Validation of the Modified MARS Code for Modeling of $S\text{-}CO_2$ Cycle Using Compressor Test Results from KAIST

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1. Introduction

Recently, the supercritical carbon dioxide cycle (S-CO_2) has attracted attention as the next generation power conversion system of nuclear power plants. There have been many studies to apply the S-CO_2 cycle to pressurized light water reactors (PWR) as well as high-temperature gas reactors (HTGR) [1,2]. To analyze thermal hydraulic phenomena in normal operation and abnormal conditions of nuclear systems, a system analysis code is required. Most nuclear thermal hydraulic codes are focused on safety analysis and the modeling of the power system is not their strength. However, due to the growing demand for load-following operations on nuclear systems, not only the accident analysis but also the performance analysis of the power conversion system has become important. The authors previously modified the MARS-KS code, the 1-D nuclear safety analysis code used by the Korean regulator KINS, to simulate the S-CO_2 power conversion system applied to PWR [3]. In this paper, validation of the modified MARS code has been performed through comparison with the results of the compressor performance test conducted at KAIST.

2. S-CO_2 Compressor Test

Fig. 1 shows the S-CO_2 compressor test loop installed in KAIST. As shown in the figure, this facility is constructed with the S-CO_2 turbo alternator compressor (TAC) and a cooling loop. Design conditions of the compressor are summarized in Table I. The target pressure ratio is 1.3 and mass flow rate is 3 kg/sec.

Cho conducted compressor performance tests using this facility to collect fundamental experimental data for the S-CO_2 compressor and validate in-house turbomachinery design code [4]. Although equipped with TAC, the compressor performance test was performed without the turbine to carry out experiments step by step. Therefore, the S-CO_2 flow within the experimental loop is compressed through the compressor and expanded through two control valves (CV). The water flow rate in cooling part was controlled to maintain the inlet conditions of the S-CO_2 compressor.

Experiments were conducted for three rpm cases: 32,000 rpm, 36,000 rpm, and 40,000 rpm. The compressor performance was measured by adjusting the opening fraction of control valves at each rpm. For each rpm case, the CV-1 opening fraction was set to 10% and the CV-2 opening fraction was reduced from 100%. In this study, the data obtained when the valve opening area of CV-2 was changed from 100% to 50% for 36,000 rpm is compared to the MARS-KS simulation results.

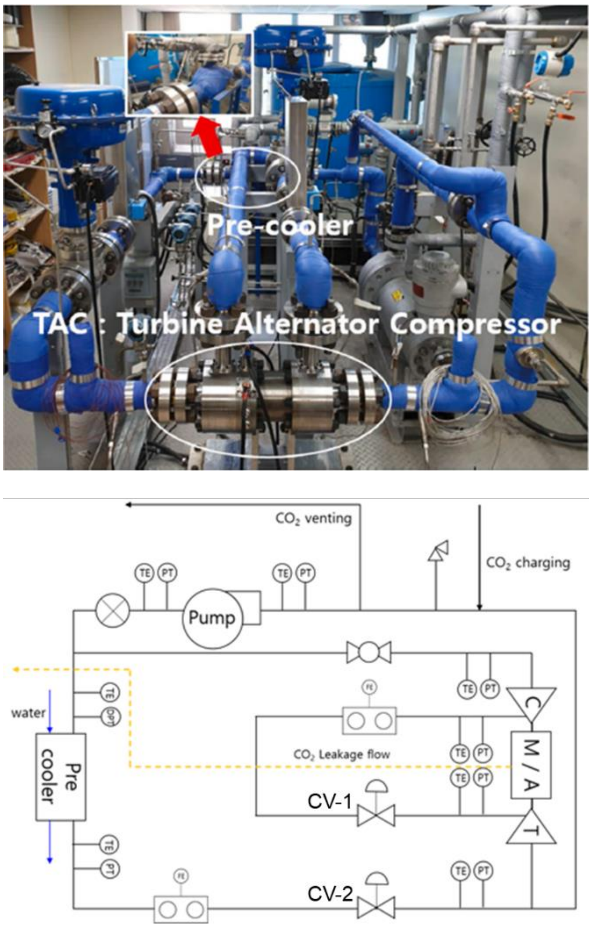

Fig. 1. Compressor performance test loop in KAIST and schematic diagram

Table I: Design condition of KAIST compressor

Pressure ratio	1.3
Inlet total temperature	31.36 ℃
Inlet total pressure	7599 kPa
Efficiency	56 %
Rotating speed	40,000 rpm

3. MARS Code Modeling

The authors previously modified the MARS code to model the S-CO_2 cycle as follows. First, the NIST property data program was linked to accurately calculate rapidly changing CO_2 properties near the critical point. Second, the printed circuit heat exchanger (PCHE) correlation was added to the heat structure. Third, the turbomachinery model was modified to correctly model the pressure ratio and the isentropic efficiency of a turbomachinery via off-design performance map.

Fig. 2 shows the nodalization diagram of MARS code input for the compressor test facility. The cooling part was treated as boundary conditions and only the S-CO_2 flow part was modeled. The compressor is modeled with the off-design performance map derived from the performance test results shown in Fig. 3. 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. 4.

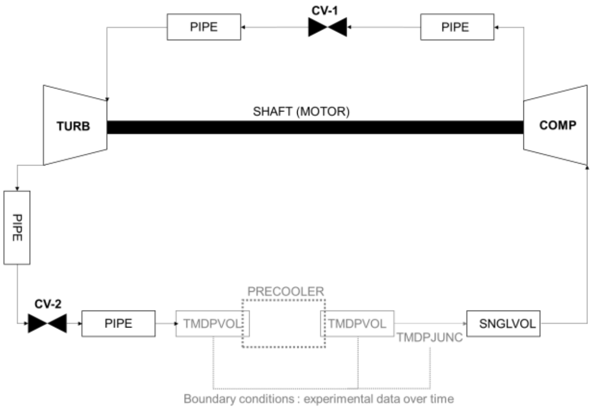

Fig. 2. MARS modeling for compressor test facility

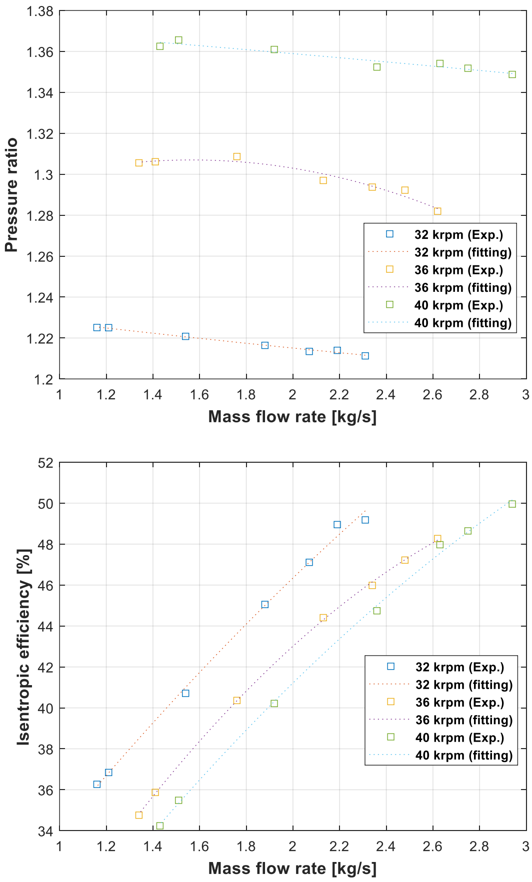

Fig. 3. Off-design performance map derived from the compressor test

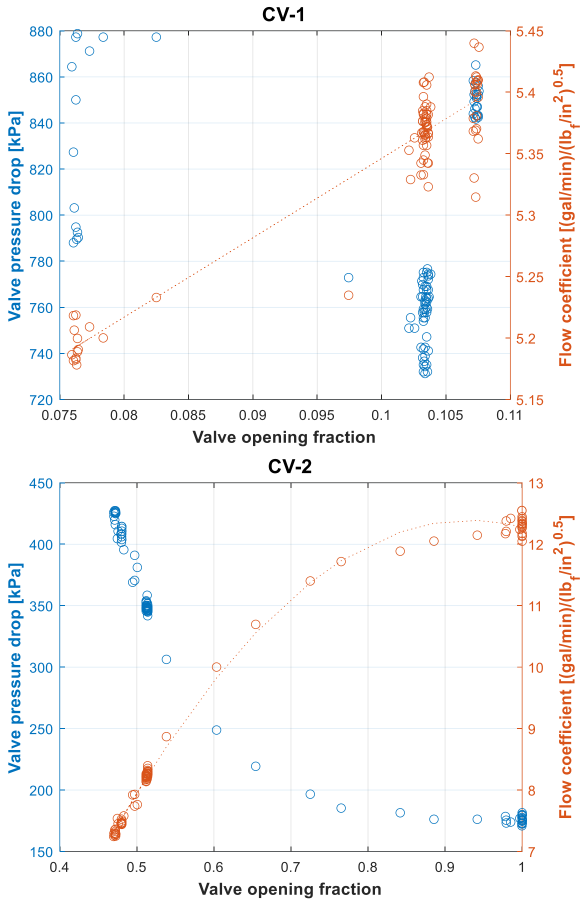

Fig. 4. Flow coefficient for normalized area of each control valve

The opening fraction of each valve is shown in Fig. 5. The valve opening rate over time was measured in the experiment and it was applied to the MARS input.

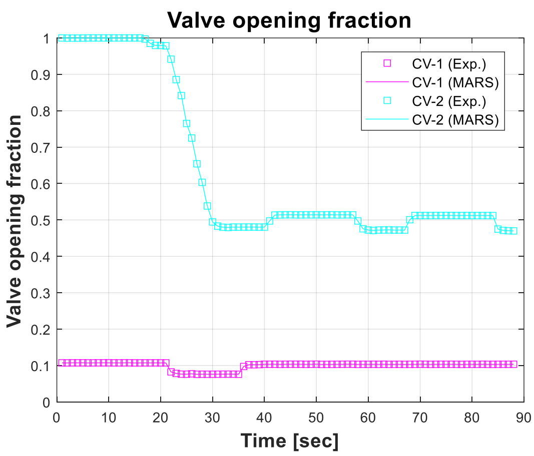

Fig. 5. Valve opening fraction over time

Figs. 6-8 show the comparison of the MARS code simulation results to the experimental results. In some areas, there is a slight difference in temperature and pressure values at the inlet and the outlet of the compressor. This seems to be caused by the uncertainty propagation of temperature and pressure to enthalpy since the experiment was performed in a region very close to the critical point. This is expected to be confirmed again by simulating the experimental results in the region relatively far from the critical point in the future. The simulated mass flow rate, pressure, and temperature show generally good agreement with the experimental results.

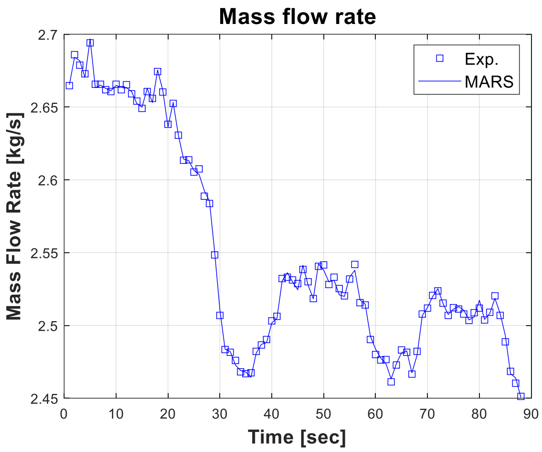

Fig. 6. Comparison of mass flow rate in test loop

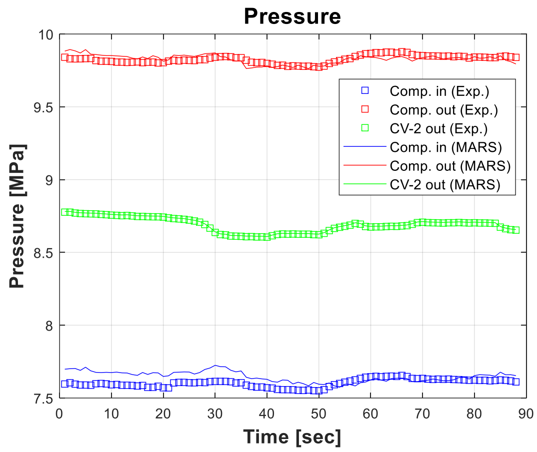

Fig. 7. Comparison of pressure at each point

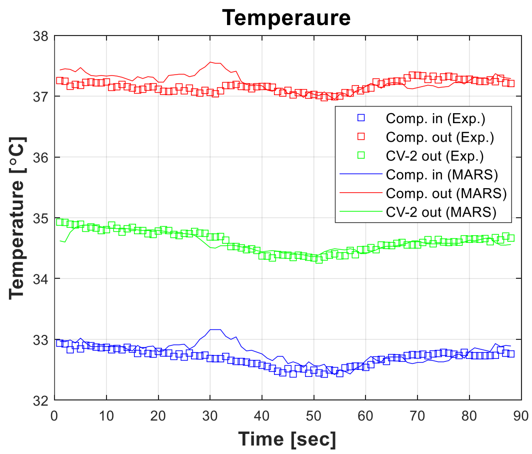

Fig. 8. Comparison of temperature at each point

4. Summary and Further Works

In this study, the S-CO_2 compressor test loop was modeled and a transient simulation was conducted to validate the modified MARS-KS code. Through the simulation of the compressor performance test, it was confirmed that the modified MARS-KS code can model the S-CO_2 system quite reasonably well. In the future, safety analysis and performance analysis of the nuclear system with the S-CO_2 cycle will be carried out using the modified MARS-KS code.

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