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Impact of the Cooled-Vessel Design on RPV Peak Temperature According to VHTR Inlet Temperature Conditions

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1. Introduction

In the previous study [1], it evaluated the impact of the cooled-vessel (CV) design [2] on the peak fuel temperature of 350MW$_t$ VHTR(Very High Temperature Gas-Cooled Reactor). It showed that the peak fuel temperature is 4 ^{o}C ~ 8 ^{o}C increased during the accident conditions due to the reduction of graphite heat capacity. The main purpose of CV design is to make the temperature of SA508/533 reactor pressure vessel (RPV) maintain below the ASME code, which is 371 ^{o}C during normal operation and 538 ^{o}C for up to 1000 h during accident conditions [3]. Thus, the coolant riser channels are located into the permanent side reflector (PSR) in order to avoid the direct contact of the high temperature coolant to RPV. This paper intends to evaluate the impact of CV design on RPV maximum temperature and the main components maximum temperature according to the reactor inlet temperature conditions (290, 350, 390, 415, 490 ^{o}C), based on the GAMMA+ code [4] simulation on normal operation and the LPCC (Low Pressure Conduction Cooling) event for a 350 MW$_t$ VHTR with 850 ^{o}C of the reactor outlet temperature. This provides a basic design data for the selection of the optimum reactor inlet/outlet temperature conditions.

2. Calculation Conditions

Fig. 1 shows the cooled-vessel design of 350MW$_t$ VHTR core where the coolant riser channels are located into PSR. The CV design has 48 holes of 180 mm diameter where two riser holes are located into a PSR block. The total flow area (1.22 m^2) of the CV is almost same with the flow area (1.21m^2) of NGNP [5] where twelve riser ducts are located into the annulus between core barrel (CB) and RPV. Fig. 2 shows GAMMA+ simulation modeling of solid structure system and fluid system of 350MW$_t$ VHTR. The fuel core is composed of 66 fuel block (FB) array and 9 fuel block columns. GAMMA+ code model simulates 1/3 symmetry core containing 22 fuel block array. Unlike NGNP design, this design should remove the riser ducts between core barrel (CB) and RPV because the riser holes are located into a PSR block. As the previous study [1] mentioned the need of the insulation, the kawool insulation of 2 cm thickness is modeled on the bottom head sphere in order to avoid the direct contact of the high temperature coolant to RPV. The fluid system is composed of the primary reactor cooling system (RCS) in which the helium coolant flows into the core and the reactor cavity cooling system (RCCS) in which the air naturally circulates outside RPV to remove the reactor residual heat. This simulation assumed the axial power distribution of Fig. 3 in which three profiles represent the axial power peaking factor of FB-3, FB-10, and FB-18 in the inner ring, the middle ring, and the outer ring FBs, respectively. During the normal operation of 350MW$_t$ VHTR, it operates with the outlet temperature of 850 ^{o}C and the outlet pressure of 6.96 MPa. It assumes the atmosphere air temperature of 43 ^{o}C. According to the reactor inlet temperature conditions (290, 350, 390, 415, 490 ^{o}C), the RPV maximum temperature and the total core flow rate changes. It assumed the transient sequence of LPCC event which 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 less than 6.244 MPa.

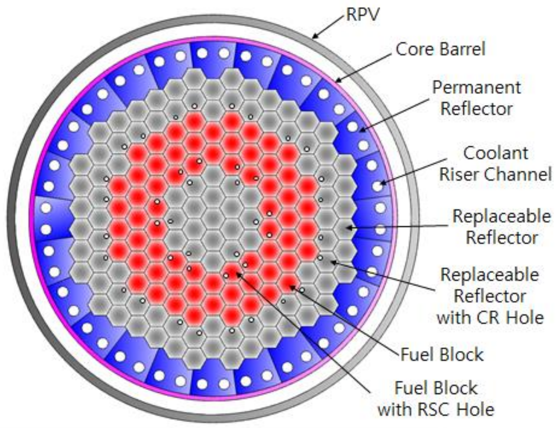
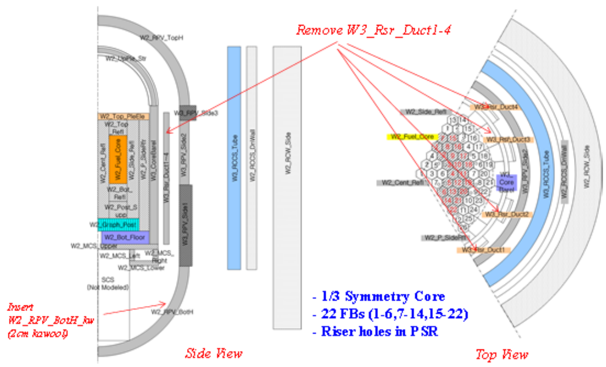
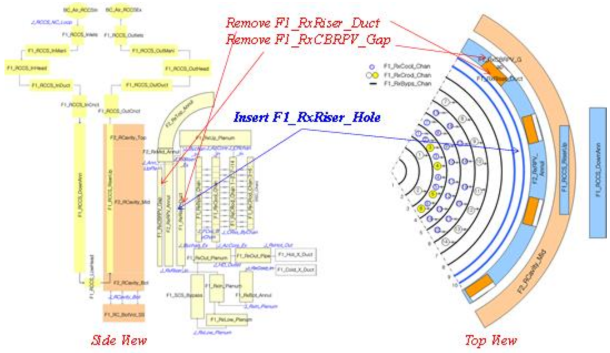


Fig. 1 Cooled-Vessel Design of 350MW$_t$ VHTR Core



(a) Solid Structure System



(b) Fluid System

Fig. 2 GAMMA+ Simulation Modeling of 350MW$_t$ VHTR Core System

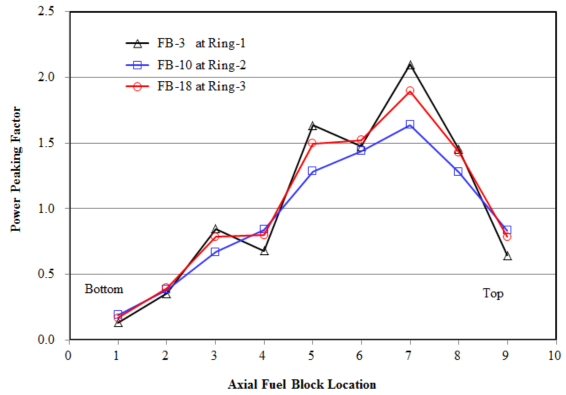


Fig. 3 Axial Power Distribution of 350MW$_t$ VHTR Core

3. Calculation Results

3.1 Results of the Normal Operation

Table 1 shows the normal operation conditions of 350MW$_t$ VHTR with the outlet temperature of 850 °C according to the various inlet temperature conditions. All operating parameters like the core flow rate, core pressure drop, RCCS flow rate, RCCS heat removal and RCCS exit temperature are increased as the increase of the inlet temperature. That is, the core flow rate is increased because the temperature difference between the core outlet and the inlet is decreased as the increase of the inlet temperature. The core pressure drop is proportional to a square number of the flow rate. In case of 490 °C inlet temperature, the core pressure drop of 81.6 kPa becomes much higher than the NGNP design of 46.5 kPa [1]. It shows that the higher inlet temperature provides the higher heat loss, air flow rate and exit temperature in RCCS system. Table 2 shows the maximum temperatures of main core components at the normal operation according to the various inlet temperature conditions. Due to the increase of core flow rate, the maximum fuel temperature is decreased as the increase of the inlet temperature. On the other hand, the maximum temperature of RPV becomes increased as the increase of the inlet temperature. Except for the case of 490 °C inlet temperature, the RPV maximum temperatures for all cases are evaluated less than SA508/533 ASME code limit of 371 °C. In case of 490 °C inlet temperature, the maximum temperature is 382 °C. The difference between the inlet temperature and the RPV maximum temperature is 42 °C, 76 °C, 87 °C, 93 °C and 108 °C for the inlet temperature conditions of 290 °C, 350 °C, 390 °C, 415 °C and 490 °C, respectively.

Table 1 Normal Operation Conditions According to the Various Inlet Temperature Conditions

Parameter	T_{in}=290 °C	T_{in}=350 °C	T_{in}=390 °C	T_{in}=415 °C	T_{in}=490 °C
Core Flow Rate (kg/s)	120.0	134.4	146.1	154.3	186.4
Core Pressure Drop (kPa)	31.3	40.2	48.3	54.4	81.6
RCCS Air Flow (kg/s)	9.16	9.92	10.37	10.64	11.36
RCCS Heat Removal (MW)	0.667	0.904	1.084	1.205	1.621
RCCS Exit Temperature (°C)	114.5	132.4	145.3	153.9	182.3

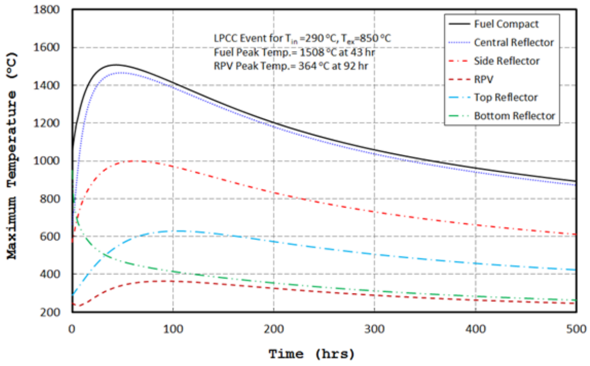
Table 2. Maximum Temperatures of Core Components at the Normal Operation

Component	T_{in}=290 °C Maximum Temperature (°C)	T_{in}=350 °C Maximum Temperature (°C)	T_{in}=390 °C Maximum Temperature (°C)	T_{in}=415 °C Maximum Temperature (°C)	T_{in}=490 °C Maximum Temperature (°C)
TRISO kernel	1146	1132	1123	1118	1103
Fuel compact	1132	1118	1109	1104	1089
Fuel block	998	980	967	962	943
Central reflector	666	665	667	669	679
Side reflector	570	595	612	623	655
PSR	678	670	714	724	755
Core barrel	290	347	386	410	484
RPV	248	274	303	322	382
RCCS riser tube	152	180	200	213	254
RCCS wall	142	167	185	197	235
Upper plenum shroud	282	338	376	399	469
Top reflector	292	351	391	415	490
Bottom reflector	949	935	927	923	908
Graphite support post	791	804	809	812	823

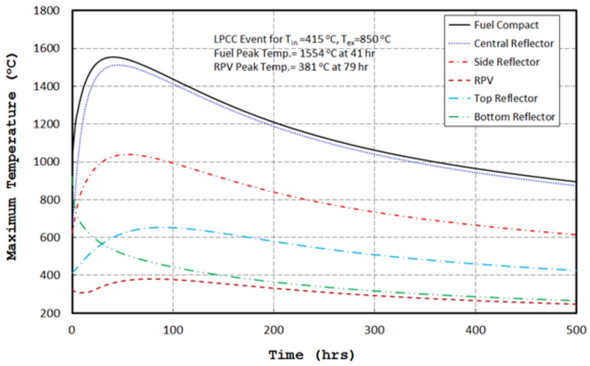
3.2 Results of the Accident Conditions

Fig. 4 shows the behavior of the peak temperatures of main core components during LPCC Event. The peak temperature of fuel compact is 1508 °C at 43 hr for the case of 290 °C inlet temperature and 1554 °C at 41 hr for the case of 415 °C inlet temperature, respectively. The peak temperatures of core components during LPCC event for all cases are listed in Table 3. Unlike the normal operation in Table 2, the peak fuel temperature becomes increased as the increase of the inlet temperature due to the no coolant flow during the accident conditions. For all cases, the peak fuel temperature is less than the transient fuel design limit of 1600 °C. In addition, it shows the peak temperature of RPV becomes increased as the increase of the inlet temperature. That is, the peak temperature of RPV is 364 °C for the case of 290 °C inlet temperature and 392 °C for the case of 490 °C inlet temperature, respectively.

For all cases, it satisfies SA508/533 ASME code limit during accident conditions (538 ^{o}C for up to 1000 h).



(a) 290 ^{o}C



(b) 415 ^{o}C

Fig. 4 Peak Temperatures during LPCC Event

Table 3. Peak Temperatures of Core Components during LPCC Event

Component	T_{in}=290 °C	T_{in}=350 °C	T_{in}=390 °C	T_{in}=415 °C	T_{in}=490 °C
	Maximum Temperature (°C)	Maximum Temperature (°C)	Maximum Temperature (°C)	Maximum Temperature (°C)	Maximum Temperature (°C)
TRISO kernel	1508	1529	1545	1554	1585
Fuel compact	1508	1529	1545	1554	1585
Fuel block	1507	1529	1544	1554	1584
Central reflector	1466	1487	1503	1512	1543
Side reflector	999	1018	1031	1039	1066
PSR	739	753	762	768	788
Core barrel	505	515	522	527	541
RPV	364	371	377	381	392
RCCS riser tube	232	236	239	241	254
RCCS wall	212	216	219	221	235
Upper plenum shroud	417	424	429	432	469
Top reflector	629	640	648	653	671
Bottom reflector	949	935	927	922	908
Graphite support post	791	804	809	812	823

4. Conclusions

GAMMA+ code simulations are performed for the 350MW$_t$ VHTR core with the cooled-vessel design on the normal operation and LPCC event according to the various reactor inlet temperature conditions. As the increase of the reactor inlet temperature, the maximum fuel temperature at normal operation is decreased due to the increase of the core flow, but the peak fuel temperature during LPCC event is increased and the maximum temperatures for all cases are less than the transient fuel design limit of 1600 ^{o}C. It is evaluated that the decrease of RPV maximum temperature due to the cooled-vessel design becomes high as the increase of the reactor inlet temperature. That is, it shows that the difference between the inlet temperature and the RPV maximum temperature is 42 ^{o}C, 76 ^{o}C, 87 ^{o}C, 93 ^{o}C and 108 ^{o}C for the inlet temperature conditions of 290 ^{o}C, 350 ^{o}C, 390 ^{o}C, 415 ^{o}C and 490 ^{o}C, respectively. Considering the RPV design temperature, the available maximum temperature of the reactor inlet temperature is 415 ^{o}C because the maximum temperature of 382 ^{o}C, in case of 490 ^{o}C inlet temperature, is greater than SA508/533 ASME code limit of 371 ^{o}C.

ACKNOWLEDGEMENTS

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