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MODELING OF AUTONOMOUS BRAYTON CYCLE LOOP WITH GAMMA+ CODE FOR MICRO MODULAR REACTOR SIMULATION APPLICATION

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ABSTRACT

The Supercritical carbon dioxide (S-CO_2) cycle is considered as a promising power conversion system for numerous power applications, because it has relatively high thermal efficiency and compact component size. This paper shows the validation of GAMMA+ code, which was originally developed by Korea Atomic Energy Research Institute to analyze the gas-cooled reactors, by comparing the experimental data obtained from Autonomous Brayton Cycle (ABC) loop constructed in Korea Advanced Institute of Science and Technology (KAIST) and calculation result from the code. ABC loop is a simple recuperated closed S-CO_2 Brayton cycle constructed by the KAIST research team. ABC loop consists of a turbine-alternator-compressor (TAC), electric heater, recuperator, precooler and control valves. Previously, GAMMA+ code was already validated with the experimental data obtained from SCO_2PE and SCIEL facilities. In contrast to the ABC loop, only cooling and compression of the S-CO_2 were tested. With ABC loop, not only cooling and compression of the S-CO_2 were tested, but also the heating and recuperation were experimented. The ABC loop was modeled using GAMMA+ code and the calculation from the code is in accordance with the experimental data. Thus, GAMMA+ code can accurately simulate the S-CO_2 system in the future, for example a Micro Modular Reactor (MMR) utilizing as S-CO_2 power system.

INTRODUCTION

With the development of technologies, the Small Modular Reactors (SMRs) are receiving more attention due to their advantages, such as modularity and siting flexibilities. Previously, for the conventional nuclear power plants, the steam Rankine cycles were widely used. However, with the ongoing research on the nuclear power plant, more compact, yet effective nuclear reactors were designed, which caused the increase of the nuclear reactor outlet temperature. The nuclear reactor outlet temperature of the previous nuclear reactors was near 330°C, whereas, that of the advanced reactors are above 500°C. With the increased core outlet temperature, the turbine inlet temperature (TIT) also increases in the power conversion system. As shown in Figure 1, as the turbine inlet temperature increases, the cycle efficiency of the steam Rankine cycle is less than the Supercritical Carbon dioxide (S-CO_2) cycle.

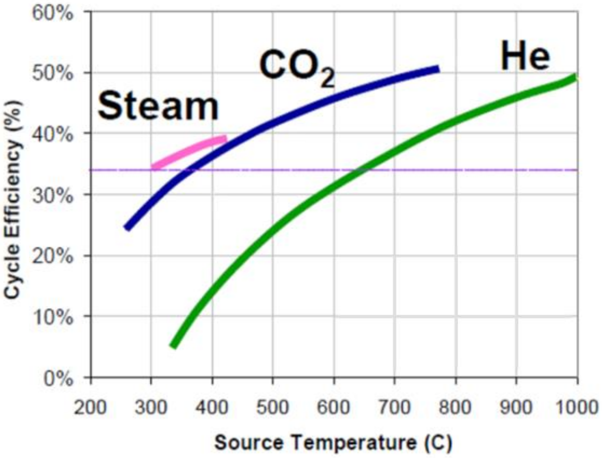

Figure 1. Comparison of cycle efficiency along different TIT

Thus, the S-CO_2 power cycles are regarded as a promising power cycle for the next generation nuclear reactors, because they have high thermal efficiency with compact component size, as shown in Figure 2. The size of S-CO_2 cycle main components,

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including turbine, compressor and cooler, can be compact, because CO_2 behaves as an incompressible fluid, reducing compression work dramatically [1].

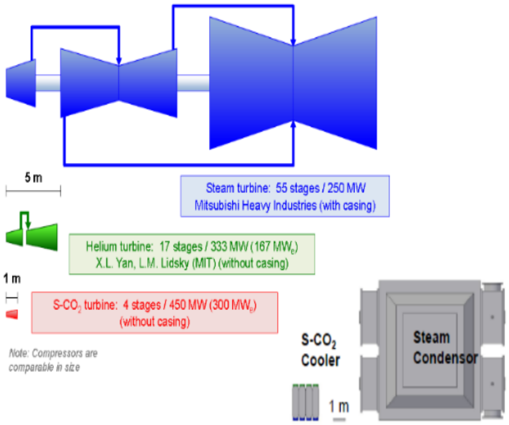

Figure 2. Main Component Size comparison for S-CO_2 and Rankine Cycle

Based on the advantages of S-CO_2 power cycle and next generation nuclear reactor, Korea Advanced Institute of Science and Technology (KAIST) research team has developed a direct S-CO_2 cooled Small Modular Reactor, KAIST-MMR. KAIST-MMR is an SMR to generate required energy in remote regions [2]. One of the most important features of KAIST-MMR is that it is designed to be controlled autonomously [3].

During the previous researches, the transient analysis and autonomous control of KAIST-MMR have been studied with system simulation code [3-4]. Based on the simulation results, KAIST-MMR can be operated safely and autonomously with reduced loads. However, the validity of the system code used to simulate KAIST-MMR system could be questioned. In this paper, the validation of GAMMA+ code was validated with the Autonomous Brayton Cycle (ABC) Loop experiment data.

GAMMA+ CODE

General Analyzer for Multi-component and Multi-dimensional Transient Application (GAMMA+) code was originally developed by Korea Atomic Energy Research Institute (KAERI) to simulate the gas-cooled reactors [5]. The original GAMMA+ code calculated the fluid thermal properties based on the ideal gas correlations. Since the CO_2 behaves as a real gas near the critical point (7.38 MPa, 30.98 °C), the thermal properties calculated by the code deviated from the real values. Thus, NIST-REFPROP fluid thermal property database was implemented to GAMMA+ code. In addition, turbomachinery modeling module was added to predict the off-design performance of the turbomachineries. Figure 3 shows the overview of the modified GAMMA+ code.

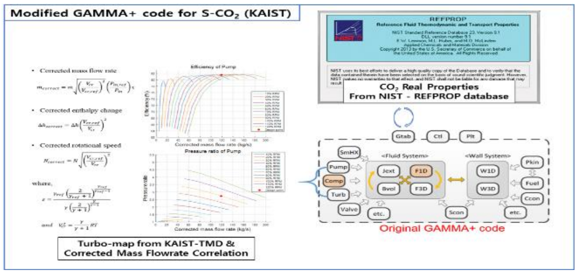

Figure 3. Modified GAMMA+ code Overview

The modified GAMMA+ code was initially validated with two different experiment facility: Supercritical CO_2 Brayton Cycle Integral Experiment Loop (SCIEL) and Supercritical CO_2 Pressurization Experiment (SCO_2PE) [6].

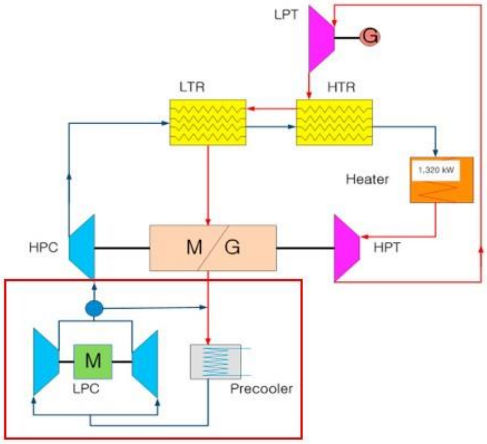

Figure 4. Layout of SCIEL Experiment Facility

Figure 4 shows the layout of SCIEL experiment facility located in KAERI, and the components in the red box are simulated by GAMMA+ code and compared with the experiment results. During the experiment, the heat sink water flow was slightly varied, and the whole experiment was conducted at compressor rotational speed of 35000RPM. Figure 5 shows the compressor pressure predicted by the GAMMA+ code simulation and the experiment data [7].

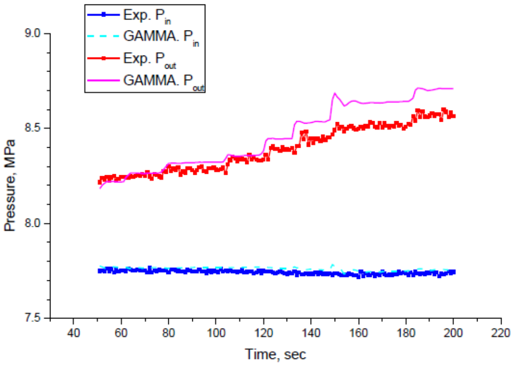

Figure 5. Compressor Pressure comparison between SCIEL experiment and GAMMA+ code

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Figure 6 shows the SCO$_2$PE experiment facility. It is a S-CO$_2$ experiment facility built by KAIST research team to conduct experiments for S-CO$_2$ compression and cooling. It consists of canned-motor type compressor, spiral type pre-cooler and globe valve.

Figure 6. General view of SCO$_2$PE

Similar to the SCIEL experiment, the SCO$_2$PE experiment was conducted by reducing the mass flow rate of the cooling water in the facility, and experimental data, such as compressor pressure and pre-cooler temperature, were obtained. Using GAMMA+ code, the SCO$_2$PE was modeled as Figure 7.

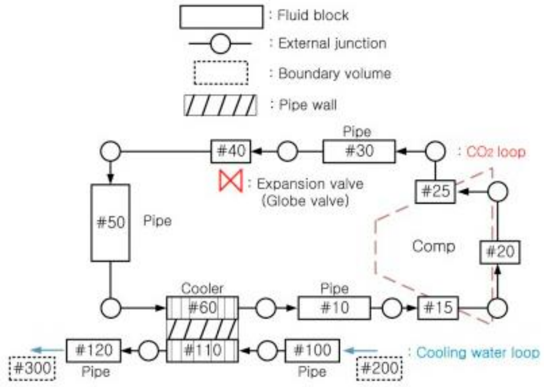


Figure 7. SCO$_2$PE modeling for GAMMA+ code

With the nodal shown in the figure, the SCO$_2$PE experimental data was predicted by GAMMA+ code, and the results are shown in the following figures. As shown in Figures 8 and 9, the calculation result of GAMMA+ code is in accordance with the actual experiment data. Thus, based on the SCIEL and SCO$_2$PE experiments, the GAMMA+ code is well validated about the compression and cooling of the S-CO$_2$.

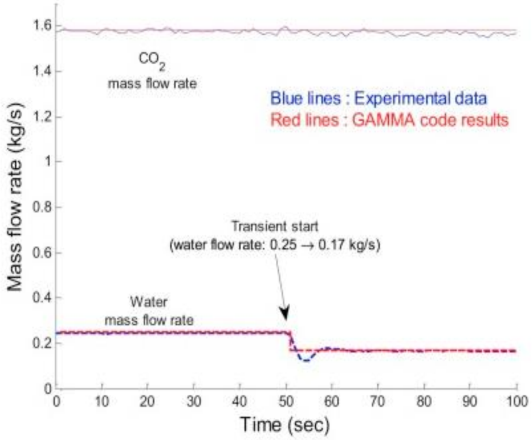


Figure 8. Mass Flow Rate of SCO$_2$PE

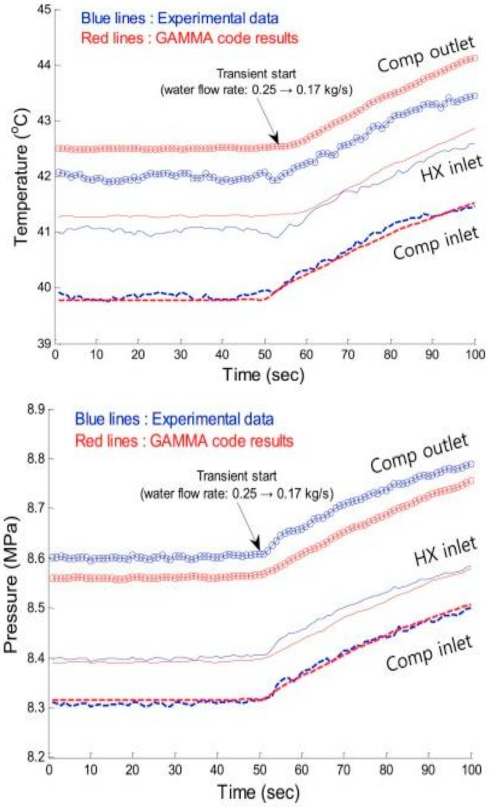


Figure 9. Pressure and Temperature of SCO$_2$PE

ABC LOOP

The ABC loop is a closed S-CO$_2$ simple recuperated Brayton cycle constructed by KAIST team. It consists of Turbine-Alternator-Compressor (TAC), electric heater, and PCHE type pre-cooler and recuperator. Also, there are several control valves in the cycle to test the autonomous control of the system. Based on the two previous experiments, GAMMA+ code is validated for the compression and cooling of S-CO$_2$. In this study, GAMMA+ code will be validated for the heating and recuperation of S-CO_2 with the data taken during a compressor surge control experiment.

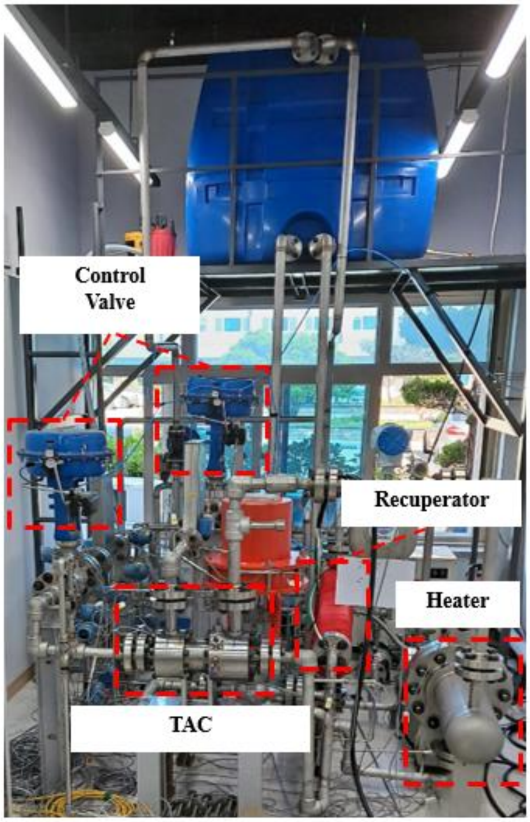


Figure 10. General View of ABC Loop

Figure 10 shows the general view of ABC loop experiment facility. Two control valves, MFC-101 and 102, are at the inlet and outlet of the compressor, respectively. For the modeling of GAMMA+ code, the cooling water mass flow rate and the valve opening area of MFC 101 and 102 were as the boundary conditions.

The experiment performed with the ABC loop is the compressor surge control experiment. Compressor surge can be regarded as the compressor operating limit in low mass flow rate region [8]. If compressor surge occurs, the structural integrity of the facility cannot be secured. Thus, there should be enough margin for the compressor mass flow rate. The compressor surge margin can be calculated from the equation below:

$$\text{Surge Margin [\%]} = \frac{\dot{m}_{comp} - \dot{m}_{surge}}{\dot{m}_{comp}} \times 100$$

For the experiment, the control valves at the inlet and outlet of the compressor are gradually closed to reduce the compressor mass flow rate. Due to this induced surge condition, the compressor surge margin will gradually drop. As the compressor surge margin becomes lower than 15%, the control valve at the compressor inlet is automatically opened to provide enough compressor mass flow rate. The experiment was conducted for five different compressor rotational speed as shown in figure 11. For the validation of GAMMA+ code, the experiment result at 35000 RPM was compared with the GAMMA+ code prediction.

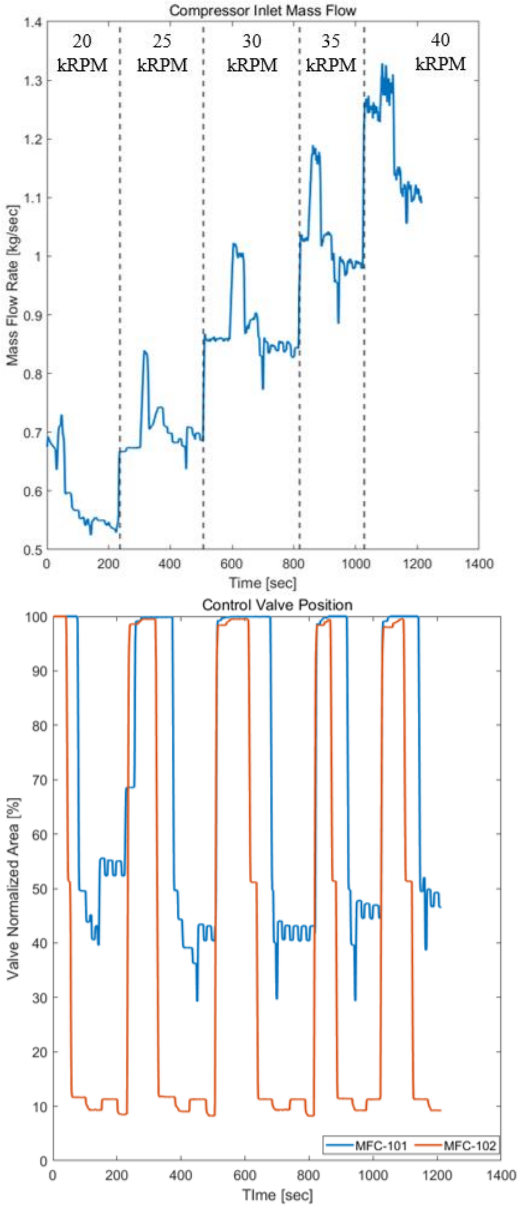


Figure 11. Compressor mass flow rate and control valve position during surge control experiment

To simulate the ABC loop compressor surge control experiment, the compressor off-design performance map is required. Figure 12 represents the compressor off-design performance map drawn from the data points. The data points were taken from the previous experiment facility at compressor rotational speed of 32, 36, and 40 kRPM. Since the compressor off-design performance data for 35000 RPM is not included in the data point, data points at 32 kRPM and 36 kRPM were interpolated to produce new data points at 35 kRPM.

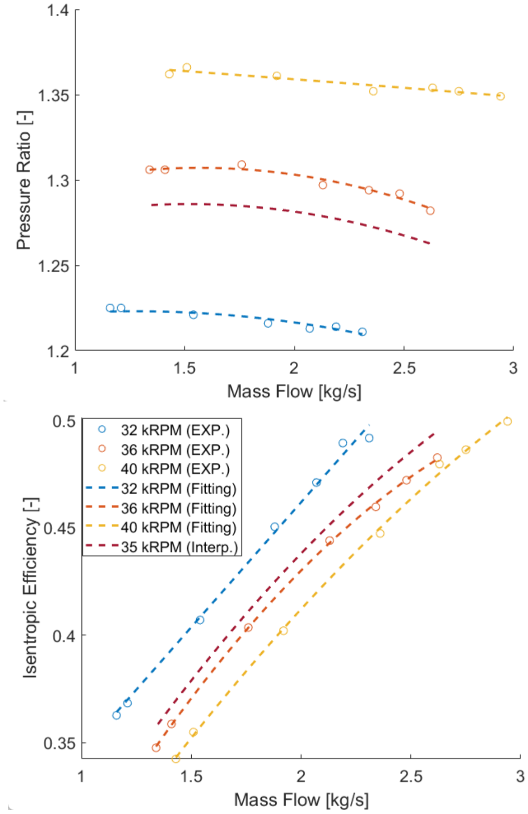


Figure 12. Off-design performance map of compressor

The power of the heater was given by the table to imitate the electric heater. Figure 13 shows the heater power calculated by the product of the heater mass flow rate and heater inlet and outlet enthalpy difference. The heater power shown in Figure 13 is data indirectly measured from mass flowrate and enthalpy difference instead of electric power input to the heater. Therefore, the heater thermal inertia and heat loss can reduce heating to the coolant even though constant heat power was applied. In the future, the system will be better insulated and more detail model will be developed to capture these effects with better accuracy. The other components, including the piping, were carefully modeled with the design or measured values. Figure 14 shows the nodalization of the ABC loop modeled in the GAMMA+ code. At this time, the turbine wheel was excluded from the experiment, thus the turbine wheel location was modeled with a single junction in the GAMMA+ code.

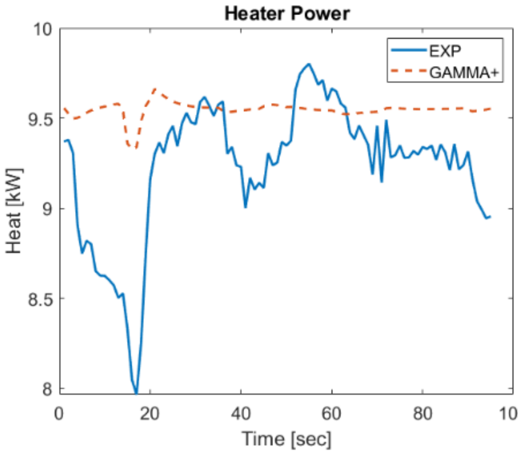


Figure 13. Heater Power Profile

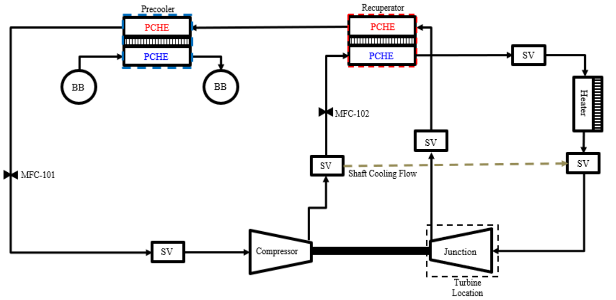
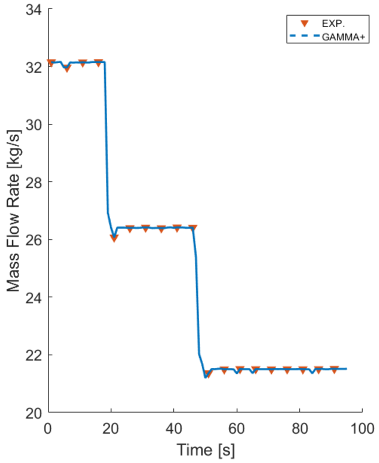


Figure 14. Nodalization of ABC loop for GAMMA+ Code

With the ABC loop nodalization modeled for GAMMA+ code, the compressor surge control experiment was simulated. The simulation results are shown in the figures below.



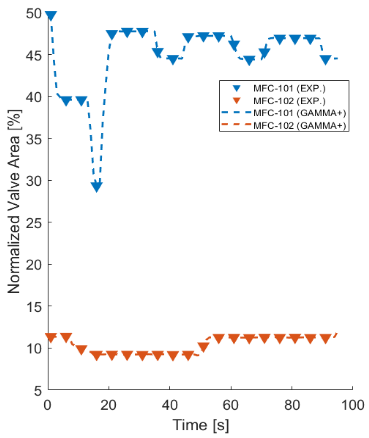


Figure 15. Cooling water mass flow rate and control valve opening area

As mentioned before, the cooling water mass flow rate and the compressor control valve opening area are given as the boundary condition. Based on these boundary conditions, the transient condition of the ABC loop was analyzed.

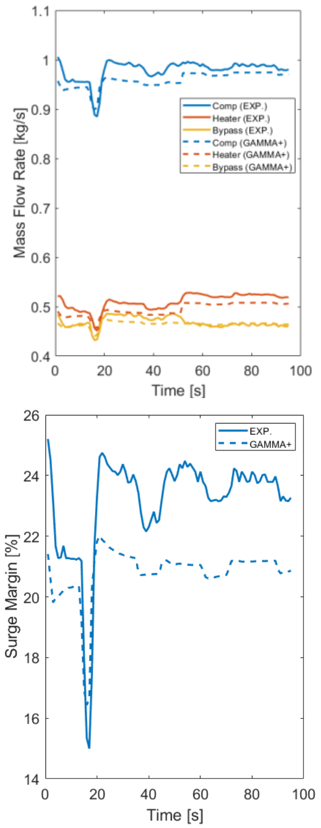


Figure 16. S-CO_2 mass flow rate and compressor surge margin at 35 kRPM

Figure 16 shows the mass flow rate of S-CO_2 and compressor surge margin calculated by the equation above. As the control valve at the compressor inlet and outlet closes, the compressor mass flow rate and the compressor surge margin decrease. When the compressor surge margin falls below 15%, the control valve at the compressor inlet is opened, securing enough compressor mass flow rate. The compressor pressure and temperature predicted by GAMMA+ code were compared with the actual compressor pressure and temperature from the experiment data in Figure 16. As shown in the figure, GAMMA+ code accurately predicted the compressor inlet and outlet pressure. Also, the compressor temperature calculated by the GAMMA+ code reflected the temperature change in the real experiment data.

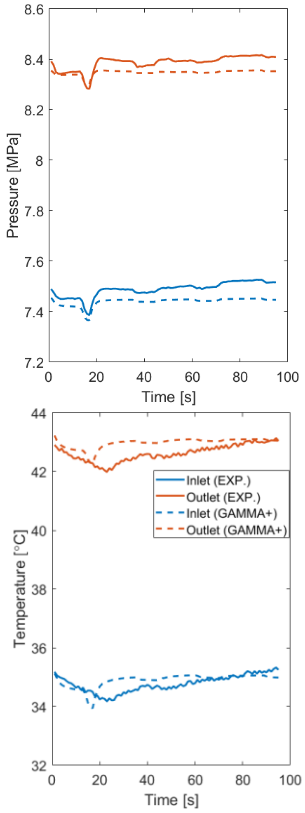


Figure 17. Compressor pressure and temperature

The calculation results of heater and recuperator part of the ABC loop are shown in Figures 19 and 20. The pressure and the temperature of each heat exchanger have subtle difference between the GAMMA+ prediction and the actual experiment value. However, the overall trend of the GAMMA+ prediction value is in accordance with the experiment value. For the recuperator temperature predicted by GAMMA+ code seems quite different from the actual recuperator temperature. The difference comes from the error in the steady-state condition modeling. Therefore, the amount of heat transferred in the recuperator was calculated by the following equation:

$$Q_{transferred} = \dot{m}\Delta H$$

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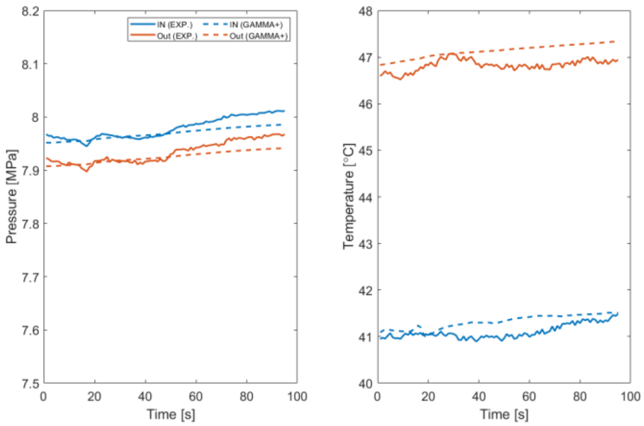

Figure 18. Heater pressure and temperature

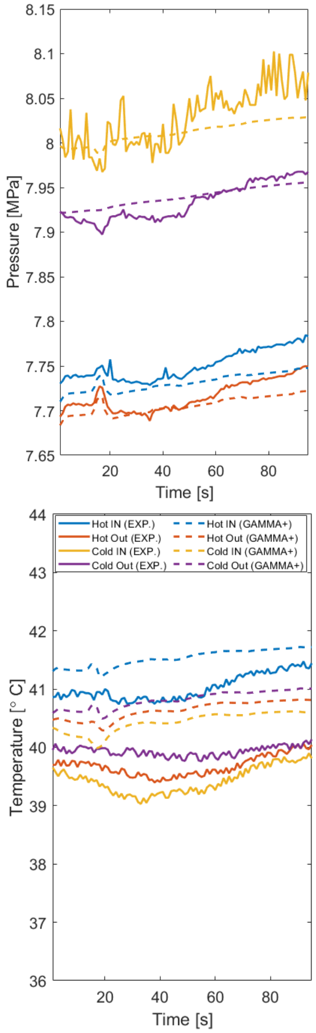

Figure 19. Recuperator pressure and temperature

By comparing the amount of heat transferred in the recuperator hot side and cold side, it is concluded that the GAMMA+ can predict the experiment data reasonably well for the heated condition as well. The source of error in the heat transferred is the error in the mass flow rate and the recuperator temperature difference. Therefore, with ABC loop experiment facility, the GAMMA+ code is validated not only for the compression and cooling of S-CO_2, but also for the heating and recuperation of the S-CO_2.

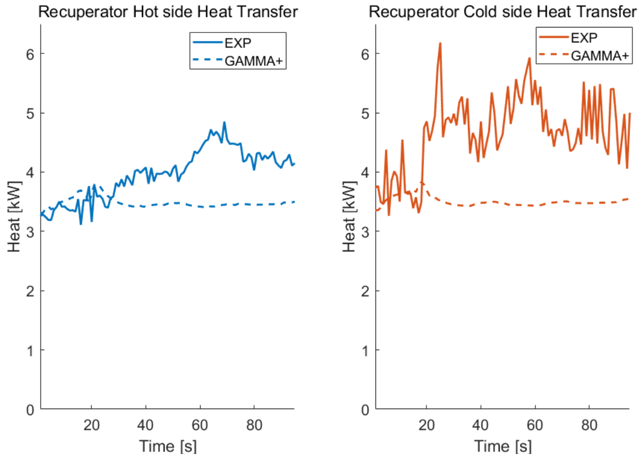

Figure 180. Recuperator heat transferred

CONCLUSIONS & FURTHER WORK

GAMMA+ code is a system simulation code developed by KAERI to simulate gas-cooled reactors. The NIST-REFPEOP database was implemented to GAMMA+ code to accurately obtain the thermal property of CO2 near the critical point. Using the modified code, various simulations for compact nuclear systems, including the transient analysis of KAIST-MMR was conducted previously. To examine how well the simulation result reflects the real operating condition, the code was validated with the compression and cooling data previously. With the newly constructed ABC loop at KAIST, the GAMMA+ code was again validated not only about the compression and cooling of S-CO2, but also for the heating and recuperation processes of S-CO2 power cycle. As the future work, experimental data with turbine will be obtained and will be again compared to GAMMA+ code prediction for validating the turbine model in the code.

As shown in this study, the GAMMA+ code is validated using the ABC loop with the data taken during a compressor surge control experiment. However, the experiment conditions were limited to the low pressure range and small temperature difference due to the hardware limitations on the ABC loop facility at the time. Currently, the ABC loop is being improved to expand capability of the facility. In near future, the experiment will be conducted in wider operating range (i.e. higher pressure ratio and larger temperature difference), and GAMMA+ code will be validated with new experiment data.

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NOMENCLATURE

$\dot{m}: mass\ flow\ rate\ \left[\frac{kg}{s}\right]$

$\mathrm{C_p}: Specific\ Heat\ capacity\ \left[\frac{J}{kg \cdot K}\right]$

$\Delta T: Temperature\ difference\ [K]$

$\dot{m}_{comp}: Compressor\ mass\ flow\ rate\ \left[\frac{kg}{s}\right]$

$\dot{m}_{surge}: Compressor\ surge\ mass\ flow\ rate\ \left[\frac{kg}{s}\right]$

$Q_{transferred}: Transferred\ Heat\ [W]$

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