Code-to-code Validation of a Closed Multichannel Analysis Code for Core Flow Distribution in Pressurized SMR using MARS-KS

Juhyung Lee*, K. W. Seo, H. Kwon, S. J. Kim, H. Seo, D. H. Hwang,
SMART Reactor Design Division, Korea Atomic Energy Research Institute,
989-111, Daedeok-daero, Yuseong-gu, Daejeon, 34057, Korea
**Corresponding author: juhyunglee@kaeri.re.kr*

1. Introduction

A prototype of reactor has been studied in KAERI for design of integral-type small modular reactor (SMR) cooled by pressurized light water. The core of the prototype reactor consists of hundreds of closed-channel type fuel assemblies (FAs) connected in parallel to common headers at top and bottom of core, which is one of different core design features compared to existing commercialized pressurized water reactors (PWRs) using open fuel bundles. In this type of reactor, inlet core flow distribution is directly influencing on thermal margin of the core since the mass flow inflowed at each FA is axially maintained throughout the FA. Therefore, optimization of core flow distribution called "hydraulic profiling" becomes a main core thermal-hydraulic (T/H) design process for these reactors.

A computer code, COMA (Core One-dimensional Multichannel Analyzer) has been developed by KAERI in order to perform hydraulic profiling as well as hot channel analysis [1] for T/H design of the closed multichannel core.

In this study, a new methodology has been proposed to demonstrate hydraulic profiling performance and validity in core flow distribution analysis of COMA code for a core consisting of closed-channel type FAs, based on code-to-code validation using MARS-KS code.

2. COMA Code

Detailed description of COMA code can be found in references [1, 2], brief description of COMA code related to core hydraulic profiling and flow distribution optimization is only summarized:

2.1 Hydraulic Profiling

COMA code analyzes a closed multichannel core, considering each closed FAs as 1-D single channels. Cross-sectional average of thermal properties over flow area in single channel are used in T/H calculations. During the analysis, COMA code categorizes FAs into several hydraulic regions in which inlet orifices of FAs are equal to each other. Inlet loss coefficients of hydraulic regions are optimized to maximize thermal margin in thermally limited channel (hot channel) by performing calculations for entire burnup states of core. Code inputs include boundary conditions (BCs) such as FA geometric dimensions, core operating conditions, fuel loading pattern, and power distributions provided by nuclear design group.

Hydraulic profiling is performed by the code while satisfying with mass and momentum balances as follows:

The pressure drop through a channel *i*, will be the same with the core pressure drop;

$$\Delta P_i = \frac{1}{2} K_i' G_i^2 = \frac{1}{2} K_C' G_C^2 = \Delta P_C \tag{2.1}$$

which leads to

$$G_i / G_C = \sqrt{K_C' / K_i'} \tag{2.2}$$

where, $K'=K/\rho$ is the effective loss coefficient, K is the channel loss coefficient, ρ is the density, G is the mass flux, and i and C imply specific FA and core average, respectively.

Based on the continuity equation,

$$\sum_i G_i A_i = G_C \sum_i A_i \tag{2.3}$$

the effective loss coefficient of the core can be derived as

$$K_C' = \left\{ \sum_i A_i \Big/ \sum_i \frac{A_i}{\sqrt{K_i}} \right\}^2 \tag{2.4}$$

From Eqs. (2.2) and (2.4), it can be concluded that core flow distribution is determined when effective loss coefficients of all FAs are determined.

COMA code searches optimal channel loss coefficients (i.e. inlet loss coefficients for given pressure drop and outlet loss coefficients), while satisfying 1-D momentum balance which includes accelerational and gravitational terms as well:

$$\frac{dP}{dz} = \frac{1}{2}\left(\frac{K_{in,i}\Delta z_{in}}{\rho_{in}} + \frac{f_i}{D_{e,i}\bar{\rho}_i} + \frac{K_{out}\Delta z_{out}}{\rho_{out,i}} \right) G_i^2 + \frac{d}{dz}\left(\frac{1}{\rho_i}\right) G_i^2 + \bar{\rho}_i g \tag{2.5}$$

2.2 COMA Friction Factor

As seen in Eq. (2.5), friction factor is one of important parameter determining channel loss coefficients, and that is different from the model implemented in MARS-KS code. In COMA code, Reynolds number dependent model similar to Blasius & McAdams friction factor is adopted:

$$f_{iso} = a\,\mathrm{Re}^{b} \tag{2.6}$$

where a and b are given from the user in code input, which are determined based on out-pile testing of FAs.

The friction model described above applies to unheated surfaces. It is required to correct isothermal friction factor in order to consider the variation of fluid viscosity near a heated surface. COMA code adopted the correction relationship proposed by Sieder and Tate [3]:

$$f / f_{iso} = \left(\mu_{wall} / \mu_{bulk}\right)^{0.14} \tag{2.7}$$

where, μ_{wall} and μ_{bulk} are viscosities at wall and bulk temperatures, respectively.

3. MARS-KS Modeling

MARS-KS code is a best-estimate multi-dimensional system code developed by KAERI, based on consolidation of the RELAP5/MOD3 and COBRA-TF codes [4]. Since various thermal-hydraulic models for nuclear system and components are provided by the code, MARS-KS code is adopted for code-to-code validation of hydraulic profiling result from COMA code.

3.1 Parallel Multichannel Core Modeling

Fig. 1 shows MARS-KS model invented for simulating a core consisting *NN* parallel closed FAs. As shown in the figure, the core model has lower and upper plenum (snglvol 200 & 900) where flows are distributed and merged, respectively. In order to impose inlet and outlet BCs such as core mass flow rate ($\dot{m}$), core inlet temperature (T_{in}), and system pressure (P_{out}), single time-dependent junction (tmdpjun 150) and two time-dependent volumes (tmdpvol 100 & 990) are adopted. Each FA is modeled using pipe component (pipe 5NN) combined with heat structures imposed convective and insulated BCs at inner and outer surfaces to reflect core power distribution ($\dot{Q}_{NN}$). Two single volumes (snglvol 3NN & 7NN) connected to pipe components are involved for simulating an entrance and a riser of FA. Inlet and outlet hydraulic losses ($K_{in,NN}$ & $K_{out,NN}$) can be set by inputs for two single junctions (sngljun 4NN & 6NN) which are connected to the pipe component. All FAs are combined with two plenum using two multiple junctions (mtpljun 250 & 850) which consists of *NN* single junctions. In addition to inputs mentioned above, geometric configurations such as flow area ($A_{c,NN}$), equivalent diameter ($D_{e,NN}$), and heated perimeter ($P_{h,NN}$) of each FA are reflected on corresponding components illustrated in the figure.

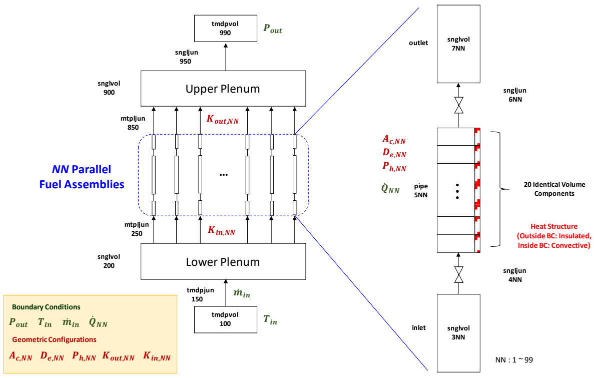


Fig. 1. MARS-KS model for closed multichannel core

3.2 MARS-KS Friction Factor

The models of single-phase isothermal friction factor for laminar and turbulent flow regions adopted in MARS-KS [5] are listed below.

- Laminar region ($0 < \mathrm{Re} \le 2200$); Darcy-Weisbach

$$f_{iso} = 64 / \left(\mathrm{Re}\,\Phi_s\right) \tag{3.1}$$

- Turbulent region ($\mathrm{Re} \ge 3000$); Zygrang-Sylvester [6]

$$\frac{1}{\sqrt{f_{iso}}} = -2\log_{10}\left\{\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}}\left[1.114 - 2\log_{10}\left(\frac{\varepsilon}{D} + \frac{21.25}{\mathrm{Re}^{0.9}}\right)\right]\right\} \tag{3.2}$$

For transition region ($2200 < \mathrm{Re} \le 3000$), the friction factor is calculated by reciprocal interpolation.

Similar to COMA code, MARS-KS code is correcting friction factor for heated wall cases in relation of

$$\frac{f}{f_{iso}} = 1 + \frac{P_h}{P_w}\left[\left(\frac{\mu_{wall}}{\mu_{bulk}}\right)^{D} - 1\right] \tag{3.3}$$

where, P_w and D are wetted perimeter and viscosity ratio exponent. In order to match correction factor from COMA code (i.e., Eq. (2.7)), D=0.14 and P_h= P_w are set in the inputs for heat structures.

4. Validation Methodology

4.1 Friction Comparison

As seen in the previous chapter, isothermal friction models between COMA and MARS-KS codes are different from each other, which can cause differences in effective FA loss coefficients as well as core flow distribution even for same BCs and geometric configuration. Fig. 2 shows comparison between friction models for normal operating condition with the assumption of core average temperature ($T_{avg} = (T_{in} + T_{out})$

/2). As seen in the figure, COMA code predicts 16% higher friction factor than MARS-KS model predicts under smooth surface condition (ε = 1.0 μm). This discrepancy can be decreased by increasing wall roughness and calculated friction factors become equal at relatively rough surface condition (ε = 5.0 μm). Since friction models are dependent on Re as well, discrepancy of code predictions can also change according to Re (Fig. 3).

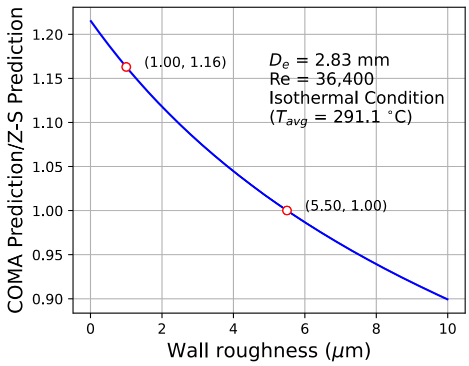


Fig. 2. Comparison between single phase friction models of COMA and MARS-KS codes (vs. wall roughness).

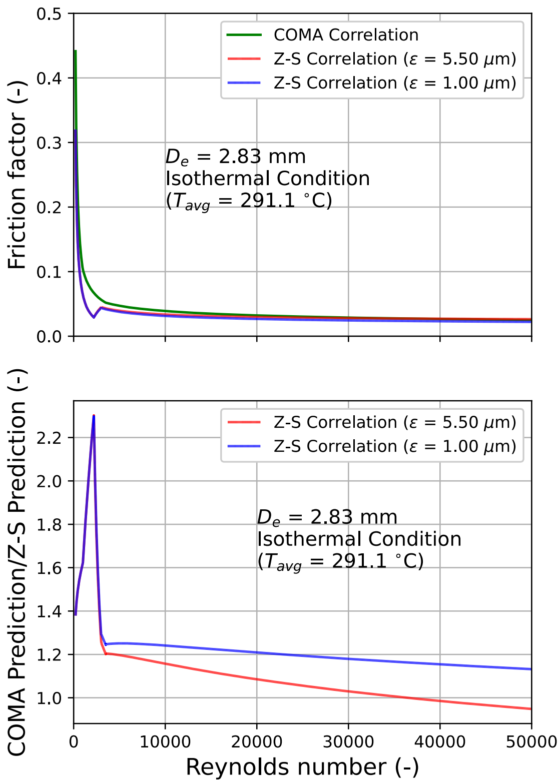


Fig. 3. Comparison between single phase friction models of COMA and MARS-KS codes (vs. Reynolds number).

4.2 Roughness Optimization

In this study, both smooth surface (ε = 1.0 μm) and rough surface (ε = 5.0 μm) conditions are reflected on MARS-KS simulations to see effects of friction factor model on code-to-code validation. The case of rough surface is considered as an optimized model at the core-scale level since both predictions for friction factor become identical at core averaged flow and temperature conditions. Furthermore, roughness distribution can be optimized at FA scale level based on flow predictions of COMA code as seen in Fig. 4. One example of optimized roughness distribution on the basis of FA to eliminate friction model effect in code-to-code validation is shown in Fig. 5. It shows that more rough surfaces of FAs in outside hydraulic region are required to match friction losses between two codes due to relatively low mass fluxes in that region (see Fig. 3). MARS-KS simulation with optimized roughness distribution is also included in code-to-code validation of COMA code.

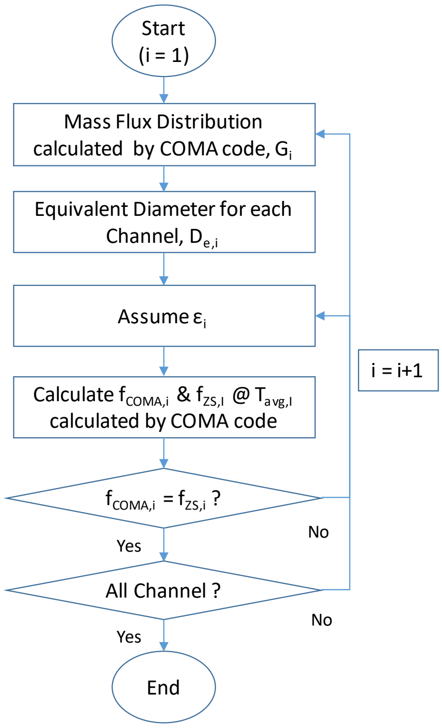


Fig. 4. Optimization of FA wall roughness for code-to-code validation – process

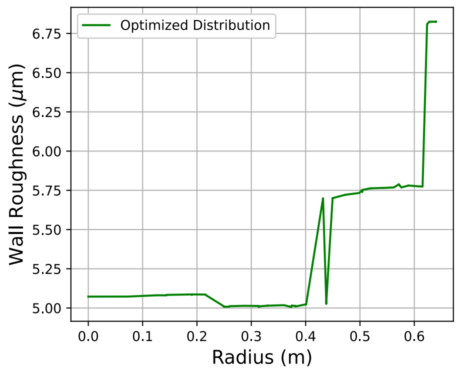
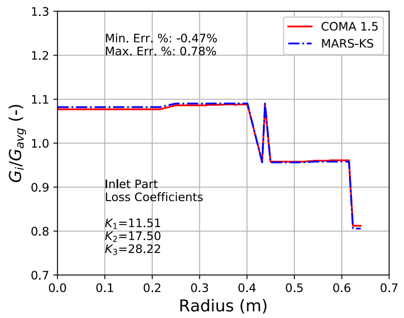


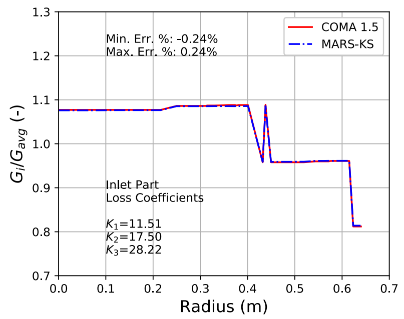
Fig. 5. Optimization of FA wall roughness for code-to-code validation – result

5. Results and Discussion

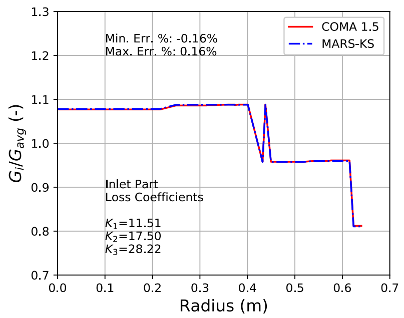
The code-to-code validation results for FA flow distribution under a reference operating condition are shown in Fig. 6 in which the origin indicates the core center and FA mass fluxes are normalized by core average. As seen in Fig. 6 (a), it was found that MARS-KS model with smooth surface predicts more flow is introduced into core center due to relatively low friction calculation. The prediction ratio is less sensitive to flow rate in this case (Fig. 3). In the case of rough condition, however discrepancies between two friction models are reduced more at high Re which implies more increase of friction factor with higher flow region. Therefore, core flow is more distributed to the outer FAs in MARS-KS simulation with rough surfaces and the difference between code predictions is highly reduced (Fig. 6 (b)). As expected, a better agreement between COMA and MARS-KS codes is achievable when roughness distribution is optimized based on FAs (Fig. 6 (c))



(a) ε = 1.00 μm



(b) ε = 5.50 μm



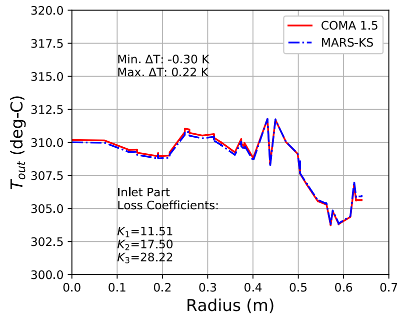
(c) ε_i optimized for T_i

Fig. 6. Code-to-code validation results – flow distribution

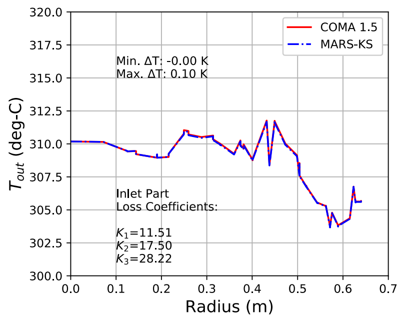
Core outlet temperature distributions predicted by two codes are also compared as shown in Fig. 7. Fairly good agreement between two codes is found for core-wise and FA-wise optimized MARS-KS models. The small differences are expected to be related to minor differences in model and method such as thermal property calculation or numerical scheme. Finally, results of code-to-code validation are summarized in Table I. In terms of equilibrium quality, discrepancy of predictions between two codes is less than 0.1 %.

Table I: Summary of code-to-code validation - prediction differences

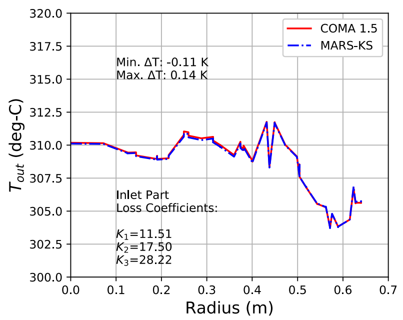
Distribution	Smooth surface (ε = 1.0 μm)	Core wise averaged (ε = 5.5 μm)	FA wise averaged (ε_i optimized)
Flow	-0.47 ~ 0.78 %	-0.24 ~ 0.24 %	-0.16 ~ 0.16 %
Exit Temp.	-0.30 ~ 0.22 K	-0.00 ~ 0.10 K	-0.11 ~ 0.14 K
Exit Quality	< 0.002	< 0.001	< 0.001



(a) ε = 1.00 μm



(b) ε = 5.50 μm



(c) ε_i optimized for T_i

Fig. 7. Code-to-code validation results – exit temperature

6. Conclusions

In this study, code-to-code validation using MARS-KS code has been performed to validate prediction capability of COMA code for hydraulic profiling and flow distribution in a core consisting of closed-channel type fuel assemblies. A MARS-KS model for parallel multichannels simulating the closed multichannel core is newly devised. In addition, validation methodology and process are proposed to overcome differences between implemented friction models which can cause discrepancy between codes. Fairly good agreement between two codes is achieved in the code-to-code validation, which can be concluded that COMA code is reasonably valid for simulating flow distribution in a closed multichannel core.

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