Validation of KAIST-STA (System Transient Analysis) Code with CO_2 Experimental Data under the Trans-critical Operating Condition.

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1. Introduction

A power conversion system using CO_2 as a working fluid over the critical point of CO_2 is known to achieve high performance with its compact footprint, simple layout and no phase change. This promising system, typically called a S-CO_2 Brayton cycle, is being studied for various power generation applications including the next generation nuclear systems. These advantages of S-CO_2 Brayton cycle mainly come from its lower compressing work by pressurizing the CO_2 near the critical point. However, this also implies that the system can be operating under two-phase sub-critical state during transients [1].

A few studies on the S-CO_2 system transient analysis with analytical codes have been previously carried out [2-4]. However, the analysis for the CO_2 two-phase analysis near the critical point is very rare. To overcome the two-phase errors in system analysis codes and lack of research near the critical point of CO_2, the authors have been developing a 1-D system dynamic analysis code using Homogeneous Equilibrium Model (HEM), called KAIST-STA (KAIST-System Transient Analysis) code [5]. Some research works of using the HEM to a simulation of CO_2 expansion inside two-phase ejectors for refrigeration systems can be found in the open literature. These studies shows the HEM is a good assumption for the flow near or above the CO_2 critical point [6-11]. S-CO_2 Brayton cycles are typically designed to operate closely above the critical point at the main compressor, the minimum temperature and pressure state of cycle, the cycle conditions wouldn't be far from the critical point even under transient conditions. Thus, HEM is adopted in the KAIST-STA. The field equations of KAIST-STA code for continuity, momentum and energy conservations are represented below.

1. Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho V)=0 \qquad (0)$$

2. Energy conservation equation

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x}(\rho HV)=\frac{\partial P}{\partial t}+V\frac{\partial P}{\partial x}-\frac{\partial q''}{\partial x}+q_w''' \qquad (2)$$

3. Momentum conservation equation

$$\frac{\partial}{\partial t}(\rho V)+\frac{\partial}{\partial x}(\rho VV)=-\frac{\partial P}{\partial x}-\rho g-\rho\left(\frac{f}{d}+K\right)V^2 \qquad (3)$$

The developing code was verified with the GAMMA+ code as a reference, developed as a gas system transient analysis code in KAERI [12-13]. In this study, a validation result of KAIST-STA code is presented. The experimental data is from the CO_2 compressing test facility called SCO_2PE (Supercritical CO_2 Pressurizing Experiment) at KAIST.

2. Modeling and Validation Results

Prior to the simulation of whole SCO2PE facility, the major components, the canned motor type compressor and PCHE type heat exchanger, were separately modeled and simulated with KAIST-STA code. It is the first validation of KAIST-STA code with an experimental data under the critical point of CO_2, so the test facility is modeled as an opened system as shown in Fig. 1. The loop is divided at the pipe between the expansion valve and the heat exchanger, and the both boundary conditions were set as time dependent volumes considering the experimental data in accordance with the time. Thus, the pressures, temperatures and the mass flow rates of CO_2 were provided in the boundary volumes via lookup tables, and also the pressure drop in the expansion valve was inserted as an input data due to the lack of information of the glove valve for modeling.

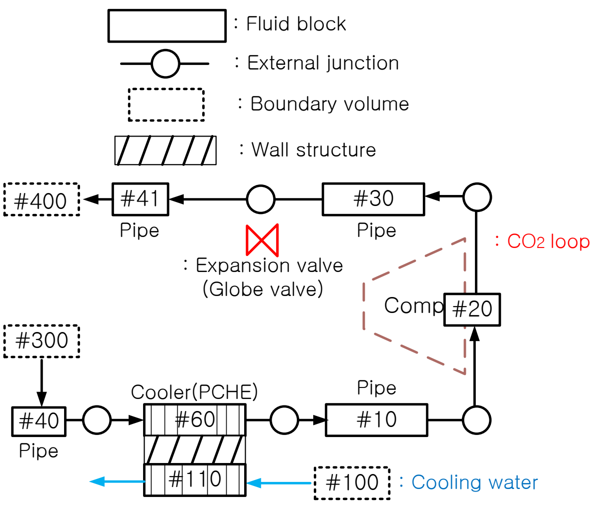

Fig 1. Nodalization of SCO2PE test facility for modeling with KAIST-STA code

There are 3 measuring points in the facility, the compressor inlet, compressor outlet and the heat exchanger inlet. In this study, it is set up such that the compressor inlet condition is 33.35℃, 7.41Mpa and 0.96kg/s of CO_2 mass flow rate at steady-state, and the cooling water mass flow rate increases from 0.055kg/s at the steady-state condition to 0.15kg/s for going through CO_2 2 phase state.

Fig. 2 shows the cooling water mass flow rate variation versus time.

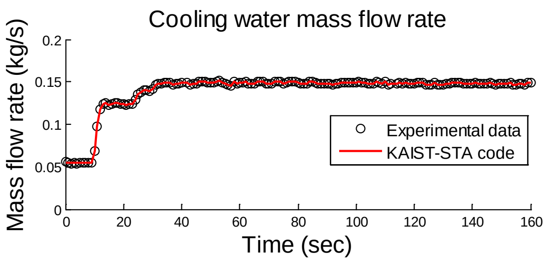

Fig 2. The cooling water mass flow rate variation versus time

Figs. 3-5 show the validation results between the experimental data (the black rounded symbols) to KAIST-STA code (the solid lines) at the compressor inlet point. The PCHE experimental correlations of SCO2PE facility were used in the code. Fig. 6 is the variation of the cooling water outlet temperature. The compression result shows that the developed code with the PCHE correlation can predict the PCHE heat transfer performance with a good agreement. Fig. 7 represents the compressor inlet condition variation during the transient state. It is shown that the code can simulate the system with a similar tendency not only in the single-phase situation but also for the 2 phase-state.

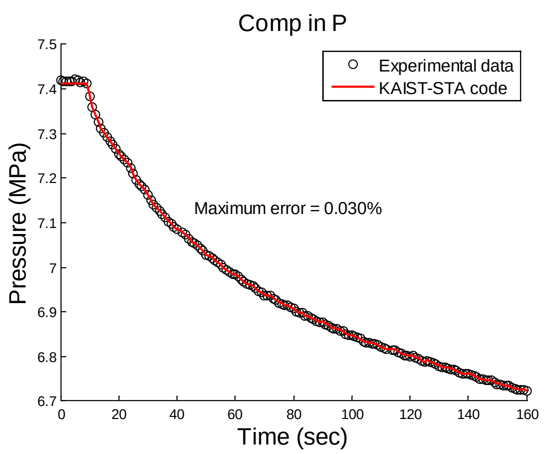

Fig 3. Pressure trend comparison at the CO_2 compressor inlet of SCO2PE

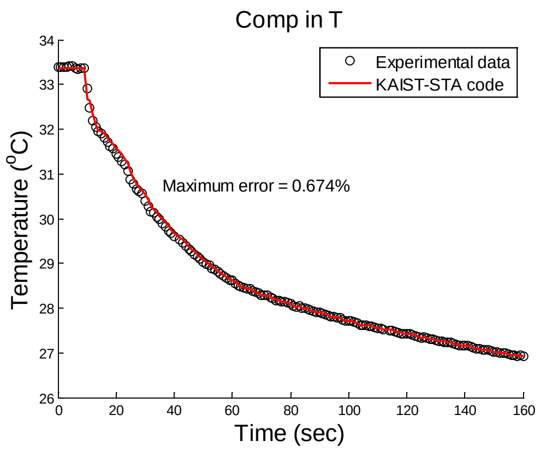

Fig 4. Temperature trend comparisonat the CO_2 compressor inlet of SCO2PE

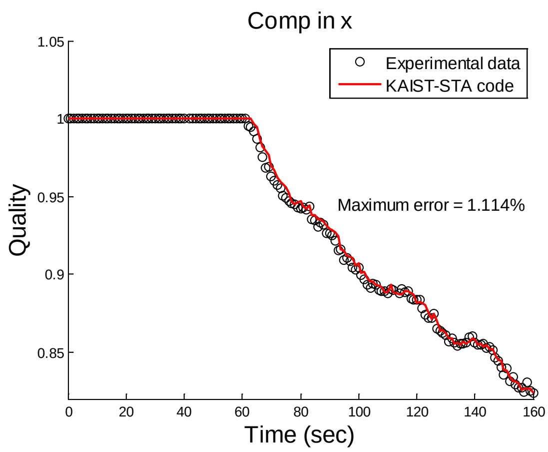

Fig 5. Quality trend comparison at the CO_2 compressor inlet of SCO2PE

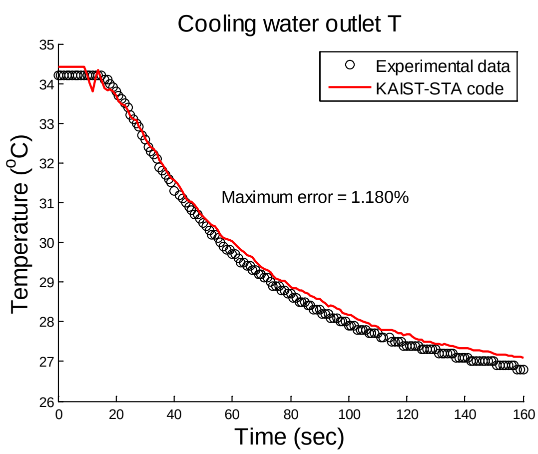

Fig 6. Temperature trend comparison at the cooling water outlet of the PCHE

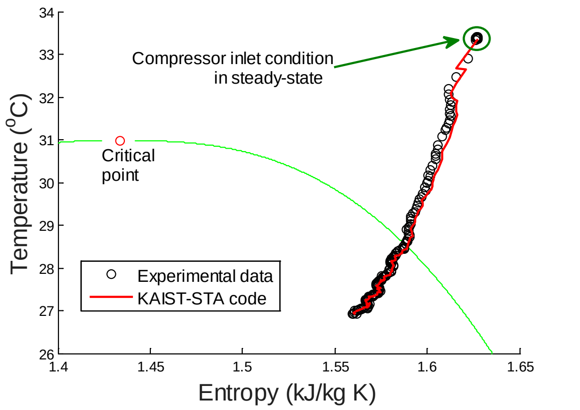

Fig 7. T-s diagram of the experiment and KAIST-STA code analysis at the compressor inlet point

Figs. 8 and 9 are the validation results of compressor outlet pressure and temperature. The code results show quite good agreement compared to the experimental data.

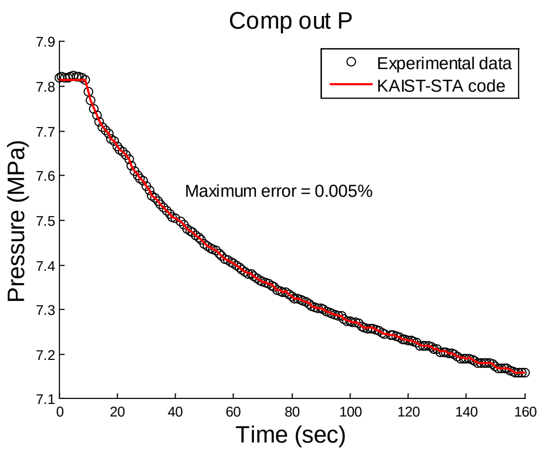

Fig 8. Pressure trend comparison at the CO_2 compressor outlet of SCO2PE

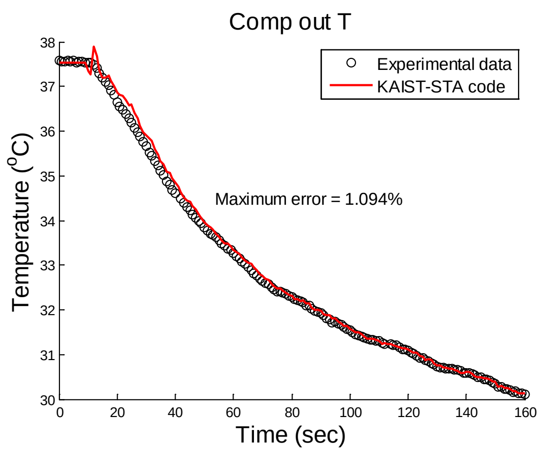

Fig 9. Temperature trend comparison at the CO_2 compressor outlet of SCO2PE

3. Conclusions

In this study, the validation of KAIST-STA code with a trans-critical CO_2 experimental data going through the supercritical-state to 2 phase-state is presented. Since the authors have experienced some limitations for modeling the test facility due to lack of information, the test facility is initially modeled as an open system with time dependent volumes.

The validation results are satisfactory as shown in the results. The T-s diagram shows that the code using HEM shows a good agreement for this case comparing with the experimental data not in the single-phase situation but also within the 2 phase-state.

This is a simple approach to validate a system code with experimental data. To perform more reasonable validation with the experiment, the calculation with a closed loop modeling will be continuously carried out as the next step.

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