Design Improvement of the Core Inlet Flow Path for a High Temperature Gas-cooled Reactor

Churl Yoon*, Sung-Deok Hong, Sin-Yeob Kim, Hyeonil Kim, Chan Soo Kim
High Temperature Reactor Development Division, Korea Atomic Energy Research Institute
111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon 34057, Korea
**E-mail: cyoon@kaeri.re.kr*

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1. Introduction

As one of HTGRs (High Temperature Gas-cooled Reactors) which are characterized as fully passive cooling and improved safety features for the Generation IV nuclear reactor [1], KAERI has been developing the HECTAR (HElium Cooled Thermal Application Reactor) targetting a 60-year operating lifetime and industrial process heat uitilization [2].

Figure 1 shows the flow directions of the primary helium coolant through the CIFP (Core Inlet Flow Path) [3]. The helium coolant with the total mass flow rate of 38.54 kg/s congregating in the CUP (Core Upper Plenum) passes through the core from the top to the bottom, being heated up to 750°C. The heated helium gathered in the core lower plenum goes to the heat exchanger through the inner pipe of the CV (Cross Vessel), and then comes back to the RPV (Reactor Pressure Vessel) through the annular outer section of the CV at a lower temperature of 300°C after losing heat to the secondary side of the heat exchanger. The returned cold helium goes into the 8 flow compartments of the MCSS (Metallic Core Support Structure) and then flows back to the CUP through the 8 vertical flow channels installed outside of the core barrel.

The MCSS, which is located at the bottom of the core, supports the weight of the core, the reflectors and the graphite core support assembly [3]. Since the core maximum temperature reaches over the melting point of some metallic structures, the MCSS should be properly cooled by the coolant flows through the internal cooling passages. The MCSS internal coolant flow passages should be designed to minimize pressure drops while flowing through.

The previous study by Yoon et al.[4] evaluated the flow distribution over the 8 flow compartment of the original HECTAR MCSS and identified the flow maldistribution (FM) over the 8 MCSS flow compartments and the veritcal channels. This flow maldistribution increases uncertainty levels of the heat removal capability of the coolant in the core as well as the core inlet flow conditions from the CUP. In this study, a design improvement of the HECTAR MCSS was proposed to minimize the flow maldistribution and proved by using CFD (Computational Fluid Dynamics) analysis technique.

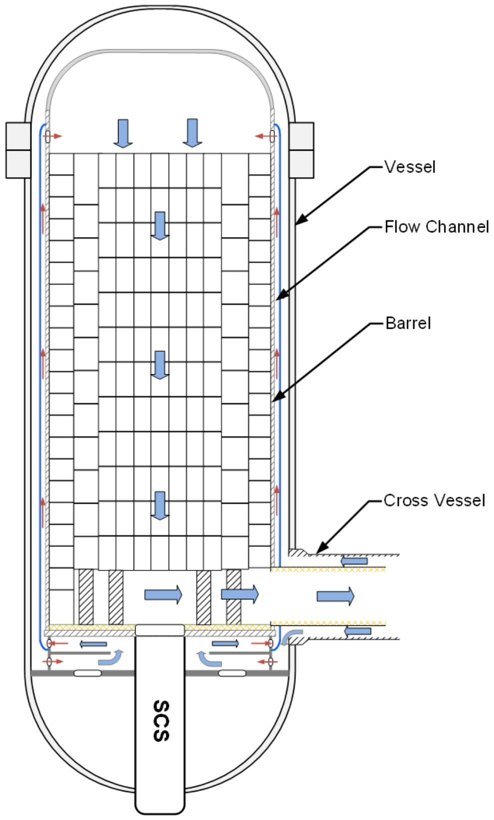


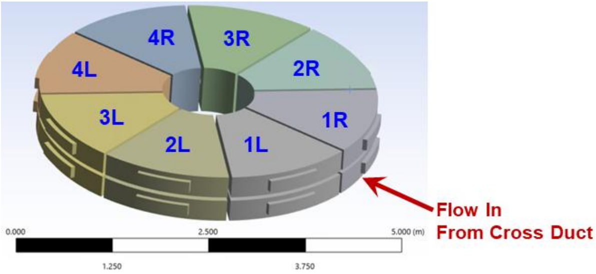
Fig. 1. Helium flow path of the HTGR primary system.

2. Design Improvement of the CIFP

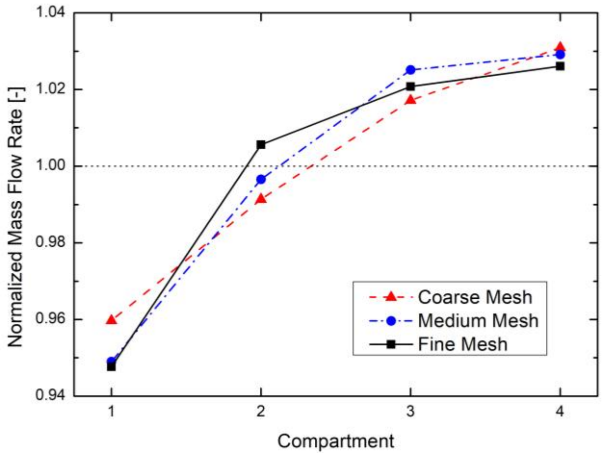
In this section, the flow maldistribution over the HECTAR MCSS flow compartments, vertical flow channels, and CUP is identified by reviewing the previous study first. Then a design change of the MCSS is proposed to minimize the flow maldistibution. Finally, the design improvement of the MCSS is confirmed by simulating the flow characteristics over the CIFP using CFD technique.

2.1 Flow Maldistribution of the Old CIFP Design

Yoon et al.[4] studied the flow maldistribution over the original design of the HTGR CIFP, quantitatively and qualitatively. Steady-state isothermal helium flows over the original CIFP was analyzed by using ANSYS CFX [5], a general-purpose commercial CFD tool.



(a) Naming of MCSS flow compartments



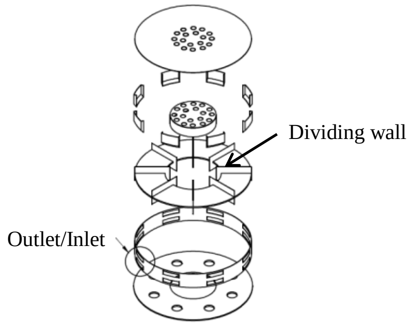
(b) Normalized mass flow rates depending on mesh densities
Fig. 2. Average mass flow rates of the original MCSS flow compartments.

Three unstructured tetrahedral meshes with 7 prism layers were generated with different mesh densities. SST turbulence model with the Automatic Wall Function was applied to simulate turbulent flows.

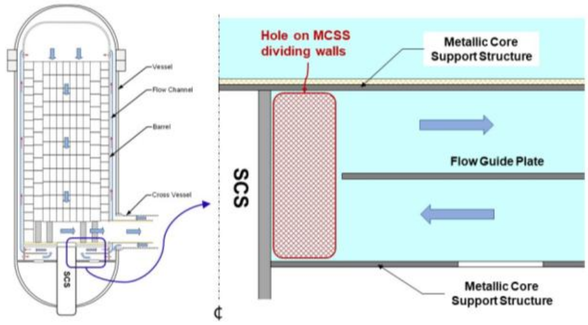
Figure 2 presents the average mass flow rates depending on three defferent mesh densities, over the original MCSS flow compartments. Here, the word of ‘average’ means the average of the left and right flow compartments. Figure 2(a) depicts the naming method of the MCSS flow compartments. Numbers were named serially from the closest to the farthest to the CV inlet. ‘L’ and ‘R’ stands for the left and right sides viewing from the CV inlet. Figure 2(b) shows a clear tendency as the mesh density increases that the mass flow rates of compartment far away from the CV are larger than those of the closer compartments. This tendency can be explained by the simulated flow results that the cold helium inlet fluids from the CV impinge onto the outer surface of the core barrel, go around the annular space between the core barrel and the RPV to meet at the opposite side, and then flow into the MCSS flow compartment consecutively from the farthest one to the closest.

2.2 Design Change of the MCSS

Since the flow maldistribution was identified in the HECTAR CIFP, a design change on the MCSS was proposed to make the mass flow rates more even. Figure 3 presents design improvement of the HECTAR MCSS. Figure 3(a) shows the disassembled MCSS and



(a) Disassembled MCSS



(b) Suggested hole design on the dividing walls
Fig. 3. Design improvement of the HECTAR MCSS.

Fig. 3(b) shows the proposed hole design on the MCSS dividing walls. Since the helium flow rates through the each compartment are different, these newly installed holes are supposed to make the helium fluids in each MCSS compartment flow across the dividing walls and be mixed togather. The holes are located near the SCS (Shotdown Cooling System) outer wall, because the inward fluids would hit the SCS outer wall and disperse at all directions around this region. The remaining sills around the holes will help the MCSS play its main role to support the core weight. At the four corners of the quadrilateral holes, concave fillets could be applied to increase mechanical strength by reducing the stresses concentrated at the corners.

2.3 CFD Analysis for the Improved CIFP

To prove the design improvement, the similar CFD simulation as in section 2.1 was performed on the modified MCSS design. The resultant mass flow rates through the modified MCSS flow compartments are compared with the results of the original MCSS design in Fig. 4. Compared to the original flow rates, the MCSS flow rates appears to be more even since the helium fluids exchanges and are mixed across the compartments through the newly installed holes on the dividing walls.

Figures 5 and 6 show pressure distributions on the selected horizontal planes, where A planes present the MCSS inlet, B planes present the MCSS outlet, and C planes present the CUP plane at the flow channel inlet level. In Figures 5(b) and 5(c), the pressure distributions show a big differences in level across the compartments. On the other hand, the pressure distribution of Fig.6(b) appears to be more even compared to that of Fig. 6(c), since helium fluids would mix together at the downstream of the holes in the MCSS flow conpartments.

Since the 8 vertical flow channels installed outside of the core barrel have the equally spaced positions and the same geometric configuration, the helium mass flow rates depend only on the pressure differences between the MCSS compartment outlet and the CUP.

$$\dot{m}_{FC,i} = \rho u_{FC,i} A \propto \Delta P_{MCSS,i-CUP} \qquad (1)$$

where $\dot{m}$ = mass flow rate [kg/s],
ρ = density [kg/m^3],
u = velocity [m/s],
A = cross-sectional area [m^2], and
P = pressure [Pa],

with the subscripts of FC = flow channel, CUP = core upper plenum, MCSS = metallic core support structure, and i = the FC channel and the MCSS compartment number.

The more uniform the outlet pressures of the MCSS flow compartments becomes, the more similar the mass flow rates through the vertical flow channels. As a result, the mass flow rates through the vertical FC of the modified MCSS design woud be more homogenized, which induces the symmetricity of the helium fluid flows inside the CUP and reduces the uncertainties due to the flow maldistribution.

3. Conclusions

By using CFD technology, the flow maldistribution phenomena were found out to be induced by the biased geometry of the original HECTAR CIFP. To reduce the flow maldistribution tendency, the design of the HECTAR MCSS was performed and the effectiveness was verified by using CFD simulation. As simulation results, it is found that the newly installed quadrilateral holes allow fluid exchanges between the MCSS flow conpartments and that the pressure ditribution becomes more homogenized in the downstream section of the MCSS flow region. This homogenous pressure at the outlet section of the MCSS guarantees more uniform mass flow rates through the vertical channels as well as the MCSS flow compartments.

In the future study, the modified design of the MCSS would be adjusted more precisely by the CFD predictions with improved mesh qualities.

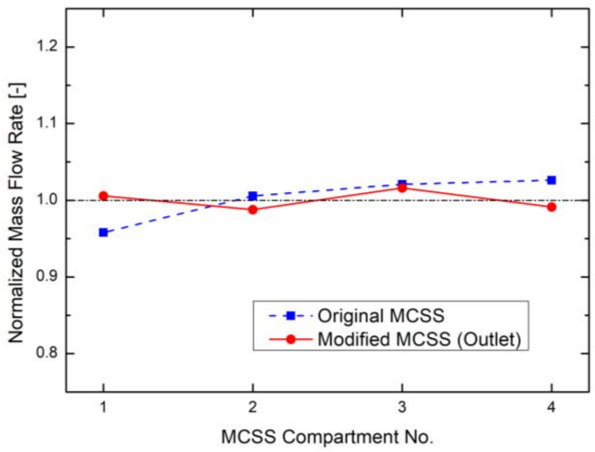


Fig. 4. Comparison of the mass flow rates over the MCSS flow compartments between the original and modified designs.

ACKNOWLEDGEMENT

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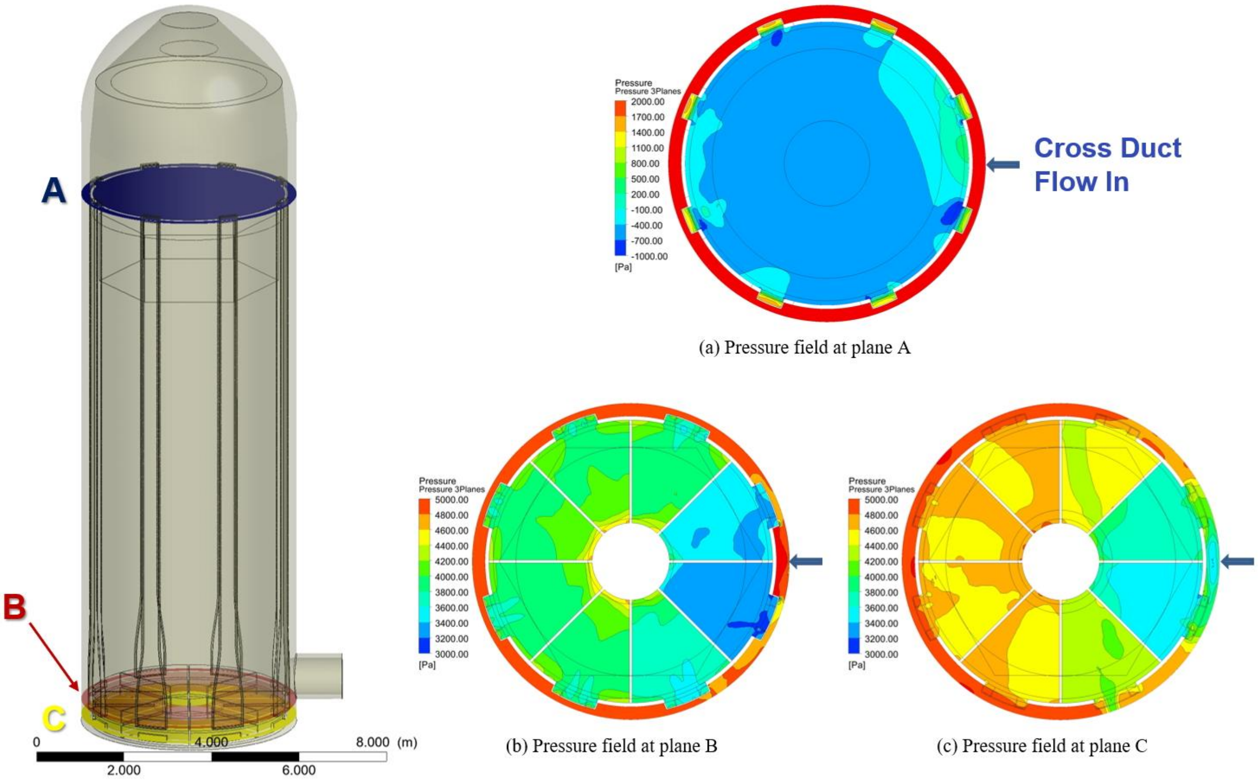
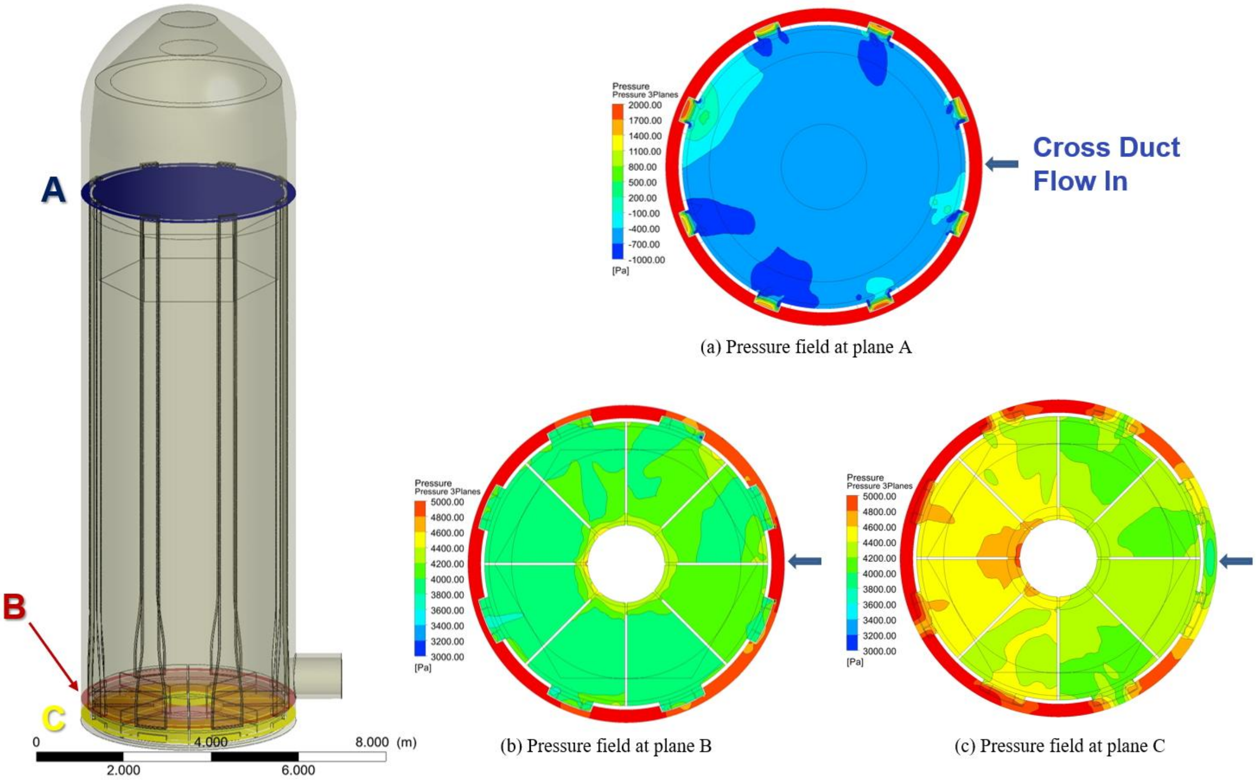


(a) Pressure field at plane A

(b) Pressure field at plane B

(c) Pressure field at plane C

Fig. 5. Pressure distribution over the selected horizontal planes of the original MCSS design.



(a) Pressure field at plane A

(b) Pressure field at plane B

(c) Pressure field at plane C

Fig. 6. Pressure distribution over the selected horizontal planes of the modified MCSS design.