2023-sCO2.eu-110

STUDY OF PID-BASED S-CO_2 PRECOOLER SYSTEM CONTROL METHOD

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ABSTRACT

The distributed power supply must change its output according to the surrounding demand. Therefore, in order to use the supercritical CO_2 Brayton cycle for a distributed power source, the output of the power generation cycle must be controlled according to the needs of the surroundings. This study focuses on the precooler among the various components of the Brayton cycle of supercritical carbon dioxide and conducts control studies. The design of the controller that fixes the temperature at the outlet of the precooler through the control of the precooler was carried out through the Autonomous Brayton Cycle loop in KAIST. In this study, a control methodology is first developed from a computer simulation code. The experimental data from the Autonomous Brayton Cycle loop, computational simulation is performed and the response to the input of the precooler system is calculated. PID controller is designed by modeling the precooler system and using classic control theory. The suggested controller development process in this study can reduce trial and error in future control development for the supercritical CO_2 power cycle.

INTRODUCTION

The S-CO_2 Brayton cycle is attracting attention as a power generation cycle that can be used for the next-generation nuclear power plants instead of the steam cycle currently used. The S-CO_2 Brayton cycle is an original technology applicable to nuclear power generation and various fields such as waste heat recovery and solar power generation [1]. There are several reasons why the S-CO_2 Brayton cycle is receiving attention. First, when the turbine inlet temperature condition exceeds 500 °C, the efficiency of the S-CO_2 Brayton cycle becomes higher than that of the steam Rankine cycle or the helium Brayton cycle [2]. In addition, the compression work of the S-CO_2 Brayton cycle can be significantly reduced due to the compression process taking place near the critical point of CO_2 [3]. Therefore, the size of components such as turbines and compressors can be significantly reduced.

Due to its small size and high efficiency, the S-CO_2 Brayton cycle is suitable for small modular reactor (SMR) applications. The small size and high efficiency of the SMR are positive factors for using the SMR as a distributed power source. Distributed power generation is a power generation method in which the power source is placed near the power demand, unlike the existing centralized power source. This generation method is receiving attention because it can reduce the number of transmission facilities, improve system stability, and reduce the initial investment burden. To use any power generation system as a distributed power source, the output of the power generation system should be able to adjust according to the needs. Due to this requirement, various attempts have been made to control the output of the S-CO_2 Brayton cycle under different circumstances.

Currently, many S-CO_2 Brayton cycles proposed for output control are turbine bypass control and inventory control. If these two control methods are applied to a simple recuperated cycle, it is shown in Figure 1 [4 & 5].

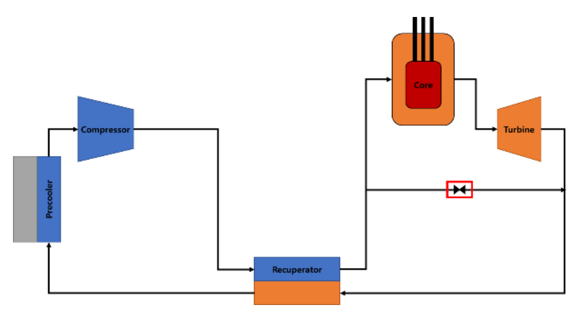

Fig. 1(a) Simple recuperated with turbine bypass control

DOI: 10.17185/duepublico/77265

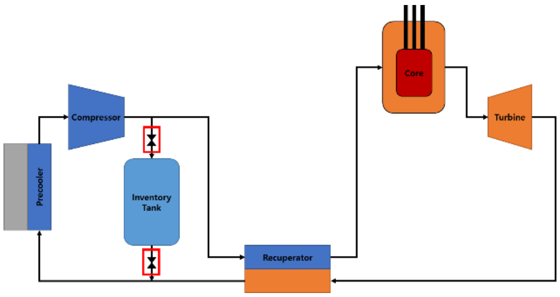

Fig. 1(b) Simple recuperated with inventory control

The turbine bypass control in Figure 1(a) and the inventory control in Figure 1(b) are aimed at global control of the system output. However, experiments on the system suggest that a controller for each component as well as a global controller is needed for a stable S-CO_2 system. For example, in the Sandia report published in 2019, it was mentioned that perturbation occurred in the heating and cooling of the close loop due to manual control, which caused instability of the turbomachinery and imposed faster thermal transients than required for equipment [7]. Therefore, this study discusses the PID controller design methodology to keep the CO_2 temperature at the outlet of the precooler constant. This solves the problem raised in the Sandia report by maintaining the compressor inlet temperature condition constant, thereby securing the stability of the turbomachinery.

If PID control is used, it is necessary to appropriately determine the PID control parameters to properly control the system. However, due to the limitations of the experimental system that can test the S-CO_2 Brayton cycle, these control methods and control parameters are calculated and verified through the system simulation code in the open literatures [7,8,9,10]. In this paper, the authors aim to obtain actual experimental data from a supercritical Brayton cycle experimental facility, Autonomous Brayton Cycle (ABC) test loop, and to establish PID control logic using the obtained data so that it can be used for the power cycle control in the future.

ABC TEST LOOP

ABC test loop is an abbreviation for the Autonomous Brayton Cycle test loop. This experimental facility was constructed for an integrated experiment on the simple recuperated S-CO_2 cycle. ABC loop is made of a turbo alternator compressor (TAC), printed circuit heat exchanger (PCHE) type recuperator, electric cartridge type heater, and precooler. In addition, for the control experiment, control valves are attached to the inlet and outlet of the compressor, and other control valves are attached to the water flow path of the precooler. The turbine bypass flow path and turbine bypass valve are attached for the experiment on turbine bypass control.

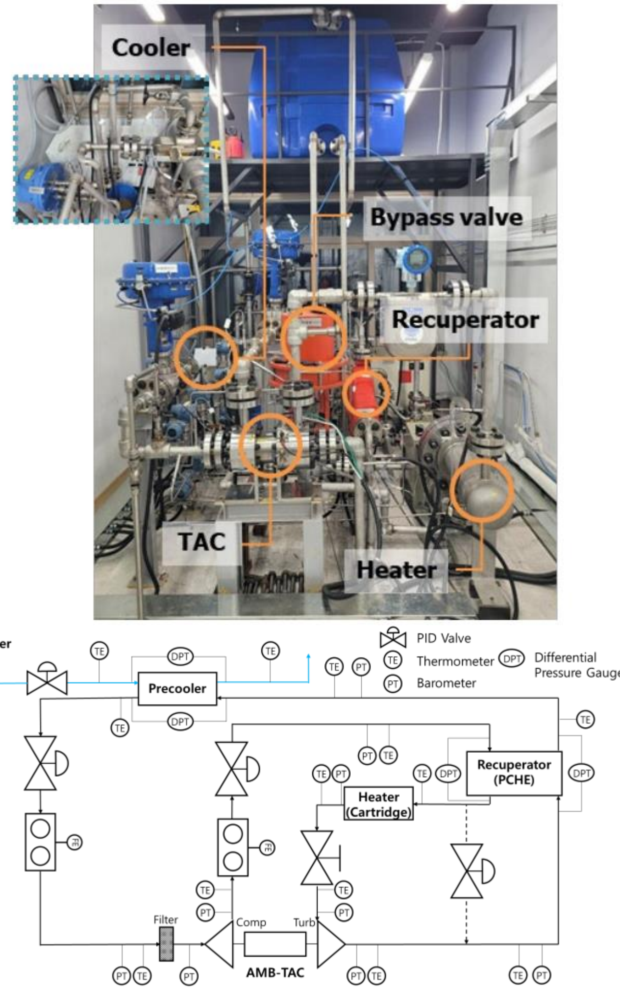

Fig. 2 ABC test loop and schematic diagram [11]

As the name suggests, the ABC test loop is designed to enable the I/O of data using the computer to automatically test the S-CO_2 Brayton cycle. The pressure, temperature, and mass flow rate of each flow path are converted into digital signals and input to the computer in real-time through the Programmable Logic Controller (PLC). The computer controls the opening/closing degree of the control valve and the heater output through the PLC by performing calculations based on the received data and the user's input. In addition, it is possible to calculate values such as enthalpy or the effectiveness of a heat exchanger that cannot simply be measured with a measuring instrument in real-time. Calculation of thermodynamic data is performed in real-time based on NIST's REFPROP and the measured physical quantity, and it is programmed so that the user can easily change the physical quantity to be calculated.

Since the ABC test loop is designed to perform an integrated experiment on the Brayton cycle, there are various experiments performed with the test loop so far. One of them is the compressor surge protection control experiment. A surge is a phenomenon that occurs when the mass flow rate in the compressor decreases below a certain value, the surge limit.

DOI: 10.17185/duepublico/77265

When a surge occurs, the compressor generates strong vibration and noise, which may damage or even destroy the compressor. Therefore, it is important to secure the surge margin above a certain level, which is a number that indicates how far the compressor is from the current surge limit.

The compressor surge protection control experiment is an experiment to check whether the surge margin can be restored by automatically recognizing a dangerous situation when the surge margin of the compressor falls below a certain value. For the experiment, the control valves of the inlet and outlet were reduced while maintaining the rotational speed of the compressor. This reduces the compressor inlet mass flow and therefore the surge margin. Baek showed that when the surge margin falls below 15%, the experimental device automatically recognizes it and opens the valve to restore the surge margin, thereby avoiding a surge [11].

As such, various experiments are possible with the current ABC test loop, and further improvements and upgrades are planned for expanding the capabilities of the test loop. Recent improvements include increasing the power output of the electric cartridge heater and replacing the bearings of the TAC from ball bearings with magnetic bearings. The target of recent experiments using the ABC test loop is to demonstrate stable operation over a wide range of magnetic bearing TAC.

MARS

The Multi-dimensional Analysis of Reactor Safety (MARS) code is a nuclear thermal-hydraulic safety code developed by Korea Atomic Energy Research Institute (KAERI). MARS was developed based on USNRC's RELAP5/MOD3.2.1.2 and COBRA-TF to calculate the transient multi-dimensional behavior of thermal-hydraulic systems in light water reactors [12]. The basic field equation of the MARS code consists of two phasic continuity equations, two phasic momentum equations, and two phasic energy equations. This code is being used by the Korea Institute of Nuclear Safety (KINS) to evaluate the safety of actual nuclear power plants [13].

In this study, data obtained from actual experiments with the ABC test loop will be simulated using the MARS code, and the open loop characteristics of the heat exchanger used for the precooler will be analyzed from the MARS simulation. There are two main reasons for not using the actual ABC test loop experimental data immediately and simulating the system with MARS code. First of all, in the actual system, there are many other components such as compressors, turbines, and heaters in addition to the heat exchanger, so it is difficult to see the response of only the heat exchanger. In addition, to design the controller, the response of the open loop system should be analyzed. However, in the ABC test loop, the fluid in the precooler passes through the other components and back to the heat exchanger. This causes feedback that is physically difficult to interpret, making the open loop system uninterpretable.

Therefore, the MARS code should be able to properly simulate the experimental equipment and predict the experimental results. That is, the MARS code must accurately calculate the heat exchange between CO_2 and water in the precooler under transient conditions. However, since the MARS code is designed to evaluate the safety of a water-cooled reactor, the physical properties of S-CO_2 are not applied. In addition, since the heat exchange model was created centered on the reactor core, the transient behavior of PCHE was not well simulated. The KAIST research team solved these problems as follows. First, the precise physical properties of CO_2 were implemented to the MARS code based on NIST's REFPROP database. Second, the heat transfer correlation of PCHE was added to the heat structure set of the MARS code [14].

The results of the compressor surge avoidance control experiment were used to simulate with the MARS code. The result of comparing the MARS code with the actual experimental data is shown in Figures 3 to 5. It can be confirmed that the MARS code simulates the actual experiment well.

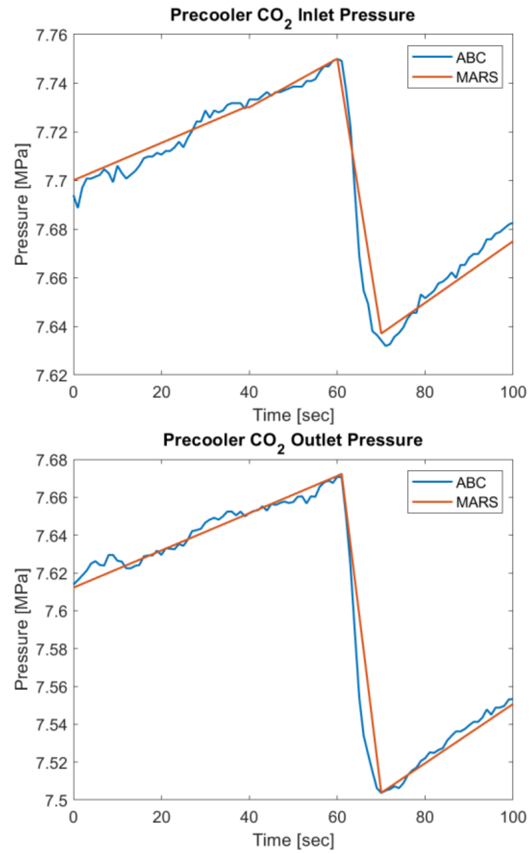

Fig. 3 CO_2 pressure comparison of ABC compressor surge avoidance control experiment and MARS simulation

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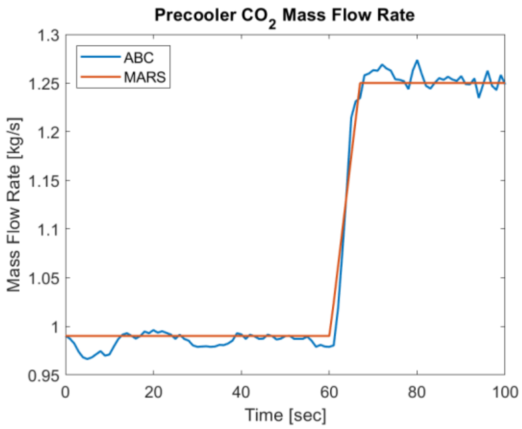

Fig. 4 CO_2 mass flow rate comparison of ABC compressor surge avoidance control experiment and MARS simulation

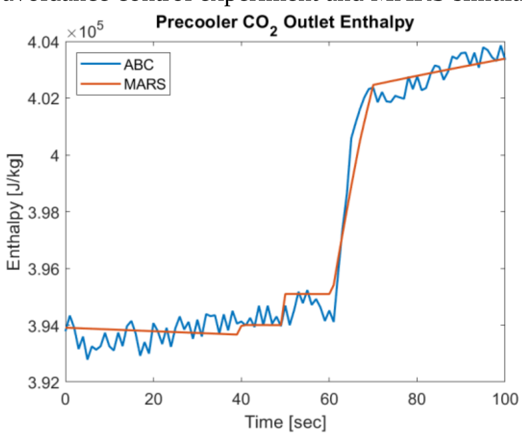

Fig. 5 CO_2 outlet enthalpy comparison of ABC compressor surge avoidance control experiment and MARS simulation

DIGITAL CONTROL

The ABC test loop in the real world is, of course, a system in which a physical quantity continuously changes with time. However, the computer controls the ABC test loop, which is digital. The process of the computer controlling the ABC test loop is as follows. The physical quantity of the ABC test loop is converted into an electrical signal through a measuring instrument. The electrical signal output from the instrument goes through the PLC and is measured once per iteration for each time the computer passes through the iteration. For a single iteration, the computer performs calculations based on the measured data. The computer controls by sending a signal to the ABC test loop based on the calculated result and the user's input. That is, the computer replaces the controller of the classical control system, which receives the output value of the system, and controls the system by giving feedback. Therefore, to control the ABC test loop, the system must be analyzed in the discrete-time domain rather than the continuous-time domain.

The signal in the discrete-time domain uses Z-transform to figure out the characteristic of the signal in the frequency domain. This is one of the differences between the discrete-time domain signal to the continuous-time domain, and the characteristic of the continuous-time domain signal is analyzed using Laplace transform. Z-transform is a transformation that transforms a discrete-time domain signal into a complex frequency-domain form and is defined as the following equation for signal *x(k)*, whereas *k* is a positive integer.

$$X(z) = Z\{x(k)\} = \sum_{k=0}^{\infty} x(k)z^{-k} \quad (1)$$

Using Z-transform, it is possible to obtain a transfer function that is a linear transformation between the discrete-time input signal *u(k)* and the output signal *y(k)* for any system. The transfer function is important in designing the appropriate controller and system characteristics. If the Z-transforms of *u(k)* and *y(k)* are *U(z)* and *Y(z)*, the transfer function *G(z)* is given as follows.

$$G(z) = \frac{Y(z)}{U(z)} = \frac{Z\{y(k)\}}{Z\{u(k)\}} \quad (2)$$

OPEN LOOP SYSTEM ANALYSIS

In general, to design a controller for an arbitrary system, the process variable (PV) must first be determined. Next, check which variable to manipulate in the system to control the PV as a setpoint (SP). Then, devise the model for the given system. Finally, the controller can be designed based on the model and the appropriateness of the controller can be checked by applying the designed controller to the system. The PV of the controller targeted in this study is the compressor inlet temperature, that is, the pre-cooler CO_2 outlet temperature. The variable of the system to control this is the control valve attached to the waterside pipe. Therefore, the system that uses the opening/closing rate of the control valve as the system input and the CO_2 outlet temperature as the system output is a precooler system that must be controlled. Figure 6 shows this as a block diagram.

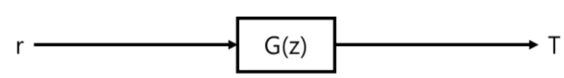

Fig. 6 Block diagram of precooler open loop system

According to the results of previous studies, in the case of a steam-water heat exchanger, a transfer function exists between the flow rate of water and the outlet temperature of the water, and it can be calculated physically [15]. Assuming that S-CO_2 precooler will respond similarly, it will be possible to design a controller that controls the outlet temperature by adjusting the flow rate using the previously proposed function for steam-water heat exchanger. Similarly, to design the controller of the precooler system, the characteristics of the open loop system should be identified and the open loop transfer function should be calculated. However, the precooler system in this study, there is no linear relationship between system input and output because the physical properties of CO_2 are non-linear near the critical point. Therefore, it is necessary to separate the non-linear elements from the system and approximate the system as a linear system, and the method to calculate these non-linear elements is required.

To approximate the precooler system linearly, this study focused on the amount of heat exchanged in the precooler. The

DOI: 10.17185/duepublico/77265

heat gained by water and the heat lost by CO_2 has to be the same if heat loss is neglected, and this amount of heat is calculated as in Equation (3).

$$\dot{m}_{water} c_{p,water} \Delta T_{water} = \dot{m}_{CO_2} \Delta h_{CO_2} \quad (3)$$

From the equation, the amount of heat gained by water increases linearly with the mass flow rate of water. In addition, CO_2 loses heat as much as the amount of heat gained by water, and the enthalpy of CO_2 changes. Therefore, in this study, it is assumed that the relationship between the mass flow rate of water and the outlet enthalpy of CO_2 can be approximated as a linear system. With this assumption, the block diagram in Figure 6 can be redrawn as in Figure 7.

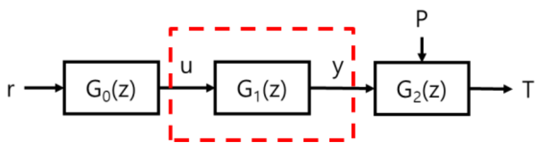

Fig. 7 Modified block diagram of precooler open loop system

In Figure 7, the nonlinear elements are separated from the system, and the remaining part is approximated as a linear system. To avoid confusion in the future, the system inside the red dotted line will be referred to as a linearized precooler system, and the entire system will be referred to as a precooler system. $G_0(z)$ is a relational expression between the valve open fraction and the water mass flow. This relationship has a different formula depending on the type of valve and can be calculated using the flow coefficient and formula provided by the valve manufacturer. In the case of $G_2(z)$, the formula is to convert the CO_2 outlet enthalpy to the CO_2 outlet temperature. If the CO_2 outlet pressure and CO_2 outlet enthalpy are known, so it can be calculated in various ways, such as using the REFPROP library directly. Therefore, it is possible to calculate $G_2(z)$ with one additional pressure measurement at the precooler outlet. That is, if only the linearized precooler system $G_1(z)$ is obtained, the characteristics of the entire open loop system can be identified, and an appropriate controller can be designed according to the classical control theory.

ON-DESIGN TRANSFER FUNCTION

For the on-design conditions of the ABC test loop, CO_2 from the recuperator enters the precooler at 321.74K, 8.6MPa, and exits at 308.15K, 7.6MPa. In addition, the inlet temperature and pressure of water were kept constant at 298.15 K and 1 bar, respectively during the experiment. To calculate the transfer function of the open loop linearized precooler system under the on-design conditions, the response of the system was simulated using the MARS code when the water flow rate was doubled while the CO_2 inlet condition was fixed to the on-design conditions.

The input signal of the system is the water flow rate, and the output signal of the system is the CO2 outlet enthalpy. In order to adjust the input signal u(k) of the transfer function to the unit step input and set the initial value of output signal y(k) as 0, the original input signal u0(k) and the output signal y0(k) were normalized using Equation (4).

$$u(k) = \frac{u_0(k)}{u_{0,min}} - 1$$
$$y(k) = 1 - \frac{y_0(k)}{y_{0,max}} \quad (4)$$

The output signal *y(k)*, which is the response of the system to the input signal *u(k)* to which normalization of Equation (4) is applied, is shown in Figure 8.

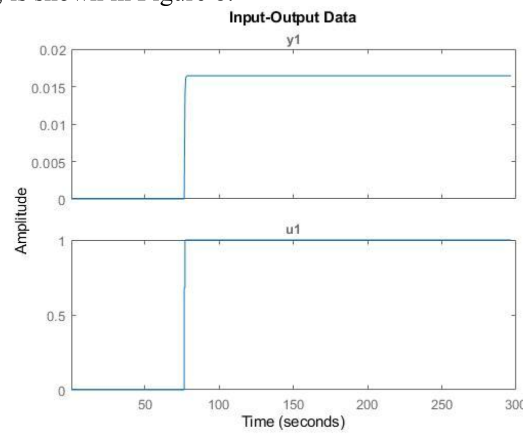

Fig. 8 System response for a unit step input

When the transfer function $G_1(z)$ is obtained from the step response using the least square method, it can be approximated by Equation (5) having 1 zero and 2 poles.

$$G_1(z) = \frac{0.02004\, z + 0.001064}{z^2 + 0.3433\, z - 0.05896} \quad (5)$$

Figure 11 compares system responses between the transfer function and the actual system for a unit step input. The blue line is the response of the transfer function whereas the grey line is the response of the MARS simulation. The transfer function perfectly simulates the real system, so it is possible to approximate the linearized precooler system with the transfer function $G_1(z)$.

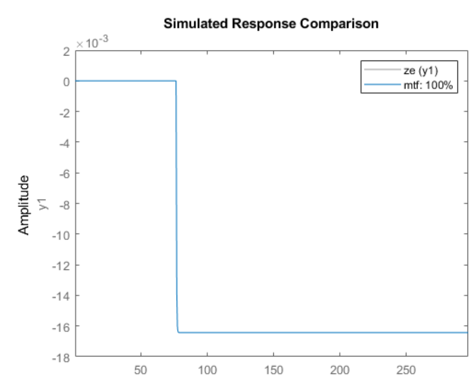

Fig. 9 System response comparison for a unit step input

DOI: 10.17185/duepublico/77265

In addition, poles, which are values that make the denominator of this transfer function as zero, are -0.4690 and 0.1257. The poles of transfer function G1(z) are located inside the unit circle on the complex plane. Since the poles of the linearized precooler system in the discrete-time domain exist inside the unit circle, the linearized precooler system is asymptotically stable. If the system is asymptotically stable, every mode converges to zero as time approaches infinity, which results in output convergence. In other words, the heat exchanger performance does not diverge and become unstable during operation.

To examine whether the approximate transfer function simulates the actual heat exchanger well, the test case of Figure 10 consisting of unit step input and ramp function was used.

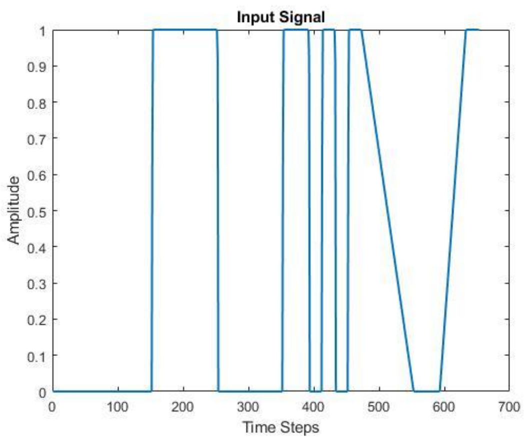

Fig. 10 Complex input signal for system test

Figure 11 shows the comparison between the simulation result using the MARS code and the result calculated through the transfer function. In this case, the y-axis is the actual enthalpy value, not the normalized value from Equation (4). The error between these two enthalpy values is 1.06%. Therefore, as shown in Figure 11, it can be confirmed that the response of the system calculated from the transfer function closely simulates the response of the real system even for more complex inputs.

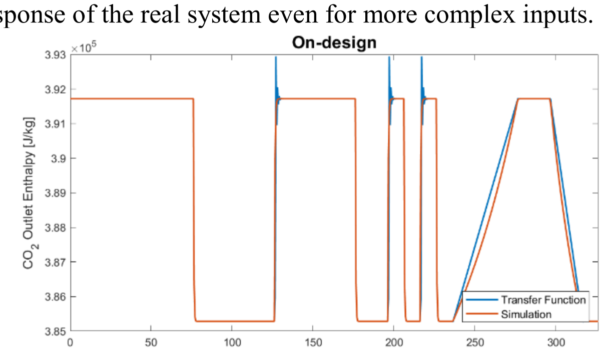

Fig. 11 On-design system response comparison for complex signal

OFF-DESIGN TRANSFER FUNCTION

Kwon et al. work presented a method for approximating the amount of heat transferred from the recuperator and precooler under the off-design condition in the S-CO_2 Brayton cycle [16]. In this study, it was shown that the amount of heat transferred from the precooler in the off-design condition can be obtained by multiplying the constant calculated using the on-design condition in the original logarithmic mean temperature difference (LMTD) method and the linear correction value obtained in the off-design condition. Inspired by this, this study hypothesized that the response of the linearized precooler system under the off-design conditions could be obtained by multiplying the transfer function to the on-design conditions by the correction value.

To verify the hypothesis, the test case of Figure 10 used input as an input signal for 8 different off-design conditions, and the system response was investigated with the transfer function and MARS code. The inlet condition of the water remained the same at the on-design condition. Each off-design condition is indicated by an arrow drawn from the CO_2 inlet condition to the outlet condition in Figure 12. The middle red arrow indicates the on-design condition.

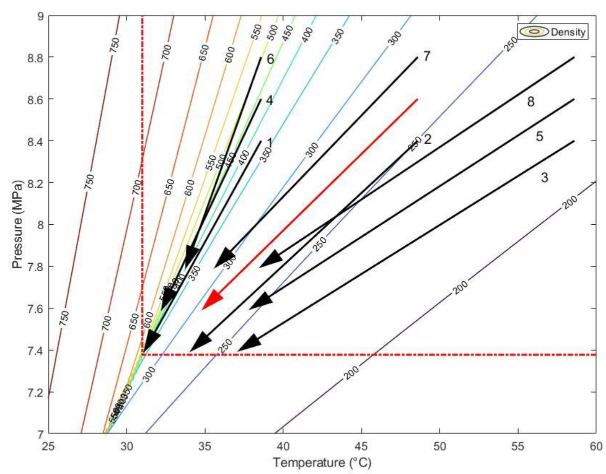

Fig. 12 Off-design CO_2 conditions

Figure 13 shows the comparison of the response of the system under off-design condition 1 and the response calculated with the transfer function shown in Equation (4). As shown in the figure, the transfer function predicts the response of the system similarly, but incorrectly predicts the amplitude of the response.

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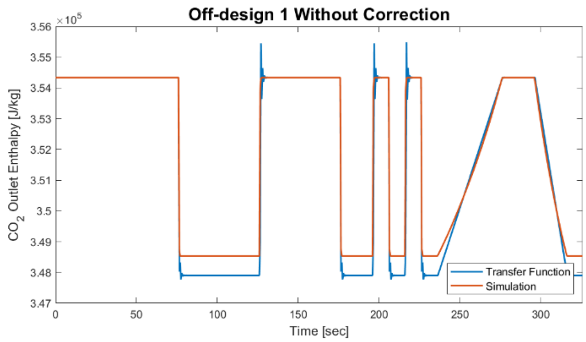

Fig. 13 Off-design response estimation without correction

Therefore, the amplitude should be corrected by multiplying the appropriate scalar C_f containing the information of the off-design condition. This correction factor was calculated as in Equation (6).

$$C_f = \frac{A_{min,on}}{A_{min,off}} \quad (6)$$

It can be confirmed that the transfer function multiplied by the correction value approximates the system response better for all 8 off-design conditions as shown in Figures 14 to 21.

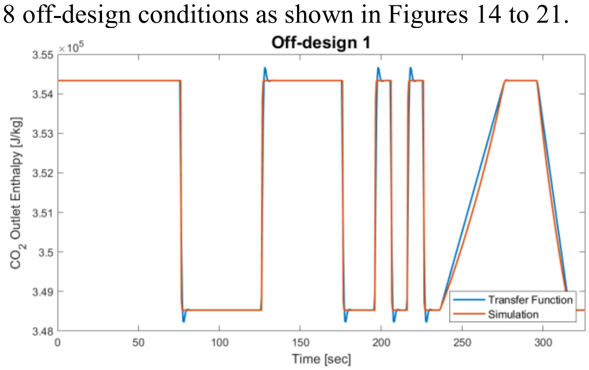

Fig. 14 Response estimation of off-design 1 (maximum error: 1.283%)

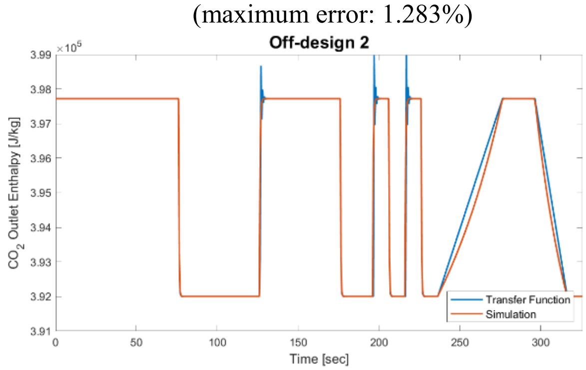

Fig. 15 Response estimation of off-design 2 (maximum error: 1.035%)

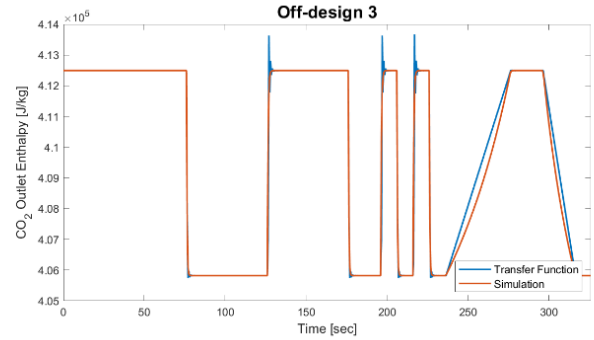

Fig. 16 Response estimation of off-design 3 (maximum error: 0.8349%)

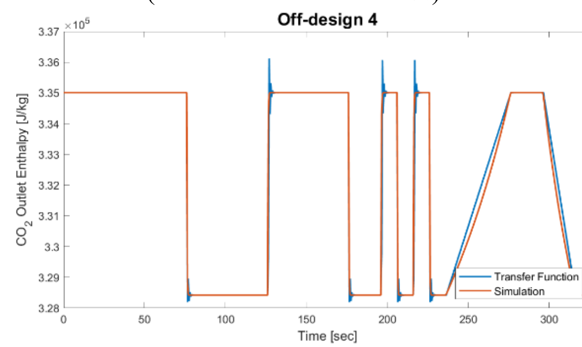

Fig. 17 Response estimation of off-design 4 (maximum error: 1.415%)

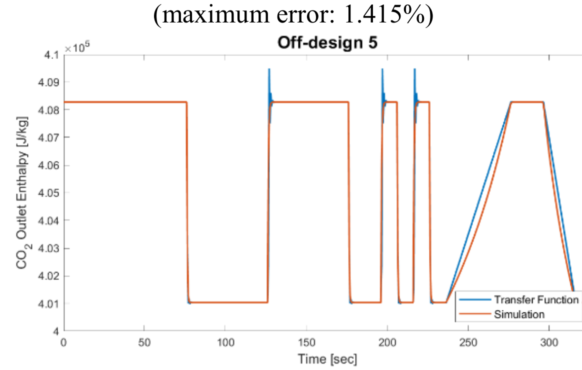

Fig. 18 Response estimation of off-design 5 (maximum error: 0.8885%)

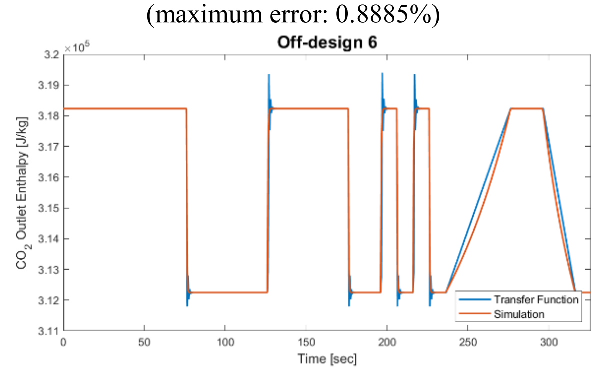

Fig. 19 Response estimation of off-design 6 (maximum error: 1.352%)

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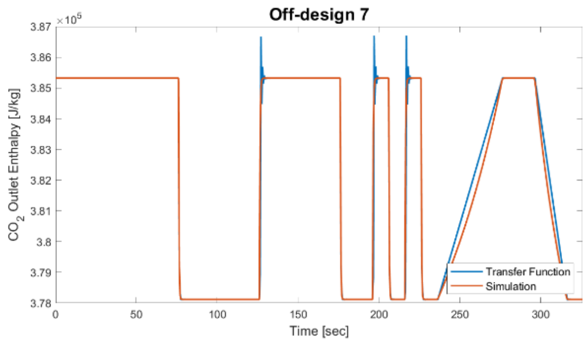

Fig. 20 Response estimation of off-design 7 (maximum error: 1.252%)

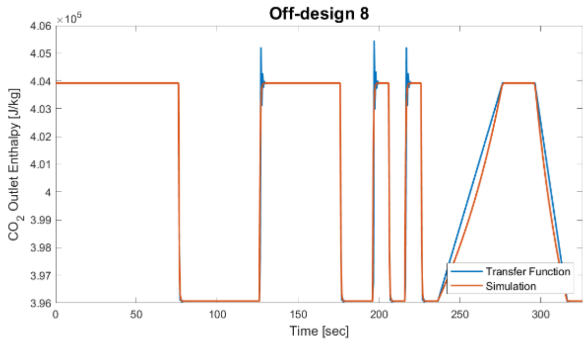

Fig. 21 Response estimation of off-design 8 (maximum error: 1.195%)

Figure 22 shows the results plotted against temperature by calculating the correction factor for each off-design condition and on-design condition. The value next to each data point is a correction factor that is exact with the design condition number, respectively. Points of the same color have the same pressure. For the same pressure, as the temperature increases, the correction factor C_f increases. Since C_f is the correction factor that is multiplied by the transfer function, the larger the C_f, the greater the change in the amount of enthalpy CO_2 loses in response to the change in water flow rate. Therefore, as the CO_2 inlet temperature increases, the CO_2 outlet temperature for the entire precooler system becomes more sensitive to changes in the water valve fraction.

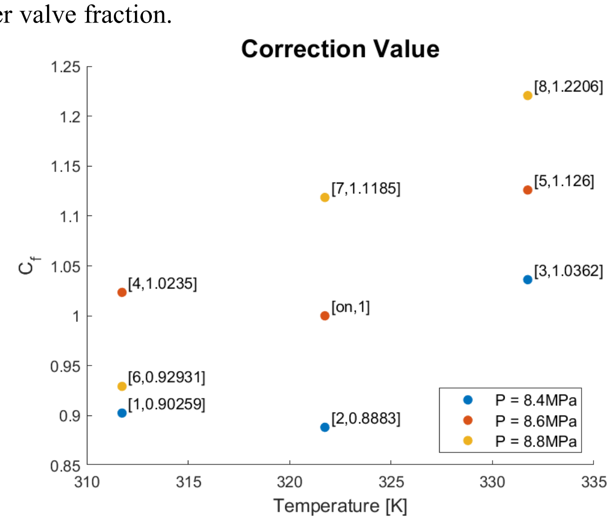

Fig. 22 Correction factor C_f of tested conditions

CONTROLLER DESIGN USING TRANSFER FUNCTION

Ziegler-Nichols method is popular to determine the PID control parameters of various system, including the S-CO_2 system. The Ziegler–Nichols method is a method for heuristically determining the parameters of the PID controller [17]. The advantage of this method is that the parameters of the controller can be obtained from iterative tuning work even without system analysis. However, the controller determined with the Ziegler-Nichols method requires additional tuning due to having an aggressive gain, and having a large overshoot and vibration response [18]. In addition, to calculate the settling time and overshoot to evaluate the system, it is necessary to attach a controller and obtain data from simulation or experiment. By finding a closed loop transfer function using the open loop transfer function of the system to be controlled, it is possible to design controller that does not suffer from the limitations of the Ziegler-Nichols method.

$$C(z) = K_p + \frac{T}{2}\frac{z+1}{z-1}K_i + \frac{z-1}{Tz}K_d \quad (7)$$

The transfer function of the PID controller in the discrete-time domain is given as Equation (7). Applying this to the open loop linearized precooler system and receiving unit feedback to apply PID control, a block diagram can be drawn as shown in Figure 23.

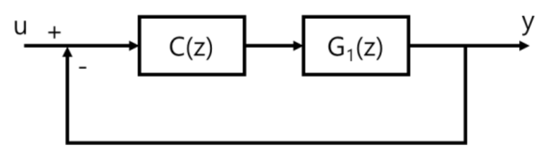

Fig. 23 Feedback loop with PID controller

The transfer function of the closed-loop system in Figure 24 is calculated as Equation (8). To determine the appropriate PID control parameters, the Equation (8) transfer function is tuned for *Kp, Ki,* and *Kd* values.

$$\frac{Y(z)}{U(z)} = \frac{G_1(z)}{1 + G_1(z)C(z)} \quad (8)$$

Using the calculation results to determine whether the settling time and overshoot of the system are appropriate, a PID controller to control the system can be designed.

Figure 24 shows the system's response for input signal at Figure 10 calculated based on the transfer function of the closed-loop system calculated using Equation (8). Where, K_p = 1.0171, K_i = 0, K_d = -0.1722. When the PD controller is applied, the system perfectly removes overshoots.

DOI: 10.17185/duepublico/77265

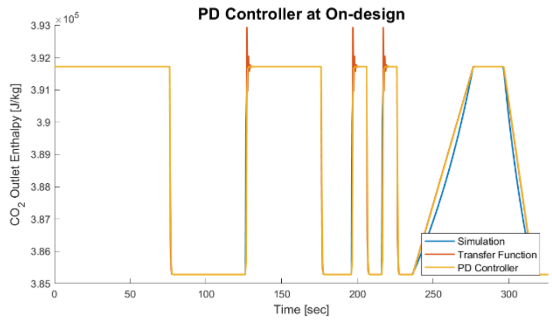

Fig. 24 Response of the system with PD controller

The PID controller in Figure 23 controls $G_1(z)$. Therefore, to control the whole precooler system in Figure 8, a little modification of the system is still required.

Figure 25 is a block diagram drawn reflecting this modification. $G_3(z)$ is a function that calculates the enthalpy of CO_2 using temperature and pressure, and $G_4(z)$ is a function that converts the flow rate of the valve into the opening/closing rate of the valve. These are the inverse functions of $G_2(z)$ and $G_0(z)$ that can be calculated using REFPROP and valve data, respectively. Therefore, the PID controller calculated using Figure 23 can be used for the whole system control.

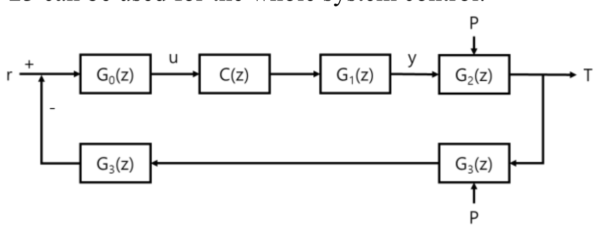

Fig. 25 Precooler system with PID controller

SUMMARY AND FUTURE WORKS

In this study, the data obtained from the ABC test loop, a simple recuperated S-CO_2 Brayton cycle experimental facility, was used for designing a controller for the S-CO_2 Brayton cycle. To obtained data was first simulated with the MARS code so that an appropriate transfer function can be found using the verified simulation. The transfer function of the open loop linearized precooler system was obtained from the response to the unit step input of the system. It was shown that this transfer function well simulates the open loop response of the linearized precooler system under the on-design condition. In addition, even when the precooler system is under the off-design conditions, it was shown that the transfer function obtained for the on-design conditions can be used by simply multiplying an appropriate scalar value. This means that if the controller is designed under any one condition, the same controller can be used in a wide range in the case of the S-CO_2 precooler controller system. Finally, it was shown that it is possible to design a PID controller to control the S-CO_2 linearized precooler system using the transfer function calculated under the on-design conditions, and a method for applying it to the entire S-CO_2 precooler system is presented.

The conclusions of this study suggest several further studies. First, the PID controller designed with the transfer function has to be applied to the actual experimental system and verified. Next, knowing the characteristics of the open-loop system in the discrete-time domain, various control techniques such as perfect tracking control, full-state feedback control, model predictive control, and disturbance observer control can be used in addition to PID control. It is necessary to study the design and application of the controller using these techniques in the S-CO_2 system. Finally, in this study, the system's response was calculated after simulating the system with the system code. To improve the method, a study to design a controller by analyzing the dynamics of the system with the system response obtained by applying an appropriate filter to the response of the actual experimental device can be also proposed.

NOMENCLATURE

$A_{min,on}$	Minimum amplitude at on-design condition
$A_{min,off}$	Minimum amplitude at off-design condition
$C(z)$	Controller transfer function
$c_{p,water}$	Water specific heat
$G_0(z)$	Valve open fraction to mass flow rate function
$G_1(z)$	Precooler system linear transfer function
$G_2(z)$	CO_2 enthalpy to temperature function
$G_3(z)$	CO_2 temperature to enthalpy function
$G_4(z)$	Valve mass flow rate to open fraction function
Δh_{CO_2}	Precooler CO_2 enthalpy difference
k	Positive integer
K_p	Coefficient of PID proportional term
K_i	Coefficient of PID integral term
K_d	Coefficient of PID derivation term
$\dot{m}_{CO_2}$	Mass flow rate of CO_2 at precooler
$\dot{m}_{water}$	Mass flow rate of water at precooler
P	Pressure
r	Valve input signal
T	Time step size at discrete-time domain
ΔT_{water}	Temperature difference of water
u	Input signal
$U(z)$	Z-transform of input signal
y	Output signal
$Y(z)$	Z-transform of output signal

ACKNOWLEDGEMENTS

This research was supported by Civil-Military Technology Cooperation Program (iCMTC) funded by the Agency for Defense Development – South Korea (17-CM-EN-04).

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DOI: 10.17185/duepublico/77265

DOI: 10.17185/duepublico/77265
URN: urn:nbn:de:hbz:465-20230427-102853-9