TRANSIENT ANALYSES OF S-CO_2 COOLED KAIST MICRO MODULAR REACTOR WITH GAMMA+ CODE

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ABSTRACT

Existing Small Modular Reactors (SMR), which have been usually cooled by water, haven't achieved a full modularization because of large steam power system and following balance of plant. However, if the working fluid of the SMR uses supercritical CO_2 (S-CO_2) as the working fluid, the SMR could be more compact and achieve better modularization. From the characteristic of S-CO_2, KAIST research team has developed a SMR targeting portable and perfectly modular reactor, namely the KAIST Micro Modular Reactor (MMR). Until now, the design work of reactor core, major components, and cycle configuration have been performed for the MMR. In this paper, transient analyses of the designed MMR are performed to check whether the designed reactor can conceptually secure satisfactory safety margin when some events occur, which could lead to severe accident. Among many events, load rejection is selected as one of important events for developing power system control logic because load rejection event can lead to SBO (Station black out) accident if any active safety features are not working after the event. Moreover, SBO accident became widely known to the even non-nuclear industry people after the Fukushima accident. In certain aspect, load rejection event response became a quantitative measurement of how the designed nuclear system can withstand such initial event. Moreover, once load rejection transient results of the MMR are obtained, the results could suggest new design criteria of the MMR. This study can provide perspective of the performance of the MMR during the load rejection event as well as the information of the control logics of the newly proposed nuclear system.

INTRODUCTION

SMR systems can gain benefit through modularization, by which the structures, systems and components are shop-fabricated then shipped and assembled on site, thus construction time for SMRs can be substantially reduced[1]. Currently developed SMRs are usually cooled by water but using water as coolant prevents SMRs from complete modularization. One of the problems is large volume for steam Rankine cycle, so that SMRs cooled by water are generally more challenged for modularization with a power conversion system. Recently, S-CO_2 is gaining attention as a working fluid for a power cycle because of simplicity and compactness [2]. Due to these characteristics of the S-CO_2 cycle, SMRs could be coupled with S-CO_2 cycle as the power conversion system [3]. Furthermore, to achieve perfectly modularized nuclear power system, a direct S-CO_2 cycle which contains reactor core and power conversion system in single loop by removing intermediate heat exchanger (e.g. steam generator) in between the core and the power conversion system can be considered. As a newly developed concept to incorporate all the aforementioned suggested ideas, the KAIST Micro Modular Reactor (MMR) is suggested. The top priority of the MMR is transportability, so that a simple recuperated cycle is selected even though the power cycle efficiency is lower than the widely known recompressing cycle [4]. The conceptual design of reactor core, heat exchangers, turbomachinery and cycle configuration of the MMR is completed [5-7].

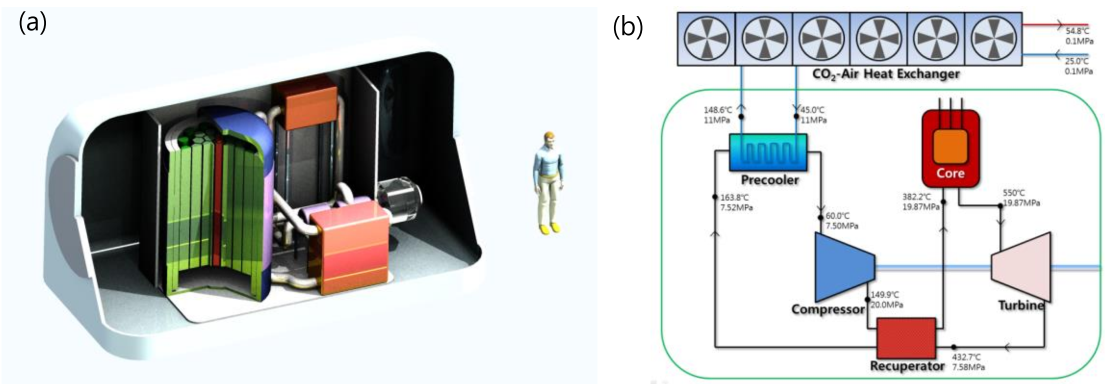


Figure. 1. Conceptual design of MMR (a) and Cycle configuration (b)

However, a nuclear power plant cannot be fully accepted with the performance for designed conditions only. The integrity of the system should be demonstrated for various selected design basis accidents. To preliminarily demonstrate the integrity of the developed MMR concept under various accident scenarios, transient simulation approaches are usually adopted. Since the MMR will be operated in the isolated regions, that the load rejection accident can occur frequently, which is unusual for a large nuclear power plant. This is because the local electric grid is operating under non-environmentally friendly condition and the grid of the remote region is much more unstable than the rural area because of the small grid capacity. Moreover, after the Fukushima disaster, more emphasis has been focused on the potential risk of an initial event which could bring out SBO accident for a nuclear system.

Thus, in this paper, the load rejection accident is first analyzed to preliminarily demonstrate the safety of the developed MMR concept. For this purpose, a code named GAMMA+ developed by Korea Atomic Energy Research Institute (KAERI) is selected for the transient simulation [8]. Originally, GAMMA+ code is developed for the High Temperature Gas Reactor (HTGR) transient analysis, so that the code is capable of performing the desired simulation with minor modifications to model the S-CO_2 system.

PROPERTIES MODELING

Inherently, CO_2 properties rapidly change near the critical point [9]. Since original GAMMA+ code is developed for HTGR analyses, the GAMMA+ code did not incorporate the exact CO_2 properties especially near the critical point (T_c=304.1282 K P_c=7.3773 MPa). To obtain the exact CO_2 properties near the critical point with GAMMA+ code, firstly REFPROP program developed by NIST has been directly connected to GAMMA+ code. However, this method consumed too much time for the simulation of a large CO_2 system. Therefore, an equation of state (EOS) of CO_2 is directly solved with the sub-function of GAMMA+ code to reduce the calculation time and improve the accuracy of the calculate CO_2 properties.

Thermal properties of CO_2 can be obtained from the Helmholtz free energy which is a fundamental EOS for pure substance.

$$\phi(\delta,\tau)=\phi^{o}(\delta,\tau)+\phi^{r}(\delta,\tau) \qquad \text{Where, } \delta=\rho_c/\rho \text{ and } \tau=T/T_c \qquad (1)$$

The first term and the second term of RHS represent ideal and residual Helmholtz energy, respectively in equation (1). The pure substance properties can be calculated by differentiating the Helmholtz energy with respect to the reduced density (δ) and the inverse of reduced temperature (τ). Table 1 lists the essential thermal properties newly implemented in GAMMA+ code.

Table 1. Thermal property equations as function of Helmholtz equation

Property		Equation
$\frac{P(\delta,\tau)}{\rho RT}$	Pressure	$1+\varnothing_{\delta}^{r}$
$\frac{s(\delta,\tau)}{RT}$	Entropy	$\tau(\varnothing_{\tau}^{o}+\varnothing_{\tau}^{r})-\varnothing^{o}-\varnothing^{r}$
$\frac{C_v(\delta,\tau)}{R}$	Isochoric Capacity	$-\tau^{2}(\varnothing_{\tau\tau}^{o}+\varnothing_{\tau\tau}^{r})$
$\frac{h(\delta,\tau)}{RT}$	Enthalpy	$1+\tau(\varnothing_{\tau}^{o}+\varnothing_{\tau}^{r})+\delta\varnothing_{\delta}^{r}$
$\frac{C_p(\delta,\tau)}{R}$	Isobaric Capacity	$-\tau^{2}(\varnothing_{\tau\tau}^{o}+\varnothing_{\tau\tau}^{r})+\frac{(1+\delta\varnothing_{\delta}^{r}-\delta\tau\varnothing_{\delta\tau}^{r})^{2}}{1+2\delta\varnothing_{\delta}^{r}+\delta^{2}\varnothing_{\delta\delta}^{r}}$
$\frac{w^{2}(\delta,\tau)}{RT}$	Speed of Sound	$1+2\delta\varnothing_{\delta}^{r}+\delta^{2}\varnothing_{\delta\delta}^{r}-\frac{(1+\delta\varnothing_{\delta}^{r}-\delta\tau\varnothing_{\delta\tau}^{r})^{2}}{\tau^{2}(\varnothing_{\tau\tau}^{o}+\varnothing_{\tau\tau}^{r})}$

Thermal properties can be calculated by inserting density and temperature as independent variables with equation (1). However, pressure and temperature have to be entered as independent variables in GAMMA+ code. Therefore, an iterative calculation is needed to obtain density which matches thermodynamically with the given pressure. The Newton-Raphson method is one of the fastest methods for this purpose and it requires one initial value to find the density. The iterative calculation is implemented as the sub-function of GAMMA+ code.

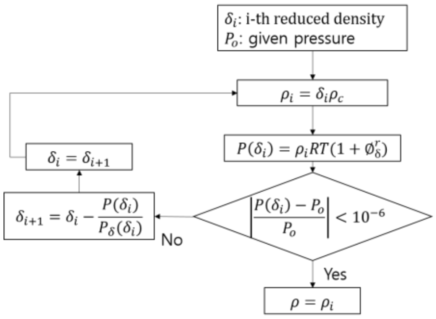


Figure 2. Flow chart to find the density of given pressure.

Transport properties, which are viscosity and thermal conductivity, are also modeled with the sub-function of GAMMA+ code.

$$X(\rho,T) = X^o(T) + \Delta X(\rho,T) + \Delta_c X(\rho,T) \tag{2}$$

Equation (2) is a basic equation for transport properties. The first term is the transport property in the limit of zero density, which assumes only two-body molecular collision occuring. The second term represents all other effects like many-body interaction and molecular-velocity correlations. The final term represents the critical enhancements near the critical point. However, critical term of transport properties is too complicated to model [10]. To solve this difficulty, a tabular fluid property is used to model the transport properties near the critical point. Unfortunately, ordinary linear interpolation is too rough to calculate the properties near the critical point. Thus, log indexed property table is inserted in GAMMA+ code to overcome the problem [11].

TURBOMACHINERY MODELING

The S-CO_2 Brayton cycle operates near the critical point for low pressure and temperature sections. At the critical point, thermal properties are rapidly changed. That means turbomachinery modeling of the S-CO_2 cycle should reflect the real gas effect, instead of simply assuming ideal gas. The isentropic efficiency is used for modeling the efficiency of the turbomachinery.

$$q_{comp} = (h_{outlet} - h_{inlet})\dot{m} = \left(\frac{h_{ideal} - h_{inlet}}{\eta_{comp}}\right)\dot{m} \tag{3}$$

$$q_{turb} = (h_{outlet} - h_{inlet})\dot{m} = \eta_{turb}(h_{outlet} - h_{ideal})\dot{m} \tag{4}$$

To obtain ideal enthalpy rise of the designed turbomachinery, the enthalpy change between inlet and outlet of the turbomachinery is needed. These two parameters, efficiency and pressure ratio, can be obtained from a pre-generated performance map and interpolation with respect to the corrected mass flow rate and RPM. The pressure ratio map is usually preferred for plotting the basic formation of the turbomachinery. The following equations represent the corrected parameters of the turbomachinery.

$$\dot{m}_{corrected} = \dot{m}\sqrt{\left(\frac{V_{cr}}{V_{cr,design}}\right)^2}\left(\frac{p_{o,design}}{p_{o,in}}\right)\varepsilon \tag{5}$$

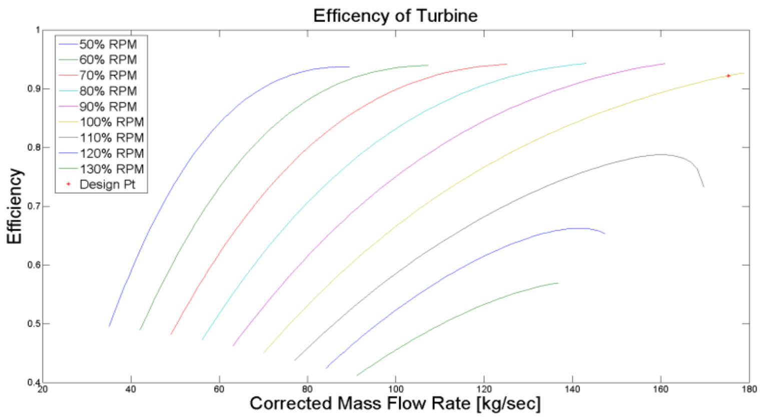
$$\Delta h_{o,corrected} = \Delta h_o \left(\frac{V_{cr,design}}{V_{cr}}\right)^2 \tag{6}$$

$$N_{rpm} = N\sqrt{\left(\frac{V_{cr,design}}{V_{cr}}\right)^2} \tag{7}$$

Where $$V_{cr}{}^2 = \frac{\gamma}{\gamma+1}RT_o\,,\quad \varepsilon = \frac{\gamma_{design}\left(\frac{2}{\gamma_{design}+1}\right)^{\frac{\gamma_{design}}{\gamma_{design}-1}}}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}} \tag{8}$$

Specific heat ratio (γ) is the inlet property of turbomachinery. Figure 3 and figure 4 show the performance map of the designed compressor and turbine for KAIST MMR, respectively [12].

(a)



(b)

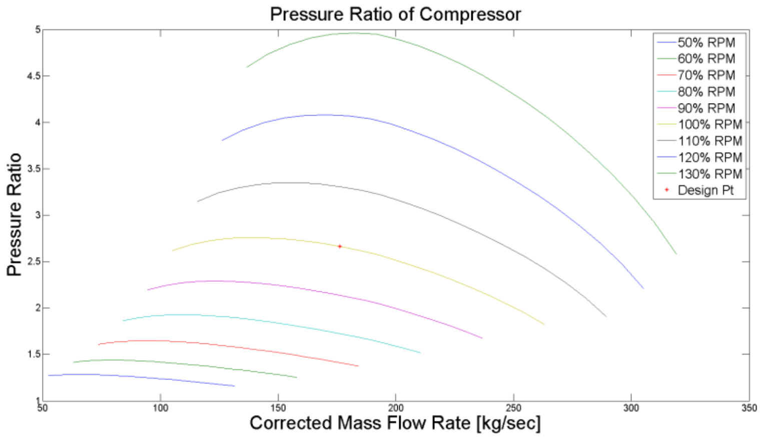


Figure 3. Efficiency (a) and Pressure ratio (b) of compressor

(a)

(b)

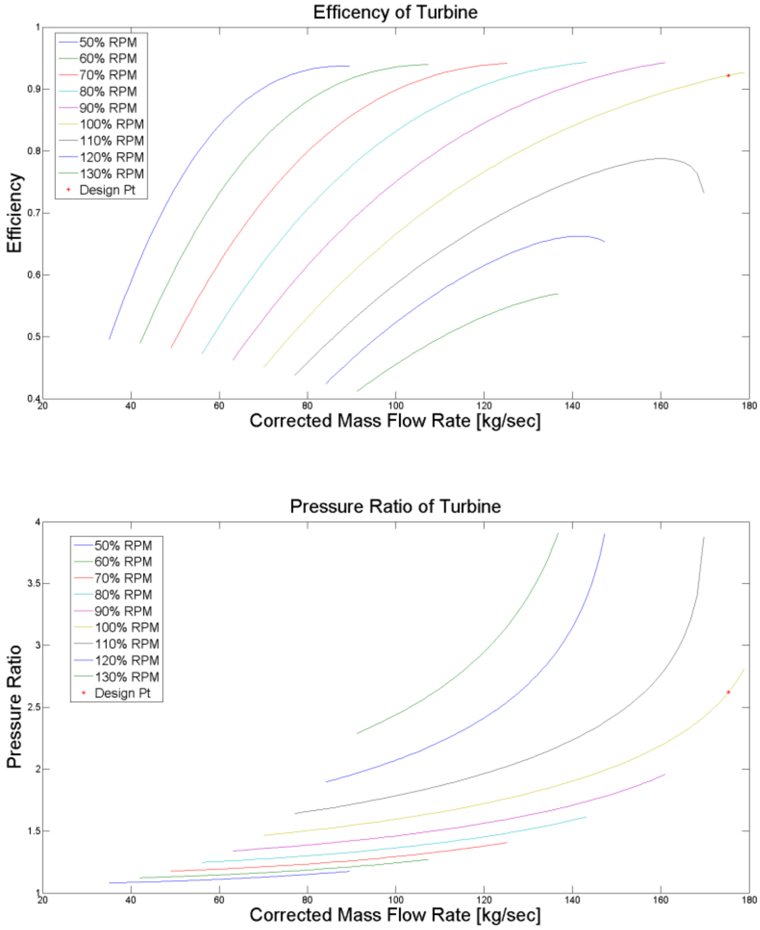


Figure 4. Efficiency (a) and Pressure ratio (b) of turbine

Even though REFPROP program can directly calculate pressure from given enthalpy and entropy, the calculation time can be shorter if tabulated properties are also used for calculating pressure from enthalpy and entropy. Consequently, a pressure table based on enthalpy and entropy was generated and implemented in GAMMA+ code. The covering ranges are the range above critical (i.e. supercritical state).

STEADY STATE MODELING OF MMR

Since the MMR is targeted to operate in the remote region like desert and pole, heat of the MMR can be rejected to ambient air via cooling fan. As shown in figure 1 (b), a precooler is not directly connected with the air cooling fan. Instead, 11MPa and 45^{o}C CO_2 loop is inter-connecting the precooler and air. This is to maintain the purity of MMR primary cycle when even the precooler channel breaks. However, the cooling loop of the MMR in GAMMA+ code is not fully modeled but simplified by simply prescribing the inlet CO_2 of the cooling loop to be11MPa and 45^{o}C

Major on-design parameters of the MMR are listed in table 2.

Table 2. On-design parameters of MMR

Reactor Power	36.2MWth	Recuperator Channel Diameter	1.8mm
Compressor inlet Pressure	7.58MPa	Recuperator Channel Number	143000
Compressor Inlet Temperature	60℃	Precooler Channel Diameter	1.8mm
Turbine inlet Pressure	19.87MPa	Precooler Channel Number	133000
Turbine inlet Temperature	550℃	Turbine Power	23.09 MW
Mass flow rate	175.34 kg/sec	Compressor Power	10.35 MW
Turbomachinery RPM	20200	Generator Power	12.74 MW

Table 3. Moments of Inertia (kg-m^2)

NPP	Generator	Turbine	Compressor	Total
MMR(36.2MWth)	15.075	12.814	4.607	32.496
Pope(2400MWth)	1000	850	305.6	2454.7

In the case of moments of inertia, Moments of inertia of MMR turbo-machineries are not fully modeled yet. Therefore, the inertia is assumed by multiplying moments of inertia of 2400MWth S-CO_2 cooled fast reactor, which is conceptually developed by Pope [13], with 36.2MWth power to 2400MWth ratio.

From these parameters, GAMMA+ code input file for the MMR load rejection analysis is developed and figure 5 represents the input nodalization of the MMR.

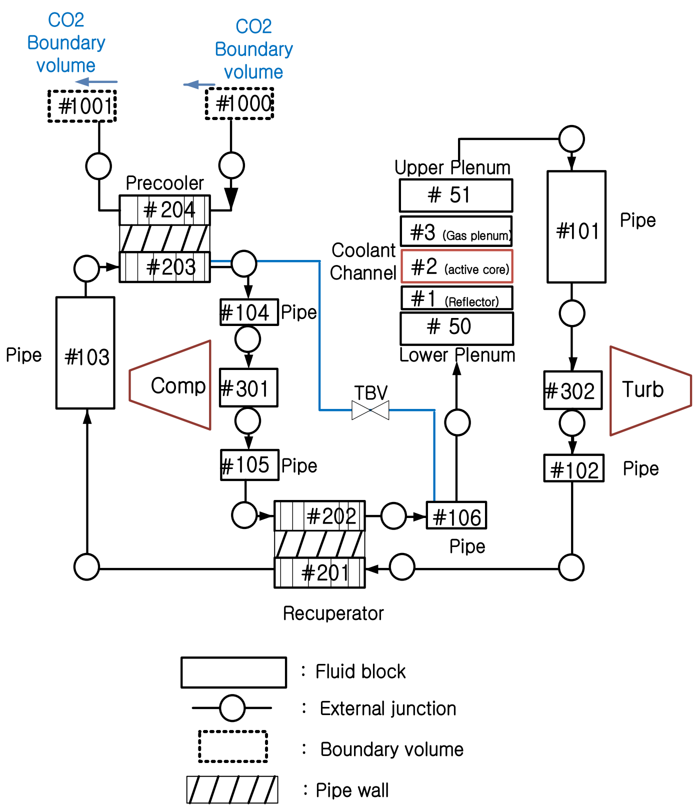


Figure 5. MMR nodalization

Below table are steady state results of the MMR by GAMMA+ code.

Table 4. steady state results of MMR

Reactor Power	36.2MWth	Mass flow rate	175.76 kg/sec
Compressor inlet Pressure	7.66MPa	Turbomachinery RPM	20200.668
Compressor Inlet Temperature	60.4℃	Turbine Power	22.62 MW
Turbine inlet Pressure	20.16MPa	Compressor Power	10.16 MW
Turbine inlet Temperature	550.3℃	Generator Power	12.46 MW

As shown from tables 2 and 3, the parameters of the MMR are mostly converged to code calculation.

LOAD REJECTION EVENT WITHOUT ACTIVE CONTROL

Load rejection event is simulated without any active control by GAMMA+ code. Load rejection event is defined as the condition in which there is a sudden load trip in the system which cause turbine to be over-frequency. The event occur at 0.0 sec with losing the grid power.

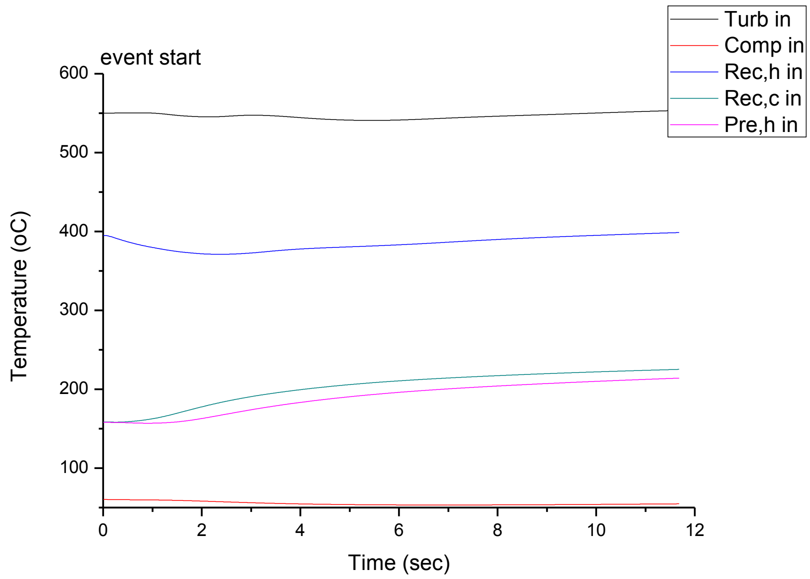


Figure 6. Temperature of MMR components on load rejection without active control

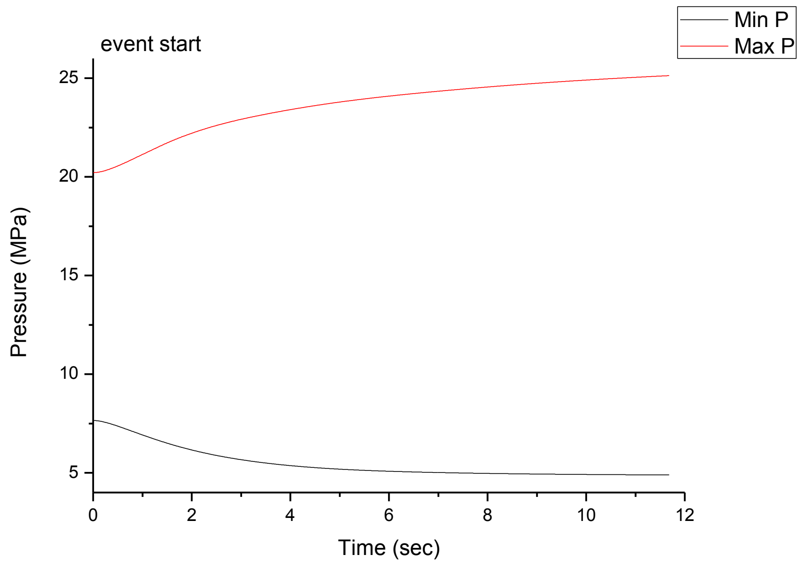


Figure 7. Minimum and Maximum pressure on load rejection without active control

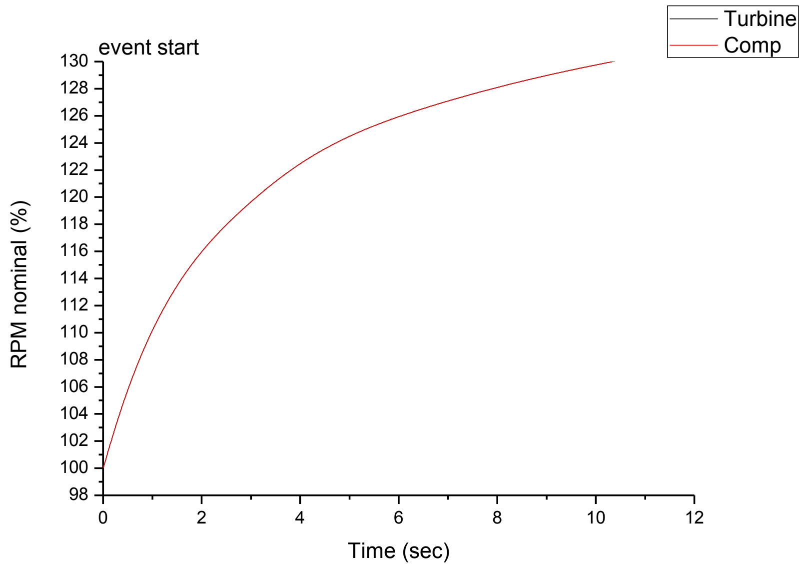


Figure 8. Turbine and Compressor RPM on load rejection without active control

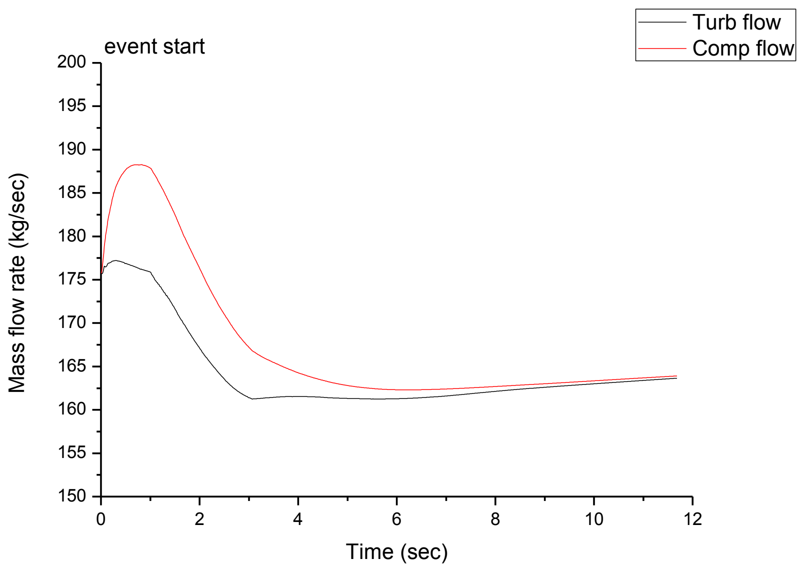


Figure 9. Mass flow rates on load rejection without active control

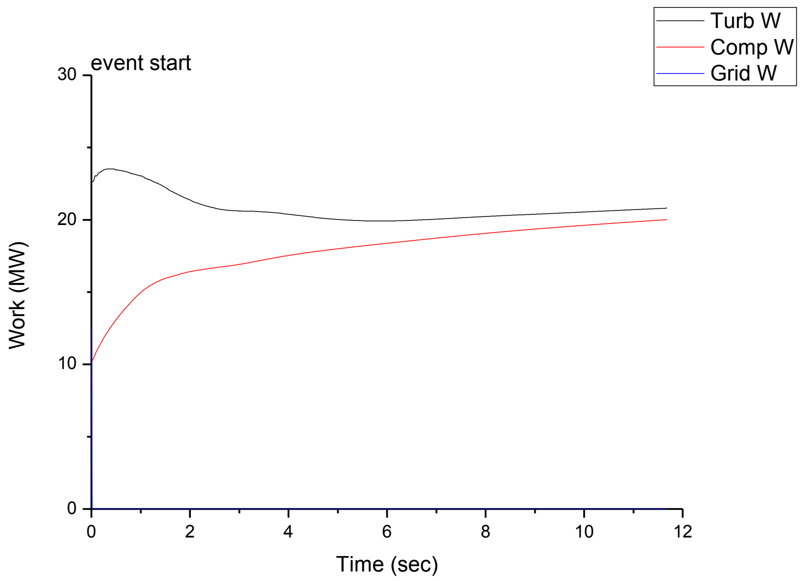


Figure 10. Work of turbomachinery on load rejection without active control

As shown in figure 6, fluid temperature is slightly decreased or maintained at the beginning of the accident. However, the heated fluid is less expanded through the turbine because generator torque is zero as soon as the load rejection event initiates. This means that the turbine energy is no longer consumed by the grid. Therefore, the generated heat from the core is not converted to the useful work, which finally results in increasing of the temperature. In the case of pressure, the minimum pressure is declined because the pressure ratio of turbine is abruptly increased along with increasing of RPM as shown in figure 4(b). Since the pressure ratio of compressor is also maximum along with increasing of RPM in figure 3(b), the maximum pressure is also increased. Moreover, rotational speed of turbine is seriously increased because load rejection could act as loss of fluid resistance, so that mass flow rate is also increased at the beginning of the event. In figure 8, the code is automatically terminated because the turbomachinery performance map can be applied up to 130% RPM only. According to the previous ANL research works, turbomachinery blades can keep their integrity up to 120~130% of the nominal RPM [14], thus the termination of the calculation is reasonable. From the changes of cycle parameters, control logic of MMR could be dimly defined.

LOAD REJECTION EVENT WITH ACTIVE CONTROL

The load rejection accident is simulated with active controls, which are core inlet bypass and power reduction by GAMMA+ code by assuming that the MMR is equipped with energy storage system that can operate at least valve systems. When the load rejection event occurs, the rotational speed must increase, so that the mass flow through the turbine is decreased to alleviate over rotational speed. During the load rejection accident, the generated heat from the core is not converted to the useful work. Therefore, the generated heat should be reduced to prevent the core from over-heating. As shown in figure 5, the core inlet bypass valve (CBV) connects between the precooler and the core inlet pipe. The reason is that coolant before passing reactor core has quite high density and low temperature than after passing the core. If hot coolant after core is mixed up with cold coolant in precooler, which can lead to thermal shock of precooler as well as inefficient bypass due to low density.

Following table represents time step control action of MMR when load rejection event is simulate

Table 5. Control action in load rejection event of MMR

Time (sec)	Event	Setpoint or Value
0.0	Load is rejected.	-
0.845	High shaft speed condition	110%
1.345	Opening of core inlet bypass	-
3.5	Shutdown of reactor	-

The setpoint of opening core inlet bypass is 110% nominal value of rotational speed of turbine. As show figure 8, rotational speed of turbine is reached to 110% nominal value at 0.845 sec so that reactor bypass valve is opened at 0.845. The meaning of 110% nominal value of turbine speed is because conventional PWR has safety limit of turbine speed as 120% nominal value. Turbine speed of PWR is generally 1500 RPM and blade length is about 2m but MMR has very high rotational speed 20200 RPM and blade length is about 0.323m so that tip turbine speed of MMR is much faster than conventional PWR. Thus, considering conservative design MMR, setpoint of opening core inlet bypass is determined as 110% nominal value of rotational speed of turbine. The opening rate of core inlet bypass valve is assumed as 1/0.5 sec. In general, limit is reactor coolant pressure boundary safety limit of 110% of design pressure in PWR case. Likewise, MMR is also operated at about 20 MPa pressure. Therefore, opening rate of valve in PWR could be similarly applied to MMR and that value is 0.5 sec. This opening rate is proposed in Section Ⅲ of ASME code mentioning all valves lift at a flow rating pressure not exceeding 110% of the set pressure. After reactor trip signal is generated, actual time to scram a core is determined as 3.5 sec in PWR. MMR also has falling secondary control element in center of the core and additionally devises drum type control element in side of core as shown following figure so that this trip delay time of PWR could be again applied in MMR

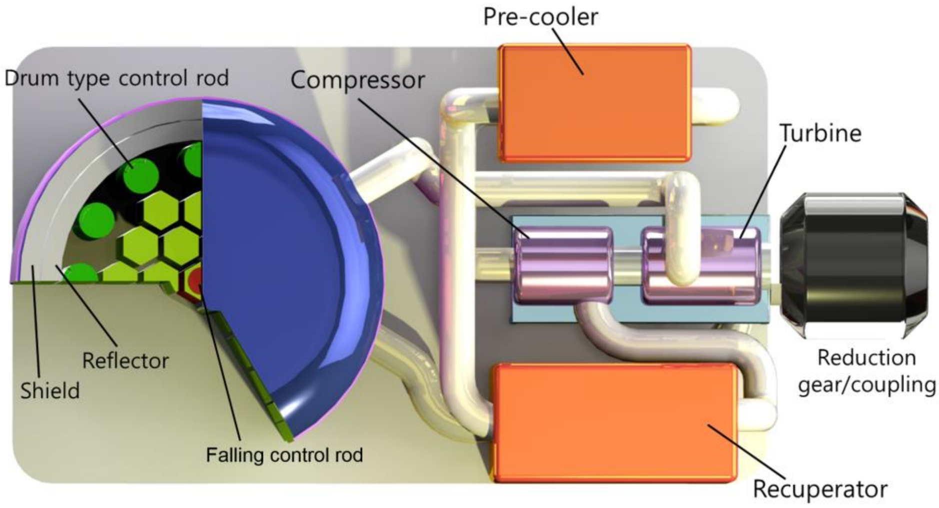


Figure 11. Temperature of MMR components on load rejection with active control

Figures 12 to 14 are the code results of load rejection event at the early stage along with time step control action

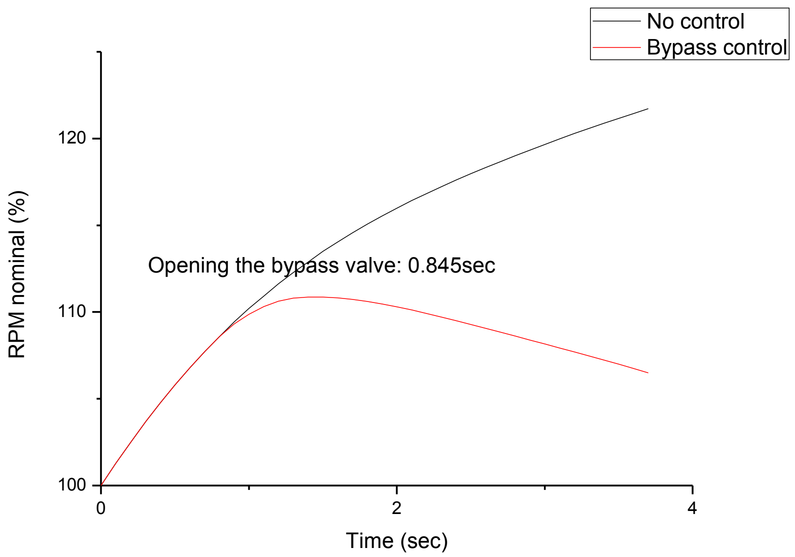


Figure 12. Rotational speed of turbine without and with core inlet bypassing

If any control action is not applied in the system, rotational speed of turbine would be steadily increased but after bypass valve is opened, rotational speed is substantially reduced because of mass flow rate that would flow into turbine is decreased.

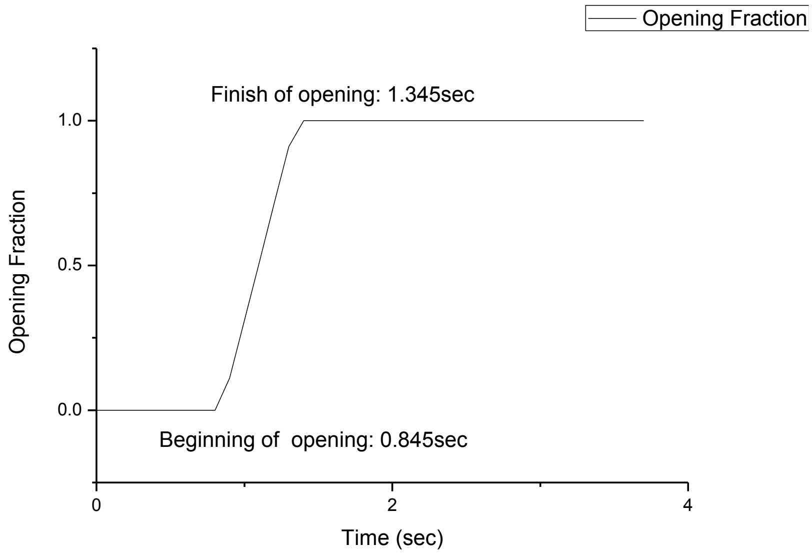


Figure 13. Core inlet bypass valve opening rate

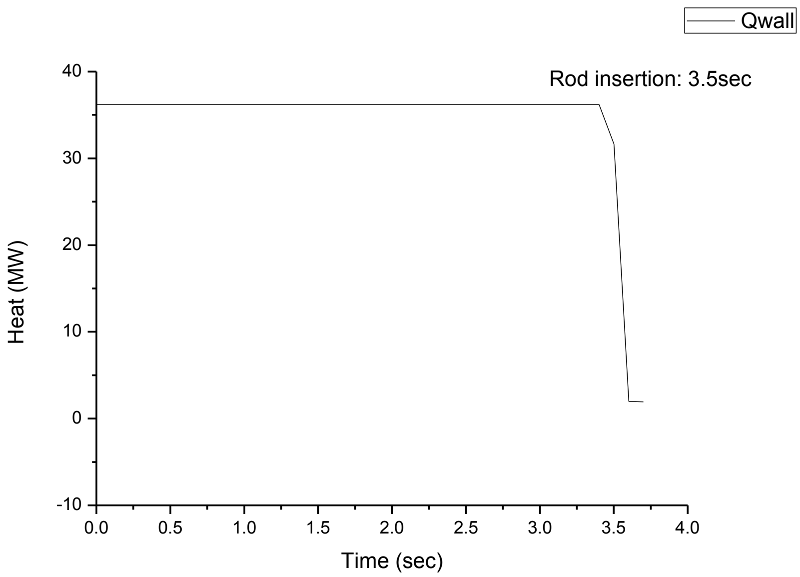


Figure 14. Reactor trip by rod insertion

After short term transient results are shown, long term transient results of load rejection event would be represented.

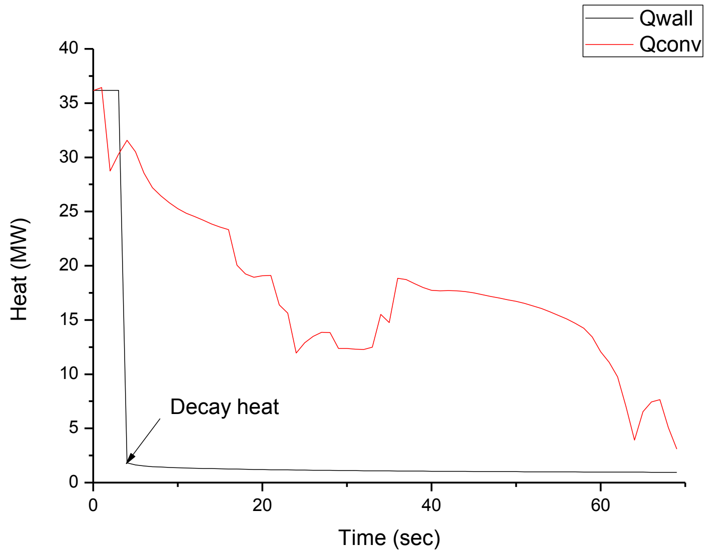


Figure 15. Heat balance of reactor core on load rejection with active control

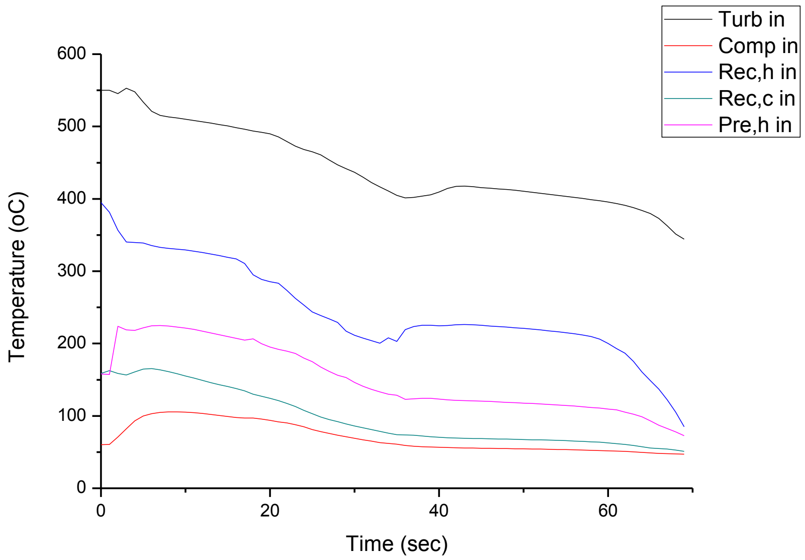


Figure 16. Temperature of MMR components on load rejection with active control

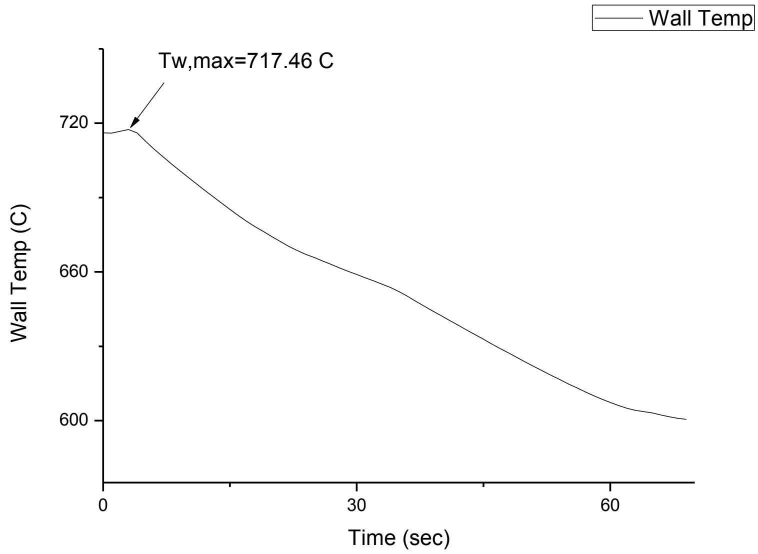


Figure 17. Wall surface temperature on load rejection with active control

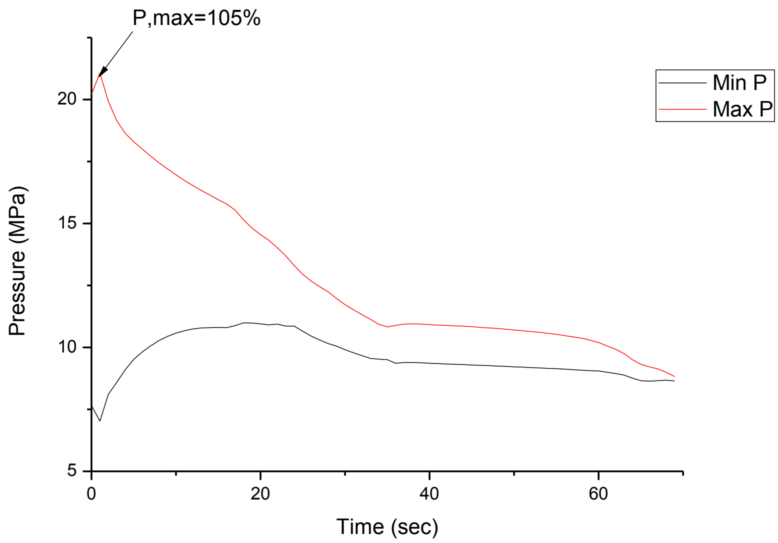


Figure 18. Minimum and Maximum pressure on load rejection with active control

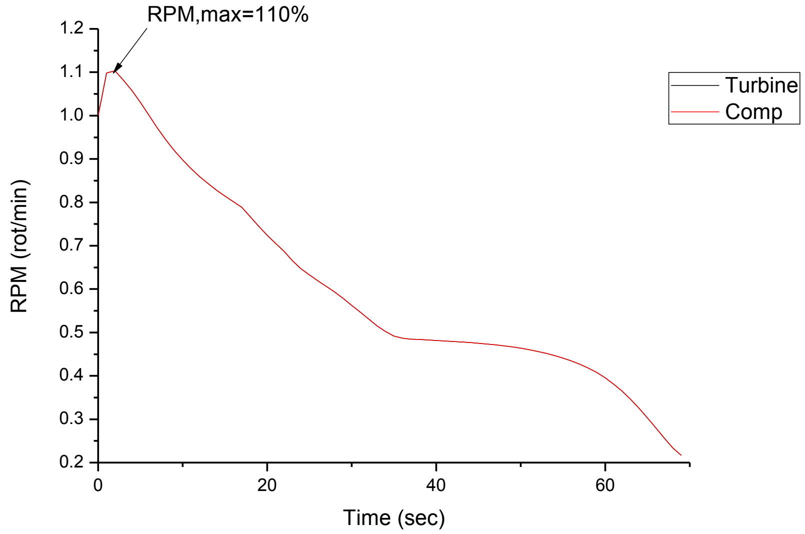


Figure 19. Turbine and Compressor RPM on load rejection with active control

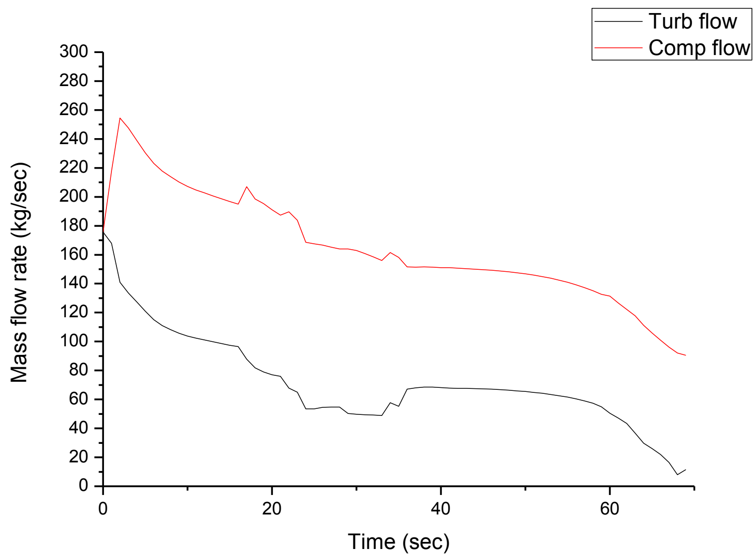


Figure 20. Mass flow rates on load rejection with active control

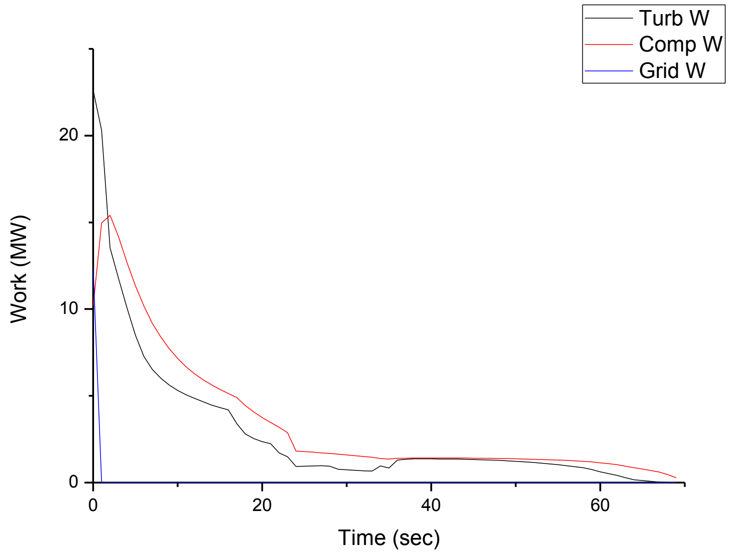


Figure 21. Work of turbomachinery on load rejection with active control

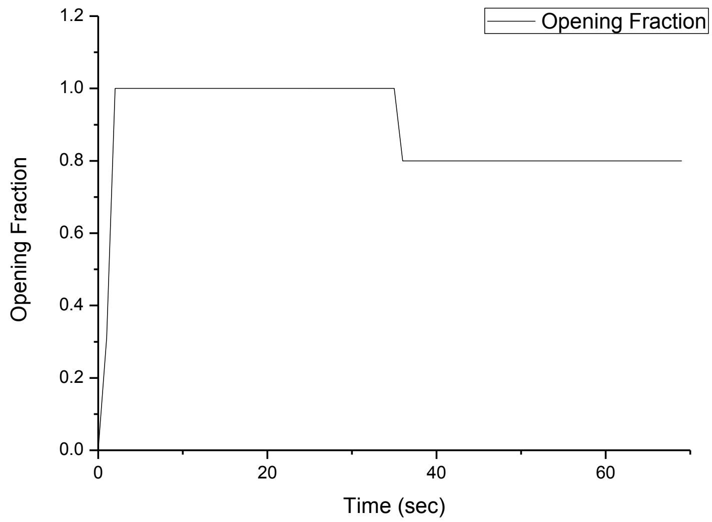


Figure 22. Core inlet bypass valve open fraction on load rejection with active control

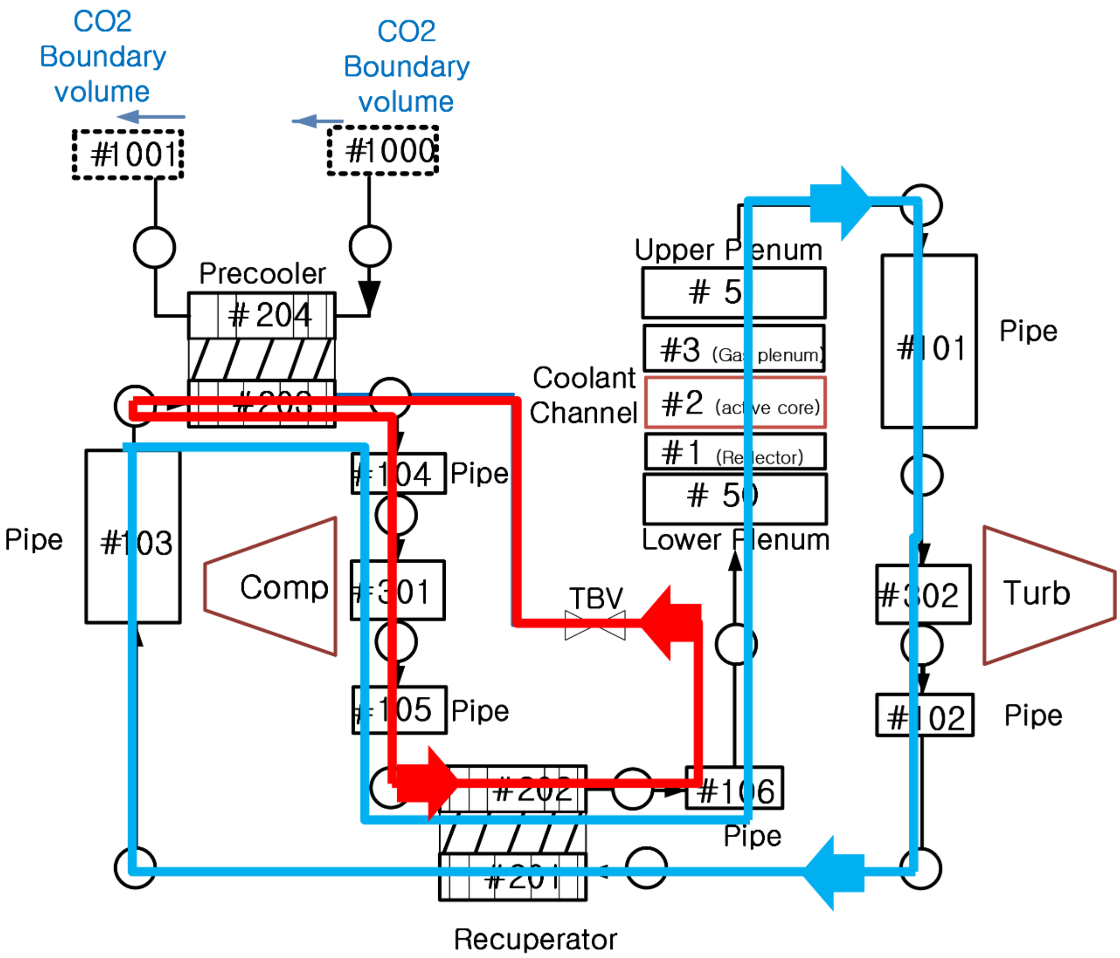


Figure 23. Two streams of MMR on load rejection with active control

If the core inlet bypass is opened, the mass flow will be divided into two streams as shown in figure 19. Thus, the mass flow rates of core, 101, 102, 201, 103 and turbine are lower than the mass flow rate of the nominal value as shown in figure 15, which is shown with red color line. On the other hand, the mass flows at location which is overlapping blue and red color streams, for instance 203, 104, 105, 202 106 and compressor, are higher than the mass flow of the nominal value.

Temperatures of core, 101, 102, 201 and 103 nodes are lower than the nominal value, because of reduction in power due to core inlet bypass. In contrast, the temperatures of 203, 104, 105, 202 and 106 nodes are higher than the nominal value as shown in red color line. The maximum and the minimum pressures have similar trend. Consequently, fluid properties between hot and cold side are smeared by core inlet bypass.

In the case of the RPM, the rotational speed is rapidly increased at the beginning of the accident but after the core inlet bypass is opened, the RPM is substantially reduced because the mass flow passing through the turbine is decreased. The generated work of the turbomachinery is also decreased due to the reduction of the rotational speed and the mass flow rate because pressure ratio is smaller when the rotational speed is slower and the mass flow is reduced, as shown in figures 3 and 4. Due to the bypass channel, the mass flow rate in the compressor becomes higher than the turbine work as soon as the transient starts. This can be explained from the next equation.

$$\frac{\partial \omega}{\partial t} = \frac{(W_{turb} - W_{comp})\varepsilon_{gen} - W_{grid}}{I_{tot}\omega} \tag{9}$$

Where ω is rotational speed and I_{tot} is total inertia.

In figure 19, speeds of turbomachinery reduce, thus the partial derivative term is negative in equation (9). The inertia of the rotator will feed the work to the compressor while the speed is reducing. Thus, the compressor work is higher than the turbine work until the change of rotational speed becomes zero from equation (9).

During an accident, two safety limits of MMR must be satisfied. Firstly, pressure boundary of the system shall not exceed 110% of the nominal value. In figure 18, maximum pressure is 105% of nominal value during load rejection event with control action. Secondly, cladding surface temperature should not exceed 800 ^oC because previous conceptually developed S-CO_2 gas cooled fast reactor selects this temperature for cladding safety criteria [13]. As shown figure 17, Maximum wall temperature is not exceeding 800^oC during load rejection event with control action. Consequently, preliminary research about load rejection event can approximately ensure safety of MMR with bold assumptions and presumption

SUMMARY AND CONCLUSIONS

The MMR is designed to be operable and capable of supplying energy to the remote and isolated regions. Thus, MMR should be perfectly modularized and transported to a site easily via land or sea. Generally, the population in these remote regions is small, so that the grid connected to the MMR could be easily unstable due to small capacity or tough condition of the region. Therefore, the load rejection accident is one of the first design basis accidents for the MMR to be investigated to demonstrate the feasibility of the concept. To simulate the accident, a very capable transient code is essential. In this paper, GAMMA+ code developed by KAERI was modified to analyze the S-CO_2 cycle by calculating and interpolating the tabulated thermal and transport properties of CO_2 directly. The modeling capability of the turbomachinery was approached with utilizing the pre-generated performance map. The steady state of the MMR is checked whether it is exactly modeled in GAMMA+ code or not. Consequently, the load rejection accident without active control showed that it can cause severe damage to the turbine blade and let the system to be overheated. The power reduction via core inlet bypass was selected as one of the solutions to alleviate the identified problem of the MMR. The adopted approach showed some successes. In this paper but the focus was more on the finding of adequate control logic for the load rejection accident. The current safety analysis is still at the preliminary stage since the safety important systems are not fully designed yet as well as the control systems. Thus, further investigations on various accident scenarios as well as more detail design are necessary to fully evaluate the safety of the developed concept.

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