Comparison of Axisymmetric and 3D Simulations of the Heat Transfer in RCCS

Seong Hoon Kim[a*], Nam-il Tak[a], Min-Hwan Kim[a]
[a]*Korea Atomic Energy Research Institute, 150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea*
[*]*Corresponding author: shkim822@kaeri.re.kr*

1. Introduction

RCCS (Reactor Cavity Cooling System) is the ultimate heat sink of the core decay heat under accident conditions in HTGR (High Temperature Gas-Cooled Reactor. RCCS should have a thermal capability to insure that the temperature of internal components is under the allowable maximum temperature. Due to its importance, it is required to understand and estimate the heat transfer phenomena of RCCS.

Outskirt of the reactor pressure vessel (RPV), the reactor cavity is placed. In that cavity, 292 RCCS tubes are placed circumferentially. Due to the high temperature of the reactor pressure vessel wall, a heat transfer by radiation is occurred. To reduce the wall temperature of the reactor pressure vessel, it is required to remove the heat. In present design the air-cooled RCCS in which the natural convection removes heat, is adopted.

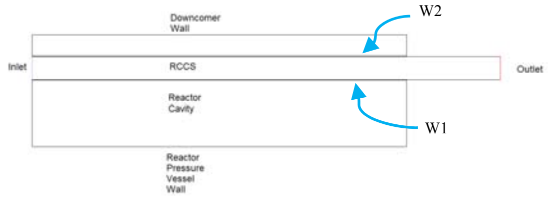
The heat transfer from the RPV wall to the RCCS tubes is mainly occurred by radiation, so it is important to estimate correctly the radiative heat transfer. In this study, we conducted the numerical simulation to estimate the performance of the RCCS using the CFD (Computational Fluid Dynamics). To simplify the problem and to reduce the computational time, the axisymmetric assumption can be applied to a simulation of RCCS. But, it is quite questionable that this assumption would give a reasonable result. In this study, we compare the result of the axisymmetric model and 3D model to answer that question.

2. Methods and Results

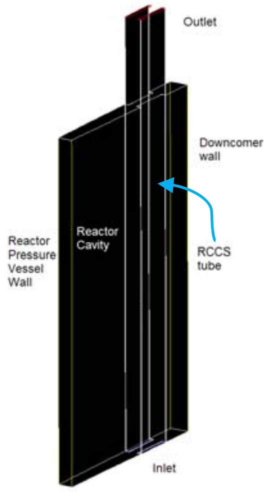
2.1 Computational Domain

An axisymmetric model and a 3D model were created for the simulation. Total numbers of the grids are 117,500 and 1,688,633 respectively. Figure 1 shows the computational domains used for the simulation. The RNG k-ε model is used and the enhanced wall function is provided the boundary condition for the turbulence quantities. Another turbulence model was tested for the axisymmetric 2D model, but it showed little difference in the estimated heat transfer rate. The reason is that the heat transfer to RCCS is contributed mainly by the radiation and that the convection, which may affected by different turbulence model, has relatively little influence to the total heat transfer rate.

The temperature and pressure of the inlet boundary condition are 45°C and 1 bar, respectively. The temperature of the RPV wall is assigned by a result of the GAMMA code, which is developed to analyze the thermo-fluid transients in HTGR. The inlet and outlet boundary conditions are the pressure boundary condition. The pressure in the reactor cavity is also 1 bar. The air properties were obtained by the database of the NIST [1] and were supplied to the simulation by a user subroutine and property input panels provided by the CFD program. The volumetric heat capacity and the thermal conductivity of the materials were given by functions of temperature. Except the downcomer wall, the walls have properties of steel.



(a) 2D axisymmetric model



(b) 3D model.

Fig. 1. Computational domain

2.2 Computational Method

The selection of the radiative heat transfer model is important to estimate correctly the heat transfer performance of RCCS. In FLUENT [2], which is adopted as a CFD tools for this study, there are five radiation models. However, due to the symmetric boundaries in the computational domain and the parallel computing for the simulation, selectable radiation models are limited. In this study, the discrete ordinates (DO) radiation model [3] was chosen. To use the DO model, it is required to select the numbers of theta divisions and phi divisions and the numbers of theta pixels and phi pixels. To increase the accuracy of the simulation, we chose 7 for the numbers of both divisions and 3 × 3 for the pixelation. These values are higher than the recommendation of the FLUENT user's guide.

2.3 Results

Table 1 shows the radiative and convective heat transfer rate on the walls. The positive value means the heat transfer from the wall to the fluid. Most of the heat transfer from the RPV wall is occurred by radiation. The radiative heat transfer rate contributes 92% of the total in the axisymmetric case and 87% in the 3D case. The estimated mass flow rates of the RCCS tubes are 12.5 kg/s in the axisymmetric case and 8.1 kg/s in the 3D case.

Since the RCCS tubes are simplified as an annulus in the axisymmetric case, the RCCS region has to be approximated as a porous region. The effective thermal conductivity in the porous medium is obtained by combining conductivities of air and steel. To match the estimated mass flow rate to the GAMMA result, the result of the axisymmetric case is obtained after adjustment of the inertial resistance factor.

In the axisymmetric case, a radiative heat transfer from the RPV wall increases the temperature of the RPV side wall (W1) of the RCCS tubes. The increased temperature of W1 induces a radiative heat transfer to the outer wall (W2) of the RCCS tubes. The flow in the RCCS receives 75% of heat from W1 and 25% from W2 by convection.

However, in the 3D case, a radiative heat transfer is a little different from the axisymmetric case. Most of heat to the fluid in the RCCS tube comes from the W3, which is not possible to be modeled in the axisymmetric case. This phenomenon can be explained that the area of W3 is 11 times bigger than W1 and W2 and that the convective heat transfer on W3 is higher due to the big area of W3 even though W1, W2, and W3 have the similar surface temperature distribution. Figure 3 shows the temperature contours of both cases.

3. Concluding Remarks.

The air-cooled RCCS performance was estimated by the simulations using CFD. The simulations with an axisymmetric model and a 3D model were conducted and compared to each other. Both cases showed that the heat transfer from the RPV wall was mainly by radiation. However, the estimated heat transfers to the flow in RCCS tubes were different from each other. The side wall of RCCS tubes was the main contributor of heat transfer, but this wall was unable to be included in the axisymmetric model. As a future work, it is required to verify whether the difference of heat transfer contributions of walls affects the estimated RCCS performance when the axisymmetric assumption is applied in transient simulations.

REFERENCES

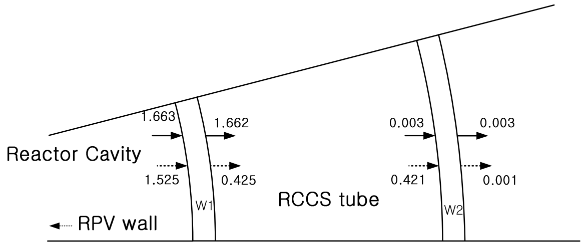
[1] REFPROP7 data base, NIST.

[2] FLUENT User's guide, FLUENT Inc., 2006.

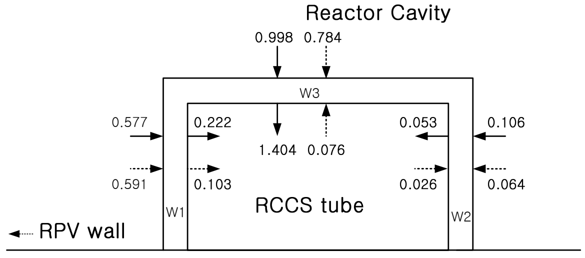
[3] E. H. Chui, G. D. Raithby, Computation of Radiant Heat Transfer on a Non-Orthogonal Mesh Using the Finite-Volume Method, Numerical Heat Transfer, Part B, Vol. 23, p. 269, 1993.

Table I: Heat Transfer Rate (in MW)

	Axisymmetric		3D	
	Radiation	Convection	Radiation	Convection
RPV wall	1.530 (92.1%)	0.132	1.458 (86.7%)	0.224
W1	0.425	1.237	0.103	0.119
W2	-0.421	0.418	-0.076	1.480
W3	N/A	N/A	-0.026	0.079
Downcomer wall	-0.003	0.003	0.010	-0.010

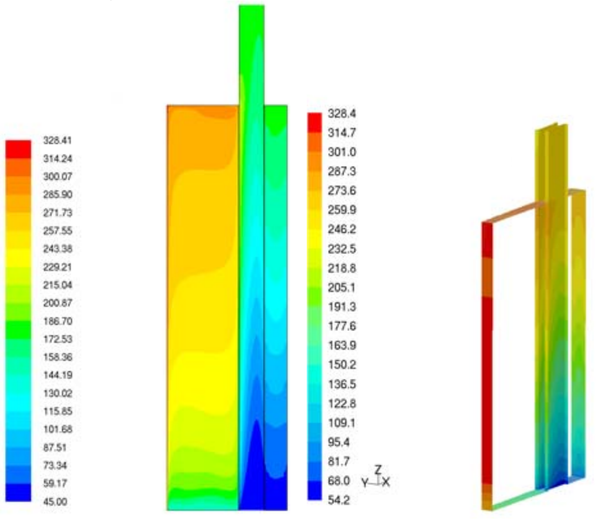


(a) Axisymmetric case



(b) 3D case

Fig. 2. Heat transfer rate at the RCCS tube walls (solid arrows: total heat transfer rate, dotted arrows: radiative heat transfer rate)



(a) (b)

Fig. 3. Temperature contours (in ^{o}C) (a) static temperature in the axisymmetric case, (b) surface temperature in the 3D case.