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Turbulence Model Assessment for Micro Modular Reactor Core

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1. Introduction

Commercial Nuclear Power Plants (NPPs) have been supplying large capacity of electricity in world-wide. Therefore, most NPP is designed as large scale. However, a new demand in a nuclear reactor core design has arisen to supply energy to remote area. The remote area where has limitation to connect power grid pays high cost to use electricity. Micro Modular Reactor (MMR) might be economically feasible to produce clean and sustainable energy to remote area. Korea Atomic Energy Research Institute (KAERI) has been studying Micro Modular High Temperature Reactor (MiHTR) as micro modular reactor type [1][2]. The MiHTR follows the concept of High Temperature Gas-cooled Reactor (HTGR) which has inherent safety under severe accidents. A passive safety system with natural air-circulation has strong advantages at remote areas where are difficult to access from outside. KAERI has researched to find an optimized reactor core for long time operations without refueling and selected a preliminary core layout [1][2]. A Core Reliable Optimization & thermo-fluid Network Analysis (CORONA) code [3] which is used to analyze HTGR core was selected to analyze the hot spot temperatures in the reactor core during normal operations. On the previous calculation, a simple verification was conducted to assure the CORONA algorithms with single fuel block [2]. In the studies reported here, a one-sixth core is selected to compare the calculated results.

2. Methods and Results

The MiHTR core layout selected by KAERI is shown in Fig. 1. A fuel compact is cooled with surrounding coolant. A core power is 10MWth. The inlet temperature and pressure are set at 300 °C and 3 MPa, respectively.

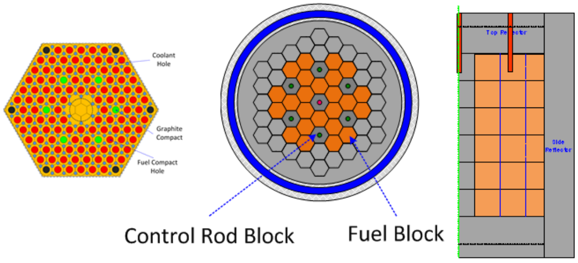


Fig. 1. Schematic of MiHTR core [1]

The comparison of single fuel block was suitable to verify the CORONA algorithms. However, it was not sufficient to compare the fluid distributions and heat transfer between the fuel blocks in the core. Even if the CORONA code was verified and validated for the reactor type of MHTGR350, the CORONA code should be verified again for the MiHTR type core. The coolant in the MHTGR350 type core showed fully turbulent flow in the coolant channels. However, the coolant in the MiHTR showed transitional flow about Re ≈ 2000 ~ 4000 in the coolant channels due to relatively small size of coolant hole diameter. Therefore, various case studies are in demand to find a suitable heat transfer model in the core.

2.1 Modeling

The CORONA code was applied to analyze the thermo-fluid phenomena in the MiHTR core. The CORONA code has developed to predict a hot spot temperature and the temperature distributions in a HTGR core[3]. The CORONA code models the fluid in one-dimension and the solids in three dimensions to provide the reasonable results with fast computation speed. The fluid equations are written below. A network algorithm was applied to calculate multi-coolant channels.

$$\frac{\partial(\rho_f wA)}{A\partial z} = 0 \tag{1}$$

$$\frac{\partial p}{\partial z} + f\frac{\rho_f w|w|}{2D_h} = 0 \tag{2}$$

$$\frac{\partial(\rho_f wAC_f T_f)}{A\partial z} - \frac{1}{A}\frac{q_f^{conv}}{\partial z} = 0 \tag{3}$$

The equation in solid region is written as

$$\rho_f wC_f T_{f_I} = \rho_f wC_f T_{f_{I-1}} + q'''_{conv,I}\delta z \tag{4}$$

The laminar Nusselt numbers in the CORONA code are set as 4.364 and 8.23 for coolant and bypass channels, respectively. The fully developed turbulent flow in CORONA adopts the McEligot[4], Modified Dittus-Boelter[5], Gnielinski[6] models as user option. If the Reynolds number in the channels is between 2300 and 5000, the following equation is applied.

$$Nu = (1-f_r)\times Nu_{fl} + f_r \times Nu_{ft} \tag{5}$$

$$f_r = \frac{(\mathrm{Re}-2300)}{(5000-2300)}$$

Commercial CFD S/W ANSYS CFX Ver. 19[7] was applied to compare the calculated results in the reactor core. The used turbulence models in the present studies are κ-ε, κ-ω, RNG κ-ε and SST models. The Cases in the present calculations are written in Table I.

Fig. 2 shows one-sixth core layout of MiHTR for the present calculations. The computational domain consists of seven columns (four fuel columns, two control columns and one moderator column) with permanent side reflector.

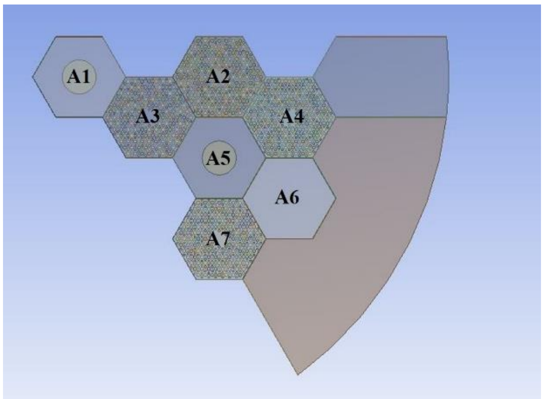


Fig. 2. One-sixth core layout of MiHTR

Table I: Turbulence model Cases

	Coolant	Bypass
CASE 1	SST	SST
CASE 2	SST with 0.3	SST with 0.7
CASE 3	SST with 0.3	Laminar
CASE 4	SST	Laminar
CASE 5	κ-ω	Laminar
CASE 6	RNG κ-ε	Laminar
CASE 7	κ-ε	Laminar

2.2 Results

Fig. 3 and 4 represent the average temperature comparison for the fuel compact and moderator, respectively. The heat transfer correlation in the CORONA code for the present calculation was modified Dittus & Boelter model. The transitional model in the CFX was a specified intermittency. By the calculations, the flow regime in the coolant channels was a transitional flow of Reynolds number ≈ 2,400 ~ 3,500 and the flow in the bypass channels was a laminar flow of Reynolds number ≈ 300 ~ 500. For all cases, the fully turbulent flow models in the coolant channels little under predicted compared to the results of the CORONA calculation. The SST model with the transitional option agrees better than the other fully turbulence models. As coolant diameter is much smaller than that in the MHTGR-350, the flow became the transitional regime. Therefore, the heat transfer ability decreased. Nevertheless, the maximum temperatures in the core were sufficiently low compared to the design limit in Table II. The transitional option is necessary to predict the temperature distribution in the MiHTR core

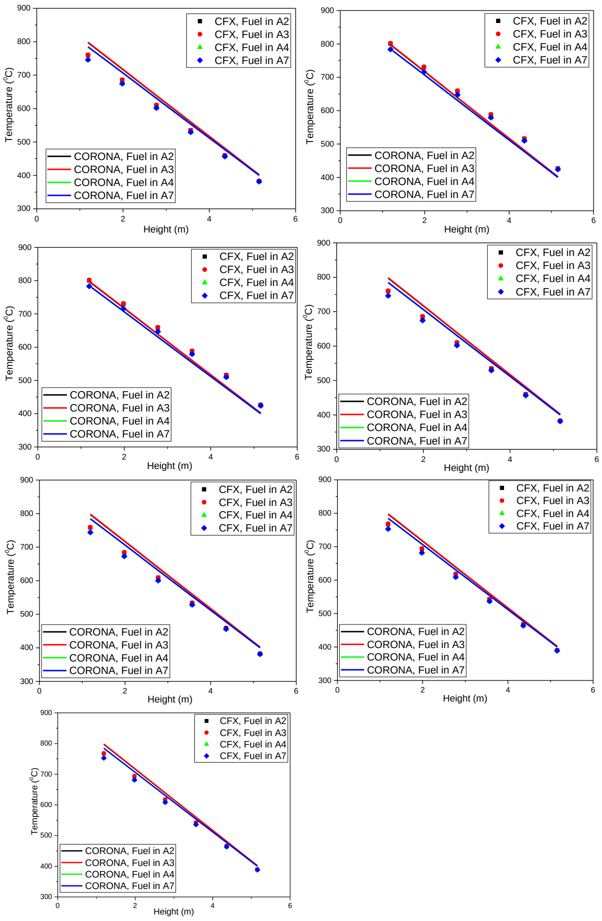
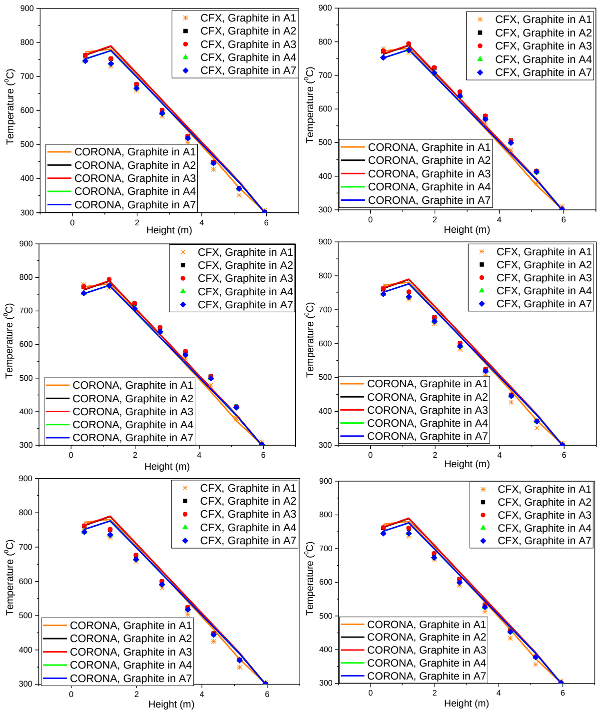


Fig. 3. Average fuel compact temperature comparison for each case



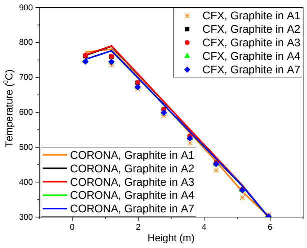


Fig. 4. Average moderator temperature comparison for each case

Table II: Maximum fuel temperatures

	Max. Temp.[°C] (CORONA : 837)
CASE 1	802
CASE 2	841
CASE 3	841
CASE 4	802
CASE 5	800
CASE 6	803
CASE 7	809

3. Conclusions

The turbulence models in the CFX S/W were assessed in this paper. The flow regime in the coolant channels of MiHTR showed the transitional area. Therefore, the full turbulence models may not predict well the temperature variation in the blocks. As the flow became the transition, the suitable turbulence model with commercial CFD S/W should be selected to investigate the temperature distribution in the core. In the present calculation, the SST turbulence model with specified intermittency was similar to the calculated data by the CORON code. The other correlation model in the CORONA code will be investigated in the further studies.

Acknowledgements

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