Computational Assessment of the Vessel Cooling Design Options for a VHTR

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1. Introduction

The Very High Temperature Reactor (VHTR) has been selected for the Nuclear Hydrogen Development and Demonstration (NHDD) project.[1] Design of the reactor pressure vessel (RPV) is very important due to the high operating temperature of the VHTR. Both the SA508/533 steel and high-Cr steels (e.g. 9Cr-1Mo-V steels) are considered for the VHTR pressure vessel. Because of its extensive experience base as an ASME Section III code-approved material for Light Water Reactor, SA508/533 steel is emerging as a strong candidate for the VHTR RPV. In order to use this material, however, the RPV temperature must be maintained below ASME code limit, which are 371^{o}C during normal operation and 538^{o}C for up to 1000h during accident conditions.

In this paper, three types of vessel cooling options for the prismatic core VHTR to keep the vessel temperature below the normal operating limit are suggested. Their performance are evaluated by using a system thermo-fluid analysis code, GAMMA+, and a commercial computational fluid dynamics code, CFX.

2. Vessel Cooling Options

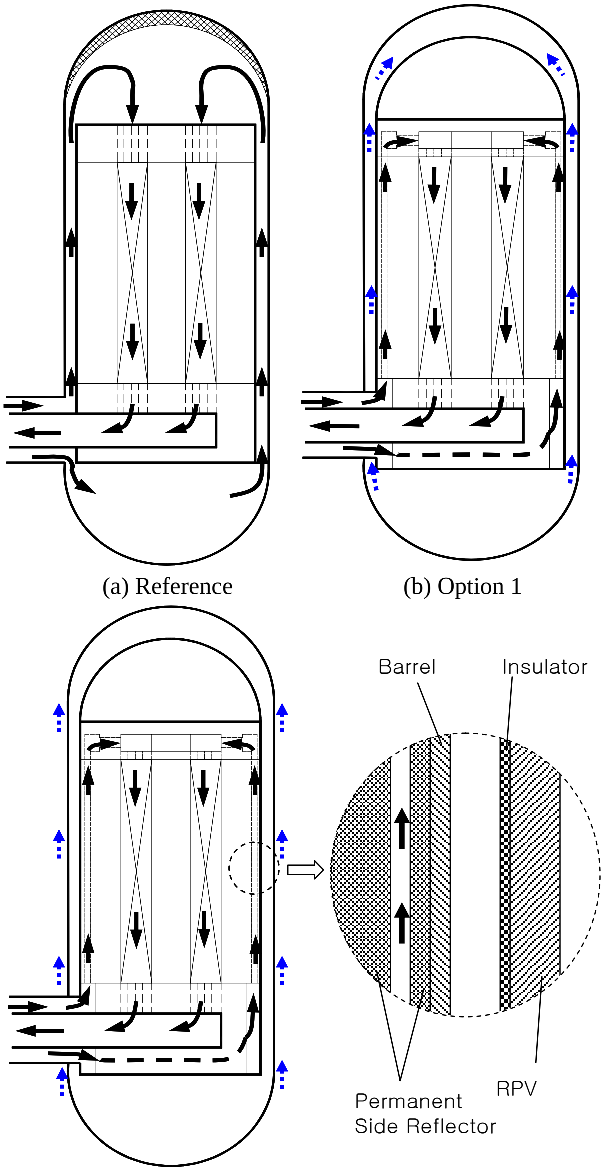
Three vessel cooling design options to maintain the RPV temperature below its operating limit are illustrated in Fig. 1.

In the reference reactor, primary coolant is supplied to the core through the annular space between the RPV and the core barrel. This configuration cannot avoid contact of the RPV with the high temperature coolant and results in exceeding the RPV temperature limit.

In the option 1, the coolant inlet flow is routed through riser channels in the permanent side reflector (PSR), which is a base configuration of all designs. A vessel cooling system (VCS) supplying cold helium flow between the RPV and the core barrel is added to cool down the RPV in the case that the temperature is still higher than its limit.

The second option is external vessel cooling with the modified inlet flow configuration. The cooling fluid is air in the reactor cavity outside of the RPV. Air blowers should be installed around the bottom side of the RPV.

The last option is to use insulation material instead of direct cooling of the RPV by internal cold helium flow or external air flow. The location of insulator can be either inner surface of the RPV or the interface surface between the PSR and the core barrel.



(a) Reference (b) Option 1
(c) Option 2 (d) Option 3

Fig. 1. Reference design and vessel cooling design options

3. Analysis and Results

Computational analyses using the GAMMA+ and CFX codes to evaluate the thermal performance of the vessel cooling design options were performed. The GAMMA+ model shown in Fig. 2 includes the reactor coolant system and the reactor cavity, the passive Reactor Cavity Cooling System (RCCS), and the CFD code uses a more detailed model in a 1/54 sector corresponding to the region associated with a single PSR riser channel, extending in the radial direction from the PSR to the RCCS downcomer wall.

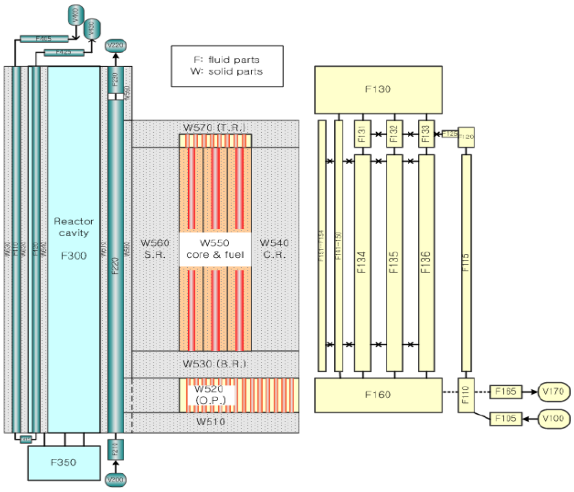


Fig.2 GAMMA+ analysis model

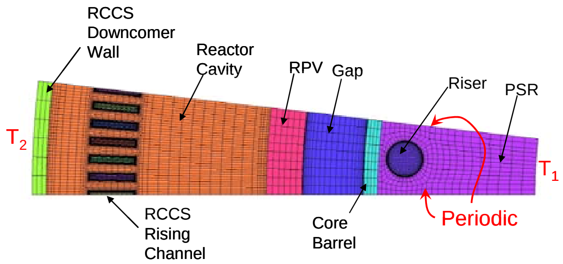


Fig. 3. CFD analysis model

The reference reactor core design used in the analysis are a reactor power of 600MWt and a core inlet/outlet temperature of 490°C and 950°C. The analysis results for option 1 are summarized in Table 1. The GAMMA+ results show that the RPV temperature is 348°C during normal operation and 519°C during the LPCC (Low Pressure Conduction Cooldown) accident, which means that the ASME code limits can be satisfied for both a normal operation and accident conditions without requiring an active VCS. The CFX result indicated that the PRV temperature cannot be below its normal operating limit without the VCS but a small amount of the VCS flow is enough to keep the temperature below the limit. The higher vessel temperature of the CFX gives rise to the higher RCCS heat loss mainly caused by a radiation heat transfer. From a detailed comparison between the results, it is found that the difference between the two results comes from the different prediction of the flow patterns and the heat transfer characteristics in the reactor cavity.

Table 1. Comparison of the results for Option 1

Parameter	GAMMA+	CFX	CFX
Max. Vessel T (°C)	348	377	311
VCS helium flow (kg/s)	0.0	0.0	4.0
RCCS Heat Loss (MWt)	1.86	1.95	1.95

For Option 2, the analysis was performed with a change of the external air cooling flow and the results are shown in Fig. 4. The CFD results show that there is no effect of the external air cooling while the GAMMA+ predicts a little effect of the air cooling on the RPV temperature. The CFX results show that the forced air cooling flow does not reach the upper region of the vessel.

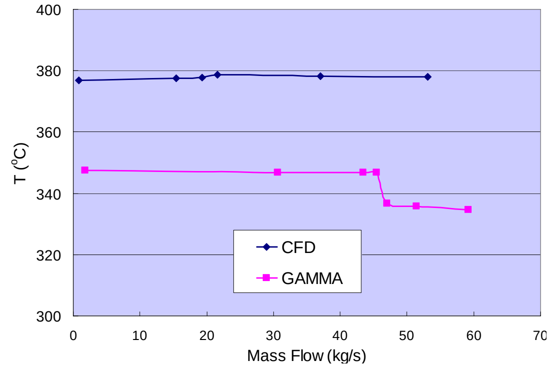


Fig. 4 RPV temperatures variation in Option 2

For Option 3, only the GAMMA+ analysis was carried out to investigate the sensitivity of the insulation thickness. Fig. 5 shows the RPV temperature distribution according to a change of the insulation thickness. The insulation effect is big enough, about a 50°C decrease for a 0.5 mm thickness. However, a larger thickness results in a peak fuel temperature increase above the limit of 1600°C during the accident conditions.

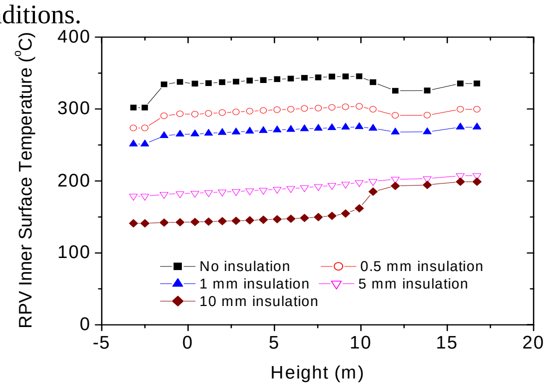


Fig.5 RPV temperature distributions in Option 3

4. Conclusions

Among the vessel cooling design options considered in the study, the modified inlet flow configuration with the VCS flow provides the most viable results. The external cooling option does not ensure an effective cooling of the RPV. The insulation option provides an effective temperature reduction of the RPV but a negative effect on the fuel safety during the accidents.

Acknowledgements

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REFERENCES

[1] J. Chang, et al., "A Study of a Nuclear Hydrogen Production Demonstration Plant," Nuclear Engineering and Technology, Vol. 39, No.2, April 2007.