Thermal Performance Analysis of a Cooled-Vessel Design Using GAMMA+

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1. Introduction

GT-MHR [1] adopts high-Cr materials, such as 2¼Cr-1Mo or 9Cr-1Mo-V steel, for the reactor pressure vessel (RPV). However, there are still open issues when manufacturing and procuring high-Cr vessels. In order to avoid these open issues, Kim and Lee [2] proposed a cooled-vessel concept as a promising option for the NHDD (Nuclear Hydrogen Development and Demonstration) system. A basic idea of the cooled-vessel concept is to use the conventional RPV materials (e.g., SA-508 or 533) instead of high-Cr materials by reducing the RPV temperature below its operating structural limit. The reduction of the RPV temperature is achieved by a change of the coolant flow path and an additional vessel cooling system (VCS) if necessary. Based on the computational fluid dynamics (CFD) analysis and the system analysis, Kim et al. [3] showed that the cooled-vessel design concept is feasible for a 600 MWth prismatic very high temperature reactor (VHTR).

In this paper, parametric calculations are made to analyze the thermal performance of a cooled-vessel design with various design conditions by using the GAMMA+ code [4]. For the two types of reactor cavity cooing systems (RCCS) (i.e., air-cooled or water-cooled RCCS), the effects of the reactor coolant system (RCS) inlet temperature and the location of the VCS injection nozzle are investigated. A 600 MWth prismatic VHTR under full power operating conditions is considered in this work.

2. System Model and Boundary Conditions

2.1 System Model

Fig. 1 shows the system model for the GAMMA+ calculations. It consists of the RCS, the reactor cavity, the RCCS, and the VCS. The system model is mainly based on that of PMR600 [5] except for the VCS. All solid regions are two- or three-dimensionally modeled with total meshes of 675. The fluid regions are modeled by a 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 modeled two-dimensionally in order to consider the natural circulation flow characteristics. The thermal radiation heat transfers are considered in 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.

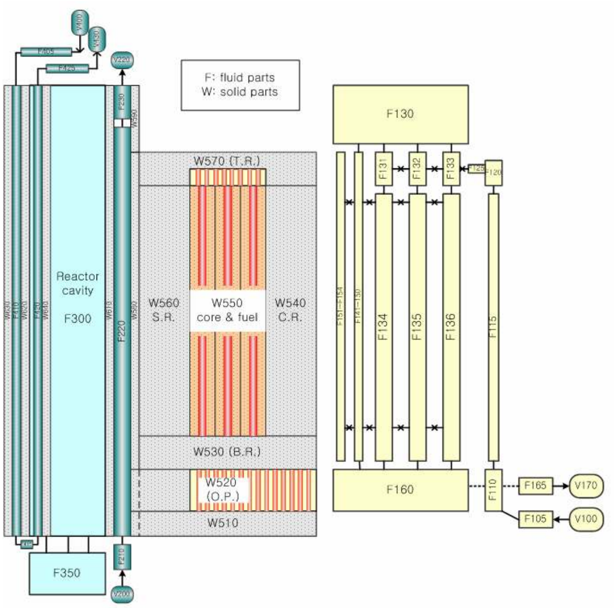

Fig. 1. System model for GAMMA+ calculations (lower head VCS injection case).

2.2 Boundary Conditions

The core power distribution at the beginning-of-cycle (BOC) condition of PMR600 is selected for the present analysis. The air-cooled RCCS is modeled based on the GT-MHR design and the assumption that the inlet pressure and the inlet temperature of the air flow are 1 bar and 43 ^{o}C, respectively. For the water-cooled RCCS option, it is assumed that the average temperature of the RCCS panel is maintained at 65 ^{o}C. Furthermore, the inlet temperature of the VCS injection flow is assumed to be 140 ^{o}C.

3. Results and Discussions

It is obvious that the RPV temperature is decreased with an increase of the VCS flow rate. In this study, the VCS flow rate is determined to ensure that the peak RPV temperature does not exceed 350 ^{o}C. Table I shows the calculated VCS flow rate and the resulting heat removal by the VCS. It is shown that for both types of the RCCS systems, the RPV temperature can be maintained below 350 ^{o}C without a VCS injection flow when the RCS inlet temperature is 490 ^{o}C. It is also found that a larger VCS flow rate is required when the VCS injection nozzle is located at the lower head.

Compared with the air-cooled RCCS, the water-cooled RCCS requires smaller VCS flow rates.

Table I: VCS Flow and Heat Removal by VCS

Air-Cooled RCCS			
Cases	Case 1A	Case 2A	Case 3A
VCS injection location	No injection	Lower head injection	Upper head injection
RCS Tin/Tout (°C)	490/950	590/950	590/950
VCS flow (kg/s)	-	3.08	2.14
Heat removal (MW)			
-By VCS	-	3.08	2.02
-By RCCS	1.76	1.36	1.64
Peak RPV temp.(°C)	348	350	350
Water-Cooled RCCS			
Cases	Case 1W	Case 2W	Case 3W
VCS flow (kg/s)	-	1.48	1.06
Heat removal (MW)			
- By VCS	-	1.74	1.10
- By RCCS	2.08	2.15	2.38
Peak RPV temp.(°C)	314	350	350

Figs. 2 and 3 show the calculated RPV inner surface temperatures. The figures clearly show that the location of the VCS injection nozzle significantly affects the temperature distribution of the RPV. Relatively flat temperature distributions are seen for Case 1 and Case 3. The flat RPV temperature distribution for Case 3 is mainly due to the fast thermal mixing of the VCS injection flow and the natural convection flow in the annulus. Such a complex thermal mixing under a very high Rayleigh number (i.e., Ra > ~10^8) needs to be clarified by an experiment or a detailed calculation (e.g., CFD analysis).

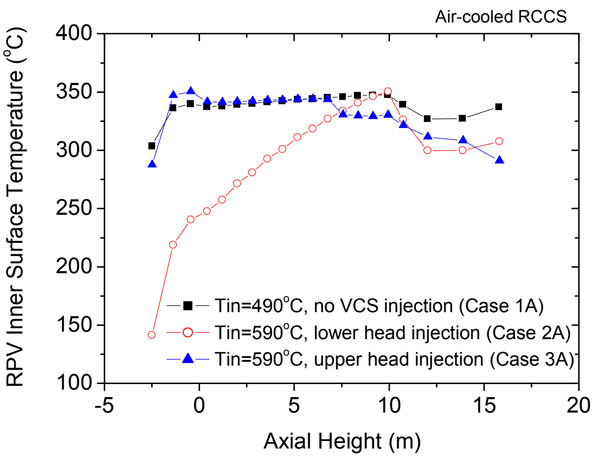

Fig. 2. Calculated RPV inner surface temperatures for the air-cooled RCCS cases.

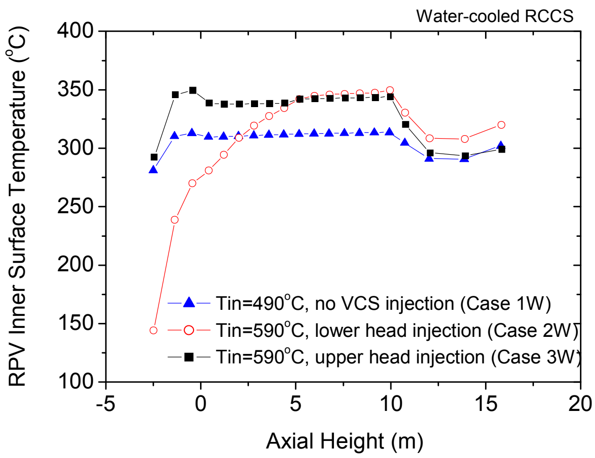

Fig. 3. Calculated RPV inner surface temperatures for the water-cooled RCCS cases.

4. Conclusions

Thermal performance of a cooled-vessel design with various design conditions was analyzed using the GAMMA+ code. The results of the GAMMA+ show that a VCS injection flow is not necessary when the RCS inlet temperature is 490 °C. Even when the RCS inlet temperature is designed to be 590 °C, a small VCS flow (2~4 kg/s) is sufficient to cool down the RPV. It is also found that the location of the VCS injection nozzle is an important parameter for the cooled-vessel design. Furthermore, in the annulus between the RPV and the core barrel, a very complex thermal mixing behavior is observed. A detailed thermo-fluid analysis on the flow characteristics in the annulus would be valuable.

ACKNOWLEDGMENTS

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