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Verification of GAMMA+ and CORONA Codes with Two-column 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. Because of its core design, some unique thermo-fluid phenomena were observed such as bypass flow and cross flow which make high uncertainty in core temperature distribution.

To evaluate thermo-fluid phenomena of core of HTGR, two codes have been developed in Korea Atomic Energy Research Institute (KAERI). One is GAMMA+ (General Analyzer for Multi-component and Multi-dimensional Transient Application) and the other is CORONA (COre Reliable Optimization and thermo-fluid Network Analysis). GAMMA+ has been developed to simulate thermo-fluid transient phenomena of HTGR system [1]. Meanwhile, to obtain more detailed information of core flow and temperature distribution of block type HTGR, the CORONA code has been developed [2].

In the previous work, in order to verify prediction capability of the GAMMA+ code, MHTGR-350 benchmark exercises [3] were tested by comparing CFD (computational fluid dynamics) analysis. The overall test results were in good agreement but some discrepancies in temperature of inner reflector block region were observed between CFD and GAMMA+.

In the core of block type HTGR, the radial heat transfer through the bypass gap would be one of the key parameters in terms of temperature distribution and the temperature of the inner reflector is determined by heat transfer through the bypass gap. In this study, therefore, verification of two codes, GAMMA+ and CORONA, was carried out with two-column problem and the bypass-gap-heat-transfer phenomena between fuel and reflector columns was discussed. For the reference calculation, a commercial CFD code, CFX [4], was used with various turbulent models and the calculation results were compared with the prediction results of GAMMA+ and CORONA.

2. Description of two-column problem

To simplify the phenomena, two-column model with one fuel column and one reflector column was simulated as seen in Fig. 1 and the nodalization of two-column problem for GAMMA+ is depicted in Fig. 2. A power of 0.53 MW was applied to the lower fuel block of the fuel column. There exists only one bypass gap between two columns, so that heat transfer between columns occurs through only the bypass gap. The working fluid is He at 7 MPa and the inlet temperature is set to be 259°C. Conditions of mass flow rates were set with reference to the conditions in the MHTGR-350 benchmark [3] as tabulated in Table I. The convective heat transfer coefficient model used in GAMMA+ and CORONA is Nusselt number correlation as Eq. (1)

$$Nu = \frac{hD}{k}, \tag{1}$$

where h, D, and k represent convective heat transfer coefficient, diameter of the flow channel, and thermal conductivity of the fluid, respectively. Nusselt number correlation for turbulence used in two codes was changed to modified Dittus-Boelter correlation for the comparison as Eq. (2).

$$Nu = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}, \tag{2}$$

where Re and Pr are Reynolds number and Prandtl number, respectively.

For laminar flow, following constants are used.

$$\begin{aligned} Nu &= 4.36 \text{ (at coolant channel)} \\ & 8.23 \text{ (at bypass gap)} \end{aligned} \tag{3}$$

CFD analysis with turbulent model sensitivity test was conducted using RNG k-ε, SST Gamma-Theta transition, and laminar model. Since the flow regime in bypass gap is laminar-turbulent transition regime, "Blended Near Wall Treatment" of "Laminar Turbulent Blend" was applied when using SST model. In addition, for the better results, the intermittency transition model [5] was adopted. Wall y^+ value at the bypass gap was approximately 2.21 and the models used in CFD calculations were summarized in Table II.

Fig. 1. Two-column problem

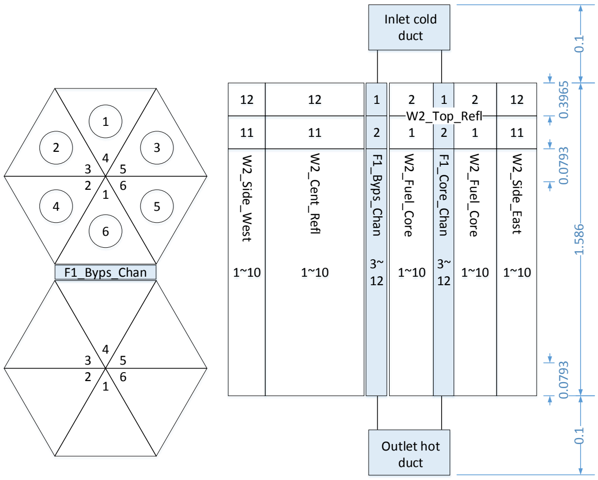

Fig. 2. GAMMA+ nodalization for two-column problem

Table I: Condition of mass flow rates

	Mass flow rate (kg/s)
Total	2.19
Coolant channel	2.18
Bypass gap	0.0123

Table II: Turbulence models used in CFD analysis

Index	Coolant Channel	Bypass gap
CFX RNG k-ε	RNG k-ε	RNG k-ε
CFX laminar BG	RNG k-ε	Laminar
CFX SST BG	RNG k-ε	SST / intermittency transition
CFX SST CH BG	SST / intermittency transition	SST / intermittency transition

3. Results

GAMMA+, CORONA, and CFX predict the same outlet temperature of 306°C. Fig. 3 shows Reynolds number along axial height in coolant channel and bypass gap predicted by GAMMA+ and CORONA. Even though the mass flow rates in two codes were set identically, there exist slight discrepancies in Reynolds number (2.2% - GAMMA+: 3790, CORONA: 3708) because of the temperature difference at the bypass gap.

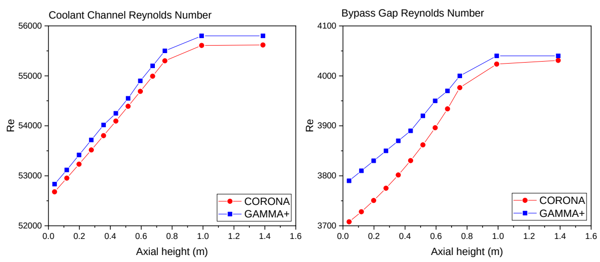

Fig. 3. Reynolds number along axial height

Since CORONA and GAMMA+ uses similar approaches in fluid analysis, they show good agreement in axial pressure distribution as seen in Fig. 4. In coolant channel, calculation results of CFX simulations are in good agreement with CORONA and GAMMA+ regardless of turbulent models. In bypass gap, RNG k-ε model shows similar results with CORONA and GAMMA+ while laminar and SST models predict lower pressure drops, which implies SST intermittency transition model treats the bypass gap flow as laminar flow. Considering their Reynolds numbers, their results are quite plausible.

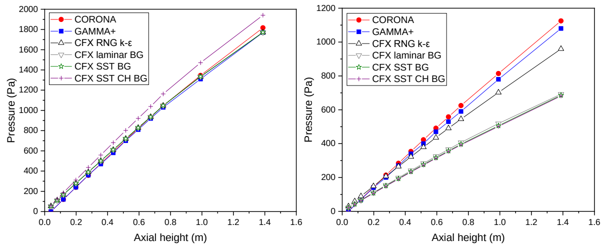

Fig. 4. Pressure distribution along axial height

The fluid temperature distributions along the axial height in the coolant channel and bypass gap were plotted in Fig. 5. All calculated results show good agreement in the coolant channel. However, CORONA predicts the bypass gap outlet temperature 19°C (5.8%) higher than that of GAMMA+. In CFX calculation, RNG k-ε model predicts 17.5°C (5.5%) higher than laminar model. Calculation results of SST CH BG and SST BG show good agreement with laminar model, which means that the SST intermittency transition model treats bypass flow as laminar flow. The prediction results of CORONA were in good agreement with those of CFX RNG k-ε model within 1.4°C (0.42%) difference and GAMMA+ predicts similar bypass gap fluid temperature with CFX laminar model within 0.3°C (0.1%).

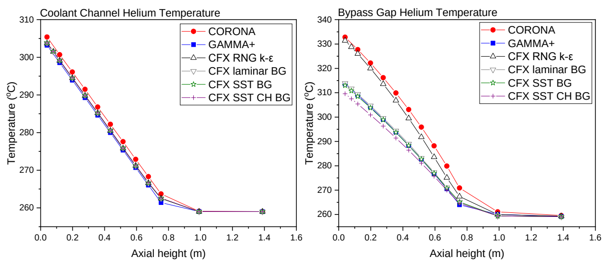

Fig. 5. Fluid temperature distribution along axial height

Since the difference of fluid temperature at the bypass gap might be affected by the prediction of the heat transfer in the bypass gap, heat transfer coefficients in the calculations of the codes were compared as presented in Fig. 6. The prediction results of GAMMA+

and CORONA were in good agreement within 0.6% difference. Even though the results of CFX are arithmetically derived from the temperature difference between wall and fluid so that it cannot be directly compared to that used in correlation, it can be said that the results were in reasonable range. In the coolant channel, SST with transitional intermittency model predicts higher heat transfer coefficient than RNG k-ε model. In the bypass gap, RNG k-ε model predicts higher heat transfer coefficient than laminar model and SST model.

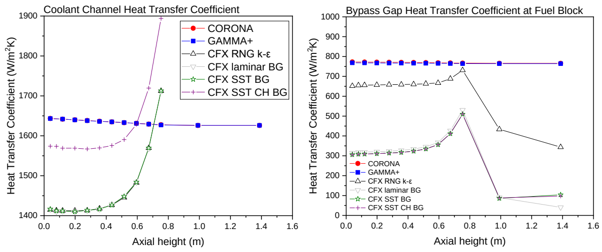

Fig. 6. Convective heat transfer coefficient along axial height

Fig. 7 indicates heat flux between structure and fluid along the axial height. GAMMA+ and CORONA show overall good agreement within 2.5% in coolant channel. Maximum difference of 35% (12400 W/m^2) were observed at the fuel block side in bypass gap while 1630 W/m^2 at the reflector block side.

In CFX calculation, difference between models in coolant channel was not significant. At the fuel block side in bypass gap, calculation results with RNG k-ε model show similar heat flux value to CORONA prediction results while those of laminar model and SST show similar trend with those of GAMMA+. At the reflector block side in bypass gap, laminar model and SST model show lower absolute value of heat flux than RNG k-ε model.

Heat flux at reflector block side in the bypass gap is affected by not only temperature difference between wall and fluid but also heat transfer through the axial conduction. Since the fluid temperature is higher than that of reflector block in the lower part and opposite in the upper part, heat is transferred from the fluid to the block in the lower part and conducted axially to the upper block and then, transferred to the fluid in the upper part as illustrated in Fig. 8.

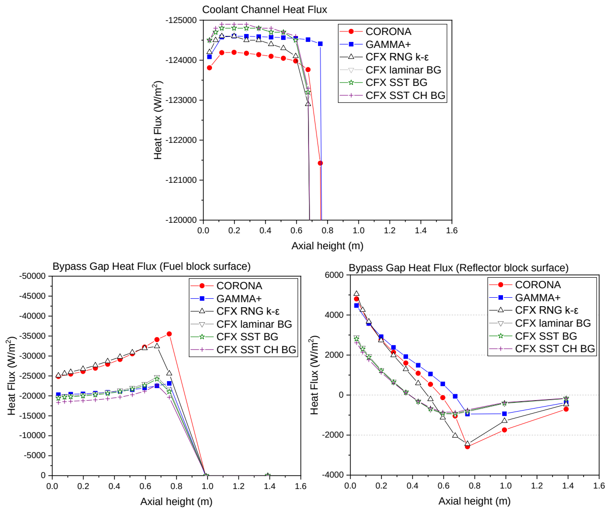

Fig. 7. Convective heat flux along axial height

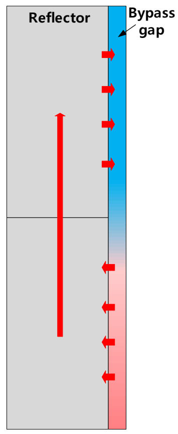

Fig. 8. Direction of heat transfer between reflector block and bypass gap

Figure 9 shows axial temperature distributions of fuel block surface in the bypass gap, fuel block graphite, and fuel compact. GAMMA+ predicts surface temperature 24°C lower than CORONA. Calculation results of CFX using laminar model is 11°C higher than that of CORONA and those of other models lie in between them. The temperature differences between GAMMA+ and CORONA predictions at the graphite and fuel compact are 10°C and 13°C, respectively. In CFX calculation, SST CH BG shows similar results with CORONA and other models show approximately 8°C higher temperature than SST CH BG at graphite and fuel compact.

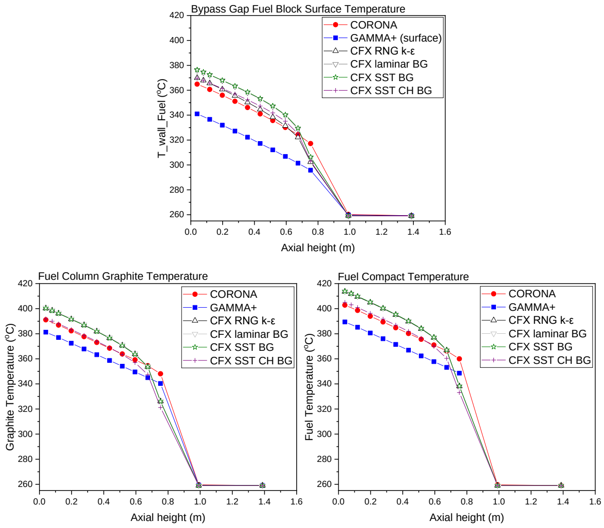

Fig. 9. Axial fuel block temperature distribution (surface in the bypass gap, graphite, fuel compact)

Figure 10 presents axial distribution of surface temperature at bypass gap and average temperature of the reflector block. CORONA predicts surface temperature approximately 18°C higher than that of GAMMA+ at the bottom of the reflector block. Surface temperature calculated in CFX using RNG k-ε model is 8°C lower than that of CORONA prediction and 10°C higher than that of GAMMA+. Meanwhile, calculation results of CFX using laminar model and SST with transitional intermittency model show lower surface temperature than those of RNG k-ε model because of their lower heat fluxes as seen in Fig. 7. Axial distribution of the reflector block average temperature is mainly affected by surface temperature of the block so that the trend is similar to the surface temperature.

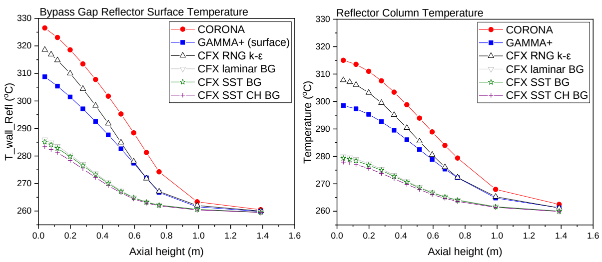

Fig. 10. Axial reflector block temperature distribution (surface in the bypass gap, average)

4. Conclusions

In this study, GAMMA+ and CORONA were verified with two-column problem by comparing CFX calculation. The difference of the results between GAMMA+ and CORONA is in the same range of the difference of the calculation results between turbulence models in CFX. Considering calculation results of GAMMA+, CORONA and CFX for the fuel block temperature and fluid temperature at the coolant channel are in good agreement which is main factor of the safety of the reactor core rather than bypass flow temperature, it can be concluded that the calculation results of GAMMA+ and CORONA are both reasonable. In addition, in CFX calculations, the large temperature difference between the turbulence models was observed in bypass gap and reflector block. Therefore, when analyzing heat transfer between fuel and reflector blocks with CFD code, turbulence model sensitivity test should be conducted and it is highly recommended that special attention is required when it comes to use of turbulence models for thermo-fluid analysis of HTGR core.

Acknowledgements

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