Adequacy Assessment on a Conceptual Design of the Water-cooled RCCS for HECTAR High Temperature Gas-cooled Reactors

Churl Yoon [a*], Sin-Yeob Kim [a], Sun Rock Choi [a], Seungjoon Baik [b]
[a]*High Temperature Reactor Development Division, Korea Atomic Energy Research Institute*
[b]*Gen-IV Reactor Technology Development Division, Korea Atomic Energy Research Institute*
111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon 34057, Korea
[*]*Corresponding author: cyoon@kaeri.re.kr*

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1. Introduction

As part of the development of the Generation IV power reactors, design methodologies and analysis techniques for high temperature gas-cooled reactors (HTGRs) have been developed by KAERI in the recent decades. HECTAR (Helium Cooled Thermal Application Reactor) is a newly designed HTGR generating 90MWt power, which adopts the water-cooled RCCS (Reactor Cavity Cooling System) [1]. The design concept of the water-cooled RCCS for HTGRs was applied and actually built in the HTR-10 (10MW High Temperature Gas-cooled Test Reactor) and HTR-PM (High Temperature Gas-cooled Reactor Pebble-bed Module) [2, 3]. In this water-cooled RCCS design, water naturally circulates in two separate closed loops removing the excessive heat from the reactor cavity and the ultimate heat sink is the air-cooled cooling towers located outside the reactor building. Figure 1 shows the conceptual diagram of the HECTAR RCCS.

In this study, computational fluid dynamic (CFD) analyses are performed to simulate the combined conduction, convection and radiation heat transfer inside the reactor cavity region, in order to determine whether the given RCCS design properly remove the excessive heat for maintaining the RPV and the concrete temperatures lower than the design limits. As analysis results, it is concluded that the given design specification shows enough cooling capacity under normal operating conditions for HECTAR HTGRs.

2. Conceptual Design of HECTAR RCCS

The HTGR RCCS should be designed to remove the excessive heat steadily from the reactor cavity under normal operating or accident conditions for maintaining the temperatures of the RPV (reactor pressure vessel) outer surface and the reactor cavity concrete inner surface below the acceptable criteria, so as to assure the high-temperature structural integrity of the RPV and the RCCS concrete. By reviewing the former HTGR design experiences all over the world, the water-cooled RCCS concept is selected for the HECTAR RCCS design and the design requirements are listed as follows [1]:

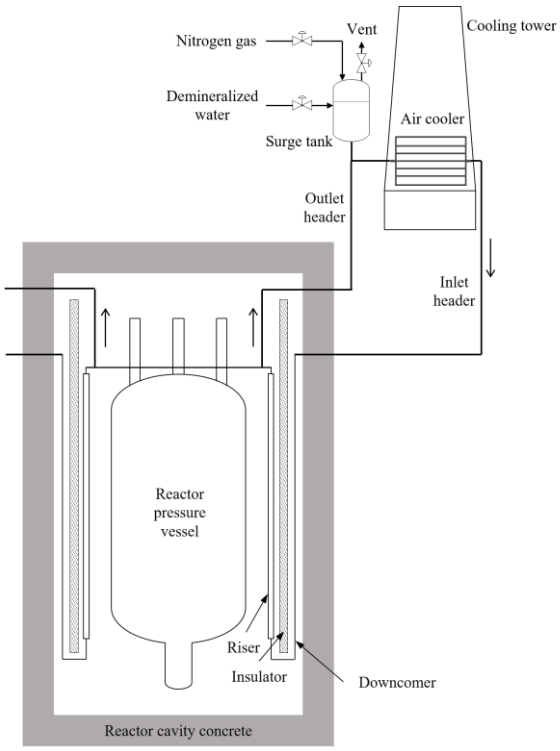


Fig. 1. Conceptual diagram of the HECTAR RCCS.

- Water-cooled RCCS concept is adopted, which will remove the excessive heat from the reactor cavity by natural water circulation inside closed loops.
- Heated water coolant dumps the heat into the atmospheric air by natural circulation cooling at the dry cooling towers.
- Temperature of the reactor cavity concrete should be maintained lower than 65°C (150°F) under normal operating conditions and 177°C (350°F) under accident conditions. [4]
- Temperature of the RPV outer surface should be maintained lower than 371°C (700°F) under normal operating conditions, 427°C (800°F) under pressurized conduction cooldown (PCC) accident conditions, and 482°C (900°F) under

depressurized conduction cooldown (DCC) accident conditions. [5]

- Heat removal capacity of the RCCS is set to be 450 kW, which is 0.5% of the normal operating reactor power generation.
- The RCCS is designed to consist of two separate closed loops, so that each water loop has the heat removal capacity of 225 kW.
- Independence, diversity, and redundancy should be assured in the RCCS design.

With the above design requirements, a conceptual RCCS design was proposed as described in the next section.

The heat removal inside the reactor cavity occurs by means of convective and radiative heat transfer from the reactor vessel outer surface to the riser tubes. Since most of the total heat transfer inside the cavity is conducted by radiative heat transfer under accident conditions [6], the emissivity values of the heat exchanging structural surfaces are the most important parameter in estimating RCCS heat removal capacity [7].

3. Adequacy Assessment by Using CFD Technique

The CFD techniques used to simulate the heat transfer phenomena inside the HECTAR reactor cavity, along with the analysis results, will be described in this section. The dry cooling tower region is excluded in the simulation domain and treated as water inlet/outlet boundary conditions.

3.1 CFD Model

The 1/60 CFD simulation geometry was built as shown in Fig. 2, in which the 6^o pie-shaped domain contains all the components from the RPV to the concrete wall. Since the total number of the riser tubes is 180, three water downcomers and risers are modeled as well in the domain. The water pipes are assumed to be the KS/JIS Sch40 40A(1-1/2") pipes. In this first trial design, the downcomer and riser pipes are attached side by side by with the steel plates twice thick of the pipe thickness. Top and bottom sections of the downcomer and riser steel plates are assumed to be closed from the atmospheric air, so that the confined air region between the downcomer and the riser plates works as a kind of insulator. Because the domain is rotational around the Y-axis, the surfaces at the highest and the lowest azimuthal angles are set to be periodic boundary conditions. All the geometries are built as close as possible to the real structure shapes.

All over the domain, the meshes of totally 27,148,325 elements (cells) are generated along with 4 prism layers in the water pipe flow regions. The SST turbulence model with the automatic wall function is applied for simulating turbulent fluid flows, and the Monte Carlo radiation model is adopted for the radiative heat transfer calculation with periodic boundary conditions [8].

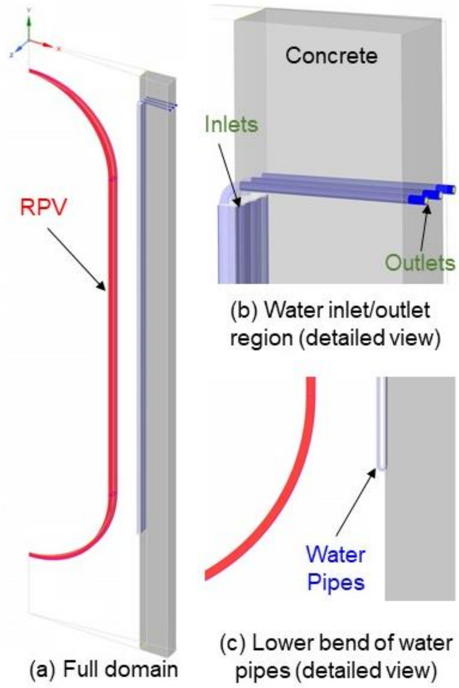


Fig. 2. Computational domain and some detailed geometries.

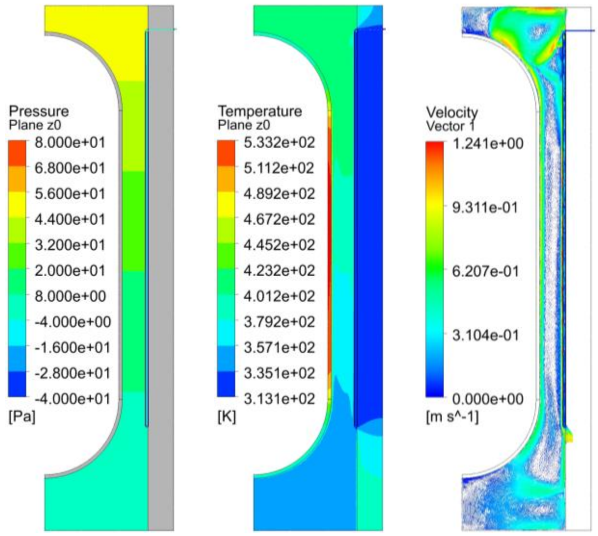
The 450 kW heat is applied to the inside wall of only the central vertical section of the RPV for conservatism, so the heat flux boundary condition on the inner wall of the central RPV is calculated to be 2271.0 W/m^2, considering the total inner surface area of the central RPV cylinder. Except the above heat flux BC, the inner surface boundary conditions of the top and bottom hemispherical RPV walls are conservatively set to be adiabatic. Water inlet temperature and pressure are respectively 40 ^{o}C and 5 bar. The emissivity (ε) values of the RPV and the concrete surfaces are assumed to be fixed as 0.8 and 0.9, respectively. Heat removal capacity of the HECTAR RCCS is most sensitively affected by the emissivity of the riser pipes. To check the sensitivity of the water pipes and connecting steel plates' emissivity to the resultant heat distribution, the following two cases are simulated:

<u>Case 1</u>: ε (Pristine water pipes & connecting steel plates) = 0.35 [9]

<u>Case 2</u>: ε (Oxidized water pipes & connecting steel plates) = 0.68 [9]

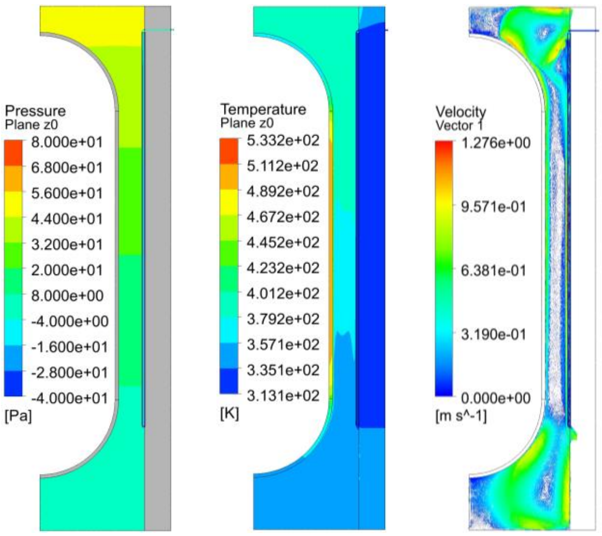
3.2 Simulation Results

Figure 3 and 4 present the pressure, temperature, and velocity fields at central vertical plane (z = 0) for Case 1 and Case 2, respectively. The resultant pressure and temperature distributions seem quite reasonable. For both cases the temperature and pressure are higher at the upper atmospheric air region, because the heated hot air gathers in that area. Due to the Buoyancy-driven flows, air circulations are clearly observed at the velocity vector fields. Here note that the pressure and



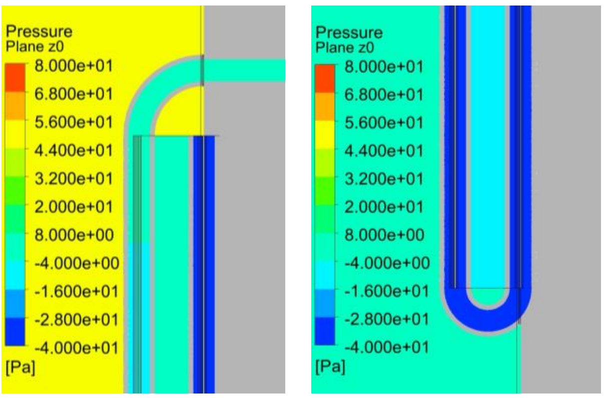
(a) Pressure (b) Temperature (c) Velocity Vector

Fig. 3. Simulation results for Case 1 (ε_{Pipes} = 0.35).



(a) Pressure (b) Temperature (c) Velocity Vector

Fig. 4. Simulation results for Case 2 (ε_{Pipes} = 0.68).



(a) Top baffle (b) Bottom baffle

Fig. 5. Pressure distributions over the top and bottom baffle interface areas between the atmospheric and the insulating air (Case 2).

temperature ranges for the legends are set to be the same for easier comparison, while the velocity ranges in Figs. 3(c) and 4(c) reflect the actual velocity magnitudes. Compared to Fig. 3(b), temperatures of the RPV, the cavity air, and the concrete wall are lower in Fig. 4(b) due to the higher emissivity value of the water pipes.

Figure 5 shows the pressure distributions around the baffle boundaries between the atmospheric air and the insulating air for Case 2. In the figures, it is clearly shown that two air regions are completely separated and that the baffle boundary conditions are correctly applied.

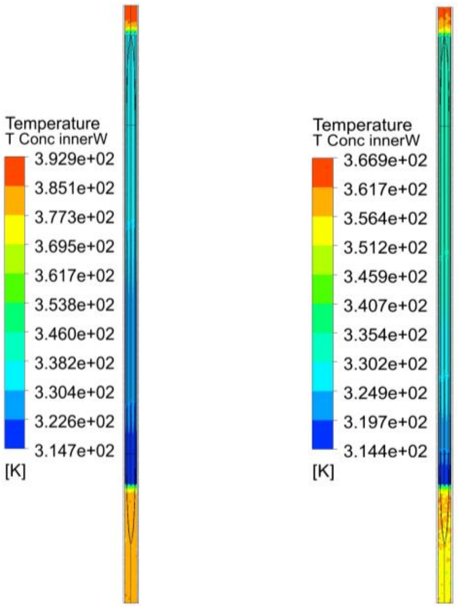
From Figs 3(b) and 4(b), it is found that the bare concrete areas above and below the water pipe and steel plate section are heated up over the design limit of 65°C. Figure 6 shows the temperature distributions on the inner bare concrete surfaces and the inner surfaces of the pipe and connecting steel plates. The maximum temperatures on the bare concrete surfaces are found at the top area near the ceiling. Table I summarizes the maximum temperatures at some selected structural surfaces, obtained from the simulation results. Even though the inner bare concrete surfaces are heated up to ~ 100 °C due to the radiative direct heating and hot atmospheric air inside the cavity, the concrete temperatures behind the pipe and connecting steel plates are maintained well below the design limit of 65 °C.

In this system, the only heat addition is applied to the inner surface of the RPV and the only heat removal occurs at the water pipe outlets. On the other hand, all the other outer boundary surfaces are assumed to be adiabatic. Therefore, the higher pipe emissivity (Case 2) gives the increased water outlet temperature and the decreased other structural temperatures. That is, it is concluded that the higher pipe emissivity increases the heat removal capacity of the water-cooled RCCS for HECTAR.

Table I: Maximum Temperatures at Selected Structural Surfaces

Surface	Maximum temperature [°C]	
	Case 1 (ε_{Pipe} = 0.35)	Case 2 (ε_{Pipe} = 0.68)
RPV_{bot} outer surface	185.22	158.87
RPV_{center} outer surface	261.23	222.89
RPV_{top} outer surface	197.72	165.20
Inner bare concrete surface	118.74	93.20
Pipe-&-SteelPlate inner surface	62.05	62.75
Interface between the Pipe-&-SteelPlate and the concrete	58.34	57.14
T_{riser_top} (at center-line of center pipe)	54.05	54.47
T_{outlet}^{*} (center pipe)	54.78	54.94
Concrete outer wall (with adiabatic BC)	109.60	80.97

* Mass-flow-rate weighted average



(a) Case 1 (b) Case 2

Fig. 6. Temperature distributions on the inner surfaces of the bare concrete and the pipes and connecting steel plates (view from the center)

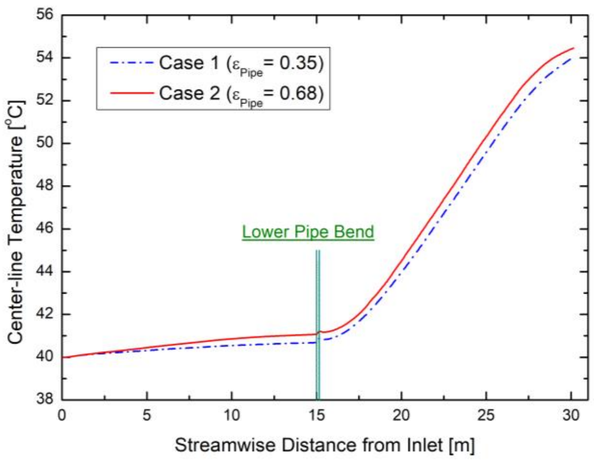


Fig. 7. Center-line water temperature profile along the streamwise distance from the inlet.

Figure 7 shows the center-line water temperature profiles along the stream-wise distance from the inlet. For both Case 1 and Case 2, the water temperatures at the riser top does not exceed 55ºC. The reason why the water outlet temperatures (Table I) are higher than the maximum temperatures of Fig. 7 is assumed to be that the pipe water was additionally heated up during passing through the concrete wall after leaving the riser tube sections.

4. Conclusions

CFD simulations were performed on the conceptual design of the water-cooled RCCS for HECTAR HTGRs. As a result, it was confirmed that the temperatures of the RPV, the cooling water, and the concrete behind the downcomers were well maintained below the design limits under normal operating conditions, with the given design specifications. One important unexpected finding in this CFD analysis is that the top and bottom bare concrete surfaces could be heated up over the design limit of 65ºC due to radiative direct heating and hot atmospheric air.

Therefore, some measures to prevent the concrete surfaces from being heated up over the design limit should be developed and added to the future design improvements.

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