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Computational Assessment of the Reactor Vessel Cooling Options in a prismatic core VHTR

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1 ABSTRACT

The design of the reactor pressure vessel is one of the important issues in the VHTR design due to its high operating temperature. Because of its extensive experience base as an ASME Section III code-approved material for Light Water Reactor, the SA508/533 steel is emerging as a strong candidate for the VHTR reactor pressure vessel. In order to use this material, however, the RPV temperature must be maintained below the ASME code limit, which is 371°C during normal operation and 538°C for up to 1000h during accident conditions.

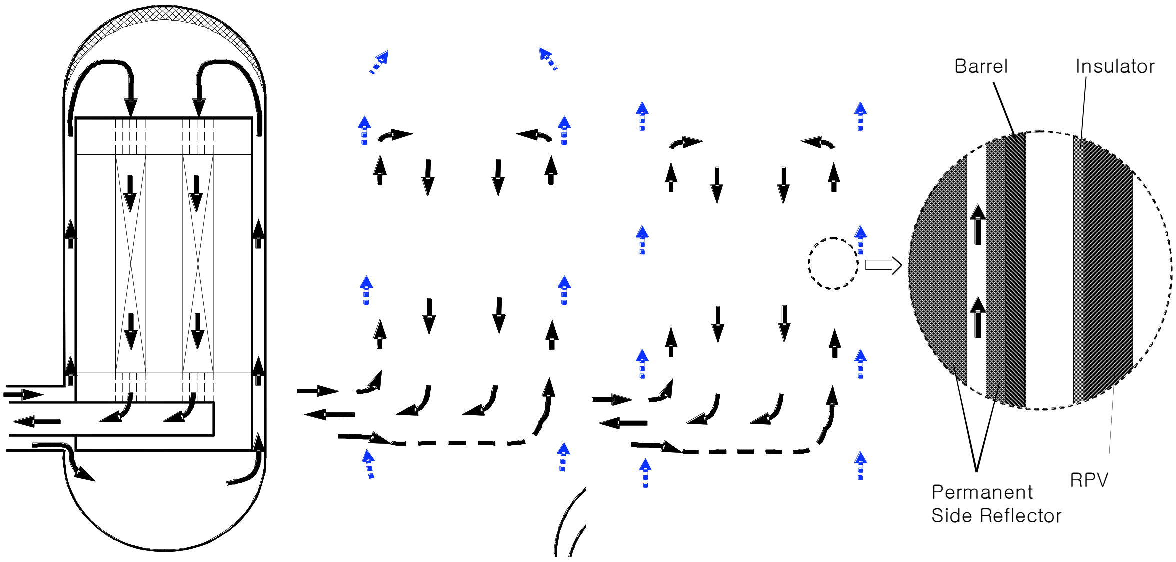
Three types of vessel cooling options for a prismatic core VHTR to keep the RPV temperature below the normal operating limit are suggested: An internal vessel cooling, an external vessel cooling, and an internal insulation. The performances of the vessel cooling options are evaluated by using a system thermo-fluid analysis code, GAMMA+, and a commercial computational fluid dynamics code, CFX, during normal operation and accidents. The results suggested that the internal vessel cooling with the modified inlet flow path is the most promising option. 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.

2 INTRODUCTION

The Very High Temperature Reactor (VHTR) has been selected for the Nuclear Hydrogen Development and Demonstration (NHDD) project. [Chang et al. (2007)] For the NHDD plant, the primary coolant inlet and outlet temperatures are considered to be 490 and 950 °C, respectively. Due to its high operating temperature, the design of the reactor pressure vessel (RPV) is one of the important issues in the NHDD design. Both the SA508/533 steel and high-Cr steels (e.g. 9Cr-1Mo-V steels) are expected to be candidate materials for the VHTR pressure vessel. Because of its extensive experience base as an ASME Section III code-approved material for Light Water Reactor, the SA508/533 steel has emerged as a strong candidate for the RPV. In order to use this material, however, a design is needed to maintain the RPV temperature below the ASME code limit, which is 371°C during normal operation and 538°C for up to 1000h during accident conditions. [ASME (2001)]

In this study, three types of vessel cooling options for a prismatic core VHTR to keep the RPV temperature below the operating limit are suggested as shown in Fig. 1. In option 1, the coolant inlet flow is routed through riser channels in the permanent side reflector (PSR), which is a base configuration of all three options. [Kim et al. (2008)] A vessel cooling system (VCS) supplying cold helium flow between the RPV and the core barrel is added to cool down the RPV in case that the RPV temperature is still higher than its limit. In option 2, external vessel cooling is introduced with the modified inlet flow configuration. The cooling fluid is air existing in the reactor cavity, the outside of the RPV. Air blowers are installed around the bottom side of the RPV. The last option is to use insulation material instead of the direct cooling of the RPV by the internal or external cooling flows. The location of the insulator can be either on the inner surface of the RPV or at the interface surface between the PSR and the core barrel.

The performance of the vessel cooling options is investigated by computational analyses using the GAMMA+ and CFX codes. The GAMMA+ code [Lim et al. (2006)] is a system thermo-fluid analysis code developed for the analysis of VHTR thermo-fluid transients at KAERI. The CFX code [ANSYS Inc. (2006)] is a commercial code for computational fluid dynamics (CFD). The results are compared with the ASME code limit of allowable operating temperature during normal operation and accident.

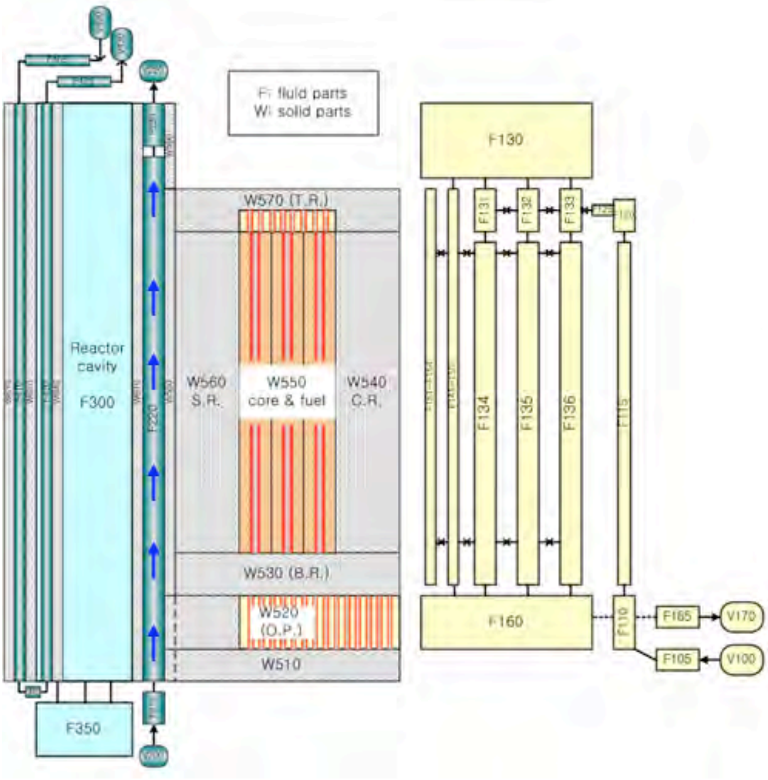


(a) Reference (b) Option 1 (c) Option 2 (d) Option 3

Figure 1. Reference design and vessel cooling options

3 COMPUTATIONAL METHODS

Thermal analyses during normal operation and postulated accidents were performed by the GAMMA+ code. The detailed modelling from the permanent side reflector (PSR) to the reactor cavity cooling system (RCCS) was performed by using the CFX code.



Component	Description	Meshes
F105,F165	Coaxial pipe	1,2
F110	Inlet bottom plenum	1
F115	Inlet riser holes	12
F120, F125	Inlet top plenum	1,2
F135	Top head	1
F131~3	Core top void	2
F134	Inner coolant channel	12
F135	Middle coolant channel	12
F136	Outer coolant channel	12
F141~150	FA bypass channel	14
F151,154	CR bypass channel	14
F152,153	RSC bypass channel	12
F160	Outlet plenum	4
F210,230	VCS inlet & outlet	1,1
F220	Vessel cooling channel	3x11
F300	Reactor cavity (RCCS)	3x20
F350	Reactor cavity (remain)	1
F405	RCCS inlet header	1
F410	RCCS downcomer	12
F415	RCCS lower plenum	1
F420	RCCS tube riser	12
F425	RCCS outlet header	1
W510	Bottom support	14x3
W520	Outlet plenum	14x2
W530	Bottom reflector	11x2
W540	Central reflector	5x10
W550	Fuel & core reflector	3x10
W560	Side reflector	3x10
W570	Top reflector	11x2
W580	Core barrel	3x14
W590	Upper shroud	3x3
W610	Reactor pressure vessel	5x20
W620	RCCS downcomer wall	3x20
W630	Reactor cavity wall	4x20
W640	RCCS panel	2x20x4

Figure 2. Analysis model of the GAMMA+ for option 1

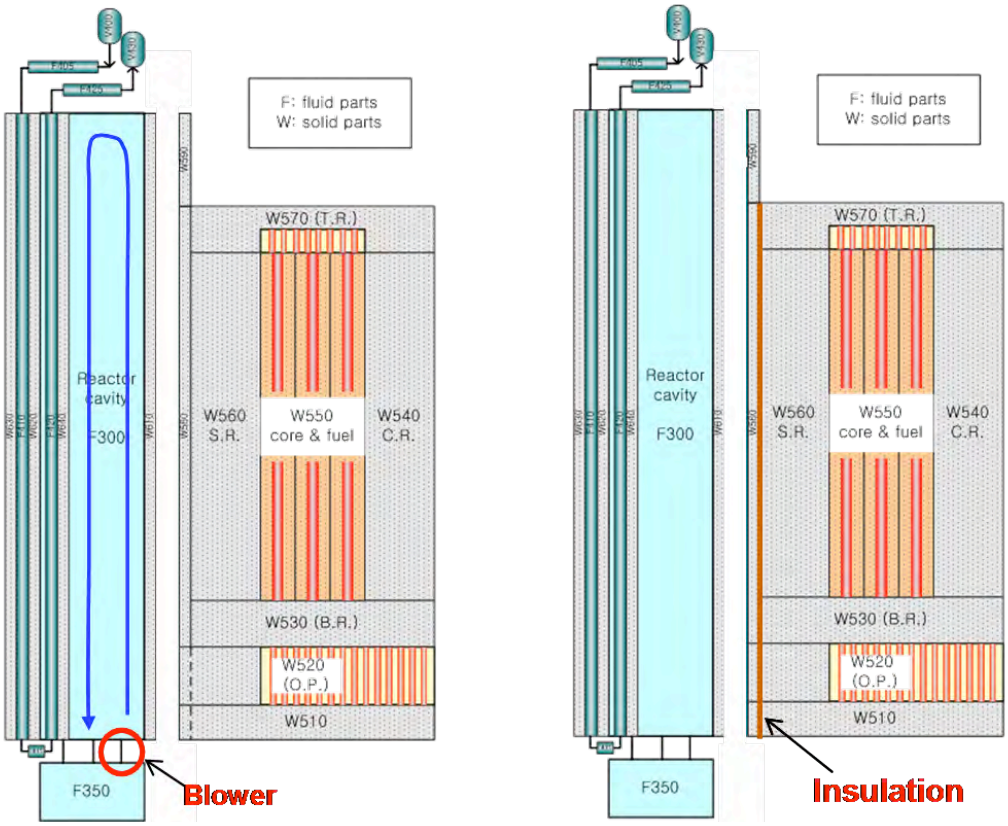
Figure 2 shows the GAMMA+ model used for the first option which is the basis model for the other options. The model includes the reactor coolant system, the reactor cavity, the RCCS, and the VCS. All solid regions are two- or three-dimensionally modelled having total meshes of 675. The fluid regions are modelled by the combination of two- and one-dimensional flow networks with total meshes of 375. In particular the reactor cavity and the annulus between the core barrel and the RPV are modelled two-dimensionally in order to consider the natural circulation flow characteristics. The thermal radiation heat transfer is considered in the regions such as the top plenum, the annulus between the core barrel and the RPV, the reactor cavity containing the RCCS panels, and the annulus between the downcomer wall and the reactor cavity wall. Free convection heat transfer occurs not only in the reactor cavity but also in the annulus between the core barrel and the RPV when the internal vessel cooling is not available. In order to quantify free convection heat transfer from the core to the RCCS, the following heat transfer correlation for a vertical annulus [Keyhani (1983)] is used.

$$Nu = 1.406 Ra^{0.077} \text{ for } Ra \le 6.6 \times 10^3$$

$$Nu = 0.163 Ra^{0.322} \text{ for } Ra > 6.6 \times 10^3$$

It is assumed that the vessel cooling is supplied to the annular space between the RPV and the core barrel. The source of cold helium is expected from a slipstream from the helium purification system. When the cold helium flow required is bigger than the capacity of the helium purification system, a designated vessel cooling system will be introduced. The temperature of cold helium is assumed at 140°C.

Figure 3 shows the modified GAMMA+ models for the analyses of options 2 and 3. For the second option of external air cooling, blowers are installed at the bottom side of the RPV to circulate the air in the reactor cavity. The blower is simulated by a junction model of a momentum source in the GAMMA+ code. In other words, the flow rate of the blower can be controlled by adjusting the pressure gradient at the junction. On the other hand, the insulation for the third option is provided on the inner surface of the core barrel.



(a) Option 2

(b) Option 3

Figure 3. Analysis model of the GAMMA+ for the option 2 and 3.

Detailed steady-steady thermo-fluid analyses using a CFD model are carried out not only to investigate the detailed flow and heat transfer phenomena that occur in the cooled vessel design but also to verify the performance of the GAMMA+ analysis in the prediction of complex heat transfer phenomena in a multi-dimensional flow region such as the reactor cavity.

The CFD analysis of the cooled-vessel design needs to consider the thermo-fluid phenomena consisting of multi-dimensional heat conduction, conjugate heat transfer between solid and fluid, convective heat transfer, buoyancy, and radiation heat transfer. Buoyancy induced turbulent flows are expected in the reactor cavity and the gap between the RPV and the core barrel, where the Rayleigh numbers based on the width are estimated to be larger than 10^7. [Holman, 1986] The Reynolds number at the inlet of the riser hole is ~765,000. Therefore, a highly turbulent flow is expected in the riser hole. The k-ε turbulence model with the scalable wall function is applied to the fluid flows in the reactor cavity, the gap between the RPV and the core barrel, and the riser hole. The Boussinesq approximation model is used to consider buoyancy effects in the reactor cavity. The estimated buoyancy reference temperature and buoyancy reference density are used by using the CFD solutions with initially guessed values. For the radiation heat transfer, the discrete transfer model (DTM) is applied with the option of "surface to surface transfer mode". [ANSYS Inc, (2006)]

A CFD simulation of the entire vessel geometry including the reactor cavity and the RCCS requires tremendous computing resources. In this study, therefore, a 1/54 model is used for efficient calculations by using a rotational periodic assumption. Figure 4 shows the computational domain and model for the CFD analysis. The domain includes the 1/54 section of the graphite reflector, the riser hole, the gap for vessel cooling, the RPV, the reactor cavity, the RCCS tubes, and the downcomer wall (or cavity wall). The height of the domain is 19.873 m. Spherical shell geometry of the vessel head is modelled as an annulus for simplicity but maintains its heat transfer area. Furthermore, it is assumed that six RCCS tubes are located in the 1/54 section, which results in a total of 324 tubes. Part of the reactor cavity is selected as a sub-domain to apply a momentum source for modelling the blower of the option 2.

The temperature boundary conditions on the inner surface of the PSR and the core barrel are fixed with the distribution obtained from the GAMMA+ results. All the surfaces in the circumferential direction are treated by a periodic condition. The mass flow rate corresponding to the 1/54 of the total core flow rate is fixed at the riser inlet while static pressure condition is used at the riser outlet. The inlet temperature of the RCCS rising channel is set as 46°C and the 1/54 of the RCCS flow rate, 12.58kg/s, obtained from the GAMMA+ analysis is fixed at the RCCS channel inlet. At the RCCS outlet, a constant static pressure condition is applied.

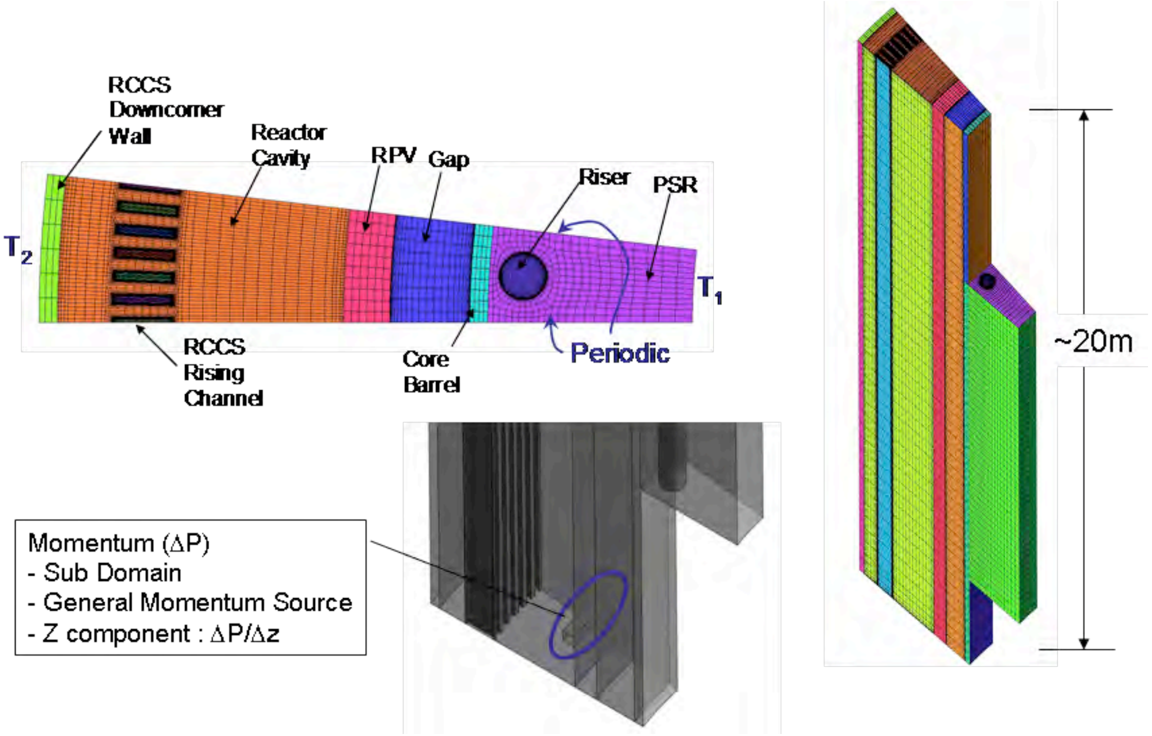


Figure 4. Computational domain and model for the CFD analysis

4 RESULTS AND DISCUSSIONS

The reference core design selected in the present analysis is a prismatic core whose thermal power is 600MWt and a core inlet/outlet temperature of 490°C and 950°C. Detailed design parameters are summarized in Table 1.

Table 1. NHDD design parameters.

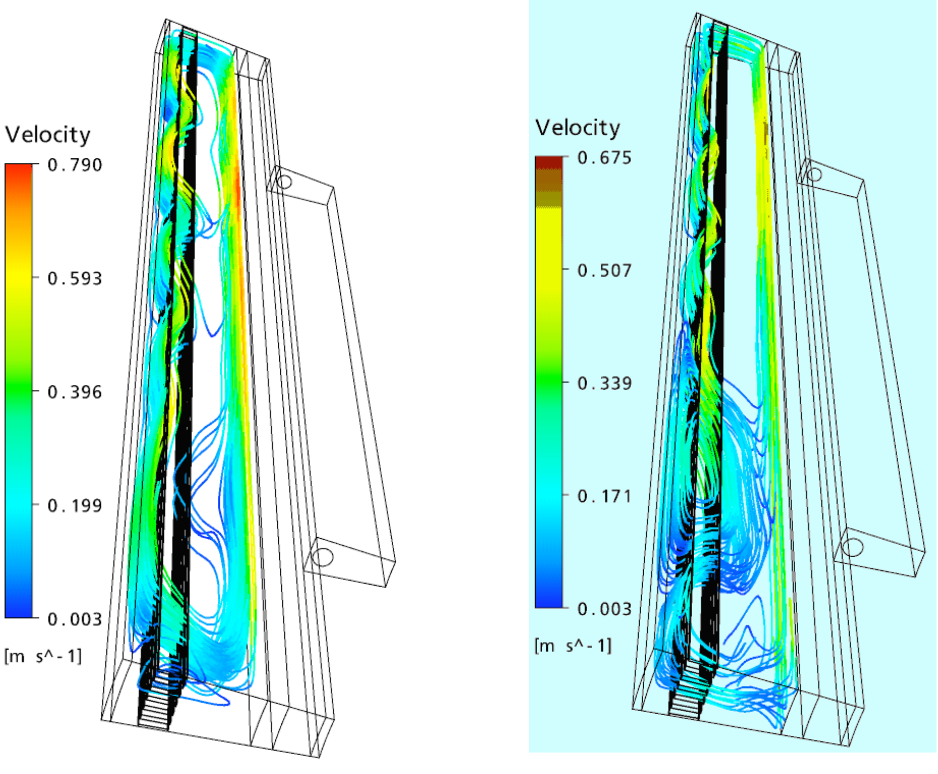
Design Parameters	Values
Core Thermal Power (MWt)	600
Number of Fuel Columns	102
Number of Fuel Block Layers	10
Thermal Power Density (MW/m^3)	6.6
Effective Inner Diameter of Active Core (m)	2.95
Effective Outer Diameter of Active Core (m)	4.83
Height of Active Core (m)	7.93
Height of Top/Bottom Reflector	1.59
Outer Diameter of Side Reflector	6.85
Number of Riser Holes (m)	54
Diameter of Riser Hole (m)	0.2
Diameter of Riser Hole Position	6.57
Core Inlet Pressure (MPa)	7.0
Core Inlet Temperature (°C)	490
Core Outlet Temperature (°C)	950
Coolant Flow Rate (kg/s)	250
RPV Material	SA 508/533 Steel
Outer Diameter of RPV (m)	8.04
Thickness of RPV (m)	0.19
Width of RCCS Channel (m)	0.0458
Length of RCCS Channel (m)	0.254
Thickness of RCCS Channel (m)	0.0048

4.1 Internal vessel cooling

Table 1 compares the results for the first option. According to the GAMMA+ analysis, the vessel temperature can be maintained below its operational limits of 371°C during the normal operating condition which means the vessel cooling system (VCS) is not required. On the contrary, the CFD results showed that the RPV temperature is about 30°C higher value than the GAMMA+ result, indicating that the RPV temperature cannot be below its normal operating limit without the VCS. Providing a small amount of the VCS flow less than 5% of the total core flow, however, the RPV temperature can be kept sufficiently below the normal operational limit. The higher vessel temperature of the CFX gives rises to the higher RCCS heat removal mainly caused by a radiation heat transfer. The heat removal by a convection heat transfer is much bigger in the GAMMA+ result than the CFX, which is one of the main reasons for the difference of the maximum RPV temperature between the GAMMA+ and the CFX results.

Table 2. 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 removal (MWt)	Total	1.86 (100%)	1.95 (100%)	1.26 (100%)
	Radiation	1.39 (74.7%)	1.67 (85.7%)	1.04 (82.4%)
	Convection	0.47 (25.3%)	0.28 (14.3%)	0.22 (17.6%)



(a) Without VCS flow

(b) With VCS flow

Figure 5. Streamlines in the reactor cavity

Streamlines in the reactor cavity region are shown in Fig.5. The case without VCS flow shows a natural circulating flow across the entire height of the reactor cavity. The upward flow along the RPV wall shows a stable flow pattern whereas the downward flow along the RCCS channels reveals a rather unstable one. This phenomenon can be explained as follows. The radiation from the RPV surface reaches not only the surface of the RCCS channels but also the downcomer wall through the space between the RCCS channels. The temperature of the downcomer wall is higher than that of the RCCS channels because part of the heat transferred to the RCCS channels is removed by the inside air cooling flow. Thus, the higher temperature at the downcomer wall heats the flow moving downward to induce an adverse pressure gradient by buoyancy which leads to the separation of the flow from the downcomer wall. As the downward flow pushed by the separation meets the RCCS channels, the relatively low temperature of the RCCS channel makes the flow cool down. Then the cooled flow moves back to face the downcomer wall and it is heated again, which results in a repeated wavy flow pattern. In the GAMMA+ analysis, on the other hand, the wavy pattern in the downward flow is simply modelled by the correlation obtained from well-established natural circulation flow in a vertical annulus which is appropriate for the flow in the annulus between the core barrel and the RPV. The case with the VCS flow shows a similar flow pattern to the one without the VCS flow except for the bottom region. The cold helium supplied from the bottom makes the RPV temperature at the bottom region decrease, resulting in a decrease of the buoyancy force along the vessel wall and the reduction of the natural circulation size in the reactor cavity.

Transient analyses are performed both for the High Pressure Conduction Cooldown (HPCC) accident and for the Lowe Pressure Conduction Cooldown (LPCC) accident. The HPCC accident is the limiting case for vessel heat-up at high pressure condition whereas the LPCC accident is for vessel heat-up at low pressure condition. Only the GAMMA+ code is applied for the transient analyses. It is assumed that the RCS and VCS flows decrease to zero in 60 seconds for the HPCC accident and in 10 seconds for the LPCC accidents, and the RCS and VCS pressures remain at 70 bar for the HPCC accident and decrease to 1 bar in 10 seconds for the LPCC accident. The RPV temperature transients for the HPCC and LPCC accidents are presented in Fig. 6. The existence of the VCS flow has not influence on the maximum RPV temperature during the accidents because the RPV temperature is governed by initial stored energy in the reactor core. In other words, the initial RPV temperature does not affect the maximum RPV temperature during the accidents. The ASME code allows the SA-508/533 steel to be operated below 538 °C below 1000 hours during accident conditions. The GAMMA+ results show that the maximum RPV temperatures keep below 432°C for 220 hours for the HPCC accident and 519°C for 480 hours for the LPCC accident, which means that the present design satisfies the ASME code limit.

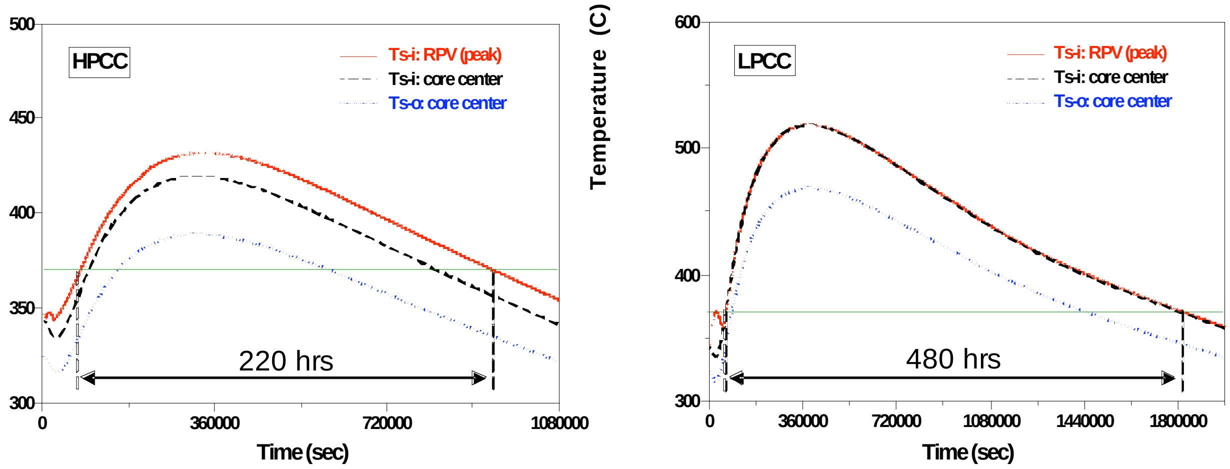


Figure 6. RPV temperature transients during the HPCC and LPCC accidents

4.2 External vessel cooling

Analyses were performed for the external vessel cooling option in which blowers are installed near the bottom surface of RPV. The flow of the blowers is changed by applying a different momentum source of pressure difference across a selected sub-region. Fig. 7 shows the maximum RPV temperature variation according to the change of the air cooling flow. The CFD result shows nearly uniform RPV temperatures regardless of the change of the air cooling flow while the GAMMA+ result reveals a little effect of the air cooling on the RPV temperature. A step-like decrease in the GAMMA+ result means that there is a change of heat transfer correlation accompanied by a selection of flow regime according to the criteria on local Reynolds and Grashof numbers.

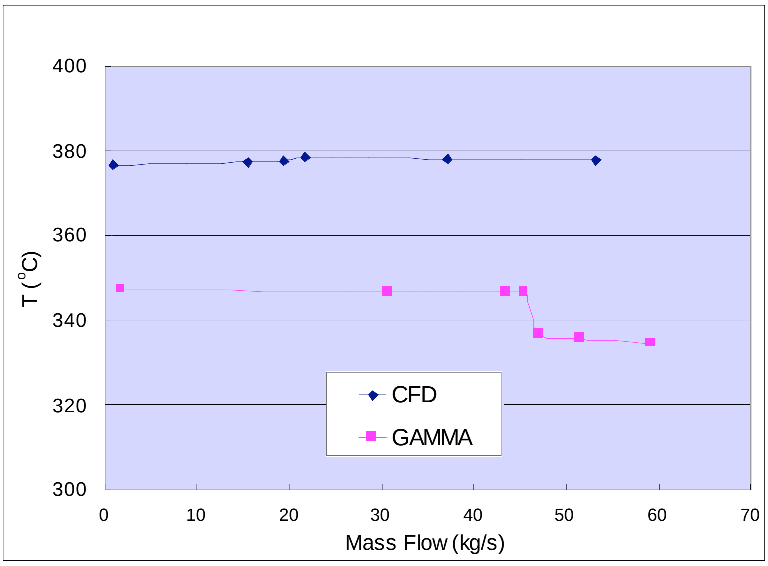
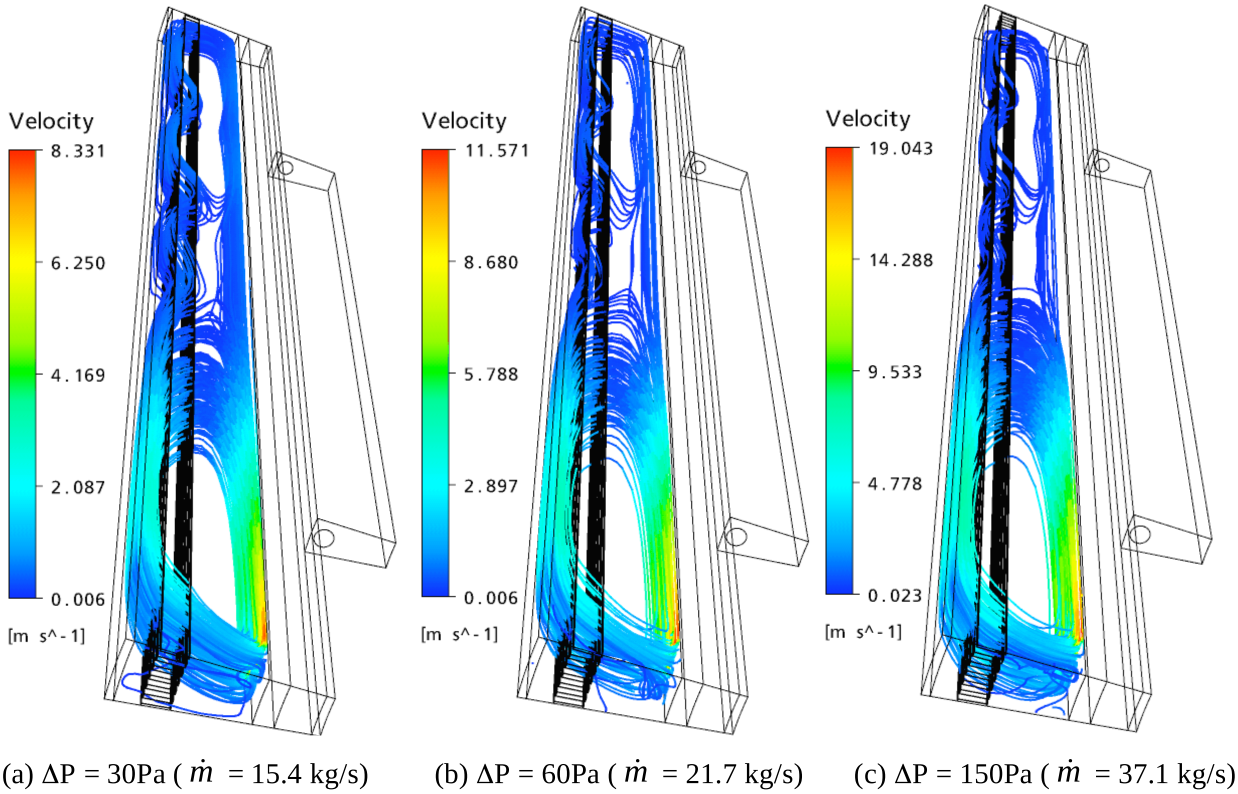


Figure 7. Maximum RPV temperature variation with the change of external cooling flow



(a) ΔP = 30Pa ($\dot{m}$ = 15.4 kg/s) (b) ΔP = 60Pa ($\dot{m}$ = 21.7 kg/s) (c) ΔP = 150Pa ($\dot{m}$ = 37.1 kg/s)

Figure 8. Streamlines for the case of external air cooling in the reactor cavity

Streamlines for the case of external vessel cooling shown in Fig.8 explain why the external cooling does not have any effect on the reduction of the RPV temperature. For the cooling flow of 4.0 kg/s, the flow discharged from the blower moves along the RPV surface in a form of wall jet flow but does not reach the upper part of the RPV surface. As the cooling flow is increased, the range affected by the cooling flow is expected to increase but confined to the region in the result of smaller cooling flow with the flow pattern in the upper part unchanged. Fig. 9 shows temperature distribution along the RPV outer surface with the change of the external cooling flow. It is certain that an increase of cooling flow results in a decrease of the RPV temperature in the region affected by the cooling flow while the region not affected by the external cooling reveals a slight increase of the temperature that is caused by an increase of the average air temperature in the reactor cavity.

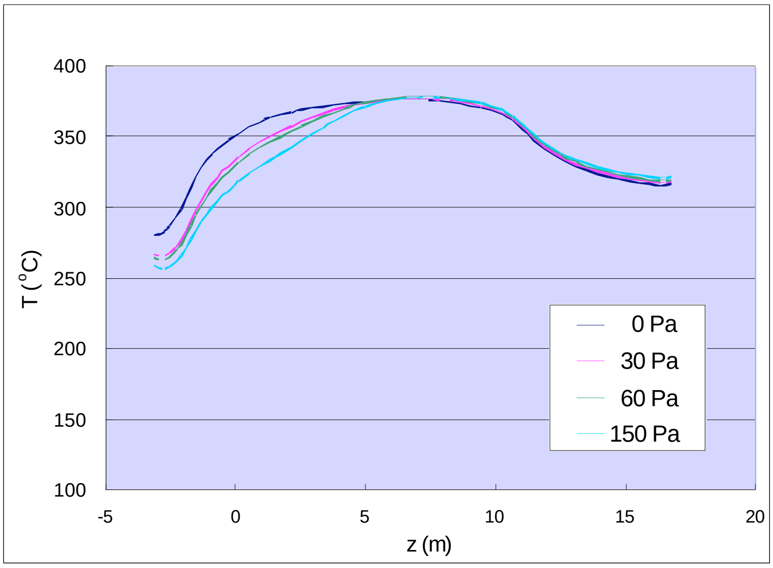


Figure 9. Temperature distribution along the RPV outer surface for the case of external cooling

4.3 Internal insulation

Analyses for option 3 were performed by using GAMMA+ code with the assumption that the insulation material for the vessel cooling is attached on the inner surface of the core barrel.

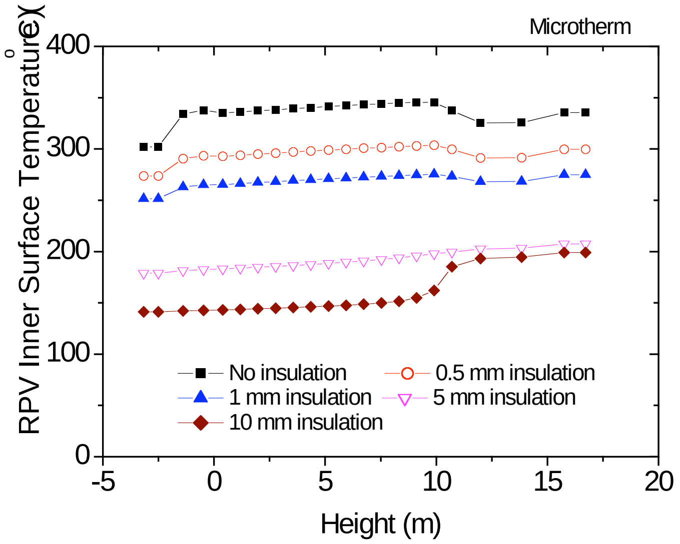
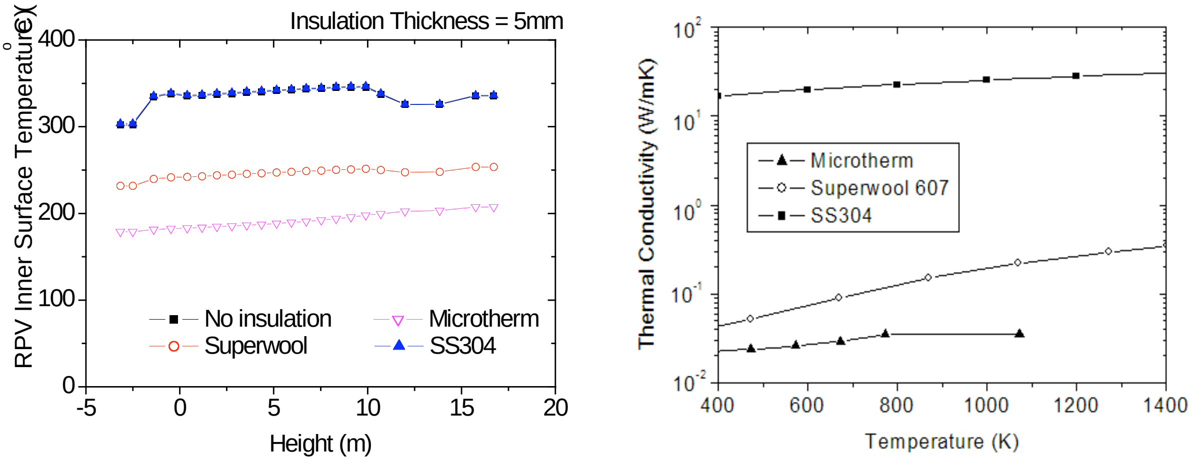


Figure 10. RPV temperature distribution with the change of insulation thickness

Microtherm used in the GT-MHR is selected as an insulation material for a sensitivity assessment of insulation thickness, the thermal conductivity of which is about 0.03 W/m·K. Fig. 10 shows RPV temperature distribution according to the change of insulation thickness during the normal operation. Installing an insulation material is an effective way to reduce the RPV temperature during normal operations. Even a thin insulation with the thickness of 0.5mm results in lowering the RPV temperature by about 40°C. The insulation of 1mm reduces the RPV temperature by as much as 100°C



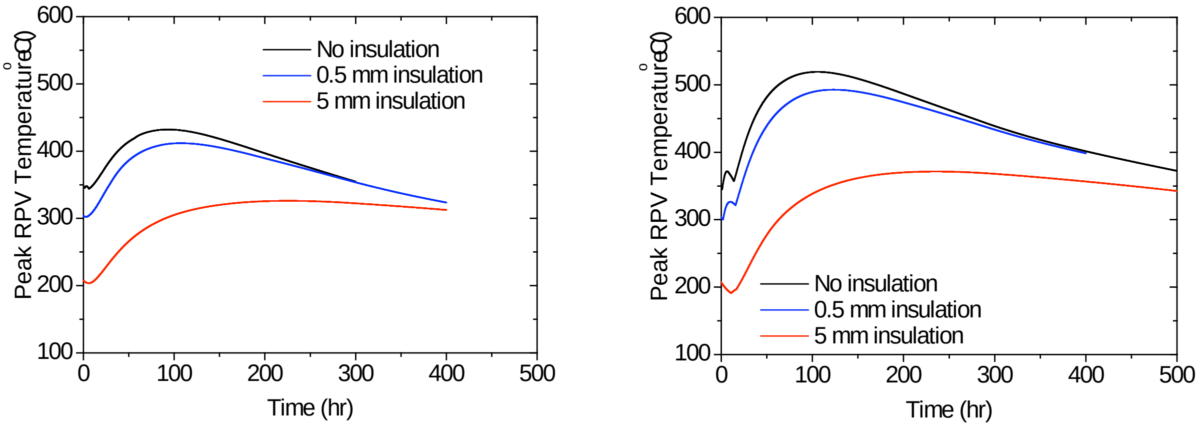
(a) RPV temperature

(b) Thermal conductivity

Figure 11. RPV temperature distribution with the change of insulation material

The effect of insulation material types are shown in Fig. 11. The considered materials are Microtherm, Superwool 607, and Stainless Steel 304 (SS304) of which the thermal conductivity changes are shown in Fig. 11(b). The insulation thickness is fixed at 5mm. The result shows the lower thermal conductivity the larger reduction of RPV temperature. Steels such as SS304 having relatively higher thermal conductivity reveals no effect of the insulation. Therefore, increasing the thickness of the core barrel or installing steel or graphite insulation material with a high thermal conductivity is not an effective way to reduce the RPV temperature.

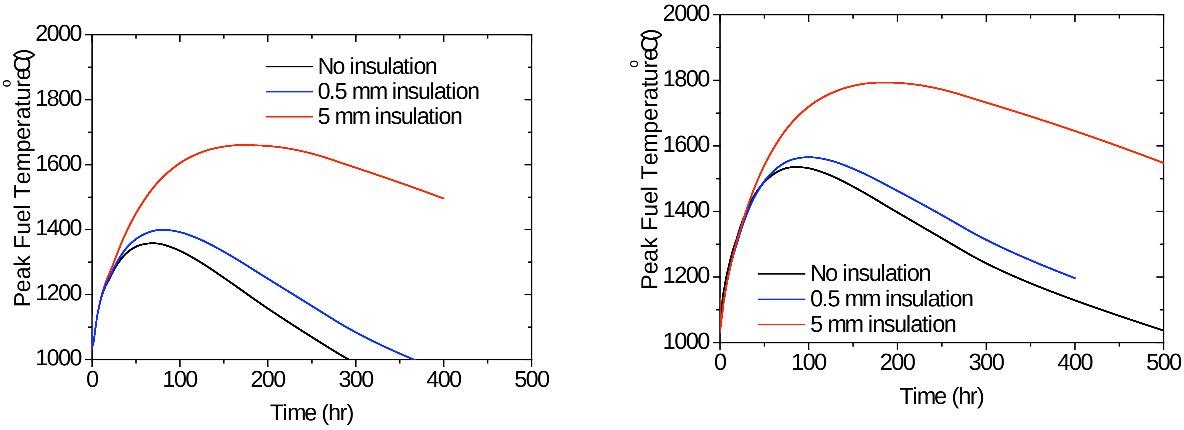
As shown in Fig. 10, the internal insulation by Microtherm results in an effective reduction of the RPV temperature during the normal operation but its validity should be identified in accident conditions. Transient analysis is performed for the HPCC and LPCC accidents. The Micortherm insulation thicknesses of 0.5mm and 5mm are selected. Figs. 12 and 13 show the effect of insulation thickness on the maximum RPV temperature and the peak fuel temperature during the HPCC and LPCC accidents, respectively. When compared to the case without the insulation, the maximum RPV temperature during the accident can be reduced below the ASME code limit of 371°C for the case of 5mm insulation. However, it fails to maintain the peak fuel temperature below the accident limit of 1600°C. In the case of 0.5mm insulation, the peak fuel temperature is increased to about 40°C for the HPCC and 30°C for LPCC respectively but still below the limit of 1600°C both for the HPCC and LPCC accidents.



(a) HPCC

(b) LPCC

Figure 12. Maximum RPV temperature variation during the HPCC and LPCC accidents with the change of insulation thickness



(a) HPCC

(b) LPCC

Figure 13. Peak fuel temperature variation during the HPCC and LPCC accidents with the change of insulation thickness

5 CONCLUSION

Three vessel cooling options for a prismatic core VHTR to keep the RPV temperature below the normal operating limit are suggested: an internal vessel cooling, an external vessel cooling, and the vessel insulation. All the options have a modified inlet flow configuration routing the inlet flow path to the core through the riser holes in the permanent side reflector. . The performance of the vessel cooling options was evaluated by using a system thermo-fluid analysis code, GAMMA+, and a commercial computational fluid dynamics code, CFX, during normal operation and accidents. The results are summarized as follows.

The GAMMA+ analysis for the case without the internal vessel cooling showed that the RPV temperature can be maintained below 371°C during normal operation and below 538°C for 1000hr during the LPCC accident. According to the CFD analysis, the RPV temperature exceeds the normal operating limit without the internal vessel cooling but a small amount of VCS flow, less than 1.6% of the RCS flow, is sufficient to keep the RPV temperature below the limit.

For the external cooling option, both the GAMMA+ and the CFX results showed that the external cooling by blower installed in the reactor cavity does not ensure an effective cooling of the RPV because the cooling flow does not reach the upper part of the RPV. An increase of the cooling flow is also useless.

Internal insulation gives rise to an effective reduction of the RPV temperature. The results showed that a thin insulation of 0.5 mm in thickness decreases the RPV temperature by 30~50°C during normal operation. However, the insulation prevents the heat removal from the core to the RCCS and increases the peak fuel temperature by 30~40°C during accident conditions, which has a negative effect on the fuel safety during accidents.

In conclusion, the results showed that the modified inlet flow configuration with the internal cooling is much more effective than the external cooling to maintain the RPV temperature below the operational limit of SA-508/533 steel. Although the vessel cooling by an internal insulation could also be selected as a viable option, the results indicated that it should be carefully considered in a view of the fuel safety margin during accidents.

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