Design Considerations of the Air-Cooled RCCS on the Very Small-Size HTGR

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1. Introduction

A very small-size 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) which has a $10MW_t$ of thermal power and a small vessel size of 3 m diameter. As a low level design stage, the sizing of the RCCS (Reactor Cavity Cooling System) is needed because the RCCS is a unique safety system to remove the decay heat during the normal and the accident conditions. The function of the RCCS in the MiHTR should meet the design requirement of a fully passive cooling which is important in the large-size HTGR [1]. But, the RCCS capacity should be minimized because the MiHTR has a relatively large parasitic heat loss compared to reactor power.

This paper intends to estimate the heat loss of the MiHTR through the RPV (Reactor Pressure Vessel) surface with simulating the air-cooled RCCS [2]. The various sensitivity calculations are performed to obtain the proper RCCS design by examining the impact of the number of RCCS tube, tube size, RPV inside temperature conditions, RPV surface emissivity, CV (Cooled-Vessel) design [3] and the insulation of CB (Core Barrel). Based on the GAMMA+ code [4] simulations of the selected reactor core and RCCS design, this paper evaluates the peak temperature behavior of the main components in the $10MW_t$ MiHTR during the accident conditions like LOFC (Loss of Forced Cooling), LOFC-ATWS (Anticipated Transient Without Scram) and LPCC (Low Pressure Conduction Cooling) events.

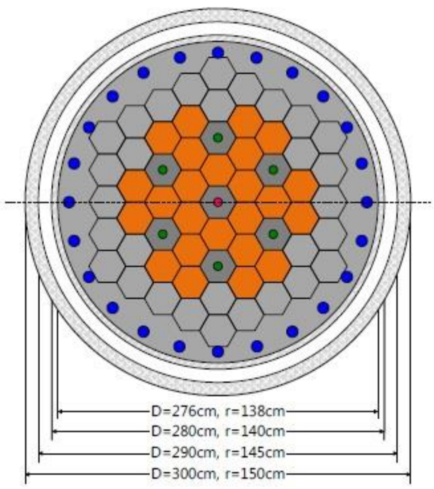
2. Calculation Conditions

Fig. 1 shows the configuration of the $10MW_t$ MiHTR core which has a RPV of 3m diameter. Fig. 1 (a) is CV designed core where 24 inlet riser holes of 60 mm diameter are located into PSR (Permanent Side Reflector). Fig. 1 (b) is the core where the inlet riser flow goes up through the gap between CB and RPV. Prior to the examining two design effects, the various sensitivity calculations are performed for the brief sizing design using the simplified HTGR model [2] with only RPV and the air-cooled RCCS as shown in Fig. 2. 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. On this model, the boundary conditions are the fixed temperature at RPV inside surface and the adiabatic at outer concrete surface. The heat loss in the $10MW_t$ MiHTR at the steady-state is evaluated according to the number of RCCS tube, tube size, RPV inside temperature conditions and RPV surface emissivity.

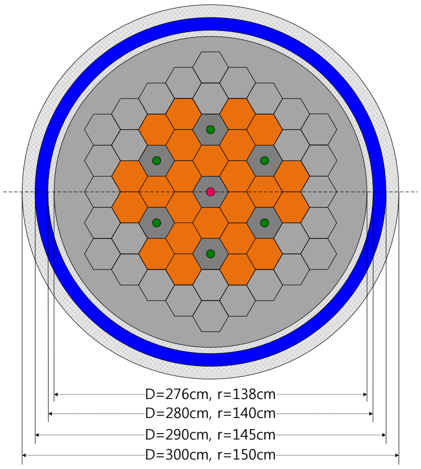
The full core configuration of Fig. 1 is modeled with an optimum design of RCCS which has minimum heat loss. The active core is composed of six block of 0.793 m height columns. GAMMA+ code model simulates 1/6 symmetry core containing eleven hexagonal block of 0.3 m flat-to-flat length arrays which are composed of four fuel blocks, two CR(Control Rod) blocks and five reflector blocks. The one-dimensional network flow inside the core is simulated by four coolant channels, two CR cooling channels, nine bypass channels, and cross flow channels between block and bypass gap.

During the normal operation of the $10MW_t$ MiHTR, it operates with the inlet temperature of 300 ^oC, the outlet temperature of 750 ^oC, the outlet pressure of 3.0 MPa, and the total core helium flow rate of 4.25 kg/s. It assumes the atmosphere air temperature of 30 ^oC. The full core steady-state calculations examine the impact of CV design, No CV design and the insulation of CB on the heat loss in the $10MW_t$ MiHTR.

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). The peak temperature behavior of the main components is examined during these accident conditions



(a) CV design



(b) No CV design

Fig. 1 Core Design of a 10MW$_t$ HTGR

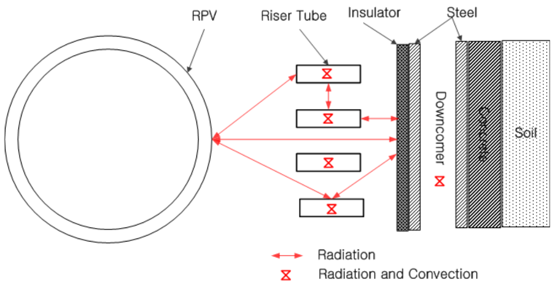


Fig. 2 RPV and the Air-Cooled RCCS Model of a 10MW$_t$ HTGR

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

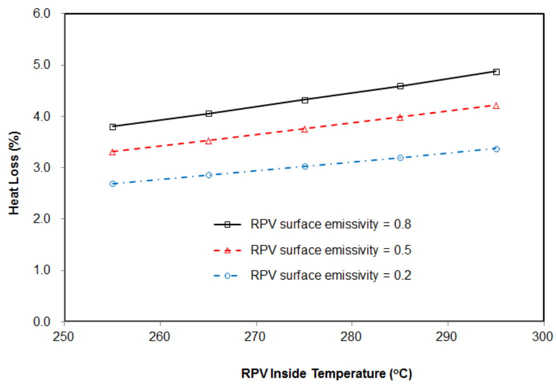
3.1 Heat Loss at the Steady-State

Fig. 3 shows the sensitivity results of heat loss in the 10MW$_t$ MiHTR according to the number of RCCS tube, tube size, RPV inside temperature conditions and RPV surface emissivity. As shown in Fig. 3 (a) for the case of 110 tubes with 2”x8” size, the heat loss is increased from 3.8% to 4.9% of the reactor power as increasing the RPV inside temperature of 255 °C to 295 °C for the case of 0.8 RPV surface emissivity. The relative heat loss of the 10MW$_t$ MiHTR is very larger than that of a 350MWt HTGR [3] which is estimated to 0.2% of the reactor power. This is caused by that the RPV surface area per reactor power of the 10MW$_t$ MiHTR is ten times greater than that of a 350MWt HTGR.

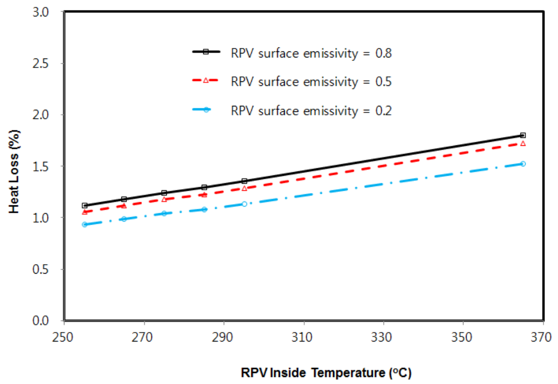
As shown in Fig. 3 (b) for the case of 64 tubes with 2”x2” size, the heat loss is decreased to the range of 1.1% to 1.4% of the reactor power for the case of 0.8 RPV surface emissivity, due to the reduced flow area in RCCS. The heat loss can be further reduced for the lower RPV surface emissivity. The 64 tubes with 2”x2” size and 0.8 RPV surface emissivity is selected as an optimum design of RCCS which is applied for the full core analysis.

Fig. 4 shows the radial core temperature distribution at third fuel block height. As shown in Fig. 4 (a) for the case of CV deign core, the temperature is gradually decreasing according to the radial locations of fuel core, PSR with riser holes, core barrel and RPV. Despite the CV design, the temperature at RPV (Max. T=399 °C) is very high due to the small reactor size and high heat loss. The riser coolant temperature in PSR is heating up to 379 °C through flowing upward. The heat loss is estimated to 1.6% of the reactor power which is very close to the sensitivity results of Fig. 3 (b) corresponding to the fixed RPV inside surface temperature of 360 °C.

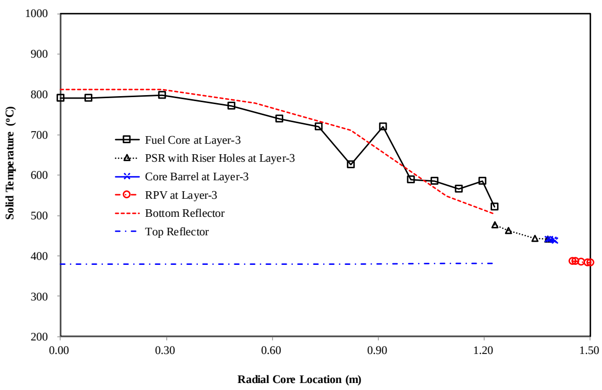
For the No CV design of Fig. 1 (b), the temperature at RPV (Max. T=370 °C) is still very high due to the small reactor size and high heat loss despite the riser flow in CB/RPV gap. Thus, the microtherm insulation of 5 mm thickness is attached to the CB inside to keep the low RPV temperature. As shown in Fig. 4 (b) for the case of No CV deign with CB insulation core, the temperature is radially flat in core until the PSR and is dropped to 300 °C in core barrel and RPV. Due to CB insulation and riser flow in CB/RPV gap, the temperature at RPV (Max. T=297 °C) keeps low. The riser coolant temperature in CB/RPV gap keeps constant very close to 300 °C where the maximum temperature at top plenum is 302 °C. The heat loss is estimated to 1.2% of the reactor power which is very close to the sensitivity results of Fig. 3 (b) corresponding to the fixed RPV inside surface temperature of 275 °C. For 0.2 RPV surface emissivity, the heat loss can be decreased to 1.0% of the reactor power.



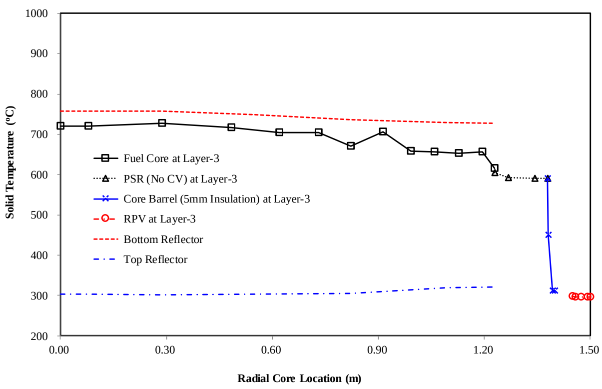
(a) Using 110 Tubes (2"x8" size)



(b) Using 64 Tubes (2"x2" size)
Fig. 3 Various Sensitivity Results of Heat Loss



(a) CV Design

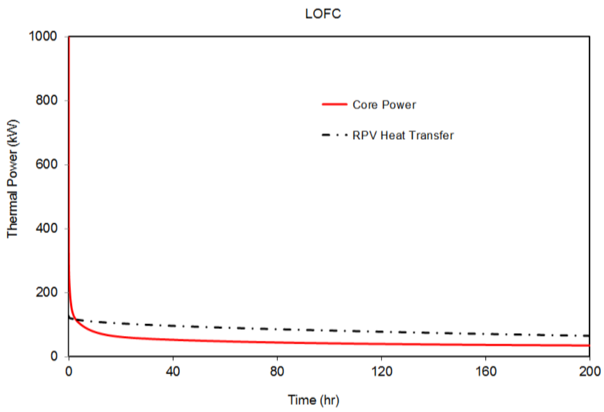


(b) No CV Design with CB Insulation
Fig.4 Core Radial Temperature Distribution

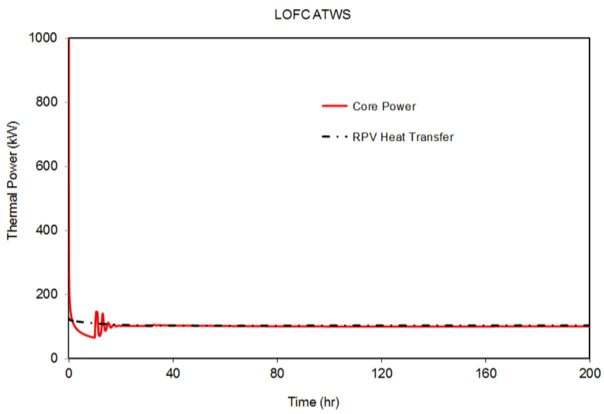
3.2 Peak Temperature Behavior during the Accident Conditions

Fig. 5 shows the behavior of the core power and the removal heat at RPV surface during the accident conditions in the 10MW$_t$ MiHTR. The core decay power is transferred to RPV surface and is removed by the air-cooled RCCS. As shown in Fig. 5 (a), the reactor power tripped by the shutdown rod becomes lower than RCCS heat removal at 2.7 hr during LOFC event. But, the reactor power during LOFC-ATWS is dropped below RCCS heat removal at 1.4 hr and jumped to re-critical peak at 10.5 hr by the reactivity feedback, and then oscillating and balancing with RCCS heat removal as shown in Fig. 5 (b). As shown in Fig. 5 (c), the reactor power during LPCC is very similar to LOFC.

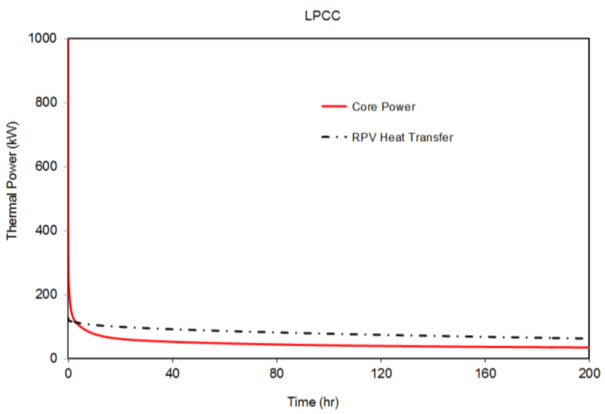
Fig. 6 shows the behavior of peak temperatures of key components during the accident conditions in the 10MW$_t$ MiHTR. For all the accident cases, the peak temperatures of fuel, RPV and concrete become cooled down without a large increase and keep much lower than the safety limits during the accident conditions due to the high capacity of RCCS heat removal in the 10MW$_t$ MiHTR.



(a) LOFC

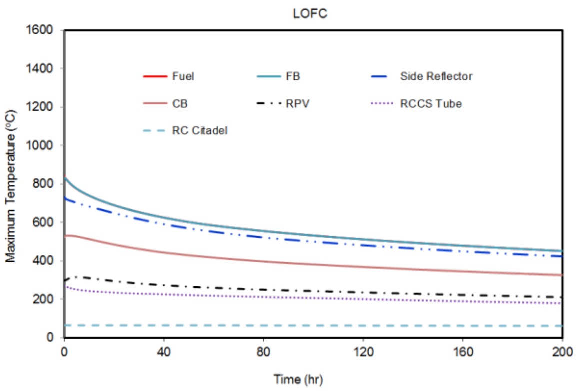


(b) LOFC-ATWS

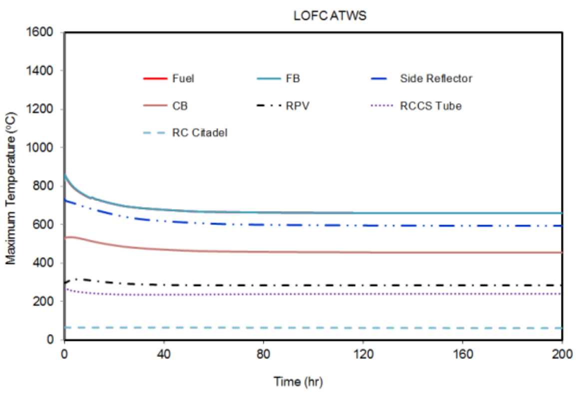


(c) LPCC

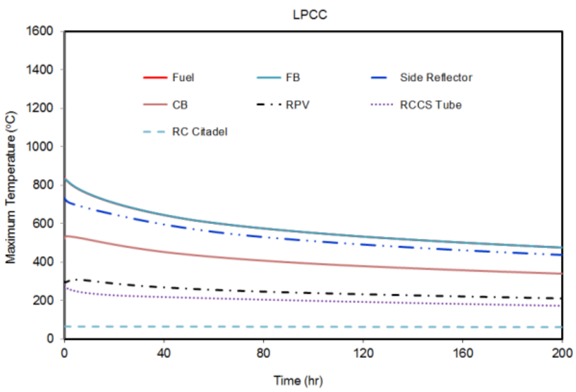
Fig. 5 Core Power and RPV Heat Transfer during the Accident Conditions



(a) LOFC



(b) LOFC-ATWS



(c) LPCC

Fig. 6 Peak Temperatures of Key Components during the Accident Conditions

4. Conclusions

Based on the various sensitivity calculations of the air-cooled RCCS, it is evaluated that 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.

The steady-state and safety analysis of the full reactor core with an optimum air-cooled RCCS give some design considerations to the MiHTR. The CV design, which is designed to keep low RPV temperature in a large-size HTGR, is not able to apply to the very small-size HTGR because the RPV temperature exceeds the design limit and the coolant of riser hole in PSR is highly heated up. Instead, the riser flow is needed to locate in gap between CB and RPV, and the insulation at CB inside surface is needed to keep low RPV temperature for the MiHTR design. Due to the high capacity of RCCS heat removal in the MiHTR, the peak temperatures of fuel, RPV and concrete keep much lower than the safety limits during all the accident cases.

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