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Various RCCS Performance Comparisons with the Air-Cooled RCCS on a Micro Modular HTGR

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1. Introduction

A micro modular HTGR (High Temperature Gas-Cooled Reactor) could be a reliable and independent power plant in the remote areas where the connection to the power grid is difficult. KAERI is developing the concept of micro modular high temperature gas-cooled reactor (MiHTR) [1] which has a 10MW$_t$ of thermal power and a small vessel size of 3 m diameter. The previous study [2] gave a reference design of core configuration and the size of air-cooled RCCS (Reactor Cavity Cooling System) for the MiHTR. The optimum air-cooled RCCS design [2] should be considered to have the reduce number and flow area of RCCS tube for the MiHTR to minimize the parasitic heat loss. In addition, MiHTR should have the riser flow located in the gap between the insulated CB (Core Barrel) and RPV (Reactor Pressure Vessel) to keep low RPV temperature.

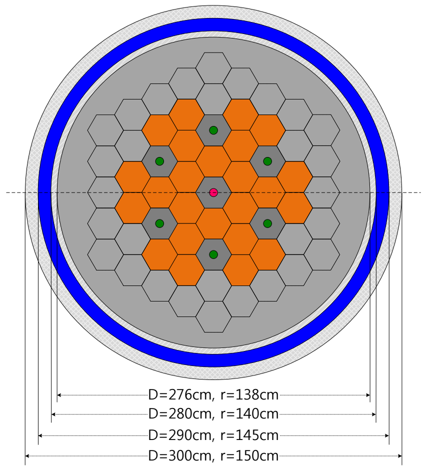
This paper considers the applications of other RCCS on MiHTR such like hybrid RCCS, water-cooled RCCS, closed-loop air-cooled RCCS and atmosphere air-cooling of onground reactor building. As for the RCCS selection study for the fully passive safety of MiHTR, based on the GAMMA+ code [3] simulations of the selected reactor core with each RCCS design, the thermal performance of each RCCS is compared with that of the air-cooled RCCS at the steady state and during the accident conditions like LOFC (Loss of Forced Cooling), LOFC-ATWS (Anticipated Transient Without Scram) and LPCC (Low Pressure Conduction Cooling) events.

2. Calculation Conditions

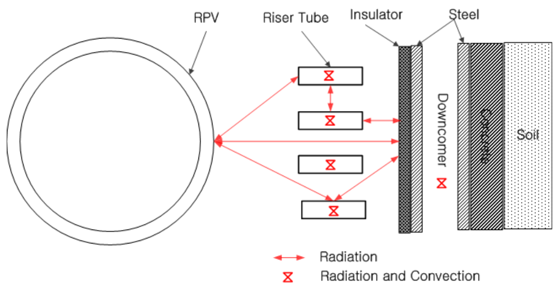
2.1 MiHTR Core with the Air-Cooled RCCS

Fig. 1 shows the reference configuration of the 10MW$_t$ MiHTR core with the air-cooled RCCS [2]. The active core is composed of six block of 0.793 m height columns. The 1/6 symmetry core with eleven hexagonal block of 0.3 m flat-to-flat length arrays is composed of four fuel blocks, two CR(Control Rod) blocks and five reflector blocks. The core has a RPV of 3m diameter and the riser flow located in the gap between the insulated CB and RPV to keep low RPV temperature.

The air-cooled RCCS is composed of riser tubes, insulated downcomer and manifold inlet/outlet ducts to keep the function of fully passive cooling at any flow blockage in a duct. The relative heat loss of the 10MW$_t$ MiHTR is very large because the very small-size HTGR has a very large RPV surface area per reactor power. Large reducing in the number of riser tube and tube flow area is needed for the air-cooled RCCS design of the MiHTR to minimize the heat loss. Thus, the previous study [2] suggested the case of 64 tubes with 2”x2” size as the optimum size and number of riser tube, based on the various calculations.



(a) MiHTR Core Configuration



(b) Air-Cooled RCCS

Fig. 1 10MWt MiHTR Core with the Air-Cooled RCCS

2.2 Application of Other RCCS

Fig. 2 shows the fluid block system for the air/water-cooled hybrid RCCS model. The riser tube part of the air-cooled is identical to the reference as described in the previous section. But, the functional conductor [4,5] is installed instead of the insulated downcomer wall of Fig. 1. In addition, the water-cooled pipe-plate is composed of 64 riser tubes with 2 cm diameter attaching to 3 mm thickness steel plate and is located at the gap between the functional conductor and the concrete wall. The functional conductor provides a low thermal conductivity at low temperature condition and a high thermal conductivity at high temperature condition. The radiation heat at the pipe-plate transferred from the functional conductor is cooled by the water natural circulation through the pipe. For the hybrid RCCS application, both the air-cooled and the water-cooled is working. But, in case of the water-cooled RCCS application, the air-cooled loop is assumed to be closed at normal operation and be opened during accident conditions.

Fig. 3 shows the fluid block system for the closed-loop air-cooled RCCS model. The 5 m pipes with 60 cm diameter are connected between inlet and outlet of the open-loop air-cooled. The heat transfer is assumed to happen only at the surface of pipe contacting 30 °C atmosphere air. The RCCS performance is evaluated according to the air heat transfer coefficients of 5, 25, and 50 W/m^2-K. Fig. 4 shows the solid block system of MiHTR in case of the atmosphere air-cooling of onground reactor building model, where the residual heat is transferred through the concrete wall to the atmosphere without any specific RCCS. It is assumed that the heat transfer coefficient of 30 °C atmosphere air is 5 W/m^2-K.

During the normal operation of the 10MW$_t$ MiHTR, it operates with the inlet temperature of 300 °C, the outlet temperature of 750 °C, the outlet pressure of 3.0 MPa, and the total core helium flow rate of 4.25 kg/s. Table 1 shows the transient sequence of HTGR accident conditions. Both LOFC and LOFC-ATWS are initiated by the flow decrease due to the helium circulator trip. The shutdown rod insertion at the low flow reactor trip signal (10% helium flow) is working on LOFC, but is not working on LOFC-ATWS event. LPCC event is initiated by the abrupt pressure decrease due to the guillotine break at the cross vessel. The reactor trip starts at the low primary pressure (6.0 bar).

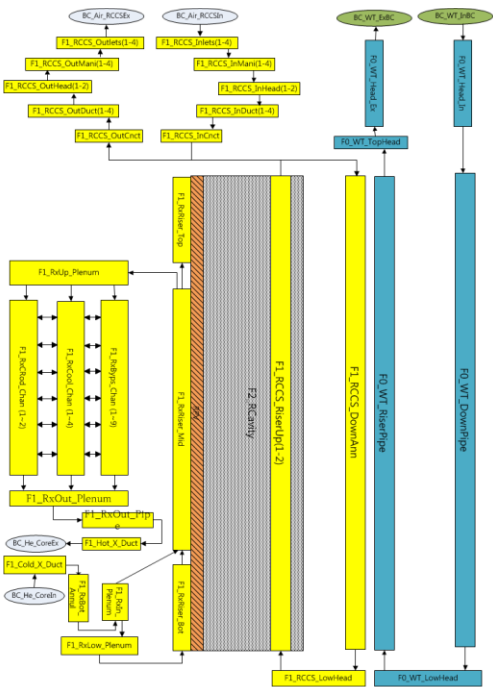


Fig. 2 Air/Water-Cooled Hybrid RCCS Model

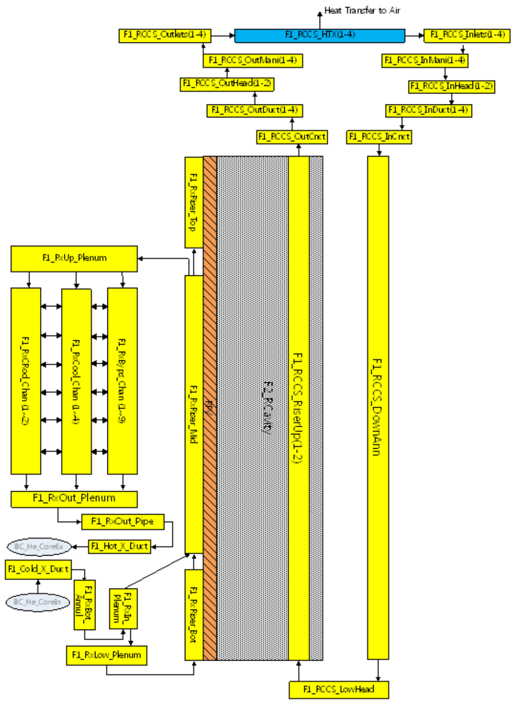


Fig. 3 Closed-Loop Air-Cooled RCCS Model

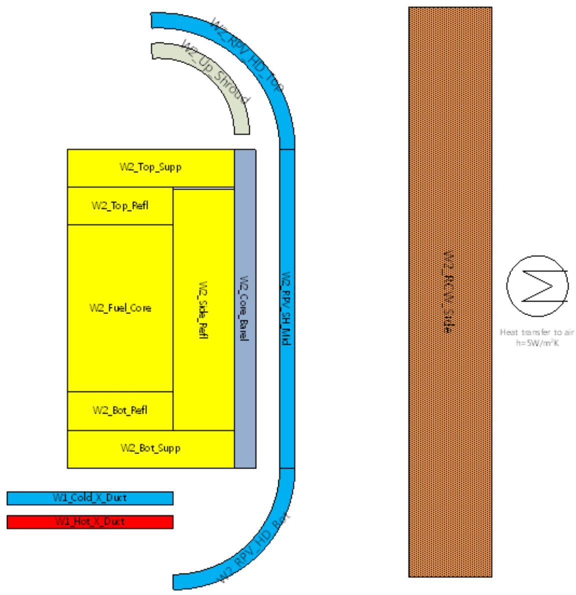


Fig. 4 Atmosphere Air-Cooling of Onground Reactor Building Model

Table 1. Transient Sequence of HTGR Accidents

(a) The Sequence of LOFC Event

Time(sec)	LOFC Event Description	Comments
0	Helium blower trip by unintended loss of primary flow	Zero flow in 5 seconds
4.6	RPS trip signal by low helium flow (10%)	
4.8	Reactor trip signal (CR-Trip)	
4.9	Shutdown rod insertion by CR-Trip	

(b) The Sequence of LOFC-ATWS Event

Time(sec)	LOFC-ATWS Event Description	Comments
0	Helium blower trip by unintended loss of primary flow	Zero flow in 5 seconds
4.6	RPS trip signal by low helium flow (10%)	
4.8	Reactor trip signal (CR-Trip)	
		No shutdown rod insertion

(c) The Sequence of LPCC Event

Time(sec)	LPCC Event Description	Comments
0	Guillotine Break at Cross-Vessel	
0.12	RPS trip signal by low helium pressure(6bar)	
0.22	Reactor trip signal (CR-Trip)	
0.32	Shutdown rod insertion by CR-Trip	

3. Calculation Results

3.1 Hybrid RCCS and Water-Cooled RCCS

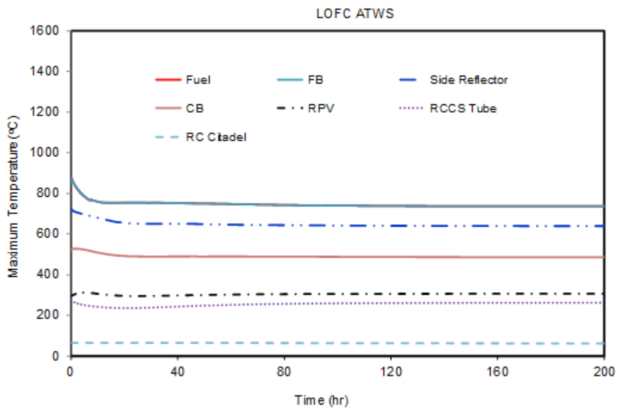
For the application of the air/water-cooled hybrid RCCS, the heat loss at the steady state is estimated to be 193 kW which is much higher than the air-cooled RCCS of 126 kW. Heat transfer by the natural circulation in the water-loop is 93 kW and no boiling occurs in the water-loop. Maximum fuel temperature of 869 °C is slightly higher than 863 °C for the air-cooled RCCS application. But, the maximum RPV temperature of 290 °C becomes lower than 297 °C for the air-cooled RCCS because the heat loss of hybrid RCCS is much higher than that of the air-cooled RCCS.

During the accident conditions, the estimated peak temperatures of key components for the hybrid RCCS application are compared with those for the air-cooled RCCS in Table 2. Because both the hybrid and the air-cooled RCCS has a large heat removal capacity, the peak temperatures of key components during LOFC, LOFC-ATWS and LPCC events become cooled down without a large increase and keep much lower than the safety limits as shown in Fig.5. The peak temperature of water riser is 42 °C, and also no boiling occurs in the water-loop during the accident conditions. The hybrid RCCS could be considered in a large HTGR in preparation for the lack of heat removal capacity when more 90% flow passes of the air-cooled loop are blocked up. Thus, it is regarded that the hybrid RCCS is an over-capacity design of heat removal for the MiHTR.

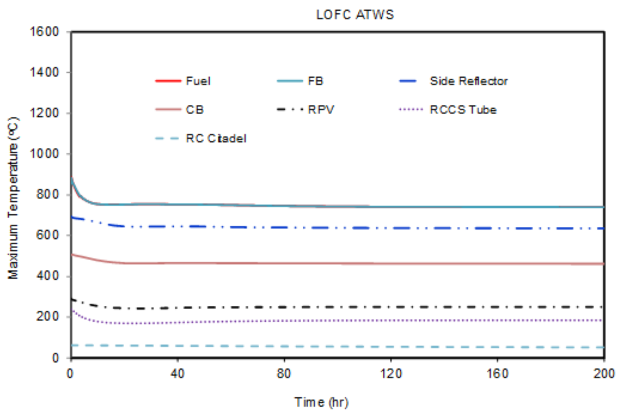
In case of the water-cooled RCCS, the heat loss of 120 kW at the steady state is very close to the air-cooled RCCS of 126 kW. Maximum fuel temperature of 872 °C is higher than 863 °C for the air-cooled RCCS application. But, the maximum RPV temperature is same with 297 °C for the air-cooled RCCS because the heat loss of the water-cooled RCCS is very close to that of the air-cooled RCCS. As the air-cooled loop is assumed to be opened during the accident conditions in the case of the water cooled RCCS model, the peak temperatures of key components show the similar behaviors of hybrid RCCS, becoming cooled down without a large increase and keeping much lower than the safety limits.

Table 2. Peak Temperatures of Key Components during the Accident Conditions for the Hybrid RCCS

	Air-Cooled RCCS			Hybrid RCCS		
	LOFC	**ATWS**	**LPCC**	**LOFC**	**ATWS**	**LPCC**
Max. Fuel Temp. (°C)	863	877	863	869	884	869
Max. CB Temp. (°C)	527	527	531	506	506	510
Max. RPV Temp. (°C)	311	311	305	290	290	290
Max. Con. Temp. (°C)	63	63	63	60	60	60
Max. W-Riser Temp. (°C)				42	42	42



(a) Air-Cooled RCCS



(b) Hybrid RCCS

Fig. 5 Peak Temperatures of Key Components during LOFC-ATWS

3.2 Closed-Loop Air-Cooled RCCS and Atmosphere Air-Cooling of Onground Reactor Building

For the application of the closed-loop air-cooled RCCS, the heat loss at the steady state is estimated to be

80, 86, and 88 kW for the air heat transfer coefficients of 5, 25, and 50 W/m^2-K, respectively, as shown in Table 3. The heat loss is much reduced, compared to the air-cooled RCCS of 126 kW. But, the maximum temperature of concrete is estimated to be 137, 123, and 118 ^oC, which is much higher than the steady state design limit of 65 ^oC. The raised heat transfer of the connecting pipe could reduce the concrete temperature, but it would produce more heat loss proportionally. Because the heat removal capacity of the closed-loop air-cooled RCCS is large, the peak temperatures of key components during the accident events become cooled down without a large increase. But, the peak temperature of the concrete still exceeds the design limit.

In case of the atmosphere air-cooling of onground reactor building model, the heat loss of 91 kW is small. But, like the case of the closed-loop air-cooled RCCS, the maximum concrete temperature of 269 ^oC is very higher than the design limit.

Table 3. RCCS Performance Comparison at Steady State

RCCS Type	**Heat Loss (kW)**	**Max. Concrete Temp (^oC)**	**Comments**
Air-Cooled	126	63	
Hybrid	193	60	air/water working
Water-Cooled	120	60	air working during accidents
Closed-Loop Air-Cooled h=5 W/m^2-K h=25 W/m^2-K h=50 W/m^2-K	80 86 88	137 123 118	heat transfer coefficient
Onground Rx Bld	91	268	h=5 W/m^2-K

4. Conclusions

As the RCCS selection study of MiHTR, various RCCS types such like hybrid RCCS, water-cooled RCCS, closed-loop air-cooled RCCS and atmosphere air-cooling of onground reactor building are compared with the performance of the air-cooled RCCS. It shows that the hybrid RCCS is an over-capacity design of heat removal due to high heat loss. The water-cooled RCCS shows similar performance of hybrid RCCS. In cases of closed-loop air-cooled RCCS and atmosphere air-cooling of onground reactor building, the design application is considered to be difficult due to the high concrete temperature despite the low heat loss. Thus, the air-cooled RCCS is an optimum design selection for the fully passive safety of MiHTR.

ACKNOWLEDGEMENTS

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