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Passive Decay Heat Removal System for Micro Modular Reactor

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1. Introduction

Micro Modular Reactor (MMR) which has been being developed in KAIST is S-CO2 gas cooled reactor and shows many advantages [1]. The S-CO2 power cycle reduces size of compressor, and it makes small size of power plant enough to be transported by trailer. Dry cooling system is applied as waste heat removal system therefore it is able to consider wide construction site. Schematic figure of the reactor is shown in **Fig. 1**.

In safety features, the reactor has double containment and passive decay heat removal (PDHR) system. The double containment prevents leakage from reactor coolant system to be emitted into environment. The passive decay heat removal system copes with design basis accidents (DBAs).

The passive residual heat removal system is designed and thermal hydraulic (TH) analysis on coolant system is accomplished. In this research, the design process and TH analysis results are presented.

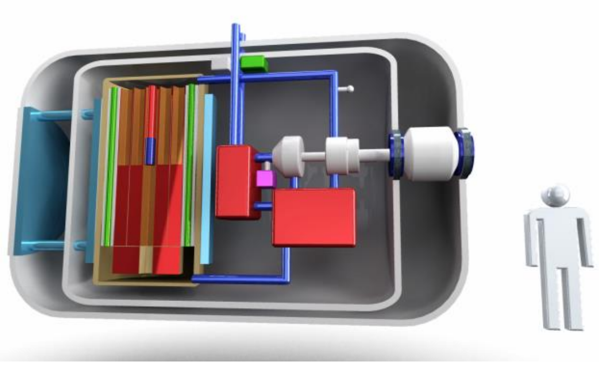

Fig. 1 Schematic of MMR

2. PDHR system concept

In this section DBAs of MMR and PDHR system configuration are described. The PDHR system is able to cope with the DBAs.

2.1 DBAs

Water and air ingress accident is one of DBAs in gas cooled reactor but MMR doesn't consider the accident. MMR doesn't uses water as coolant and all system pressure is higher than atmosphere. Without the accident, MMR considers DBAs in general gas cooled reactor and the accidents are listed in **Table 1**.

Among the DBAs D-LOFC, LOHS and SBO are the most critical accident. Depressurization of reactor coolant system decreases reactor core cooling and disable of heat sink makes enthalpy rise in reactor coolant system. Station blackout causes combined accident and forces preparation of passive safety system.

Table 1 DBAs in MMR

DBAs	Causes	Solution
P-LOFC (Loss of Forced Circulation under Pressurized condition)	Decreased flow rate of primary coolant due to the failure of compressor or turbine	Safe shutdown Natural circulation in reactor coolant system
D-LOFC (Loss of Forced Circulation under Depressurized condition)	Decreased flow rate of primary coolant due to the coolant leakage and depressurization	Safe shutdown Natural circulation in reactor coolant system Strict design criteria to prevent leakage in the primary loop
LOHS (Loss of Heat Sink)	Disabled electricity generation due to the failure of decay heat removal system	Design of heat sink for safe shutdown Decay heat removal
SBO (Station BlackOut)	Electricity-driven systems (fan-driven external heat exchanger) are not usable	Safe shutdown Passive decay heat removal system
LOEL (Loss of External Load accident)	Turbine over-speed causes blade failure	Rapid bypass system installed before turbine inlet

2.2 PDHR system configuration

Fig. 2 shows the PDHR system configuration which can cope with all DBAs. There is no additional penetration on containment due to PDHR system. In reactor coolant system, direct circulation loop between core and pre-cooler is designed. This loop keeps its integrity even main coolant line has leakage and is closed during normal operation and opened at accident. In pre-cooler reactor coolant transfers decay heat to external S-CO2 cycle coolant. The heat exchanger used to remove waste heat during normal operation is unusable at LOHS therefore additional heat sink and heat exchanger are designed.

The heat sink is water at the early stage of accident to have high performance and it is changed to air heat sink after the water is evaporated. **Fig. 3** shows the heat sink configuration. When the water is evaporated, air path on the side is open and air can flow through the path. Auxiliary heat exchanger is located under than main heat exchanger to decrease water level sufficiently. The water storage is designed to remove decay heat until 1 hour after shutdown. Nominal power of MMR is 36.2 MWth and the decay heat is calculated by Glasstone's equation [2] which shows that 2200MJ of decay heat is generated until 1 hour after shutdown. Therefore water storage is larger than 1 ton which evaporation enthalpy has 2200 MJ.

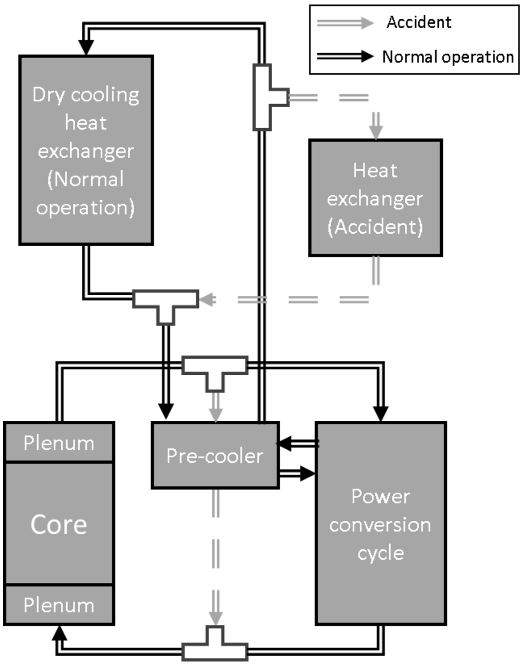

Fig. 2 PDHR system configuration

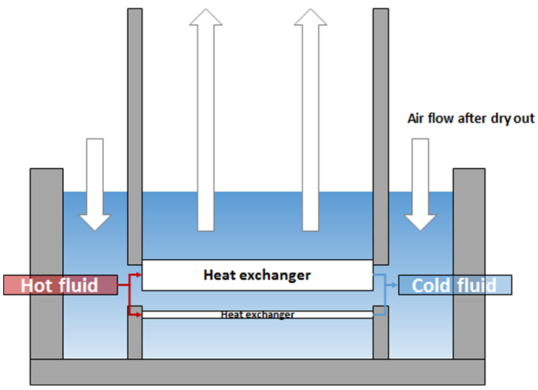

Fig. 3 Heat sink design for dry and wet cooling

$$\frac{P}{P_0} = 5\times10^{-3} a T^{-b} \text{ (Glasstone's decay heat curve)}$$

P_0 : Nominal reactor power (=36.2MW), T : Time after shutdown

Time after shutdown [sec]	a	b
0.1 – 10	12.05	0.0639
10 – 150	15.31	0.1807
150 – 10^8	27.43	0.2962

3. TH analysis

TH analysis on the water heat sink and air heat sink are accomplished. MARS-KS developed in KAERI is selected as analysis tool. Combined accident of D-LOFC, LOHS and SBO is assumed for the TH analysis.

2.1 MARS-KS node modeling

Fig. 4 shows PDHR system nodalization. At the accident scenario main stream line of reactor coolant system and waste heat removal system is closed, therefore only the loops for PDHR is modeled. Active core has 12 axial nodes and pre-cooler hot side and cold side have 7 axial nodes and they transfer heat to each other. Heat exchanger for accident (HX) has 10 nodes and is connected to heat sink. Elevation of each components is shown in Fig. 5.

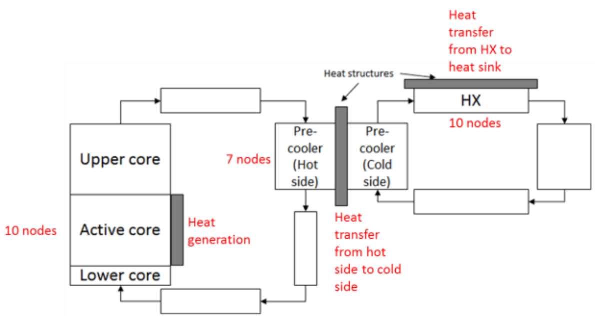

Fig. 4 MARS-KS node modeling

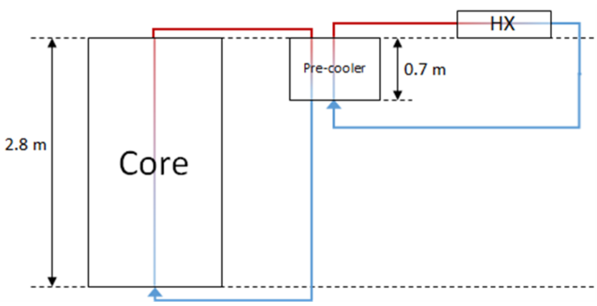

Fig. 5 Components elevation

2.2 Long term cooling analysis

PDHR is performed by air heat sink since 1 hours after reactor shutdown and it has unlimited operation time. Decay heat generation of 360 kW calculated by Glasstone's equation is given. For conservative analysis, natural convection is assumed between HX outer wall and heat sink and high temperature of atmosphere is assumed. The heat transfer is calculated by Chuchill-Chu's correlation for horizontal tube's natural convection [3] and atmosphere temperature of 50 Celsius is given.

$$h = Nu \times \frac{k}{D},\ Nu = \left\{ 0.6 + \frac{0.387\, Ra_D^{1/6}}{[1+(0.559/\mathrm{Pr})^{9/16}]^{8/27}} \right\}^2$$

$$Ra_D = \frac{g\beta \,\mathrm{Pr}(T_S - T_\infty)D^3}{\nu^2} \quad \text{(Chuchill-Chu's correlation)}$$

D : Outer diameter (Heat exchanger tube), k : thermal conductivity, Pr : Prandtl number, β : Thermal expansion coefficient, ν : Kinematic viscosity

The analysis is conducted by change of HX surface area and major components' design limitations are investigated. TH analysis shows that 100 square meter of HX surface area is able to keep design limit of cladding temperature, pressure of reactor coolant system and waste heat removal system. The results are shown in Fig. 6 and Fig. 7 and the design limit is shown in Table 2. The HX surface area is designed to have 150 square meter with 30% safety margin and 20% auxiliary HX which used for decreasing water level of heat sink.

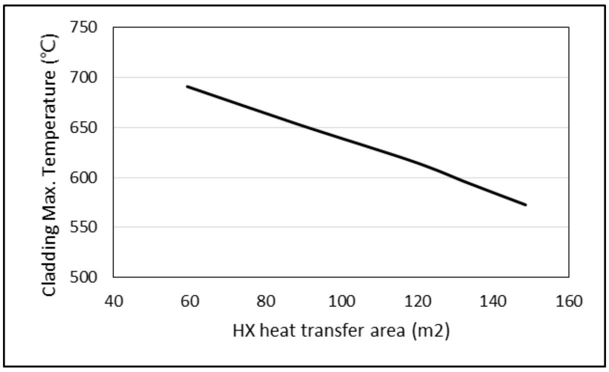

Fig. 6 Cladding maximum temperature (dry cooling)

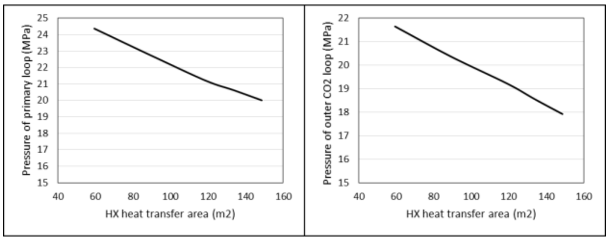

Fig. 7 Systems pressure (dry cooling)

Table 2 Design limit of major parameters

Components	Normal condition (Design limits)
Fuel cladding temperature	750℃ (800℃)
Primary system pressure	20MPa (22MPa)
Waste heat rejection system pressure	11MPa (20MPa)

2.3 Early stage of accident analysis

With HX surface area of 150 square meter the early stage of accident is analyzed. Boiling heat transfer between heat sink and HX outer wall is assumed and the heat transfer coefficient is give as 12000 W/m^2K. Initial and boundary condition are listed in Table 3. Reactor trip delay time is assumed as 1.5 s and initial flow rate in coolant system is assumed as 0 for conservative calculation. The analysis results show that major parameters are kept under the design limitation.

Table 3 Initial & boundary condition

Parameter	**Value**
Core power generation, MW	36.2, <1.5s 100% of Glasstone correlation, >1.5s
Core pressure, MPa	20
Pre-cooler hot side pressure, MPa	7.52
Pre-cooler cold side pressure, MPa	11
Primary coolant flow rate, kg/s	0
External coolant flow rate, kg/s	0

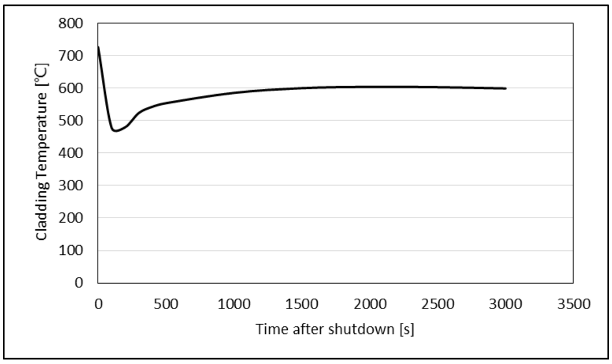

Fig. 8 Cladding maximum temperature (wet cooling)

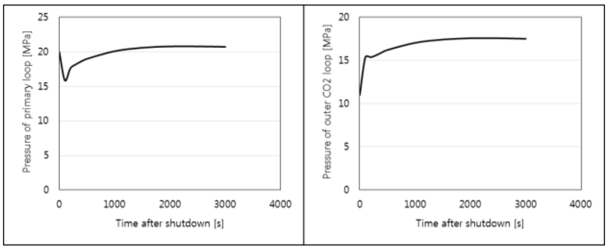

Fig. 9 System pressure (wet cooling)

4. Conclusion

PDHR system is designed for MMR and coolant system with the PDHR system is analyzed by MARS-KS code. Conservative assumptions are applied and the results show that PDHR system keeps coolant system under the design limitation. The PDHR system takes hybrid heat sink and it gives unlimited operation time of the system.

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