Thermo-Fluid Analysis of Core of Prismatic Very High Temperature Reactor using Looped Network Analysis

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1. Introduction

The core of the prismatic very high temperature reactor (VHTR) consists of hexagonal prismatic fuel blocks and reflector blocks made of nuclear grade graphite. There are interstitial gaps between blocks and the gap varies during core cycles due to the neutron-induced shrinkage and thermal expansion. If the core bypass flow ratio increases, the coolant channel flow is decreased and it can deteriorate the heat removal efficiency, resulting in a locally increased fuel block temperature.

Recently, the computational fluid dynamics (CFD) method has received a great deal of attention as a method for understanding the flow behavior in the VHTR core. However, the large computational cost and time required to implement CFD codes simulating the entire core hinder their application to analysis of the gap effect. The calculation time of design code is one of critical features since various design options and conditions should be considered and covered. Therefore, to analyze flow distribution in the core of VHTR effectively, the flow network analysis code named FastNet (Flow Analysis for Steady-state Network) which uses looped network analysis method was developed in this study.

In the VHTR core, there are three types of flow paths: coolant channel, bypass gap, and cross gap as seen in Fig. 1. The flow network analysis code presents flow paths as a network of flow resistance models. Through the models, the flow distribution can be predicted in simple way.

For heat transfer analysis, since the solid cell size is 1/6 of fuel block, the effective thermal conductivity (ETC) model was adopted for fuel blocks and the maximum fuel temperature model using unit-cell analysis was implemented.

For whole core simulation, a 3-dimensional flow network was modeled and the calculation results were compared with CFD analysis and CORONA [1] calculation results.

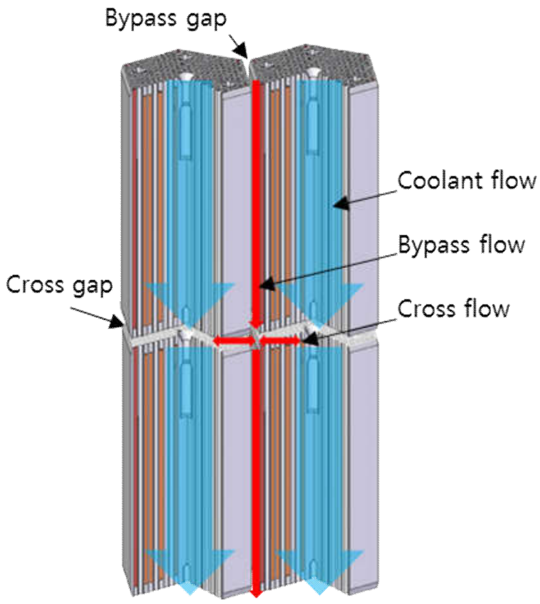

Fig. 1. Core flows in the core of prismatic VHTR

2. Governing Equations

The governing equations are based on Kirchhoff's circuit laws [2]. First, the algebraic sum of inflow and out flow discharges at a node is zero. Second, the algebraic sum of the pressure drop around a loop is zero.

2.1 Conservation of Mass

The mass conservation equation is established based on the law that the sum of inflow and out flow discharges at a node is zero.

$$F_j = \sum_{n=1}^{j_n} m_{jn} = 0 \tag{1}$$

Where m_{jn} is the inlet flow from *n-th* pipe at node *j*, and j_n is the total number of pipes at node *j*. This mass equation is used at every node in the system and so, it can be referred as nodal equation.

2.2 Conservation of Momentum

The momentum conservation equation can be represented with pressure drop. The sum of the pressure drop along a loop, as one reaches at the starting node, the net pressure drop is zero.

$$F_k = \sum_{n=1}^{kn} R_{kn} \left| m_{kn} \right| m_{kn} = 0 \tag{2}$$

Where k_n is the total number of pipes at the *k-th* loop. Since one loop has one pressure drop equation, it can be referred as loop equation.

2.3 Heat Transfer Analysis

Heat transfer analysis of FastNet consists of solid conduction and fluid heat transfer analysis. The solid conduction equation can be written as Eq. (3).

$$k_{s,i} \frac{A_{s,i}}{\delta} \left(T_{s,P} - T_{s,i} \right) = Q_{conv,s,P} \tag{3}$$

Where k, A, δ, T, and $Q_{conv,s,P}$ are thermal conductivity, surface area of the solid, distance between solid node P and solid node i, temperature, and convective heat transfer at solid node P. Subscript "s,i" is for solid node i and "s,P" is for solid node P.

The fluid energy equation can be expressed as Eq. (4)

$$\dot{m}_{f,i} C_p \left(T_{f,j+1} - T_{f,j} \right) = Q_{conv,f,i} \tag{4}$$

Where, $\dot{m}_{f,i}$, Cp, T and $Q_{conv,f,i}$ are mass flow rate at i-th flow path, specific heat, temperature, and convective heat transfer at i-th flow path. Subscript "$f,j+1$" and "f,j" is fluid node at the ends of i-th flow path.

Since the FastNet code solves fluid mass and momentum equations and fluid energy equation separately, the solid-fluid connectivity equation is required as Eq. (5).

$$Q_{conv,s,P} = Q_{conv,f,i} = h_{f,i} A_{f,i} \left(T_{s,i} - T_{f,i} \right) \tag{5}$$

Where $Q_{conv,s,P}$, $Q_{conv,f,i}$, $h_{f,i}$, $A_{f,i}$, $T_{s,i}$ and $T_{f,i}$ are convective heat transfer at solid node P, convective heat transfer at i-th flow path, heat transfer coefficient at i-th flow path, surface area at i-th flow path, temperature at solid node i, and temperature at i-th flow path.

The heat transfer coefficient is written as Eq. (6).

$$h = Nu \frac{k_f}{D_h} \tag{6}$$

FastNet uses a Nusselt number correlation for turbulence as Eq. (7).

$$Nu = 0.021 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \tag{7}$$

And for laminar flow as Eq. (8).

$$Nu = 4.364 \tag{8}$$

Where, h is heat transfer coefficient, Nu is Nusselt number, k_f is thermal conductivity of fluid, D_h is hydraulic diameter, Re is Reynolds number, and Pr is Prandtl number.

2.4 Effective Thermal Conductivity Model

Since FastNet allocates 6 cells for one fuel block, graphite block which contains multiple materials such as fuel compact, coolant hole, and fuel gap is regarded as homogeneous block which has effective thermal conductivity for radial conduction as shown in Fig. 4.1. The ETC model in FastNet is based on the Selengut relation [3] which was derived by the Maxwell model. In addition, the radiation effect was applied to the form of the corresponding conductivity to the gas conductivity. Thanks to the simple form of the model, it has the advantage of saving computing resources. The model is expressed as Eq. (9)

$$k_{eff,radial} = k_{out} \frac{1 - \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)}{1 + \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)} \tag{9}$$

Where, α_i is volume fraction of i-th dispersed component and k_i and k_{out} are conductivity of i-th dispersed component and conductivity of continuous component such as graphite, respectively.

The volume fractions of materials can be obtained as Eq. (10).

$$\alpha_i = \frac{Volume_i}{Volume_{Cell}} \tag{10}$$

For axial conduction, the form ETC model can be written as Eq. (11).

$$k_{eff,axial} = \sum_{i=1}^{N} \alpha_i k_i \tag{11}$$

2.5 Maximum Fuel Temperature Model

Because of its coarse mesh, detailed temperature distribution in the fuel block cannot be confirmed. The maximum fuel temperature should be predicted because the maximum fuel temperature is a key parameter of evaluating thermal margin of core of VHTR. To handle this problem, the maximum fuel temperature (MFT) model was introduced. The MFC model predicts the temperature at fuel center using unit-cell model of coolant channel, graphite, and fuel compact. The introduced model uses 1-D estimated conductivity for 2-D conduction problem for unit cell as described in Fig. 4.3.

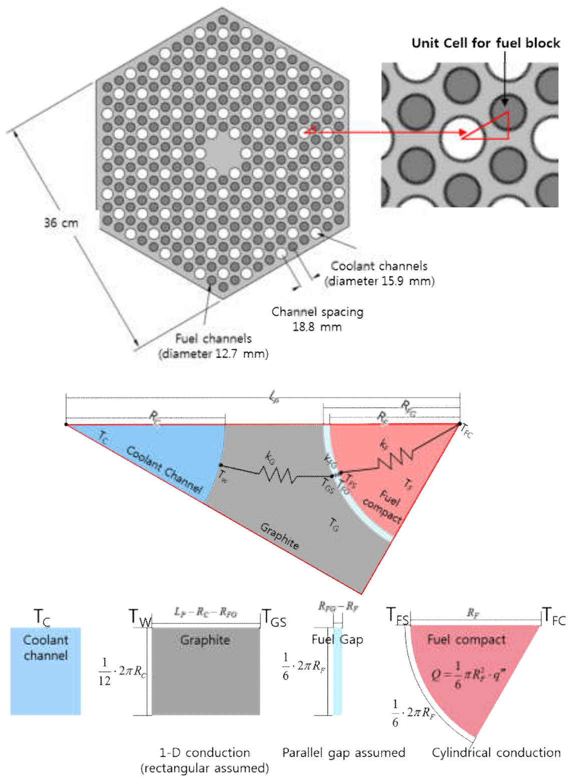

Fig. 2. 1-D estimated conduction in unit-cell model for predicting maximum fuel temperature

3. Code to Code Validation

3.1 Single Column Analysis

To evaluate the calculation capability of FastNet, a single column analysis was simulated and compared with CFD analysis and CORONA calculation results. 9 layers (6 fuel layers) were assumed and the bypass gap was set to 1 mm. CFX turbulence model was selected to RNG k- ε model. The comparison results of axial temperature distributions at the center of the hottest fuel compact were seen in Fig. 3. FastNet prediction results show good agreement with CFD analysis and CORONA calculation results. The most important characteristic of FastNet is the calculation speed. The calculation times of CFD, CORONA, and FastNet for a single column analysis are 46 hours, 362 seconds, and 0.5 seconds, respectively. It means that the calculation speed of FastNet is 700 times faster than that of CORONA in single column analysis.

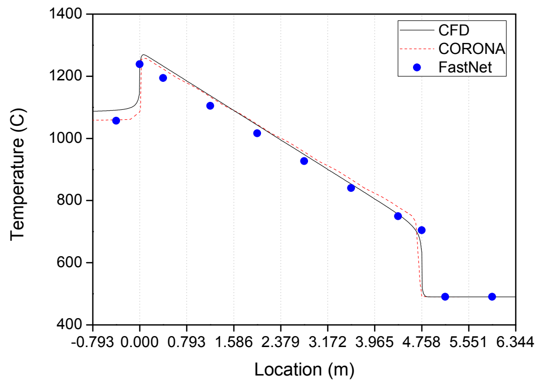

Fig. 3. Comparison results of FastNet prediction, CFD analysis, and CORONA calculation (axial distribution of hottest fuel compact)

3.2 Whole Core Analysis

To confirm calculation performance of FastNet, whole core analysis of 1/6 model of VHTR 350 MWth was carried out. The reference model is described in Ref. [4]. 6 layers and 36 columns were simulated and bypass gap was set to 2 mm. Block configuration and fuel column indexing number with power peaking factor were presented in Fig. 4. The comparison results of temperature distribution at the hot spot plane are seen in Fig. 5. The temperature distribution results of CFD, CORONA, and FastNet are in good agreement. And the difference of maximum temperature in the fuel columns between CFX and CORONA is 48°C while CFX and FastNet is 56°C. Moreover, the average differences of maximum temperatures are 25.55°C for CFX and CORONA while 23.6°C. Therefore, it can be said that the accuracy of FastNet for maximum temperature prediction is similar to that of CORONA. The calculation time of FastNet is about 30 seconds, whereas that of CORONA is 7,620 seconds with a single processor (i7-3.5GHz) calculation for whole core simulation. Even with parallel computation of CORONA, it takes about 1,980 seconds, which is much slower than FastNet's single-thread calculation. The calculation speed of FastNet over that of CORONA is tabulated in Table 1.

Table I: Calculation speed of FastNet over that of CORONA

Case		FastNet calculation speed compared to CORONA
Single column analysis		X 700
Whole core analysis	Parallel core	X 66
	Single core	X 254

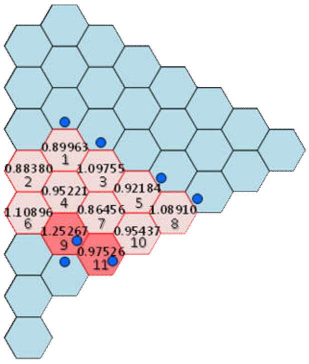

Fig. 3. Fuel column number and power peaking factor

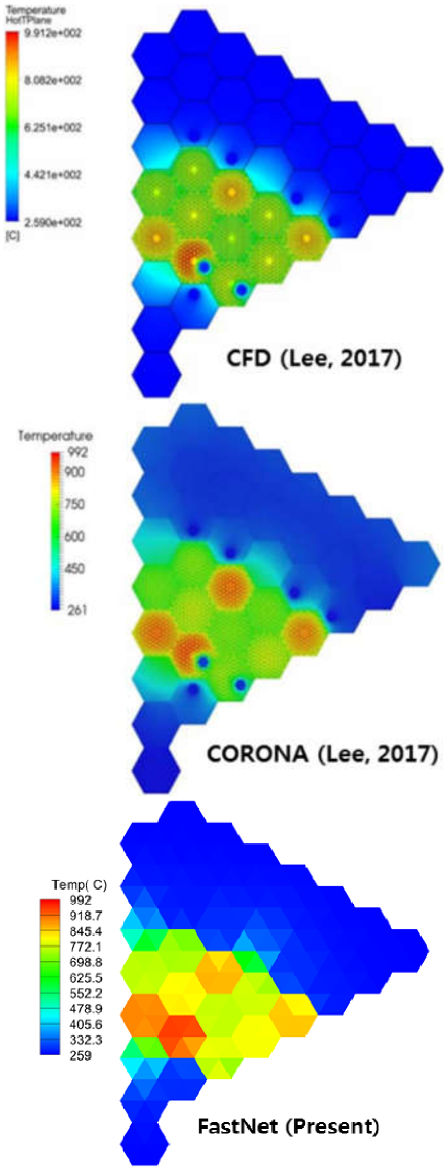

Fig. 4. Comparison results of temperature distributions at the hot spot plane (CFX, CORONA, and FastNet)

4. Conclusions

A flow network analysis code, FastNet (Flow Analysis for Steady-state Network), was developed for thermo-fluid analysis of prismatic VHTR core. For quick and simple calculations, looped network analysis method was implemented. In order to overcome its coarse mesh, ETC model was applied and maximum fuel temperature model which uses unit-cell analysis was developed and implemented to FastNet.

FastNet was validated by comparing prediction results with CFD analysis and CORONA calculation. From the validation results, the thermo-fluid analysis capability of FastNet was verified with single column analysis and whole core simulation. Not only the calculation results were in good agreement with the results of other codes, but also the calculation time of FastNet was much lower than that of other codes.

Thanks to its quick calculation, FastNet can be used for preliminary calculations for core of prismatic VHTR. It is highly expected that the FastNet code can contribute to assure the core thermal margin by predicting the bypass flow in the whole core of prismatic VHTR.

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