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Improvement of Fluid Energy Model of the CORONA Code

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been studying Very High Temperature Reactor (VHTR), one of Gen-4 reactors. The selected VHTR is graphite moderated and helium cooled prismatic reactor. Because VHTR operates under the high temperature and pressure condition range of 490^{0}C to 950^{0}C, 7MPa, it is necessary to secure thermal integrity of reactor. KAERI has been developing thermal-fluid analysis codes to predict fuel/coolant temperature distribution in the reactor core. One is GAMMA+ which is system code designed to analyze transient status. This code can be applied to wide engineering application including gas cooled reactors. However, GAMMA+ code is developed originally to transient problems, it might have problems to predict accurate fuel temperature and hot spot position in the reactor core under normal operating conditions. Computational Fluid Dynamic (CFD) could give accurate result with three dimensional fluid/solid analyses, but computational cost is very high due to large number of grids. Therefore, steady-state thermal-fluid analysis code, Core Reliable Optimization & Network thermo-fluid Analysis (CORONA)[1][2], has been under development in KAERI. This code focuses on analyzing fluid and heat transfer in the prismatic gas cooled reactor.

On the previous study[3][4], CORONA analyzed the reactor core using network model for the pressure and velocity variables. Temperature to the each node was solved with simple energy balance equation. To get more realistic data, network model for the energy equation has been applied and studied on the present study. The modified algorithm is used to predict temperature variation on the Reserve Shutdown Control (RSC) fuel assembly to verify the improvement. The data were compared with the results with the previous model and CFD data.

2. Methods and Results

2.1 Methods

Fluid region is solved by below one-dimensional governing equations.[3][4]

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial(\rho_f w A)}{A \partial z} = 0 \qquad (1)$$

$$\frac{\partial(\rho_f w)}{\partial t} + \frac{\partial(\rho_f w^2 A)}{A \partial z} + \frac{\partial p}{\partial z} + \rho_f g \cos\theta + f \frac{\rho_f w|w|}{2D_h} = 0 \qquad (2)$$

$$\frac{\partial(\rho_f C_f T_f - P)}{\partial t} + \frac{\partial(\rho_f w A C_f T_f)}{A \partial z} - q'''_{conv} = 0 \qquad (3)$$

The temperature on the each node was calculated below energy balance equation along the axial direction on the previous model.

$$\rho_f w C_f T_{f\,I} = \rho_f w C_f T_{f\,I-1} + q'''_{conv,I} \qquad (4)$$

However, this explicit method did not consider crossflow in the fluid energy equation. On the present study, network model in Eq. 5 is applied to the CORONA

$$\sum_{j \in Out} \rho_f w C_f T_{f\,e,j} - \sum_{j \in In} \rho_f w C_f T_{f\,w,j} = \sum_j q'''_{conv,I,j} \qquad (5)$$

The equation 5 can be casted with the upwind scheme like Eq. 6.

$$\sum_{j \in Out} \rho_f w C_f T_{f\,I,j} - \sum_{j \in In} \rho_f w C_f T_{f\,I-1,j} = \sum_j q'''_{conv,I,j} \quad \text{if w>0}$$

$$\sum_{j \in Out} \rho_f w C_f T_{f\,I+1,j} - \sum_{j \in In} \rho_f w C_f T_{f\,I,j} = \sum_j q'''_{conv,I,j} \quad \text{if w<0} \qquad (6)$$

The source term in Eq. 6 is separated to have stable solution and discretized below.

$$A_w + A_p + A_e = S \qquad (7)$$

$$A_w = -\max(\rho_f w C_{f,I-1}, 0),\ A_e = -\max(-\rho_f w C_{f,I+1}, 0)$$

$$A_p = \max(\rho_f w C_{f,I}, 0) + \max(-\rho_f w C_{f,I}, 0) + H,$$

$$S = H \times T_{wall},\ H = Nu \times k / D$$

In order to verify the improvement by the present model, a benchmark problem using single RSC fuel assembly was setup and analyzed.

The fuel compact has power of 28.4MWt/m^3. The inlet temperature and pressure are specified as 490^{0}C and 7MPa, respectively. 1.268kg/s of helium coolant passes the coolant channels. Commercial CFD software, CFX, was used to compare with the results of CORONA.

Fig. 1 shows the meshes of the RSC fuel assembly for CFX. The RSC hole is 9.625cm in diameter. In the RSC fuel assembly, coolant passes coolant channel and bypass gap. Top and bottom of RSC hole are blocked. There would be no mass flow inside the RSC hole for the manufactured assembly as designed dimension. However, due to irradiation to the graphite, fuel assembly might shrink during normal operation. This phenomenon makes crossflow between fuel blocks. The crossflow changes the flow distribution. Therefore, the position and magnitude of hot spot on the fuel assembly might change.

Fig. 1. CFD mesh for RSC fuel assembly

2.2 Results

The RSC fuel temperature on the hot spot by CORONA was compared with CFX data to verify the improved energy equation. The predicted temperatures without cross flow are similar for all the equations in Fig. 2.

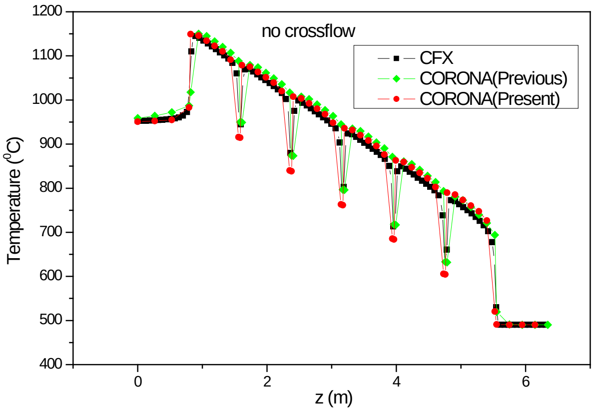

Fig. 2. Axial temperature variation for RSC fuel assembly without crossflow

Figs. 3~5 show the improvement of the present model compared with previous model on the predicted axial temperature distribution depending on the crossflow gap size between fuel blocks. It is also found that the fuel temperature is slightly different at the upper plenum depending on the turbulence model of CFX, Shear Stress Transport (SST) and RNG-$\kappa-\varepsilon$. Temperature variation of CORONA with the present network energy model is closer to the RNG-$\kappa-\varepsilon$ model of CFX than SST model. As the cross gap size increases, the exit temperature of the previous model of CORONA differs with other models. This temperature difference is from that the previous model of CORONA did not consider the energy transfer in the crossflow area. The temperature difference is shown mainly at the exit of fuel assembly. This can be explained that a large cross flow redistribution to the coolant hole from the blocked bottom of control rod hole was not properly modeled in the previous model.

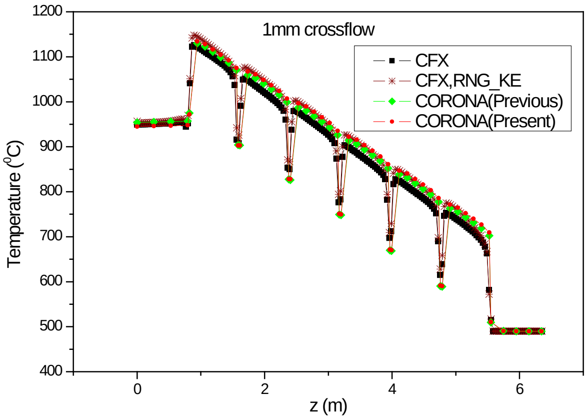

Fig. 3. Axial temperature variation for RSC fuel assembly with 1mm gap crossflow

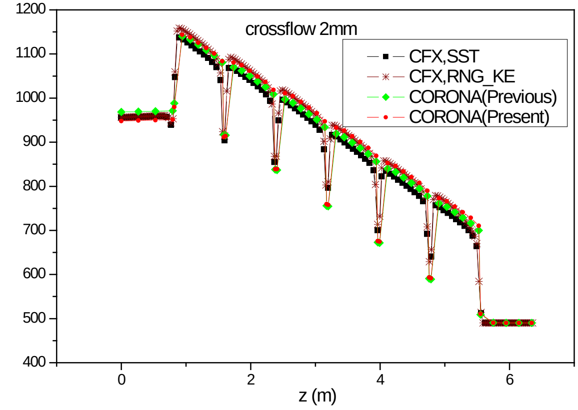

Fig. 4. Axial temperature variation for RSC fuel assembly with 2mm gap crossflow

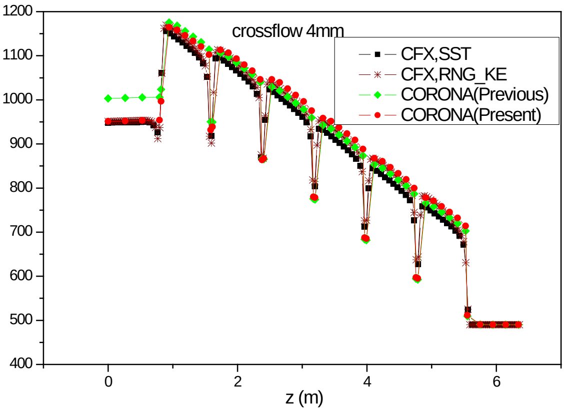

Fig. 5. Axial temperature variation for RSC fuel assembly with 4mm gap crossflow

3. Conclusions

The numerical scheme to the energy equation of CORONA, thermo-fluid analysis network code, has been improved to enhance the accuracy of the prediction with a large crossflow between fuel blocks in the prismatic VHTR. The temperature variation and exit temperature by the present CORONA model were well agreed with CFX data regardless of the gap size. The different turbulence models, SST and RNG-$\kappa-\varepsilon$, do not show large gap in the result. The study for the whole core will be conducted in the next step.

Acknowledgements

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