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LOCA Analysis of KAIST-Micro Modular Reactor with Modified GAMMA+ code

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1. Introduction

Recently, a Small Modular Reactor (SMR) is receiving a lot of attention because of its flexibility of construction, potential for distributed power source and so on [1]. The supercritical carbon dioxide (S-CO_2) power cycle is being seriously investigated around the world due to its simple layout, quite high efficiency around 500°C turbine inlet temperature, etc [2]. By combining these two ideas, the KAIST research team developed a S-CO_2 cooled SMR, called KAIST-Micro Modular reactor (MMR), which is targeting transportability and electricity supply for remote region [3]. Therefore, requirements of MMR design are factory fabrication of the total system including power conversion system to be transported and air cooling to be independent from the site selection. Until now, steady performances and sizes of components were evaluated [4, 5]. Thus, in this paper a transient performance of the MMR are simulated with special focus on the loss of coolant accident (LOCA) at cold leg pipe. The transient analysis is performed with GAMMA+ code developed by KAERI and then the code are partly modified for the S-CO_2 working fluid which has abrupt change in properties near the critical point. Since the original GAMMA+ code is developed for normal gas cooled reactor transient analysis purpose, some modifications were needed to analyze KAIST-MMR.

2. Modification of GAMMA+ code

In this section, the method of how original GAMMA+ code was modified for the S-CO_2 cycle analysis is presented.

2.1. Properties modeling

Properties of CO_2 rapidly change near the critical point. Fortunately, the equation of state (EOS) or thermal property equation of CO_2 has arithmetic equation for wide range so that the equation could be easily coded as a sub-function of GAMMA+ code. However, the transport property equation especially near the critical point (240K < T < 450K, 25kg/m^3 < ρ < 1000kg/m^3) requires very complicated process for calculation, thus when evaluating transport properties near the critical point the values are obtained from the table property [6].

2.2. Turbomachinery modeling

The performance of S-CO_2 turbomachineries is modeled with the pre-generated performance map. The performance of S-CO_2 turbomachineries, which is categorized into efficiency and corrected enthalpy change, varies with respect to corrected RPM and corrected mass flow rate, defined as below.

$$\dot{m}_{corrected} = \dot{m}\sqrt{\left(\frac{V_{cr}}{V_{cr,design}}\right)^2}\left(\frac{p_{o,design}}{p_{o,in}}\right)\varepsilon \quad (1)$$

$$N_{rpm} = N\sqrt{\left(\frac{V_{cr,design}}{V_{cr}}\right)^2} \quad (2)$$

$$\Delta h_{o,corrected} = \Delta h_o\left(\frac{V_{cr,design}}{V_{cr}}\right)^2 \quad (3)$$

$$\eta_{comp} = \frac{(h_{ideal} - h_{inlet})\dot{m}}{q_{comp}}, \quad \eta_{turb} = \frac{q_{turb}}{(h_{outlet} - h_{ideal})\dot{m}} \quad (4)$$

Where

$$V_{cr}{}^2 = \frac{\gamma}{\gamma+1}RT_o, \quad \varepsilon = \gamma_{design}\left(\frac{2}{\gamma_{design}+1}\right)^{\frac{\gamma_{design}}{\gamma_{design}-1}} \Big/ \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

From equation (1) to equation (4), each equation defines mean corrected mass flow, RPM, corrected enthalpy change and turbomachineries efficiency, respectively. Following figures show the performance map of MMR turbomachineries.

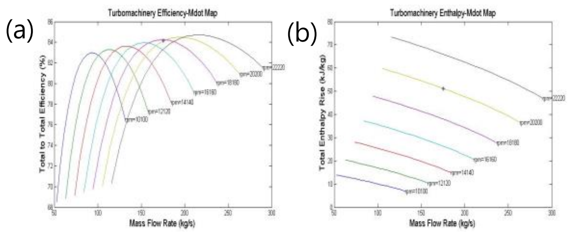

Fig. 1. Efficiency (a) and Corrected total enthalpy rise (b) of compressor

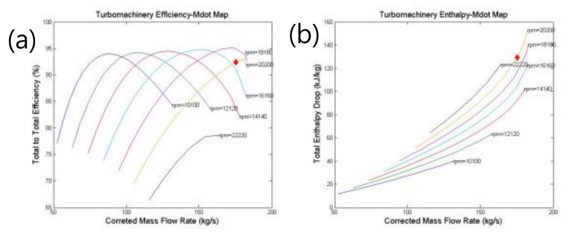

Fig. 2. Efficiency (a) and Corrected total enthalpy drop (b) of turbine

3. System modeling

In this section design parameters, steady state results with the modified code and the configuration of MMR are shown together.

3.1. Configuration of MMR.

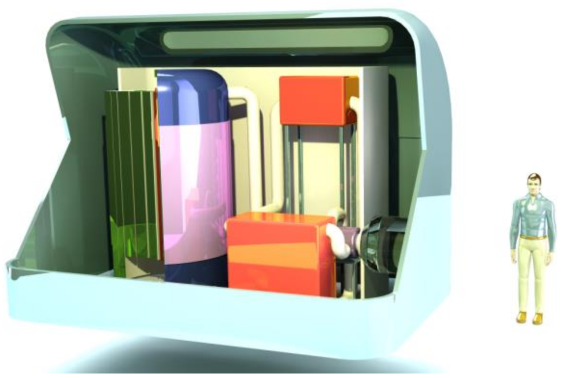

Fig. 3. Configuration of MMR with double containments

In figure 3, the plant is covered with double containment to conservatively prevent high pressure and radioactive material from leakage.

3.2. Design parameters and steady state results with the modified code.

Table 1 summarizes the design parameters and steady state results of MMR to check whether the modified code simulates the design successfully.

Table I: Design parameters and steady state results of MMR

	Design parameters	Code results
Q_{th}	36.2MWth	36.1983MWth
$T_{comp,in}$	60.0°C	60.390°C
$P_{comp,in}$	7.58MPa	7.662MPa
$T_{turb,in}$	550°C	550.256°C
$P_{turb,in}$	19.97MPa	20.15MPa
$\dot{m}$	175.34kg/s	175.75kg/s
RPM	20200	20200.668
Wturb	23.09MW	22.615MW
Wcomp	12.74MW	12.459MW
$T_{contain,in}$	36.8°C	36.8°C
$P_{contain,in}$	5.0MPa	5.0MPa

4. LOCA modeling

In this part boundary condition of LOCA and the transient results are discussed.

4.1. Boundary condition of LOCA.

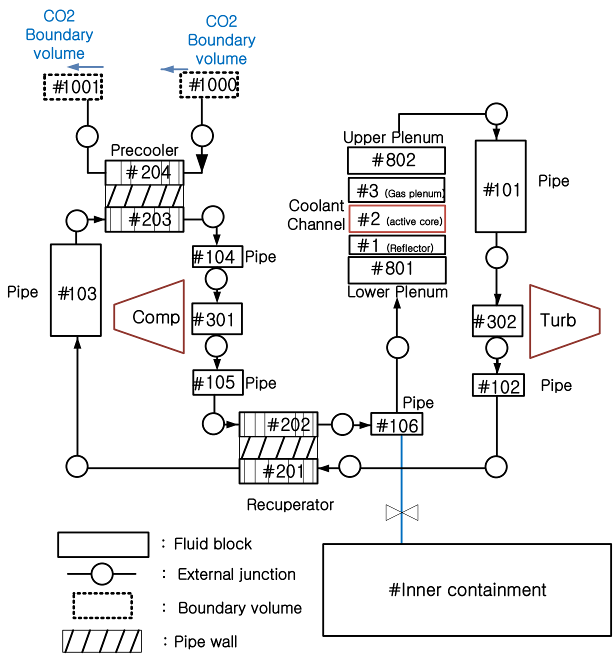

Fig. 4. Nodalization of MMR connected with inner containment

The rupture diameter of the accident is assumed to be 1cm and the location of rupture is at cold leg pipe, i.e. #106 node shown in the figure 4. During the accident analysis, some assumptions were made. The first assumption is that the integrity of two containments is guaranteed. Thus, mass and momentum between inner and outer containment is not transferred. The second assumption is that the precooler flow rate is always kept at constant during the accident. Thus, decay heat is removed via precooler after the core shuts down.

4.1. Transient results from modified GAMMA+ code.

The accident occurs at 50sec by opening the valve connected with inner containment, which mimics the break. Then, the reactor shuts down due to negative reactivity insertion from the control rod. The transient results calculated with the modified GAMMA+ code are shown in the following figures.

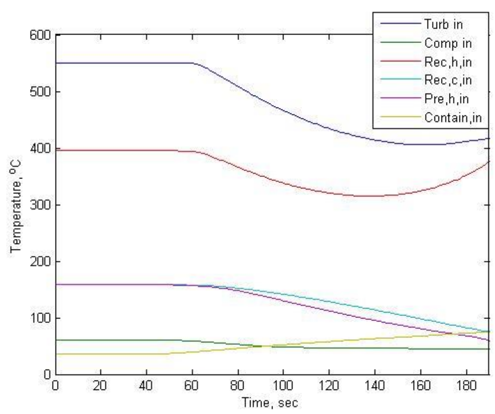

Fig. 5. Temperature trend of each components

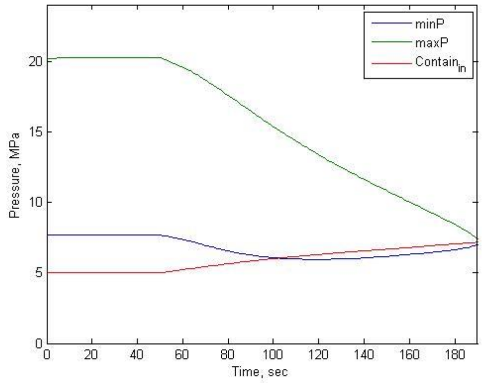

Fig. 6. Pressure of maximum, minimum and inner containment

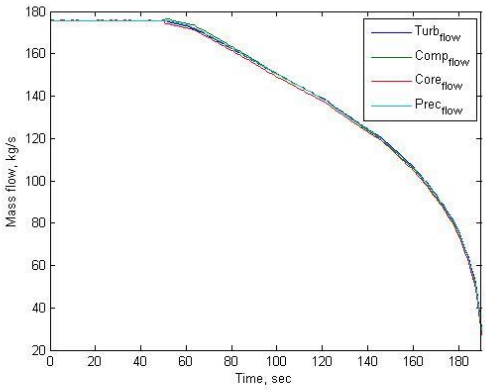

Fig. 7. Mass flow rate of each components

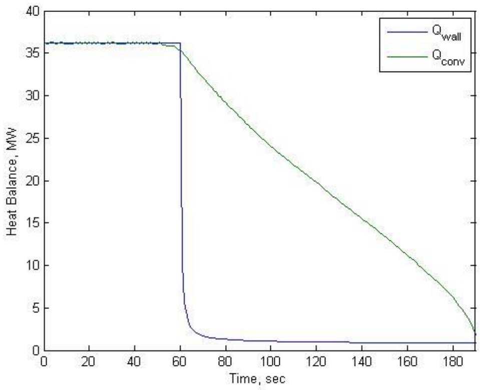

Fig. 8. Heat from core and convective heat

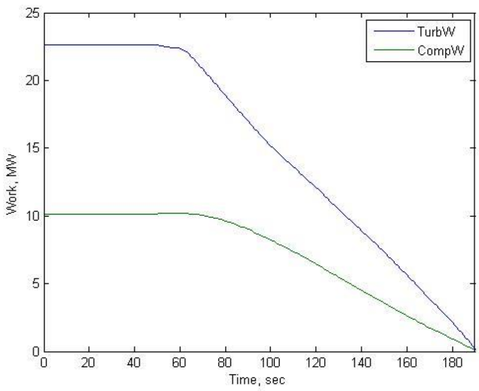

Fig. 9. Turbine and compress work

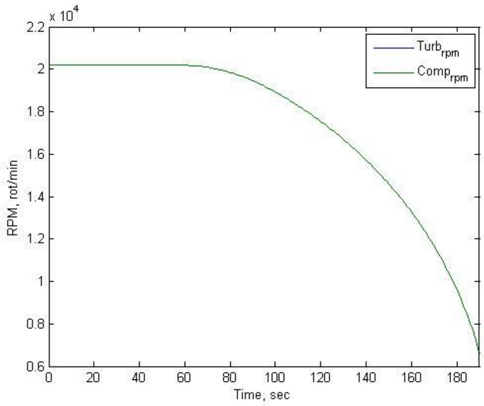

Fig. 10. Turbine and compressor RPM

In figure 5, temperatures of overall components are decreased than the nominal values but temperature of the containment is increased because low temperature of inner containment is mixed with high temperature fluid from the primary cycle due to LOCA. Similarly, the whole pressure of primary system and the pressure of containment are converged at about 7.04MPa as shown in figure 6. In figures 7 and 8, since the reactor power is rapidly reduced and CO_2 inventory of primary system is leaked into the inner containment, mass flow rate of primary cycle is decreased. Along with the reduction of mass flow rate, generated or consumed works of turbomachineries are also reduced because of equation (4) as shown in figure 9.

5. Conclusions

A transient analysis of the MMR was performed in this paper. The MMR is a newly suggested innovative small modular reactor concept by the KAIST research team. Since the MMR is cooled by supercritical CO_2, general safety codes for conventional reactors have limitations. Thus, GAMMA+ code for the transient analysis of a gas-cooled reactor was selected and modified for the S-CO_2 power system. After the modification of GAMMA+ code, LOCA is simulated, which is considered as one of the most limiting accidents in terms of safety of nuclear power plant. Furthermore, the modified GAMMA+ code can simulate change of speed of turbomachineries reasonably as well as the reactivity change. In the future, the modified GAMMA+ code will be used for analyzing other safety important accident scenarios.

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