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System Modeling of KAIST S-CO₂ ABC Test Loop

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1. Introduction

Recently, the supercritical carbon dioxide (S-CO_2) cycle has attracted attention as the promising power conversion system for various power applications. Many research institutions have built experimental facilities to study the behavior of S-CO_2 power system. In KAIST, the integral test facility has been recently constructed to experimentally demonstrate the autonomous operation of the simple recuperated S-CO_2 cycle. Through the integral test at the system level, it is expected to contribute to many areas such as experimental demonstration of S-CO_2 power system, verification of control logic, and establishment of operational strategy. It can also provide data for validation of the system analysis code.

Precise modeling into the system code is essential not only for code validation, but also for predicting results to determine the possible test range. The authors previously modified the MARS code to simulate the S-CO_2 system, and performed code validation under the component level testing using the compressor performance test results [1]. In this paper, the newly constructed test loop was modeled using the modified MARS code and compared with the compressor surge margin control test results.

2. Method and Results

2.1 ABC Test Loop

Autonomous Brayton Cycle (ABC) test loop has been built in KAIST for the integral test of simple recuperated S-CO_2 cycle [2]. It consists of turbo alternator compressor (TAC), electric cartridge heater, PCHE type recuperator, and two precoolers. In addition, to demonstrate autonomous control, there are control valves at the front and rear ends of the compressor, and a turbine bypass valve is also installed. At present, basic autonomous control tests have been performed in the initial stage, and renovation including heater power increase is in progress for more systematic tests in a wider range.

Especially for the turbomachinery, TAC with the ball bearing is now installed. It was designed a few years ago and the turbine design point was set higher than the operating conditions of the experimental facility in consideration of the scale-up of the test loop in the future. Therefore, since there is a possibility of reverse flow from the turbine side when operating under the current heat source condition, the turbine wheel was removed in this test. It is scheduled to be replaced with TAC with the magnetic bearing designed under the current operating conditions in the near future.

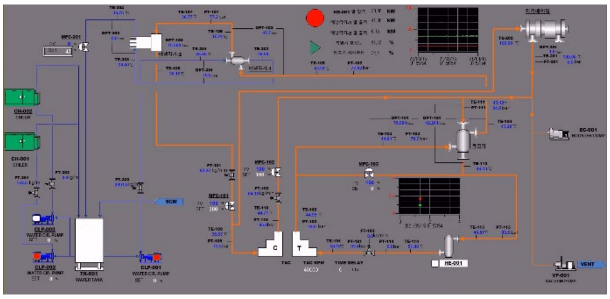

Fig. 1. Control and monitoring system.

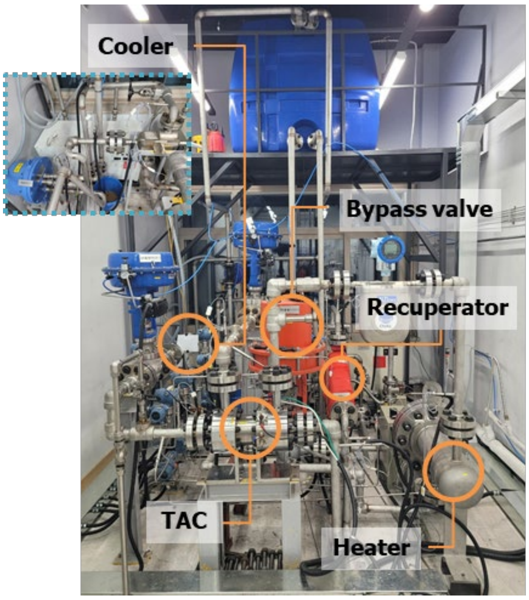

Fig. 2. ABC test loop.

2.2 Compressor Surge Control Test

In this paper, compressor surge control test results are used to validate MARS code modeling. Surge phenomenon is a boundary indicating the stable operating limit of the compressor and occurs when the mass flow rate decreases to the operating limit level. When a surge occurs, it can cause severe problems in structural integrity due to noise and vibration. Therefore, surge protection is one of the important control mechanisms in the system, and the control logic using valves was applied to secure the surge margin in the ABC test loop.

In this experiment, the mass flow was reduced by closing the front and rear control valves while maintaining the compressor rotational speed to artificially induce surge. When the surge margin falls below 15%, the valve at the inlet side of the compressor is controlled to open to ensure sufficient surge margin.

The goal is to secure a surge margin of 10% or more, and as shown in Fig. 4, the experiment was repeatedly performed while increasing the compressor rotational speed from 20 krpm to 40 krpm.

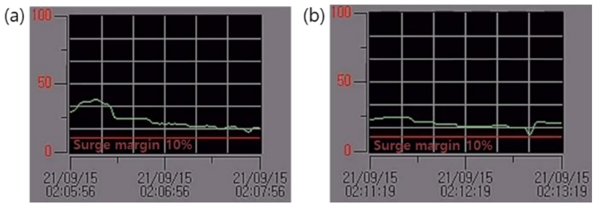

Fig. 3. Surge margin monitoring. (a) 20 krpm (b) 25 krpm

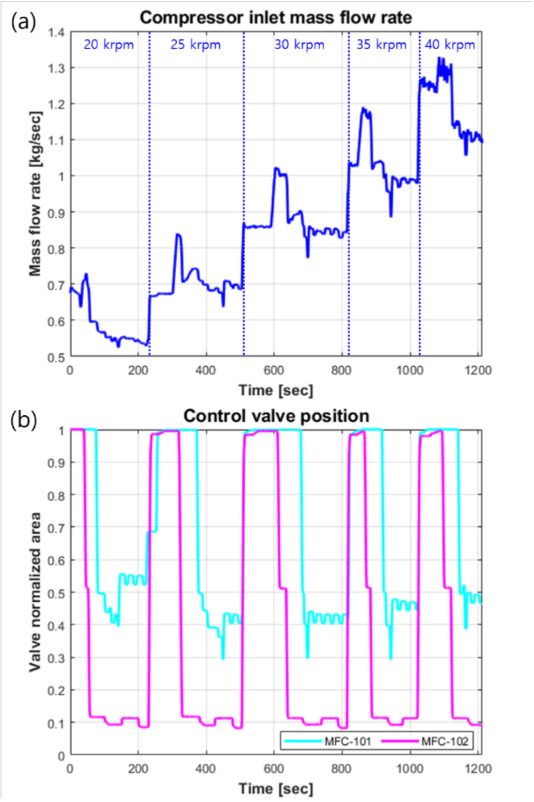

Fig. 4. Surge control test data. (a) compressor inlet mass flow rate (b) control valve position

2.3 MARS Code Modeling

Fig. 5 shows the nodalization diagram of MARS code input deck for the ABC test loop. All piping and components were modeled based on design values and measured values. In the initial stage, only the compressor was modeled for the TAC because the fluid circulated without a turbine wheel to prevent backflow as mentioned in section 2.1. The compressor was modeled based on the performance map derived from the compressor performance test in the previous experimental facility as shown in Fig. 6 [3]. Since there is no wheel on the turbine side, it was not modeled with the turbine model, but only the flow path was modeled like a nozzle by referring to the production drawing. Shaft cooling flow was modeled for the bypass flow in the TAC casing. Two control valves were modeled as a servo valve, and the flow coefficient for the normalized valve area of each valve was calculated from the measured pressure loss as shown in Fig. 7. Heater was modeled with the general table and water mass flow of cooling part was entered as the time dependent boundary junction.

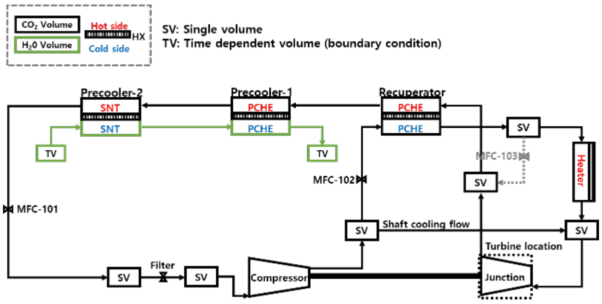

Fig. 5. MARS code modeling for ABC test loop.

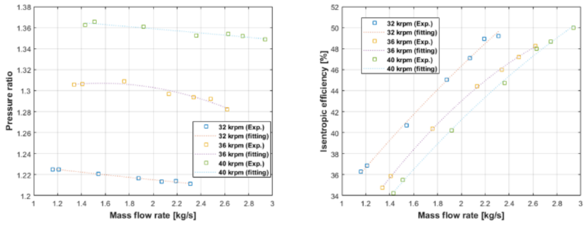

Fig. 6. Off-design performance map of the compressor

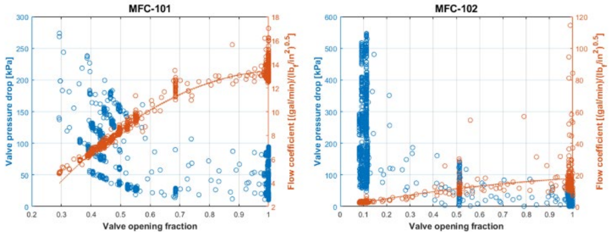

Fig. 7. Pressure loss and flow coefficient for control valves

After the steady-state calculation, transient simulation was performed under the 40 krpm case. Transient scenario was given under the test conditions of control valve opening fraction and water mass flow rate over time, as shown in Fig. 8 and Fig. 9.

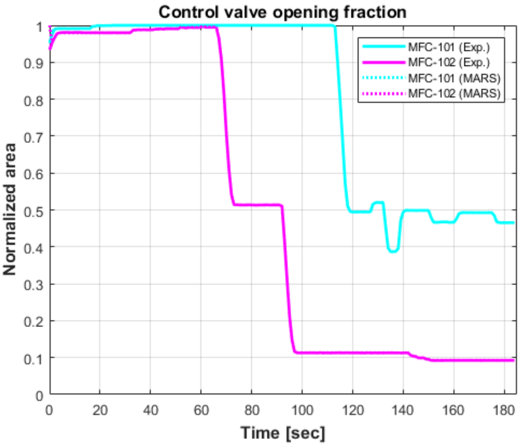

Fig. 8. Valve opening fraction over time

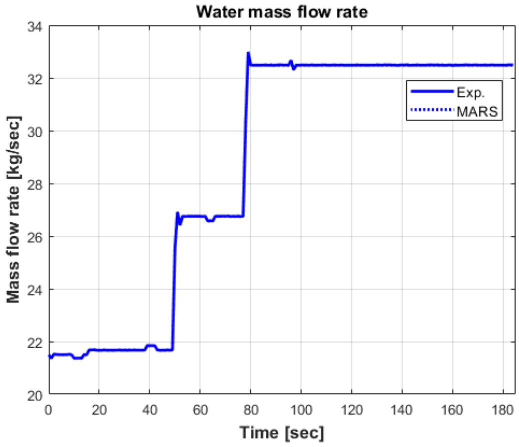

Fig. 9. Water mass flow rate over time

Fig. 10 to Fig. 12 show the comparison of experimental data with simulation results. Since there is no turbine wheel, the compressor is the main component governing the system pressure and mass flow. Therefore, the mass flow rate, temperature, and pressure at the inlet and outlet of the compressor were mainly compared. Fig. 10 shows that the MARS code accurately predicts the compressor mass flow rate and bypass flow under the transient. In the case of pressure and temperature, although there are slight differences from the experimental results, it shows similar trends over the total range. It is expected that the reason for the differences in pressure and temperature is that there is not enough time to reach steady state in each test case. Since the purpose of this experiment was to demonstrate the control performance at each rotational speed, test was proceeded very quickly as shown in Fig. 4. In the future, the test will be performed after reaching the steady-state condition more precisely. In conclusion, although it is necessary to reevaluate with other test results in the future, it is judged that MARS code modeling for the ABC test loop was performed well.

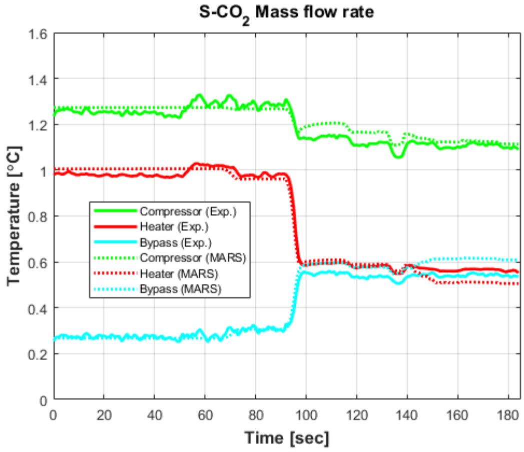

Fig. 10. S-CO$_2$ mass flow rate.

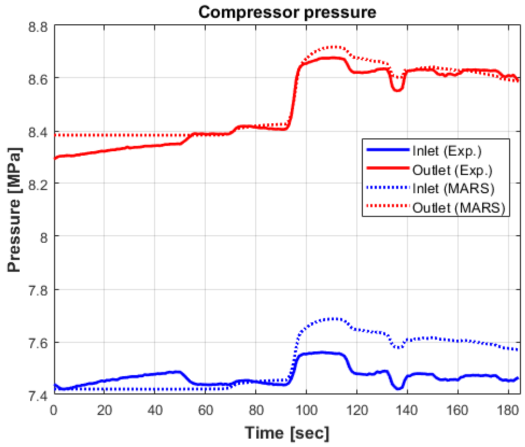

Fig. 11. Compressor pressure.

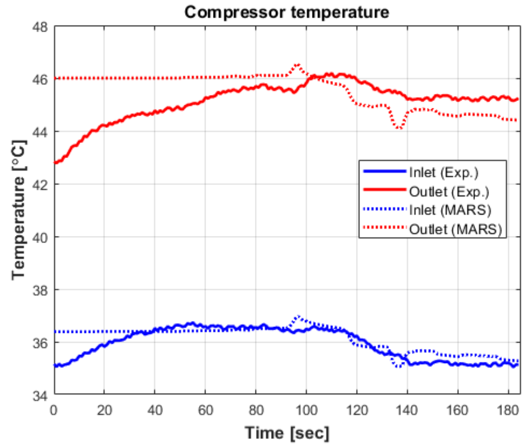

Fig. 12. Compressor temperature.

3. Summary and Further Works

In this study, the ABC test loop was modeled and a transient simulation was conducted to compare with experimental data. Through the simulation of the compressor surge control test, it was confirmed that the modified MARS code can model the S-CO$_2$ system quite reasonably well. In the future, various tests at the system level will be performed in the ABC test loop and the MARS code will be used to predict results and trends.

ACKNOWLEDGEMENT

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