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LBLOCA and SBLOCA analyses of S-CO_2 cooled KAIST Micro Modular reactor with GAMMA+ code

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1. Introduction

KAIST research team has developed a modularized Small Modular Reactor (SMR) concept for supplying distributed and flexible power source to remote region. The SMR is called KAIST Micro Modular Reactor (MMR) which adopts supercritical carbon dioxide (S-CO_2) power cycle. In the nuclear industry, water is commonly used as a working fluid of Power Conversion Unit (PCU) but Rankine cycle components usually have large volume and lower cycle efficiency than the S-CO_2 Brayton cycle when the turbine inlet temperature is higher than 500°C. Thus, SMR with a steam Rankine cycle is hard to be fully modularized including PCU. However, S-CO_2 power cycle has very compact size, so that MMR could be fully modularized while having reactor core, passive safety system and PCU in one unit. MMR also has a very compact reactor core which has uranium nitride fuel (UN) and drum type control rod to minimize volume of the core. Since MMR will be operated in the remote area, the system should maintain its integrity during any accident or event. Thus, a safety system of MMR should be designed with less dependence to an active power source. In this paper, reactor core, PCU and safety device called Passive Decay Heat Removal System (PDHR) are introduced and then break size dependency of Loss of Coolant Accident result will be discussed.

2. Systems of MMR

MMR has reactor core, PCU and PDHR in a double wall containment. This modularized plant is easy to be transported to other region with a ship or a truck with trailer. The following figure is the configuration of MMR [1].

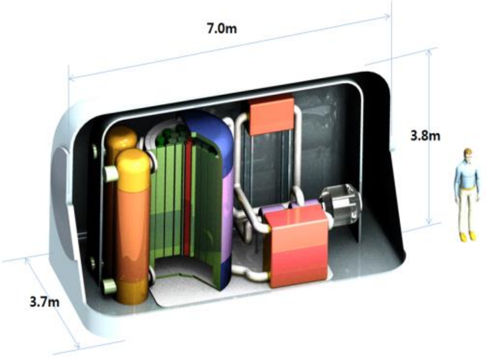

Fig. 1. Configuration of MMR

Next table contains the design parameters of MMR.

Table I: Design parameters and steady state results of MMR

	Design parameters
Q_{th}	36.2MWth
$T_{comp,in}$	60.0°C
$P_{comp,in}$	8.00 MPa
$T_{turb,in}$	550°C
$P_{turb,in}$	19.97MPa
$\dot{m}$	180.0 kg/s
RPM	19300
Wturb	22.4MW
Wcomp	10.2MW
$T_{contain,in}$	36.8°C
$P_{contain,in}$	5.0MPa

2.1 Reactor core System

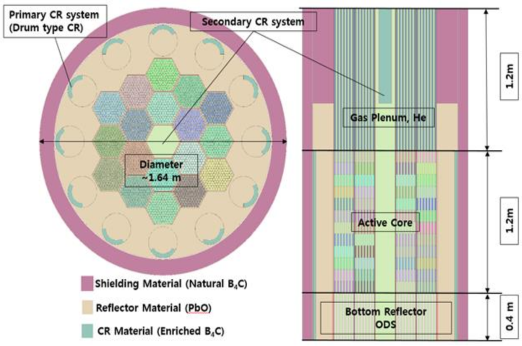

Fig. 2. Reactor core of MMR

MMR is a gas cooled fast reactor and has low enriched uranium nitride fuel (15.5%) to achieve 20 years operation without reloading. Cladding material of MMR is ODS steel which has high thermal resistance than other alloys [2].

2.2 Power Conversion unit

For compactness and high effectiveness, Printed Circuit Heat Exchanger (PCHE) is adopted as precooler and recuperator in MMR. Precooler and recuperator are designed by KAIST-HXD which is an in-house code to design a heat exchanger [3].

In case of turbomachinery, it is a radial type compressor and turbine. The turbomachineries are also designed by an in-house code which is called as KAIST-TMS. Moreover, off-design performance of turbomachineries are modeled as performance map which is drawn by KAIST-TMD. The following figure shows performance map of MMR turbomachineries [4].

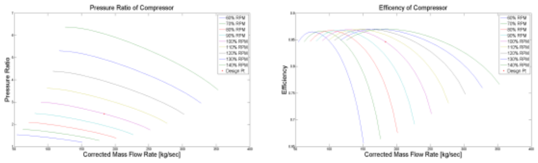

Fig. 3. Performance map of MMR compressor

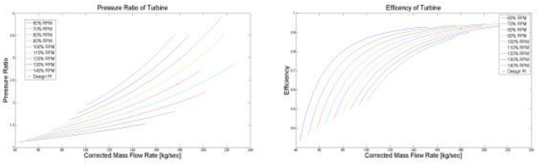

Fig. 4. Performance map of MMR turbine

Especially, MMR rejects its heat through an air heat exchanger since MMR will be set up in the remote region like desert, so that air cooling is essential.

2.3 Passive Decay Heat Removal (PDHR) System

PDHR system rejects decay heat of MMR through an air heat exchanger. The following figure shows schematic diagram of the PDHR system [5].

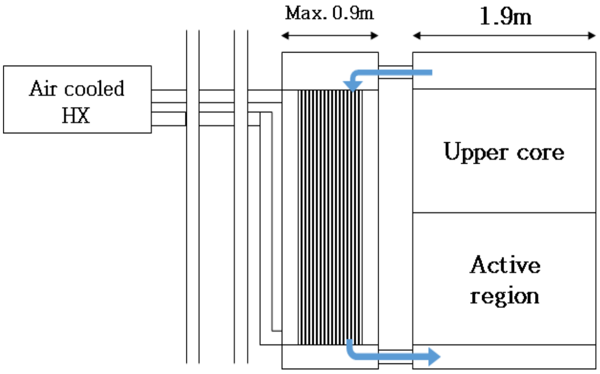

Fig. 5. Heat rejection mechanism of PDHR system

3. LBLOCA and SBLOCA

In this paper, LBLOCA and SBLOCA are simulated with the modified GAMMA+ code [6]. In both cases, it is assumed that pipe is broken at the compressor outlet. Since the compressor outlet has the highest pressure, leakage flow from primary cycle (20MPa) to containment (5MPa) will be significant. Therefore, a rupture at this region would lead to the most serious situation for LOCA. In this study, rupture sizes of LBLOCA and SBLOCA are assumed to be 100in^2 and 1in^2, respectively, by following the previous work performed by MIT [7].

3.1 Boundary condition

For a conservative modeling, it is assumed that the off-site power is not available, so the waste heat cannot be rejected through precooler during an accident. However, another assumption is that the minimum power to operate a safety valve is available. Following table represents sequence of both LBLOCA and SBLOCA events

Table Ⅱ: Sequence of LBLOCA and SBLOCA events

Time (s)	Event	Set point
0.0	Pipe is broken at compressor outlet	100in^2
0.6	PDHR valve open signal	13.46 MPa
6.0	Loss of heat rejection ability of precooler	
6.1	Compressor Feed valve open	$P_{\text{containment}} > P_{\text{comp inlet}}$

Time (s)	Event	Set point
0.0	Pipe is broken at compressor outlet	1in^2
2.46	PDHR valve open signal	13.46 MPa
6.0	Loss of heat rejection ability of precooler	
6.1	Compressor Feed valve open	$P_{\text{containment}} > P_{\text{comp inlet}}$

The containment of MMR holds of the most of CO_2 inventory, so that fluid in containment can refill the primary system during LOCA. The compressor feed valve is opened when pressure of containment is higher than the compressor inlet. The following diagram provides insight to find rupture and feed valve location.

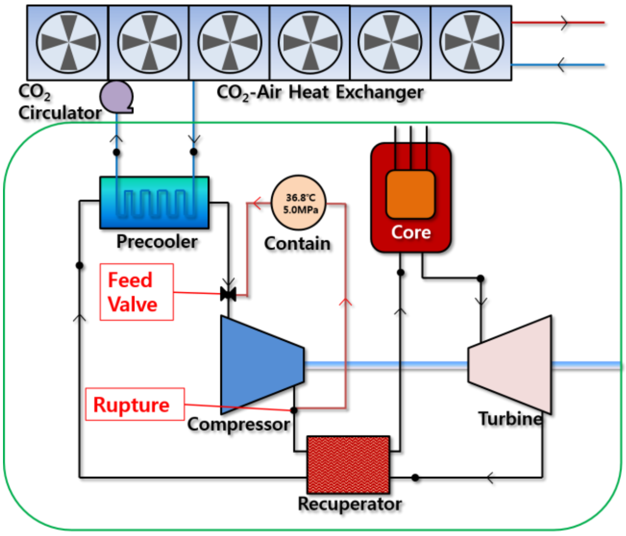

Fig. 6. Feed valve and pipe rupture location.

3.2 Results

The following figures show simulation results of LBLOCA and SBLOCA.

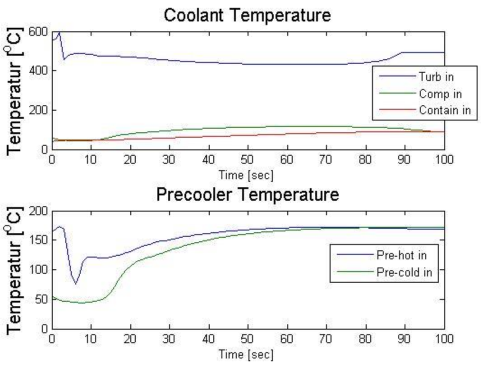

Fig. 6-1. Coolant temperature results in LBLOCA

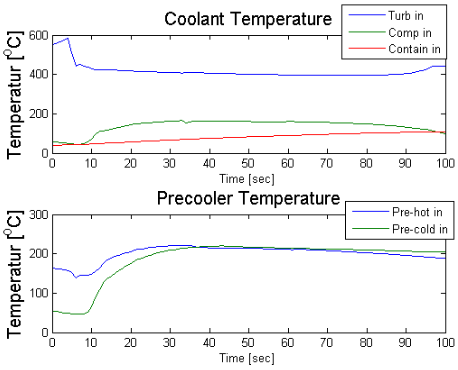

Fig. 6-2. Coolant temperature results in SBLOCA

In Figures 6-1 and 6-2, temperature of turbine inlet during LBLOCA approaches to a peak for shorter time than SBLOCA (LBLOCA: 2 sec, SBLOCA: 4 sec) because inventory in primary system is rapidly reduced in case of LBLOCA. Also, the peak turbine inlet temperature in LBLOCA is higher than that of SBLOCA.

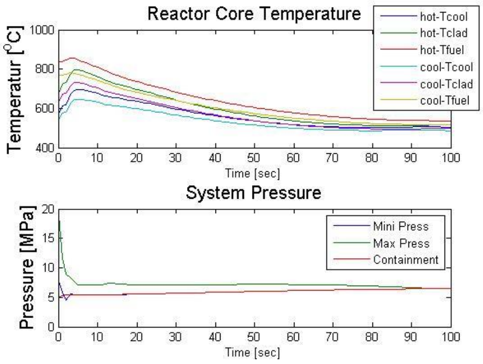

Fig. 7-1. Fuel centerline, peak cladding temperature and pressure results in LBLOCA

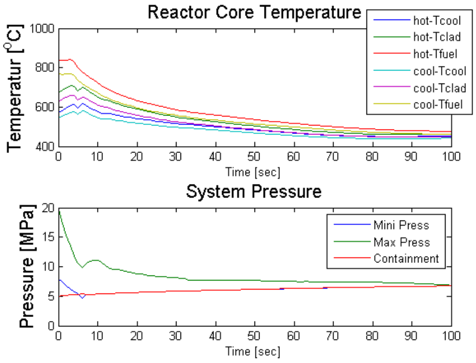

Fig. 7-2. Fuel centerline, peak cladding temperature and pressure results in SBLOCA

In Figures 7-1 and 7-2, fuel centerline and cladding temperatures in LBLOCA is higher than that of SBLOCA since the system mass flow rate in LBLOCA is lower than that of SBLOCA as shown in Figures 8-1 and 8-2. The generated heat from the fuel is removed less in case of LBLOCA. In addition, the system pressure is abruptly decreased for LBLOCA.

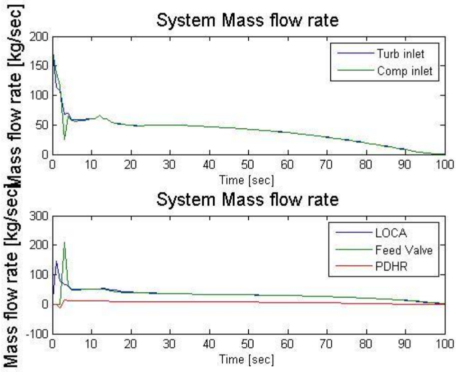

Fig. 8-1. Turbomachineries and valve mass flow rate results in LBLOCA

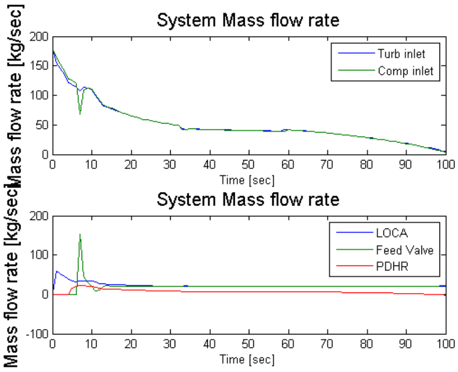

Fig. 8-2. Turbomachineries and valve mass flow rate results in SBLOCA

In Figures 8-1 and 8-2, the feed valve in LBLOCA is opened more quickly than SBLOCA and the mass flow rate at the feed valve is higher for LBLOCA.

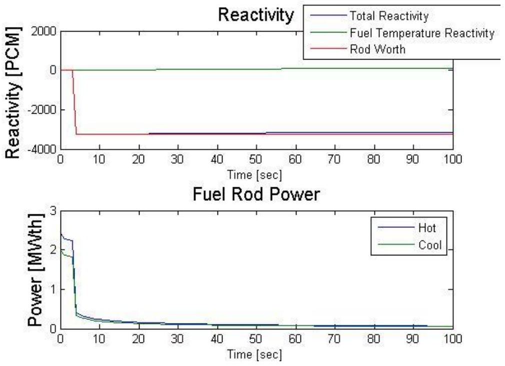

Fig. 9-1. Reactor power and reactivity results in LBLOCA

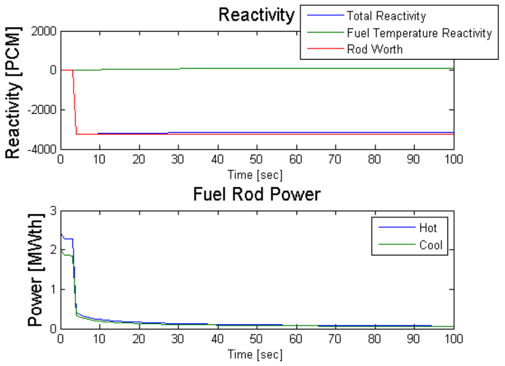

Fig. 9-2. Reactor power and reactivity results in SBLOCA

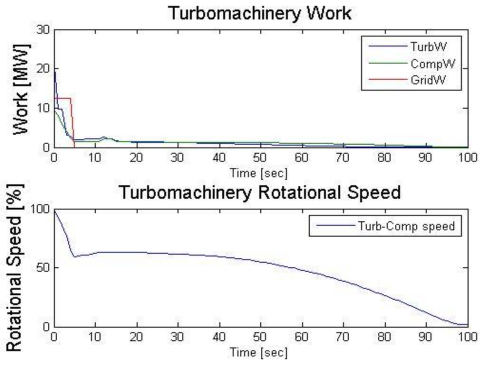

Fig. 10-1. Turbomachinery work and turbine rotational speed in LBLOCA

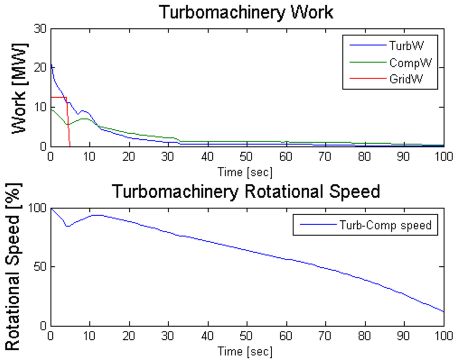

Fig. 10-2. Turbomachinery work and turbine rotational speed in SBLOCA

Since the system mass flow rate is rapidly decreased during LBLOCA, turbomachinery work is also quickly decreased. Likewise, the turbine rotational speed is also more rapidly decreased in case of LBLOCA. The following table contains the summary of safety parameters during LBLOCA and SBLOCA.

Table Ⅲ: Safety parameters of LBLOCA and SBLOCA

	Safety Limit	LBLOCA	SBLOCA
Fuel centerline Temperature	2507°C	857.9°C	842.1°C
Peak Cladding Temperature	1200°C	796.4°C	711.8°C
Core outlet coolant Temperature	676°C	593.6°C	585.05°C

4. Conclusions

KAIST-MMR is a S-CO$_2$ cooled small integral type modular reactor which contains reactor core, power conversion unit and passive safety system in one double wall containment. The safety of MMR should be evaluated under design basis accidents to be acceptable as a safe nuclear power system. Among many hypothetical accidents, the Loss of Coolant Accident is regarded as one of the most important design basis accident, so that LOCA is simulated with the modified GAMMA+ code. Since especially LOCA is dependent on the rupture size, both LBLOCA and SBLOCA are analyzed. Consequently, MMR meets all the safety limits for both cases.

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