrm{u} = -\mathbf{K}\hat{\mathbf{x}} = -C_f^{-1}\mathbf{K_0}\hat{\mathbf{x}} \cdots (6)$$

2.2 Experiment Using ABC Test Loop

The LQ controller based on modern control theory using system dynamics, as shown in Equation 3, was designed and implemented in the ABC test loop. To experimentally evaluate the LQ controller, an experiment was designed to control the disturbances introduced to the precooler during the control process used to change the overall output of the S-CO_2 system. Examples of demonstrable controls in the ABC test loop are heater output variation, turbine bypass, and turbo-alternator-compressor (TAC) rotational speed variation. Therefore, if the designed LQ controller can control the precooler under the above three disturbances to control the inlet temperature, the LQ controller can be applied to system-wide load-following control.

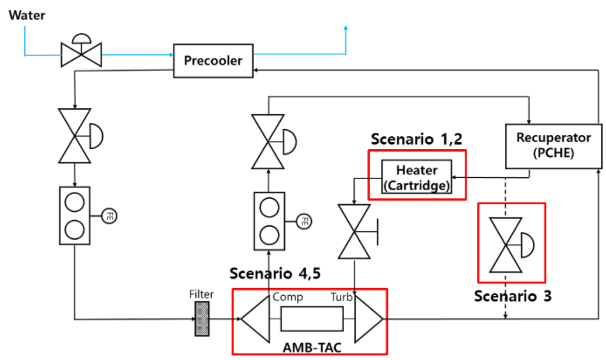

Fig. 7. ABC test loop diagram with scenario

Based on the three disturbance conditions, five scenarios were selected, including increasing/decreasing heater output, opening/closing turbine bypass valve, and increasing/decreasing TAC rpm. The LQ controller was tested for the five scenarios to evaluate the performance of the precooler controller. The portion of the ABC test loop that changes in each scenario is shown in Figure 7. The initial conditions of the compressor inlet conditions were chosen to be 35°C and 78 bar. In each scenario, the disturbance is removed after the system reaches steady state. For each disturbance in the five transient scenarios, the controller must fix the compressor inlet temperature to 35°C by controlling the water flow rate.

2.3 Evaluation

Figure 8 shows the results of controlling the compressor inlet temperature when five types of disturbance scenarios described in the previous section were inserted into the precooler system. The LQ controller was used to control the compressor inlet temperature during the experiment. The compressor inlet temperature over time is shown in blue and the target value is shown in red. In addition, the maximum positive and negative errors in each case are shown in black solid lines, and the error range ±0.5% is shown in dashed lines. The arrows indicate which disturbance scenario was applied. In between tested scenarios, there is a waiting period to restore the test conditions to initial conditions.

For the LQ controller, a steady-state error was observed: for each disturbance, the steady state was reached, but there was a constant deviation compared to the setpoint temperature. This error was caused by not calculating the lumped correction factor C_f exactly, but using an estimate. The maximum error that occurred during the control process was 0.52%. This shows that the LQ controller can achieve control goal for the five tested scenarios.

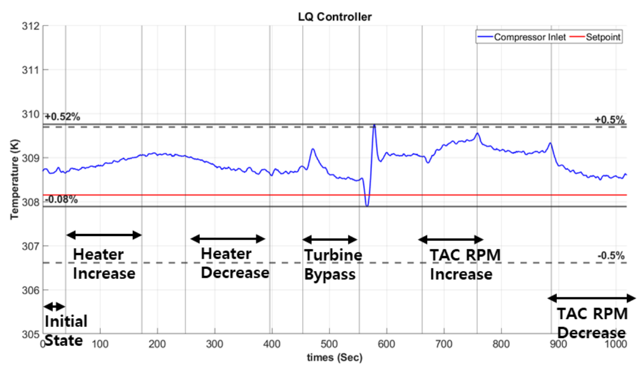

Fig. 8. CO_2 compressor inlet temperature of LQ-controlled precooler system

3. Conclusions

In this study, the LQ controller of an S-CO_2 Brayton cycle precooler is designed, which was previously verified by a computer code. First, the response of the system to a unit step input was simulated using experimental data and MARS-KS code to obtain a transfer function, which was found to be a good estimator of the open-loop response of the precooler system under the design condition. In addition, a lumped correction factor was used to ensure that the LQ controller can control not only the design condition, but also when the precooler system is operating under conditions outside the design condition. Finally, the designed LQ controller was implemented in the ABC test loop constructed at KAIST to validate the LQ controller of the S-CO_2 Brayton cycle precooler system under various off-design scenarios with experiments. The experimental results show that the designed LQ controller successfully controls the system with an error of less than 0.5%.

This study showed whether controllers designed with the MARS-KS code presented in the past studies behave as expected in real-world. The experimental results suggest that state-space based controllers designed using the MARS-KS code behave reasonably well in real world. However, the increased error from the previous estimates suggests that there is an error in the prediction of the lumped correction factor. Therefore, further research on the lumped correction factor is needed. First, research is needed on how to calculate the lumped correction factor to reflect the actual physics rather than what the MARS-KS code predicts. Next, if the lumped correction factor is difficult to compute, the development of a controller that is robust is also needed.

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REFERENCES

[1] Joung, T. H., Kang, S. G., Lee, J. K., & Ahn, J. (2020). The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. Journal of International Maritime Safety, Environmental Affairs, and Shipping, 4(1), 1-7.
[2] Kim, S. G., Yu, H., Moon, J., Baik, S., Kim, Y., Jeong, Y. H., & Lee, J. I. (2017). A concept design of supercritical CO_2 cooled SMR operating at isolated microgrid region. International Journal of Energy Research, 41(4), 512-525..
[3] Do Kyu Kim, Bong Seong Oh, and Jeong Ik Lee. "Control logic development of KAIST Micro Modular Reactor for marine propulsion." Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 18. Vol. 19. 2017.
[4] Y. Jeong, "Development of correction method considering real gas effect for S-CO_2 compressor performance evaluation and operating limits," KAIST Ph.D's thesis, 2022.
[5] Wright, S. A., Radel, R. F., Vernon, M. E., Pickard, P. S., & Rochau, G. E. (2010). Operation and analysis of a supercritical CO_2 Brayton cycle (No. SAND2010-0171). Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States).
[6] Mehrmann, V. L. (Ed.). (1991). The autonomous linear quadratic control problem: theory and numerical solution. Berlin, Heidelberg: Springer Berlin Heidelberg.
[7] Kim, Gi Hyeon, and Jeong-Ik Lee (2023, May). "Simulation of a Linear Quadratic Regulator Controller for S-CO_2 Cycle Using MARS-KS." In KNS spring meeting.
[8] Kim, Gi Hyeon, and Jeong-Ik Lee. "STUDY OF PID-BASED S-CO_2 PRECOOLER SYSTEM CONTROL METHOD." 5th S-CO_2European Conference. The European Conferences on Supercritical CO_2 (S-CO_2), 2023.
[9] Pappas, T., Laub, A., & Sandell, N. (1980). On the numerical solution of the discrete-time algebraic Riccati equation. IEEE Transactions on Automatic Control, 25(4), 631-641.