Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, November 2-3, 2006

Survey on Cooled-Vessel Designs in High Temperature Gas-Cooled Reactors

Min-Hwan Kim, Won-Jae Lee
Korea Atomic Energy Research Institute
P.O.Box 105, Yuseong, Daejeon, Korea, 305-350
mhkim@kaeri.re.kr

1. Introduction

The core outlet temperature of the coolant in the high temperature gas-cooled reactors (HTGR) has been increased to improve the overall efficiency of their electricity generation by using the Brayton cycle or their nuclear hydrogen production by using thermo-chemical processes. The increase of the outlet temperature accompanies an increase of the coolant inlet temperature. A high coolant inlet temperature results in an increase of the reactor pressure vessel (RPV) operation temperature.

The conventional steels, proven vessel material in light water reactors, cannot be used as materials for the RPV in the elevated temperatures which necessitate its design to account for the creep effects. Some ferritic or martensitic steels like $2\frac{1}{4}$Cr-1Mo and 9Cr-1Mo-V are very well established creep resistant materials for a temperature range of 400 to 550C.

Although these materials have been used in a chemical plant, there is limited experience with using these materials in nuclear reactors. Even though the $2\frac{1}{4}$Cr-1Mo steel was used to manufacture the RPV for HTR-10 of Japan Atomic Energy Agency(JAEA), a large RPV has not been manufactured by using this material or 9Cr-1Mo-V steel. Due to not only its difficulties in manufacturing but also its high cost, the JAEA determined that they would exclude these materials from the GTHTR design.[1]

For the above reasons, KAERI has been considering a cooled-vessel design as an option for the RPV design of a NHDD plant (Nuclear Hydrogen Development and Demonstration). In this study, we surveyed several HTGRs, which adopt the cooled-vessel concept for their RPV design, and discussed their design characteristics. The survey results in design considerations for the NHDD cooled-vessel design.

2. Cooled-Vessel Designs

2.1 Pebble Bed Modular Reactor (PBMR)

The first cooled-vessel concept has been adopted in the PBMR. To avoid the RPV wall temperature from exceeding its design limit, Reactor Pressure Vessel Cooling System (RPVCS) was introduced, of which the name has been changed to Core Barrel Conditioning System (CBCS).

Figure 1 presents a conceptual schematic of the PBMR reactor plant. Although the Power Conversion Unit (PCU) design has changed from a three-shaft vertical arrangement to a single-shaft horizontal arrangement, the plant layout and the main design of the system is maintained. Under a normal operation, helium gas at a temperature of 490C from the PCU enters the core through a lower plenum at the bottom, rising channels in the side reflector, and slits at the top. This inlet flow configuration prevents a direct contact of the RPV with the high temperature inlet helium and has an effect on reducing the RPV temperature.

The mixed mean core outlet temperature is 900C. Helium gas exiting the outlet plenum flows and passes into the High-Pressure Turbo-compressor (HPT), the Lower-Pressure Turbo-compressor (LPT), and the power turbine. After an expansion in the power turbine, it returns to the reactor core via the recuperator, the pre- and inter-coolers and the recuperator.

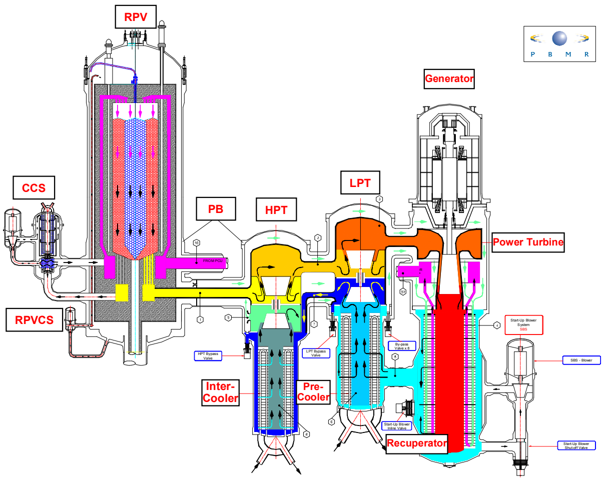

Figure 1. Schematic System Layout of PBMR[2]

As shown in Figure 1, Not only the RPV but also the Pressure Boundary (PB) enclosing the main components, like the HPT, the LPT etc., contacts with the cold helium flow which is bypassed from the HPT outlet at about 120C and 90bar. The RPVCS circulates the bypassed helium between the core barrel and the RPV. This serves to maintain the RPV wall at a more even temperature, thus eliminating hot spots.

2.2 Gas Turbine High Temperature Reactor (GTHTR)

The cooled-vessel concept similar to the PBMR is adopted in the GTHTR design. Flow path in the RPV is shown in Figure 2. The coolant is circulated to and from the core in the inner piping of a pair of coaxial vessel ducts leveled and symmetrically located near the reactor bottom. The core inlet coolant channel is embedded in the side reflector and functions to limit the RPV temperature. Heated helium coolant in the core enters the turbine and the exhausted helium enters the recuperator. After being cooled by the pre-cooler, the helium raises the pressure to 70bar at 136C by a compressor. Then, the helium is preheated to 590C at the recuperator and returned to the core.

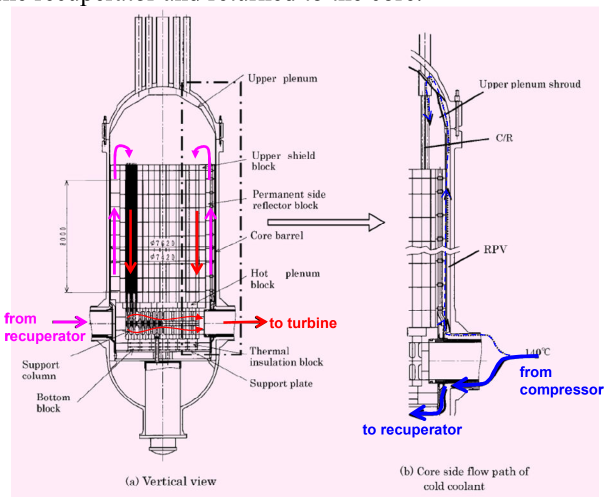

Figure 2. Flow path in RPV of GTHTR[3]

For cooling the inner surface of the RPV, a small portion of the helium flow of 140C from the compressor outlet is bypassed. A ring with small holes placed at the space between the RPV and core barrel is used for an adjustment of the flow rate for the RPV cooling.

2.3 H2-MHR

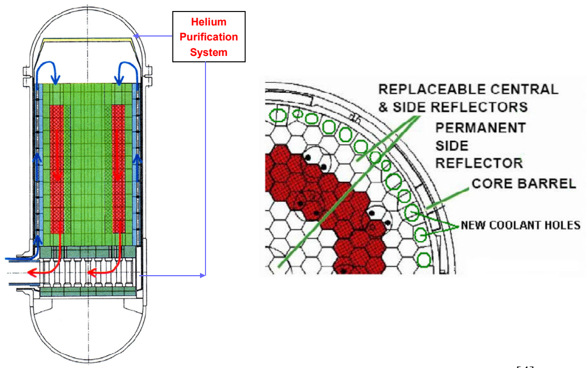

Figure 3. Inlet Flow Configuration of H2-MHR[4]

H2-MHR is the Modular Helium Reactor for the hydrogen production by Genral Atomics (GA), coupled to the thermochmical water splitting process. The reactor design is based on the GT-MHR, of which the coolant inlet and outlet temperatures are 490 and 850C.

For the H2-MHR, design points of 590 and 950C have been selected. The concern is that an increase of the coolant inlet temperature by 100C will result in the RPV temperature exceeding the limits for Cr-Mo steels if the GT-MHR flow configuration is used. Therefore, the H2-MHR decided to change the inlet flow configration by routing the flow through holes in the permanat reflector.

Although the design change for the inlet configuration has been made, the GA still has a question as to whether the Cr-Mo steel is a suitable selection for the RPV material due to its limited experience and maunfacturing difficulty of a large vessel. For this reason, a vessel cooling is considered as a design option in the H2-MHR. However, the H2-MHR has no cold helium soruce for a vessel cooling like the compressor exit. So the return path from the helium purification system (HPS) to the reactor is thought of as a viable soruce of a cold helium in the H2-MHR.

Table 1. Comparison of the cooled-vessel features

Features	PBMR (RSA)	GTHTR (JAPAN)	H2-MHR (USA)
Power (MWt/MWe)	400/165	600/300	600/-
He Pressure (bar)	90	70	70
He Temp. (in/out, ^{o}C)	490/900	590/850	590/950
He Mass Flow (kg/s)	193	439	320
RPV Material	SA508	SA533	SA533
RPV Inner Diameter/Thickness(m)	6.2/0.18	7.6/0.17	7.2/0.22
Core Inlet Flow Path	Side Reflector	Side Reflector	Side Reflector
Vessel Cooling Source	HPT Outlet	Compressor Outlet	HPS
Cooling Flow (kg/s)/Temp. (^{o}C)	18/120	2.2/140	16/140
Driving Force of Cooling Flow	CBCS Circulator	Pressure Diff.	HPS Compressor
RPV Temp.(^{o}C)	260~300	300~340/	338

3. Discussions

The cooled-vessel concepts were investigated for three representative HTGRs and a comparison of their features was made in Table 1. From the survey, we found that the following factors should be considered carefully in the design and selection of the cooled-vessel for the NHDD.

- Vessel material with corresponding codes and standards
- Inlet flow configuration
- Cold helium source for the vessel cooling
- Effect on the passive safety and the cost

Acknowledgement

This study has been carried out under the Nuclear R&D Program by MOST.

REFERENCES

[1] K. Kunitomi, et al., “Design and Development of Gas Turbine High Temperature Reactor 300 (GTHTR300),” GENESA/ANP2003, Kyoto, JAPAN, Sep. 15-19, 2003

[2] D. Matzner, “PBMR Project Status and the Way Ahead,” 2nd International Topical Meeting on HTR Technology, Beijing, China, Sep. 2004.

[3] Japan Atomic Energy Agency, “Present Status of HTGR Research & Development,” 2004 (in http://www2.tokai-sc-jaea.go.jp/httr/eng/report_eng.html)

[4] General Atomics, “H2-MHR Pre-Conceptual Design Report: SI-Based Plant,” General Atomics Report GA-A25401, April 2006