Assessment of a Cooled-Vessel Concept in a VHTR by Using a CFD Analysis

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1. Introduction

Nuclear Hydrogen Project has been launched at KAERI, which uses a Very High Temperature Gas-Cooled Reactor (VHTR) as the heat source of the Iodine-Sulfur cycle for a hydrogen production.[1] It is not determined yet whether the type of reactor core is the pebble bed reactor (PBR) represented by the PBMR or the prismatic modular reactor (PMR) by the GT-MHR. Design of a reactor pressure vessel (RPV) is very important regardless of the reactor type because the operating temperature of the RPV is much higher than the PWR. Cooled vessel concept makes it possible to use conventional SA-508 steel for a material for the RPV of the VHTR. The PBMR adopts a conventional SA-508 cooled-vessel design in which the coolant flow is directed through graphite internal structures and a vessel cooling system is used to cool the RPV inner wall. The GT-MHR, however, a prismatic modular reactor, adopts a creep resistant material for the RPV, which has not been manufactured and used for the reactor vessel. Therefore, it is necessary to develop an alternative design for the NHDD prismatic reactor.

In this study, we proposed the cooled-vessel concept applicable to a NHDD prismatic reactor, then, carried out the thermo-fluid analysis during normal operations by using the CFD code. Temperature of the RPV was predicted according to the change of the cooling flow rate. An effect of the riser location in permanent side reflectors was also investigated.

2. Computational Methods

2.1 Cooled-Vessel Concept

The GT-MHR is selected as a reference reactor of a prismatic core to apply the cooled-vessel concept. Through the survey on cooled-vessel designs[2], the following cooled-vessel concept is proposed. The inlet flow path through six riser ducts between the RPV and the core barrel is changed to 54 cylindrical riser holes through the permanent side reflector. Then, a forced vessel cooling is employed as a means of maintaining the vessel temperature within the limit of conventional SA-508 steel. Cold helium is supplied into the gap between the RPV and the core barrel. The configuration of the cooled-vessel design is shown in Fig. 1.

2.2 Analysis for the RPV temperature

Computational domain selected for the RPV temperature analysis in a steady state is shown in Fig. 2, which is a 1/54 model of the whole domain consisting of a permanent side reflector (PSR), a riser, a core barrel, a gap between the RPV and the barrel, and the RPV.

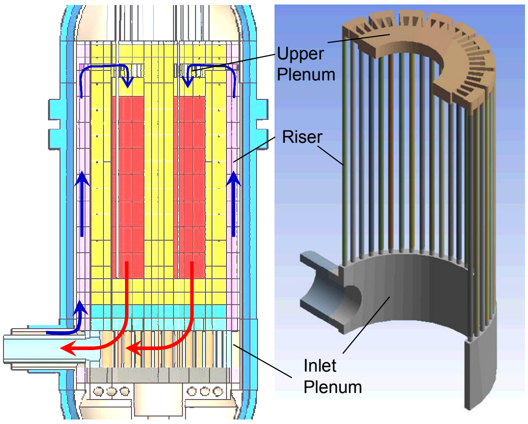

Figure 1. Configuration of the cooled-vessel design

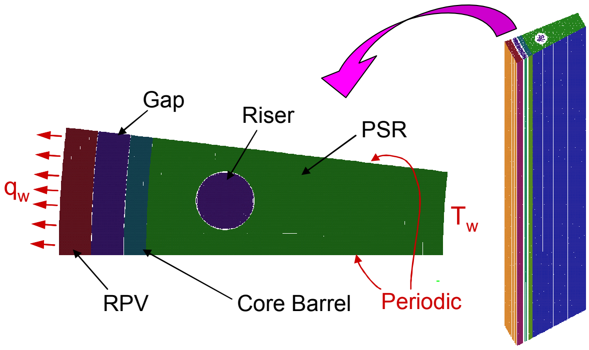

Figure 2. Meshes and boundary conditions for the RPV temperature analysis

The inner and outer radiuses of the PSR are 2.415m and 3.425m. The thickness of the core barrel, the gap, and the RPV are 75mm, 113mm, and 216mm, respectively. The diameter of the riser is 200mm. Three radius locations of the riser are used. The reference is 3.223m and the others have radius changes of ±60mm. The height of the domain is 10.305m that corresponds to one lower reflector block, ten core blocks, and two upper reflector blocks.

2.3 Boundary Conditions

Uniform flow and constant pressure are assumed at the inlet and exit of the riser and the gap. Inlet mass flow at the riser is 5.925kg/s at 590C. Periodic conditions are applied for the circumferential direction. General Grid Interface (GGI) connections in ANSYS CFX are used for the fluid-solid and solid-solid interfaces. The discrete transfer model of CFX code[3] is used for considering a radiation effect. Temperature distribution from the GAMMA code[4], a system code, is applied to the inner wall of the PSR. There is a parasitic heat loss through the RPV during a normal operation due to the reactor cavity cooling system (RCCS) removing the residual heat during an accident. The heat loss varies according to the condition of the reactor. To obtain the temperature of the RPV, we explicitly coupled the CFD code with the GAMMA code. The GAMMA is modeled from the core barrel to the RCCS. First, we assume the heat loss and obtain an average temperature of the barrel from the CFD results. Then, the temperature is applied as a boundary condition of the inner wall of the core barrel in the GAMMA and the heat loss is calculated. Again, a new heat loss is applied to the RPV boundary condition in the CFD analysis. This procedure is repeated three or four times to get a converged heat loss.

3. Results and Discussions

Fig. 3 and 4 show the computed temperature contours at the middle plane and the temperature distribution along the centerline of the middle plane for the reference riser location. Both cases with a cooling and without a cooling are compared. The effect of the forced cooling is not clearly shown at the riser but, after that, it causes a rapid decrease of the temperature when compared to the case without a cooling. The distinguished temperature jumps at the interface between the gap and the solids, the interface between the core barrel and the RPV, indicate that there is a large amount of radiation heat transfer.

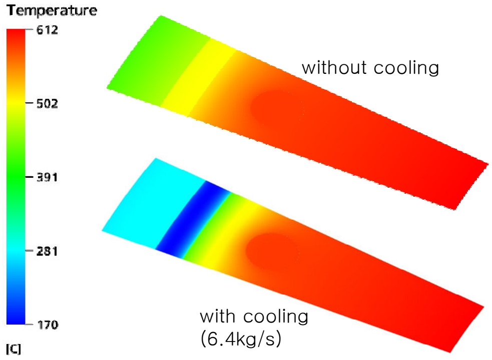

Figure. 3 Temperature contours at the middle plane

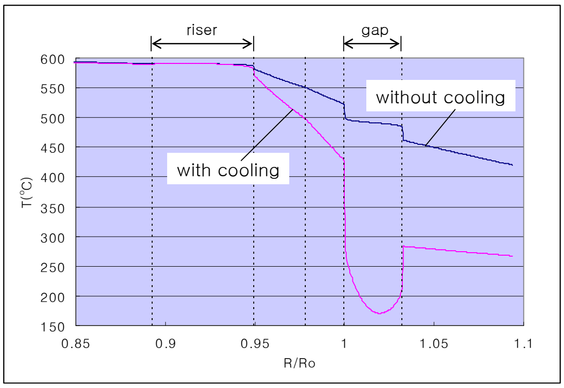

Figure 4. Temperature distribution along the centerline of the middle plane

The effects of not only the cooling mass flow but also the riser location were investigated. Fig. 5 shows the maximum temperatures of the RPV. For the case without a cooling, the RPV temperature is so high that the conventional steel with a temperature limit of 371C, cannot be used as the RPV material.

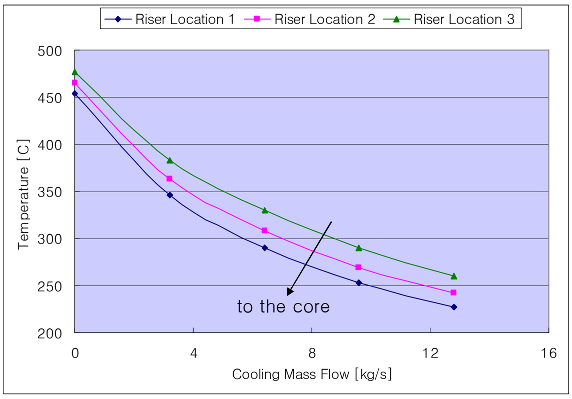

Figure 5. Maximum temperatures of the RPV vs. cooling mass flow according to the change of the riser location

Small amount of cooling, 3.2kg/s, reduces the temperature by 100C. To ensure the temperature limit of the conventional steel, 371C, more than 4kg/s of cooling mass flow is required. The change of riser location into the core results in a reduction of the temperature but the shape of the temperature variation according to the cooling flow is not changed.

4. Conclusion

A cooled vessel concept that uses an internal inlet flow path through the PSR and a forced vessel cooling was proposed and a steady state CFD analysis was performed, by being explicitly coupled with a system code. Results showed that the internal flow path has an effect of reducing the RPV temperature but the temperature is still high for the conventional steel. The forced cooling had a considerable effect on reducing the temperature. A cooling flow of more than 4kg/s is sufficient to maintain the RPV temperature within the required limit during a normal operation. It was also confirmed that moving the riser location contributes to a reduction of the temperature. It is necessary to verify the cooled-vessel concept for the accident conditions in the future.

Acknowledgement

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