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Impact of the Cooled-Vessel Design on the Peak Fuel Temperature of VHTR

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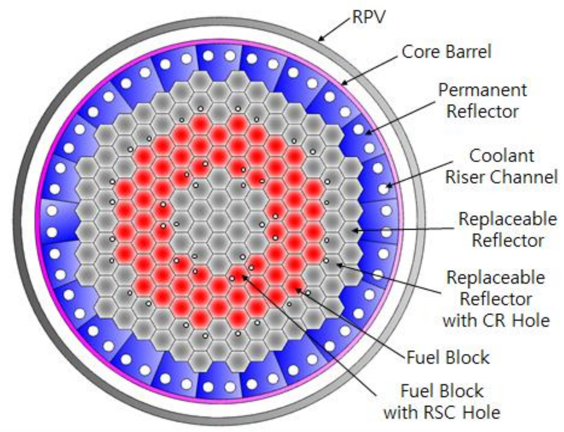
1. Introduction

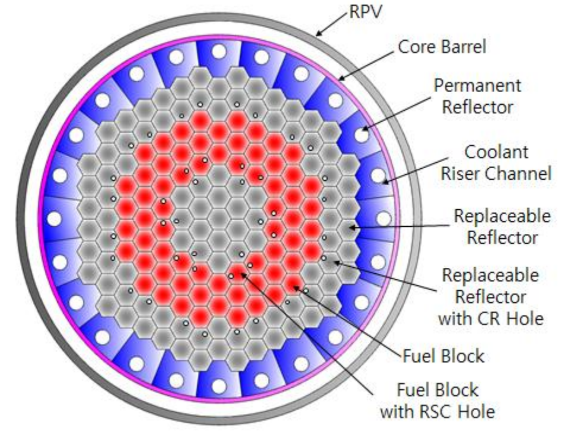
In the cooled-vessel (CV) design [1], the coolant riser channels are located into the permanent side reflector (PSR) in order to avoid the direct contact of the high temperature coolant to the reactor pressure vessel (RPV). This design can make the temperature of SA508/533 RPV maintain below the ASME code, which is 371 ^{o}C during normal operation and 538 ^{o}C for up to 1000 h during accident conditions [2]. Based on the previous NGNP design [3], KAERI is developing a 350MW$_t$ VHTR which will adopt the cooled-vessel and could be applied for the hydrogen production, the process heat and cogeneration. As a low level design stage, the sizing of riser hole is needed. The reference CV is designed to have the same flow area with that of NGNP. Because the riser hole is located into the PSR, the sizing of riser hole affects the reduced amount of the graphite in PSR. It is expected that the peak fuel temperature will be increased during the accident conditions due to the reduced amount of the graphite heat capacity. Thus, the modified CV design is considered to have a smaller flow area. Based on the GAMMA+ code [4] simulations of the reference CV and the modified CV designs, this paper evaluates the impact of the cooled-vessel design on the peak fuel temperature of a 350MW$_t$ VHTR during the accident conditions like LPCC and HPCC events.

2. Calculation Conditions

Fig. 1 shows the cooled-vessel design of 350MW$_t$ VHTR core where the coolant riser channels are located into PSR. Fig. 1 (a) is the reference CV design which has 48 holes of 180 mm diameter (two holes per PSR). The total flow area (1.22 m^2) of the reference CV is almost same with the flow area (1.21m^2) of NGNP where twelve riser ducts are located into the annulus between core barrel (CB) and RPV. Fig. 1 (b) is the modified CV design which has 24 holes of 200 mm diameter (one hole per PSR). The flow area of the modified CV is 62% of the reference design. This study is focused on evaluating how much of the peak fuel temperature for the reference CV design will be increased due to the reduction of graphite heat capacity during the accident conditions, compared to the modified CV design. Fig. 2 shows the axial power distribution of 350MW$_t$ VHTR core which 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. In Fig. 2, 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. It is expected that the top-skewed axial power distribution contributes to the lower peak fuel temperature during normal operation because the coolant flow comes from the top to the bottom fuel block. During the normal operation of 350MW$_t$ VHTR, it operates with the inlet temperature of 290 ^{o}C, the outlet temperature of 750 ^{o}C, the outlet pressure of 6.96 MPa, and the total core flow rate of 146.2 kg/s. It assumes the atmosphere air temperature of 43 ^{o}C. Table 1 shows the transient sequence of VHTR accident conditions. LPCC (Low Pressure Conduction Cooling) 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 less than 6.244 MPa. On the other hand, HPCC (High Pressure Conduction Cooling) event is initiated by the flow decrease due to the helium circulator trip. The reactor trip starts at the low flow rate less than 117.0 kg/s.



(a) ϕ180mm, 48 holes



(b) ϕ200mm, 24 holes

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

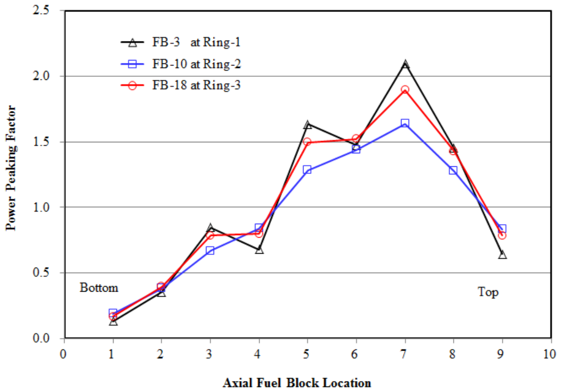


Fig. 2 Axial Power Distribution of 350MW$_t$ VHTR Core

Table 1. Transient Sequence of VHTR Accidents
(a) The Sequence of LPCC Event

Time (s)	Event Description	Comments
0	Pressure starts to decrease by the guillotine break at the cross-vessel	initiating event
0	Pressure approaches to 1 bar in 10 seconds	
1.05	The reactor trips by low primary pressure	P < 6.244 MPa
2.05	Decay heat load by reactor trip signal	1 second delay

(b) The Sequence of HPCC Event

Time (s)	Event Description	Comments
0	RCS flow starts to decrease by the HTS circulator trip	initiating event
0	RCS flow approaches to zero flow in 10 seconds	
2.00	The reactor trips by low RCS flow	m < 117.0 kg/s
3.00	Decay heat load by reactor trip signal	1 second delay

3. Calculation Results

3.1 Results of the Normal Operation

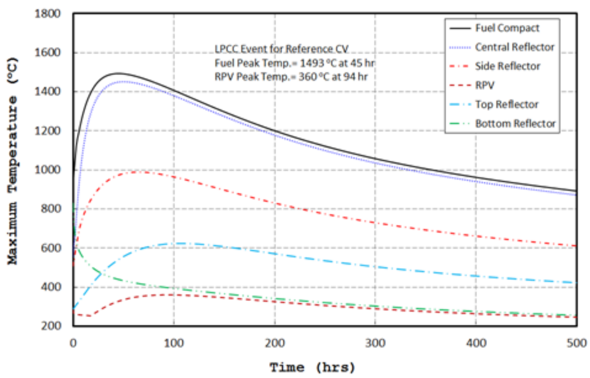
At the normal operation, the pressure drop from the cold reactor inlet to the hot reactor exit is evaluated by 45.9 kPa for the reference CV design, which is very close to the NGNP design of 46.5 kPa. The pressure drop of the modified CV design is 50.7 kPa, which is 10.4% increased due to the increase of the coolant velocity in the riser channel. RCCS (Reactor Cavity Cooling System) heat removal is 0.726 MW and 0.714 MW for the reference CV and the modified CV, respectively. RCCS air flow rate of 9.39 kg/s and 9.36 kg/s, and RCCS exit temperature of 119 ^oC and 118 ^oC are evaluated. Table 2 shows the maximum temperatures of main core components at the normal operation. Except for PSR, the maximum temperatures of components for the reference CV and the modified CV are almost same because the core flow cooling is dominant rather than RCCS cooling during normal operation. The temperature in the most parts of PSR is less than the side reflector, but, the maximum temperature is greater because the hot core bottom support is contacting with PSR at the local bottom core region. The RPV maximum temperature is close to the core inlet temperature because the bottom plenum coolant is contacting with the bottom head RPV without insulation. For the higher inlet temperature, as like top head sphere, the insulation at the bottom head sphere should be considered for the cooled-vessel design.

Table 2. Maximum Temperatures of 350MW$_t$ VHTR Core Components at the Normal Operation

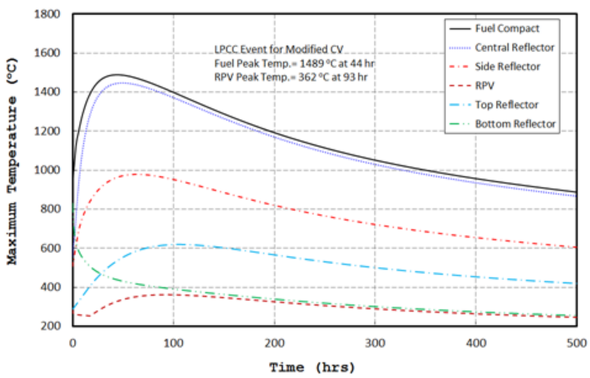
Component	Reference CV Design	Modified CV Design
	Maximum Temperature (°C)	Maximum Temperature (°C)
TRISO kernel	1036	1036
Fuel compact	1022	1022
Fuel block	873	873
Central reflector	559	560
Side reflector	509	506
PSR	614	611
Core barrel	288	288
RPV	284	284

3.2 Results of the Accident Conditions

During the accident conditions, the core decay power is removed by RCCS. The core temperature becomes increasing during heat-up phase when the decay power is higher than RCCS heat removal, and then decreasing slowly after the RCCS heat removal capacity is higher than the decay power. Fig. 3 shows the peak temperatures during LPCC Event. The peak temperature of fuel compact is 1493 ^oC at 45 hr for the reference CV and 1489 ^oC at 44 hr for the modified CV, respectively. The peak fuel temperature of the reference CV is 4 ^oC higher than the modified CV due to the reduced amount of the graphite heat capacity in PSR during LPCC Event. Unlike the normal operation in Table 2, the temperature of TRISO particle is same with that of fuel compact during the accident conditions due to the no coolant flow. Fig. 4 shows the peak temperatures during HPCC Event. The peak temperature of fuel compact is 1178 ^oC at 57 hr for the reference CV and 1170 ^oC at 56 hr for the modified CV, respectively. The peak fuel temperature of the reference CV is 8 ^oC higher than the modified CV. The peak temperature of RPV for the reference CV is 2 ^oC and 1 ^oC lower than the modified CV during LPCC and HPCC event, respectively.

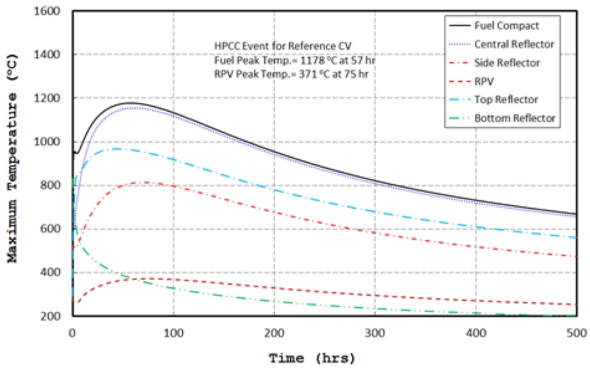


(a) Reference CV

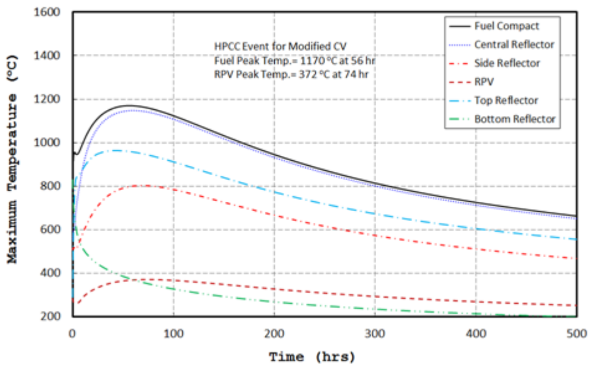


(b) Modified CV

Fig. 3 Peak Temperatures during LPCC Event



(a) Reference CV



(b) Modified CV

Fig. 4 Peak Temperatures during HPCC Event

4. Conclusions

As comparing GAMMA+ code simulation results of $350MW_t$ VHTR core using the reference cooled-vessel design with the modified cooled-vessel, it is evaluated that the peak fuel temperature of the reference cooled-vessel is 4 ^oC ~ 8 ^oC increased due to the reduction of graphite heat capacity during the accident conditions. But, the pressure drop of the modified cooled-vessel is 10.4% higher than the reference cooled-vessel due to the increase of the coolant velocity in the riser channel.

ACKNOWLEDGEMENTS

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