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The Validation and Verification of Gas System Analysis Code GAMMA+ with S-CO_2 Compressor Test Data

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1. Introduction

A Supercritical Carbon Dioxide (S-CO_2) Brayton cycle is considered as one of appropriate power conversion systems for HTGRs along with a Helium Brayton cycle. The reason is that the S-CO_2 Brayton cycle can achieve high thermal efficiency, simple cycle configuration and compact turbomachinery compared to other power cycles; air, water, helium and so on [1]. The main reason why the S-CO_2 Brayton cycle can achieve high efficiency comes from low compressing work near the critical point. However, since a potential error source of property prediction exists near the critical point without reference to a working fluid, most of the existing property databases and ideal gas assumptions are hard to use near the critical point of CO_2. So, to obtain the compressor performance data near the critical point, KAIST research team has constructed the S-CO_2 compressor test facility; SCO2PE (Supercritical CO_2 Pressurizing Experiment).

In this study, the validation and verification of the GAMMA+ code was carried out by utilizing the experimental data from the SCO2PE. For a power conversion system analysis of a High Temperature Gas cooled Reactor (HTGR), the GAMMA code was developed [2]. The code has been continuously updated to become GAMMA+. For this study, the GAMMA+ code was modified to connect with the NIST database. A novel compressor module was added to calculate the compressor map for the GAMMA+ code.

2. Methodology

2.1 SCO2PE facility

Our research team built a S-CO_2 compressor test loop, SCO2PE, to experience the S-CO_2 loop operation and to obtain compressor performances for the various compressor inlet conditions. Figs. 1 and 2 show the picture and 3-D figure of the SCO2PE facility. A canned motor pump and a shell and tube type heat exchanger are used for the facility as main components. Water is used as a coolant for cooling the CO_2 system. The SCO2PE is using a globe valve as an expander which reduces the pressure to maintain the steady state operation of the test loop and also it controls the CO_2 flow. Whole CO_2 system is designed for maximum 15 MPa and 12 MPa safety relief value is installed for an unexpected high pressure situation.

Fig. 1 Picture of SCO2PE facility

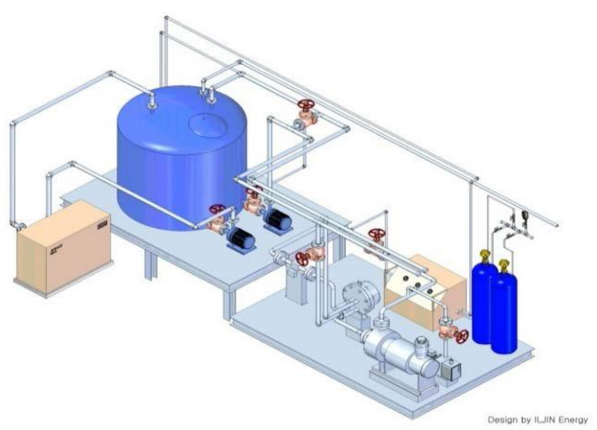

Fig. 2 3-D figure of SCO2PE facility

2.2 SCO2PE test conditions and Node construction for GAMMA+ compressor test

In this study, two compressor inlet conditions were tested with GAMMA+ to reproduce the experimental conditions in the SCO2PE. Several data were obtained for each case by adjusting the CO_2 mass flow rate. Table I shows the summarized test conditions. As a result, a few compressor performance lines are obtained for two cases.

Table I: SCO2PE test conditions.

	Case 1	Case 2
Compressor inlet temperature (˚C)	32.5	39.9
Compressor inlet pressure (MPa)	7.44	8.29
Mass flow rate (kg/s)	1.00~2.86	0.50~2.00

To simulate the SCO2PE with the GAMMA+ code, the nodalization of the real facility is necessary. Since this is a preliminary study to use the GAMMA+ with the SCO2PE data, a simple nodalization was constructed as shown in Fig. 3. The compressor outlet results will be compared to the SCO2PE results while the inlet condition is provided as the boundary condition first. As shown in Fig. 3, the compressor was described as fluid blocks #15, 20 and 25; compressor inlet, main and outlet. External junctions were located between the two fluid blocks. Initial boundary conditions and geometry information were provided from the SCO2PE experimental data.

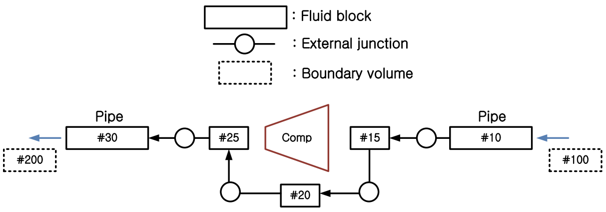

Fig. 3 Nodalization diagram for GAMMA code compressor test.

2.3 CO_2 property comparison between the GAMMA+ and NIST database

As mentioned above, the S-CO_2 Brayton cycle is difficult to use the existing property database or the ideal gas assumption, especially at the compressor inlet due to sudden changes of property near the critical point. Whereas, the GAMMA+ code utilized the Lee-Kesler method as one of Corresponding States Principles (CSPs). Therefore, there was an error or a divergence near the critical point due to the inappropriate property from the selected method. Figs. 4 and 5 respectively show the density and enthalpy comparison between the NIST data and the GAMMA data using the CSP near the critical point of CO_2 (7.5MPa, 35~70°C). As shown in the figures, the existing GAMMA+ code had trouble in simulating the SCO2PE experimental data due to the sudden property variations. In this study, the NIST database is connected to the GAMMA+ code for more accurate CO_2 properties.

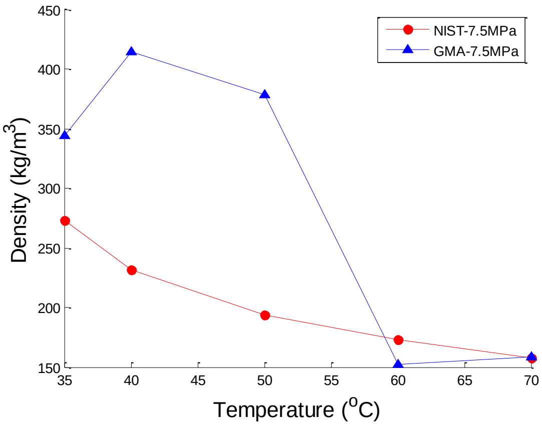

Fig. 4 Density comparison between the NIST and GAMMA+ data near the critical point of CO_2

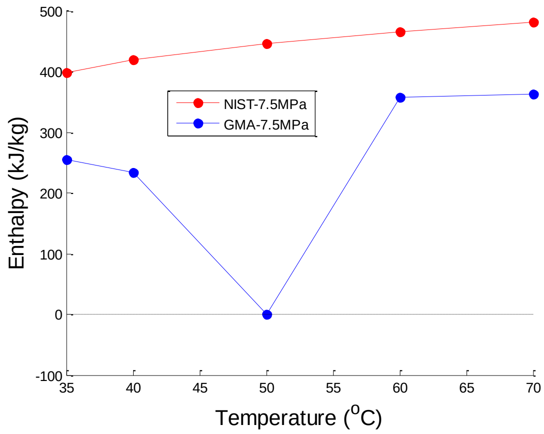

Fig. 5 Enthalpy comparison between the NIST and GAMMA+ data near the critical point of CO_2

3. Results and Conclusions

Using the updated GAMMA+ code, the results were obtained for Table I inlet conditions and calculated results are shown in Table II and Figs. 6, 7 and 8 for two cases. As shown in the results, the GAMMA+ code has shown reasonable results in comparison with the SCO2PE experiment data except for the compressor outlet temperature. In this study, the process to calculate the compressor outlet temperature was added while considering the isentropic turbomachinery efficiency from the measured performance line. However, since the pressure ratio of the SCO2PE compressor is very low, the uncertainty of measurement is quite high near the critical point, even with the NIST database. Therefore, in calculating the isentropic compressor efficiency of SCO2PE, the electric power supplied for the compressor is utilized as a denominator for the compressor efficiency formula. The isentropic compressor efficiency formulas applied for the experiment and GAMMA+ code are respectively shown in Eq. (1) and (2). Therefore, in case of the compressor outlet temperature, there is quite a difference between the experiment and GAMMA+ data

$$\eta_{Experiment} = \frac{\dot{m}(h_s - h_{in})}{\dot{W}} \quad (1)$$

$$\eta_{GAMMA} = \frac{\dot{m}(h_s - h_{in})}{\dot{m}(h_{out} - h_{in})} \quad (2)$$

This study is a preliminary study to utilize the GAMMA+ code for predicting the SCO2PE data. Thus only the steady state results are obtained so far. Further studies of transient data comparison will be performed in the near future.

Table II: Data comparison between experiments and GAMMA+ calculations for steady state SCO2PE data (at 100 sec).

<table>
<tr><th></th><th></th><th>Experiments</th><th>GAMMA</th></tr>
<tr><td rowspan="2">Compressor inlet temperature</td><td>Case1</td><td colspan="2">32.5 °C</td></tr>
<tr><td>Case2</td><td colspan="2">39.9 °C</td></tr>
<tr><td rowspan="2">Compressor inlet pressure</td><td>Case1</td><td colspan="2">7.44 MPa</td></tr>
<tr><td>Case2</td><td colspan="2">8.29 MPa</td></tr>
<tr><td rowspan="2">Mass flow rate</td><td>Case1</td><td colspan="2">2.86 kg/s</td></tr>
<tr><td>Case2</td><td colspan="2">2.00 kg/s</td></tr>
<tr><td rowspan="2">Compressor outlet temperature</td><td>Case1</td><td>38.3 °C</td><td>42.2 °C (+3.9 °C)</td></tr>
<tr><td>Case2</td><td>45.8 °C</td><td>46.8 °C (+1.0 °C)</td></tr>
<tr><td rowspan="2">Compressor outlet pressure</td><td>Case1</td><td>8.65 MPa</td><td>8.65 MPa</td></tr>
<tr><td>Case2</td><td>9.12 MPa</td><td>9.12 MPa</td></tr>
<tr><td rowspan="2">Compressor efficiency</td><td>Case1</td><td>58.60 %</td><td>58.60 %</td></tr>
<tr><td>Case2</td><td>36.07 %</td><td>36.07 %</td></tr>
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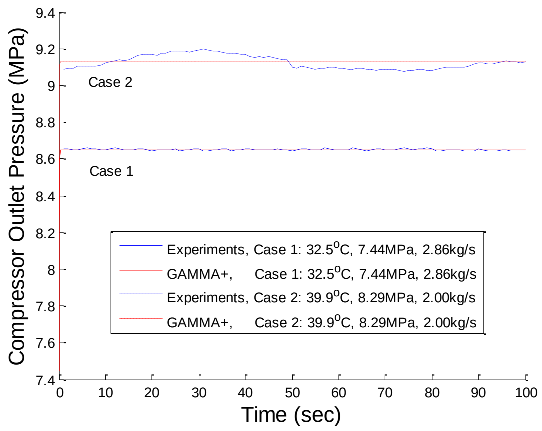

Fig. 6 Compressor outlet pressure comparison for 100 seconds

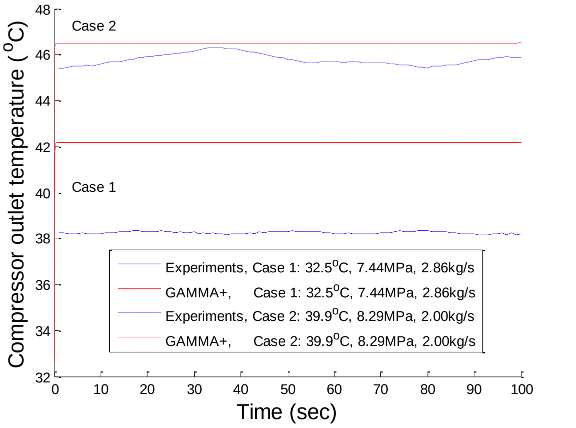

Fig. 7 Compressor outlet temperature comparison for 100 seconds

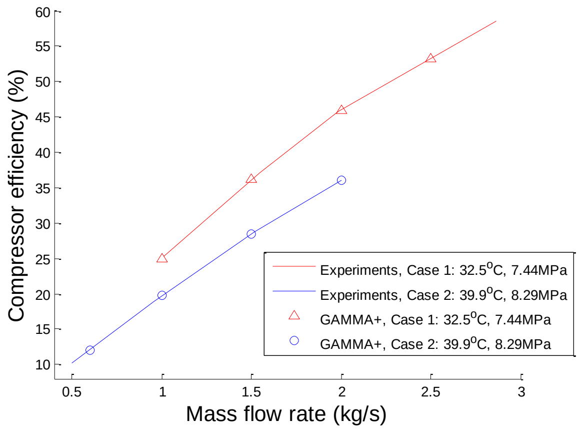

Fig. 8 Off-design compressor performance map of SCO2PE

ACKNOWLEDGEMENT

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