Verification of the Radiation Heat Transfer Model of the CORONA Code with Two-Column Benchmark Problem

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1. Introduction

The high temperature gas-cooled reactor (HTGR) is uranium-fueled, graphite-moderated and helium-cooled reactor. The prismatic block type reactor is one of main types of HTGRs which uses hexagonal graphite fuel blocks and reflector blocks. One way to analyze the temperature distribution of the reactor core is using computational fluid dynamics (CFD) codes. CFD allows observing the detailed information of temperature distribution and fluid behavior in the core. However, it requires large computational cost and time, especially for whole core simulation. The other way to analyze the thermal behavior of core of HTGR is using system codes such as GAMMA+ [1]. System codes have strengths in capability of transient calculation and low computational cost and time. Despite of its virtue of low calculation cost, there is one drawback in low resolution because of its coarse grid. For this reason, the CORONA (Core Reliable Optimization and thermo-fluid Network Analysis) code has been developed in order to analyze thermo-fluid phenomena of core of HTGR with fine solid mesh in Korea Atomic Energy Research Institute (KAERI) [2].

In this study, the radiation heat transfer model in the CORONA code was verified with two-column benchmark problem. For the reference calculation, a commercial CFD code, ANSYS CFX 19 [3], was used and the calculation results were compared with the prediction results of CORONA. The results of the GAMMA+ calculations were added for comparisons.

2. Radiation Heat Transfer in the Bypass Gap

2.1 Radiation Heat Transfer Model in CORONA

Net radiation method based on Stephan-Boltzmann law was used to simulate the radiation heat transfer through bypass gap and it is treated as radiation heat transfer between two parallel plates.

$$q_{12} = \frac{A_1\sigma}{1/\varepsilon_1 + 1/\varepsilon_2}\left(T_1^4 - T_2^4\right) \quad (1)$$

where q, σ, T, and ε are net radiation heat, Stephan-Boltzmann constant, surface temperature, and emissivity, respectively.

2.2 Condition of Two-Column Benchmark Problem

The test condition of the two-column benchmark problem is based on 350MW MHTGR [4]. The test model is two columns; one fuel and one reflector. The fuel column consists of 10 standard fuel blocks with a top reflector block and a bottom reflector block as described in Fig 1. There are 11 bypass gaps in radial direction. Working fluid is He at 7 MPa and inlet temperature is 490°C. Total flow rate is 2.22 kg/s and bypass flow rate is 0.1816 kg/s and coolant channel flow rate is 2.0389 kg/s. Power was set to be 6.499 MW for assuming 1.2 radial peaking power factor. The volumetric power density of the fuel compact is approximately 31 MW/m^3. Emissivity of the graphite block is assumed to be 0.85. Radiation heat transfer model used in CFX is DTRM (Discrete Transfer Radiation Model). The number of rays for DTRM were set to be 8. CFX simulations are performed with a steady-state incompressible Reynolds-averaged Navier-Stokes equation. The RMS residual reduction for the iteration convergence criteria is set to be less than 10^{-6}. Major variables used in calculations are summarized in Table I. In CFX calculations, since the heat transfer at the bypass gap depends on turbulent model, RNG k-ε and laminar model were applied and compared. Applied flow models in CFX calculations were tabulated in Table II.

Table I: Main variable for two-column benchmark

Parameter		Value
Fuel Column Power [MW]		6.499
Fuel compact power density [MW/m^3]		31
Pressure [MPa]		7.0
Inlet temperature [°C]		490
Mass flow rate [kg/s]	Total	2.22
	Coolant channel	2.038
	Bypass gap	0.1816
Graphite emissivity		0.85

Table II: Flow model in CFX calculation

Case index	Coolant channel	Bypass gap
CFX RNG k-ε	RNG k-ε	RNG k-ε
CFX laminar BG	RNG k-ε	Laminar

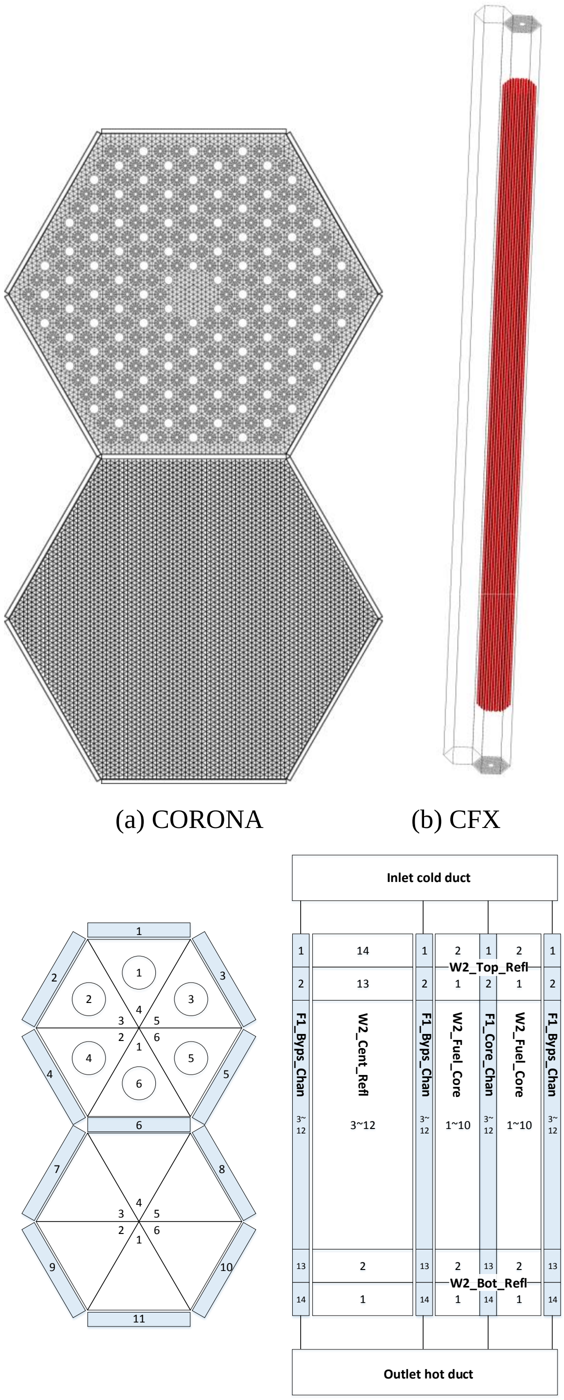

Fig. 1. Two-column benchmark target model for (a) CORONA (b) CFX, and (c) GAMMA+,

3. Results

3.1 Verification of radiation heat transfer model of the CORONA code

To ensure application of the radiation heat transfer model in CORONA properly, calculation results were compared to Eq. (1) with surface temperature and radiation heat flux along the axial nodes of 10th fuel layer. As the calculation results show good agreement with Eq. (1), it can be said that the radiation heat transfer model works properly in the code as shown in Table III.

Table III: Comparison results of CORONA and Eq. (1)

Axial node	Surface temperature [°C]		Radiation heat flux [W/m^2]	
	Fuel	Reflector	CORONA	Eq. (1)
59	1251.388	1136.675	32811	32811
60	1259.119	1144.035	33545	33545
61	1266.856	1151.425	34285	34285
62	1274.594	1158.820	35036	35036
63	1282.276	1166.095	35811	35811
64	1288.528	1172.119	36423	36423

3.2 Code-to Code comparison

Figure 2 shows comparison results of Reynolds number along the axial location in coolant hole and bypass gap for CORONA and GAMMA+ calculations. Even the different fluid temperature makes the slight discrepancy of the Reynolds number, overall results are in good agreement (Max difference: 1.8%). The Reynolds number in the coolant channel ranges from 25,000 to 41,000 and that in the bypass gap ranges from 3,300 to 4,300. It implies that flow regime in coolant channel is fully turbulent flow and that in bypass gap is transitional flow.

Comparison results of fluid temperature in the coolant channel and bypass gap along the axial location were plotted in Fig. 3. In the coolant channel, CORONA, GAMMA+, and CFX show good agreement and the radiation effect is not significant. In the bypass gap, CORONA predicts higher fluid temperature than GAMMA+ and CFX because of its higher convective heat transfer rate. The radiation heat transfer makes higher reflector block temperature and it leads to the higher bypass gap fluid temperature as summarized in Table IV.

As seen in Fig. 4, the calculation results of graphite average temperature for all cases show good agreement like the coolant channel temperature. The highest surface temperature was observed in CFX calculation with laminar BG case because of its lowest convective heat transfer. As shown in Table V, radiation heat transfer leads to the lower surface temperature of the fuel block because of heat removal.

Figure 5 presents the surface temperature of the reflector column and radial average temperature of the reflector block along the axial location. Since GAMMA+ uses cell temperature for radiation heat transfer calculation, radiation effect is slightly overestimated. CORONA shows the similar trend with CFX RNG k-ε. For CFX laminar BG case, because of its lower convective heat transfer rate, temperature difference between fuel block and reflector block is larger than other cases and it makes the large radiation effect. The results were tabulated in Tables VI and VII.

Comparison results of block radial average temperature, surface temperature and radiation heat transfer rate at 10th fuel layer are depicted in Fig. 6. Since GAMMA+ uses cell temperature when calculating radiation heat transfer, it predicts higher heat transfer rate than the other codes. The calculation results of CORONA lie between those of CFX RNG k-ε and CFX laminar BG within 20% difference. The calculation results of CORONA and GAMMA+ are provided in Tables VIII and IX. It can be said that the proportion of the radiation heat transfer rate to the fuel column power is not significant (CORONA: 0.5% and GAMMA+: 1.2%).

Table IV: Fluid temperature in the bypass gap at 10th fuel layer (°C)

	W/o radiation	W/ radiation	Difference
CORONA	915.9	928.7	12.8
GAMMA+	835.8	857.5	21.7
CFX RNG k-ε	829.2	841.8	12.6
CFX laminar BG	800.8	829.2	28.4

Table V: Surface temperature of the fuel block at 10th fuel layer (°C)

	W/o radiation	W/ radiation	Difference
CORONA	1006.5	994.6	-11.9
GAMMA+	995.5	976.4	-19.1
CFX RNG k-ε	989.4	980.0	-9.4
CFX laminar BG	1020.0	991.1	-28.9

Table VI: Surface temperature of the reflector block at 10th fuel layer (°C)

	W/o radiation	W/ radiation	Difference
CORONA	846.5	884.9	38.4
GAMMA+ (Cell T)	844.3 (754.8)	900.1 (842.3)	55.5 (87.5)
CFX RNG k-ε	844.2	884.0	39.8
CFX laminar BG	763.5	854.6	91.1

Table VII: Block radial average temperature of the reflector block at 10th fuel layer (°C)

	Block radial average temperature (°C)		
	W/o radiation	W/ radiation	Difference
CORONA	960.6	711.9	21.3
GAMMA+	651.6	709.0	57.4
CFX RNG k-ε	652.3	670.3	18.0
CFX laminar BG	614.6	655.9	41.3

Table VIII: Convective heat transfer rate and radiation heat transfer rate in the bypass gap: CORONA

CORONA	Convective heat transfer rate [W]		Radiation heat transfer rate [W]
	Fuel block	Reflector block	
10th fuel layer	-11390	7634	5447
Total	-98327	62324	32190
Proportion to the fuel column power	-1.51%	0.96%	0.50%

Table IX: Convective heat transfer rate and radiation heat transfer rate in the bypass gap: GAMMA+

GAMMA+	Convective heat transfer rate [W]		Radiation heat transfer rate [W]
	Fuel block	Reflector block	
10th fuel layer	-8419	7444	5447
Total	-68102	58959	32190
Proportion to the fuel column power	-1.01%	0.91%	1.17%

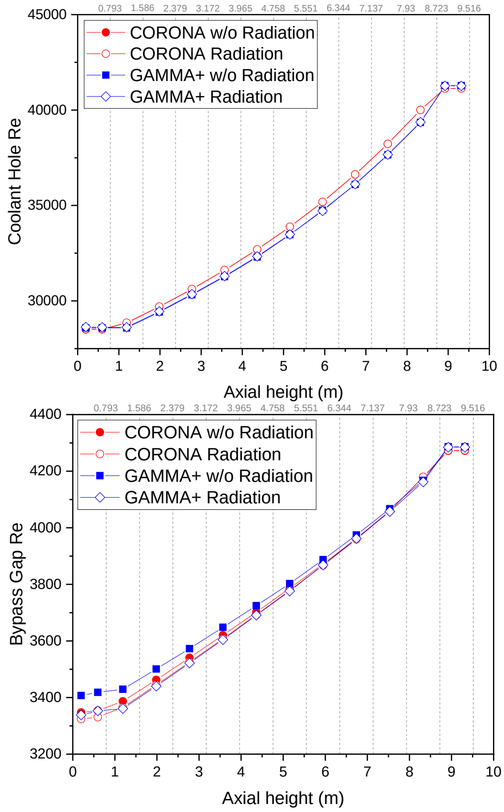

Fig. 2. Reynolds number along the axial location in coolant hole and bypass gap

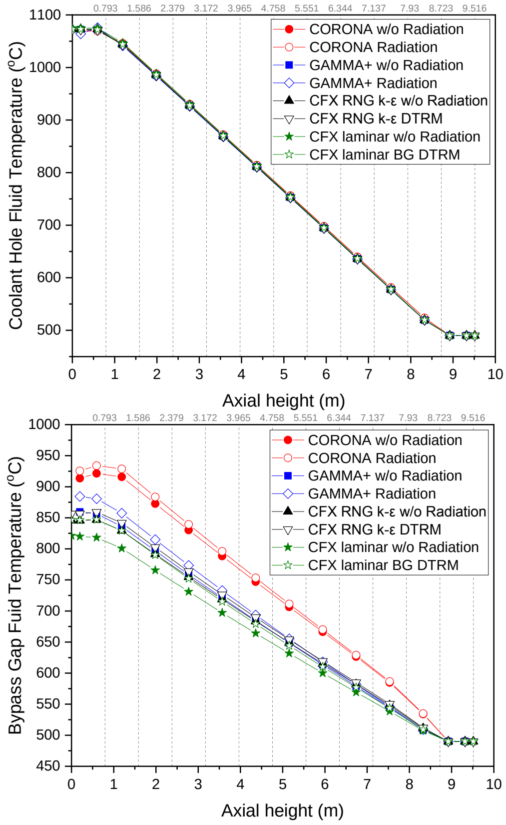

Fig. 3. Comparison results of fluid temperature in the coolant channel and bypass gap along the axial location

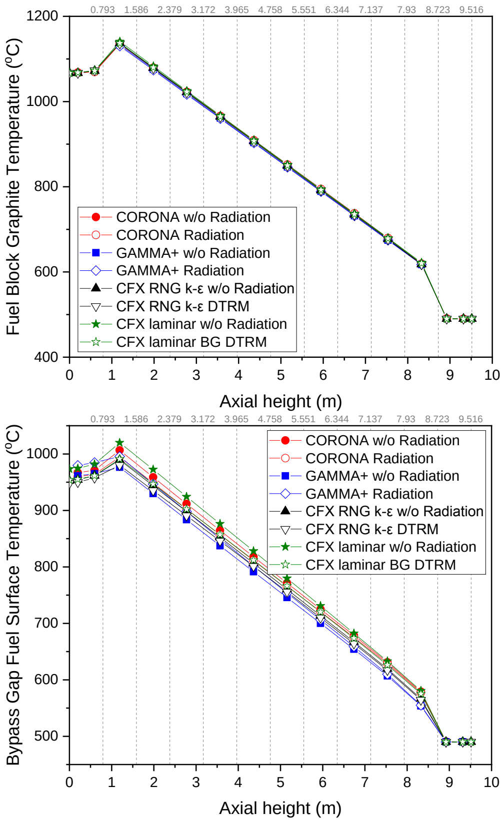

Fig. 4. Graphite average temperature and surface temperature of the fuel block at bypass gap along the axial location

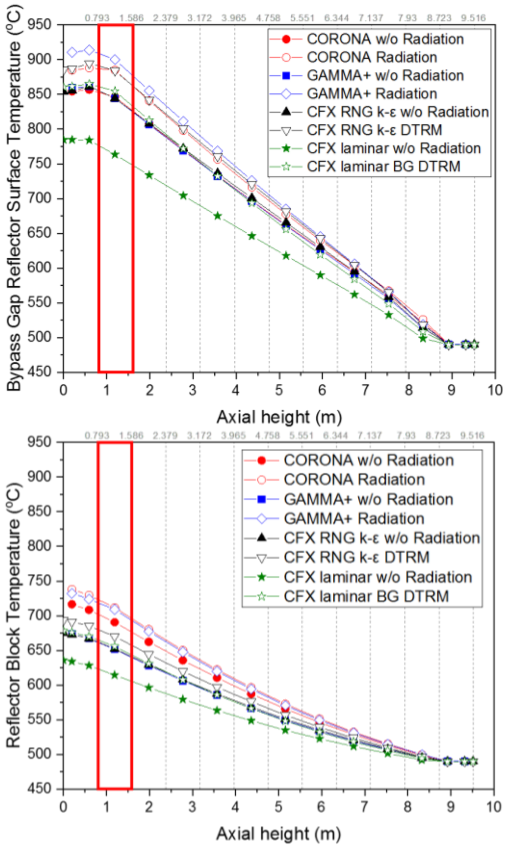

Fig. 5. Radial average temperature and surface temperature of the reflector block at bypass gap along the axial location

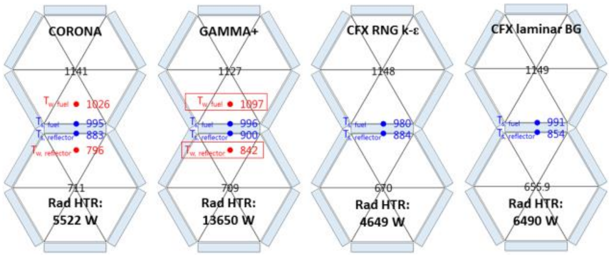

Fig. 6. Comparison results of block radial average temperature, surface temperature, and radiation heat transfer rate at 10th fuel layer

4. Conclusions

In this study, the radiation heat transfer model of CORONA was verified. It was confirmed that the model works properly in the code with comparing calculation results to the net radiation method equation. From the two-column benchmark problem, it was observed that CORONA predicts radiation heat transfer rate 15.8% higher than CFX RNG k-ε and 17.5% lower than CFX laminar BG. Considering the flow regime in the bypass gap is transitional flow, it can be said that the results are reasonable.

Because of the complexity of the phenomena including its transitional flow, the uncertainty of the prediction of the radiation heat transfer in the bypass gap is high. Despite of their high uncertainty, the proportion of the heat transfer rate to the total power is about 0.5% and it is observed that the radiation heat transfer at bypass gap makes no difference in the temperature of the fuel block and coolant channel for all cases. Therefore, it can be expected the effect of the radiation heat transfer is not significant in safety of the reactor core under full power operating conditions.

Acknowledgements

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REFERENCES

[1] H. S. Lim, General Analyzer for Multi-component and Multi-dimensional Transient Application, GAMMA+ 1.0 Volume II: Theory Manual, KAERI/TR-5728/2014, 2014.
[2] N. I. Tak, S. N. Lee, M. H. Kim, H. S. Lim, J. M. Noh, Development of a Core Thermo-Fluid Analysis Code for Prismatic Gas Cooled Reactors, Nuclear Engineering and Technology, Vol.46 (5), p. 641-654, 2014.
[3] ANSYS Inc, ANSYS CFX-Solver Theory Guide, ANSYS Inc., Canonsburg, PA., 2013.
[4] J. Ortensi, V. Seker, C. Ellis, et al., OECD/NEA coupled neutronics/thermal-fluids benchmark of the MHTGR-350MW core design. Volume I: reference design definition and Volume II: definition of the steady-state exercise. Nuclear Energy Agency, 2015.