Flow Distribution Analysis of Core of Prismatic VHTR using Looped Network Analysis Method

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1. Introduction

The Prismatic Modular Reactor (PMR) is one of the VHTR concepts, of which core is composed of hexagonal prismatic graphite fuel blocks and reflector blocks. It is difficult to predict flow distribution of core of PMR due to its inherent complex geometry. For analysis flow distribution of the core of PMR, the CFD analysis has been used. However, CFD analysis requires vast computation cost and time. The fuel block can be deformed by neutron damage and thermal expansion, which leads to changes in bypass gap. This variation makes the prediction of the flow distribution more difficult. Moreover, for design the reactor, lots of gap conditions should be considered and the CFD has limitation in calculating whole conditions. To solve this problem, in this study, the flow network analysis code, FastNet (Flow Analysis for Steady-state Network), was developed using the Looped Network Analysis Method [1]. FastNet consists of flow path resistance models and through the models, the flow distribution can be predicted in simple way. The calculation results were validated by comparing with SNU VHTR multi-block experiment. A 3-dimensional flow network was modeled and the calculation results was compared with the experimental data.

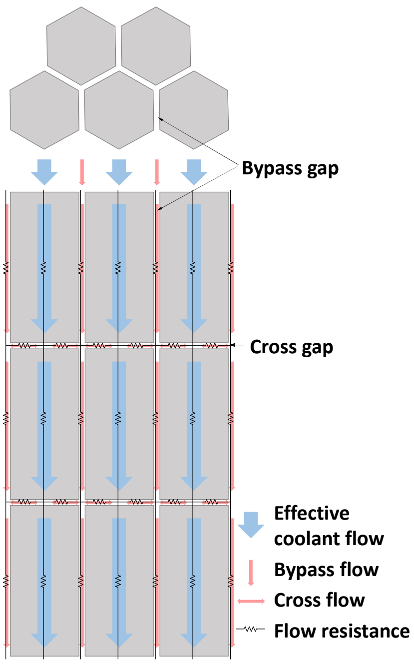

Fig. 1. Conceptual diagram of PMR core and flow network

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).

$$\sum \left(\frac{k_{eff,i} + k_{eff,n}}{2} A \frac{T_i - T_{s,n}}{\delta} \right) = -\sum \left(h_{f,j} A_{ch} \left(T_{f,j} - T_{s,n} \right) \right) - q'' \tag{3}$$

Where $k_{eff,i}$ is *i-th* solid cell's effective thermal conductivity and $k_{eff,n}$ is *n-th* solid cells which is n-th cell's effective thermal conductivity.

Since the solid cell size is 1/6 of fuel block as seen in Fig. 2, to calculate radial heat transfer effectively, a single conductivity over one solid cell is used. FastNet uses the ETC (Effective Thermal Conductivity) model for solid conduction and the ETC model based on Maxwell model was validated by Shin (2015) [3]. The ETC model can be written as Eq. (4).

$$k_{eff} = k_{out} \frac{1 - \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)}{1 + \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)} \tag{4}$$

Where α_i is volume fraction of i-th dispersed component, k_i is conductivity of i-th dispersed component (coolant, fuel) and k_{out} is conductivity of continuous component (graphite).

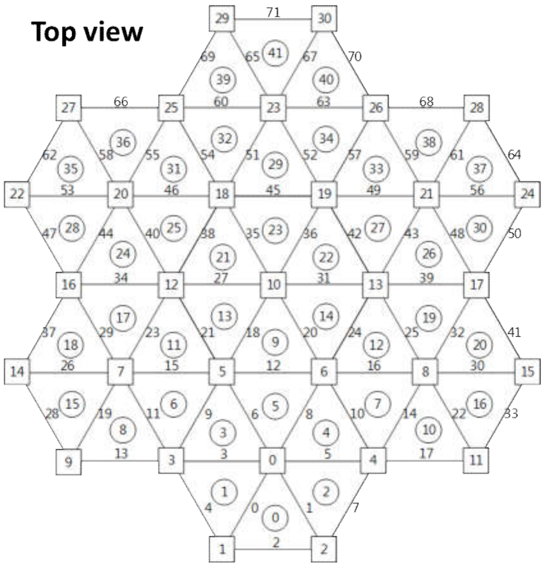

Fig. 2. Solid grid for 7 columns for conduction analysis

The fluid heat transfer analysis is calculated layer by layer. At first the fluid temperature of the top layer rises by the heat from the solid. The equation can be expressed as Eq. (5). Then, the fluid at the cross gap, the lateral thermal fluid mixing was calculated as following Eq. (6) (Fig 3.).

$$mC_P \left(T_{f,down} - T_{f,up} \right) = hA\left(T_s - T_f \right) \tag{5}$$

$$\sum m_{in} C_P T_{in} = \sum m_{out} C_P T_{out} \tag{6}$$

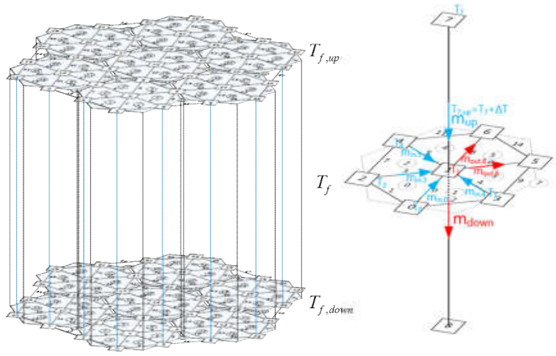

Fig. 3. Domain for fluid heat transfer analysis; temperature rising due to solid and lateral thermal fluid mixing

4. Calculation Results

To verify calculation capability of the FastNet, the SNU multi-block experiment [4] results were used. The test facility is composed of 4 layers axially and 7 columns for a layer. 5 columns are fuel block columns and 2 columns are reflector block columns. Fig. 4 shows the experimental facility and 3-D flow network model for FastNet.

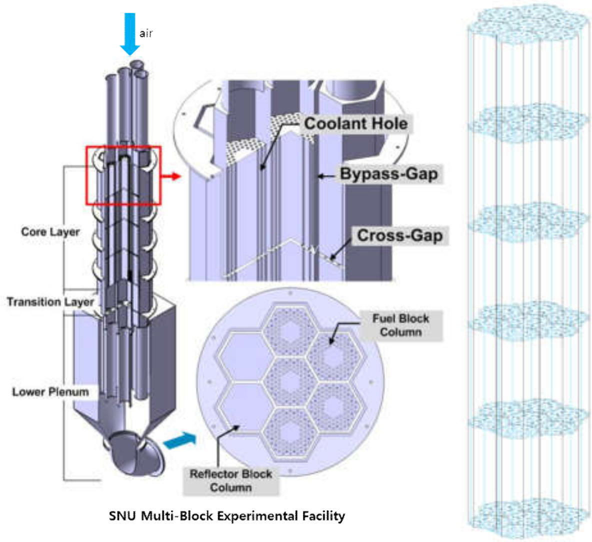

Fig. 4. SNU multi-block experimental facility [2] and 3-D flow network model for FastNet.

Fig. 5. Shows the flow chart of the FastNet code. At first, the code read input data and geometrical information. And then, the flow distribution was calculated. After that, based on the calculated flow distribution, solid conduction was predicted. Then, the fluid temperature was calculated layer by layer and this process will be repeated until the difference between previous and obtained values reaches desired value.

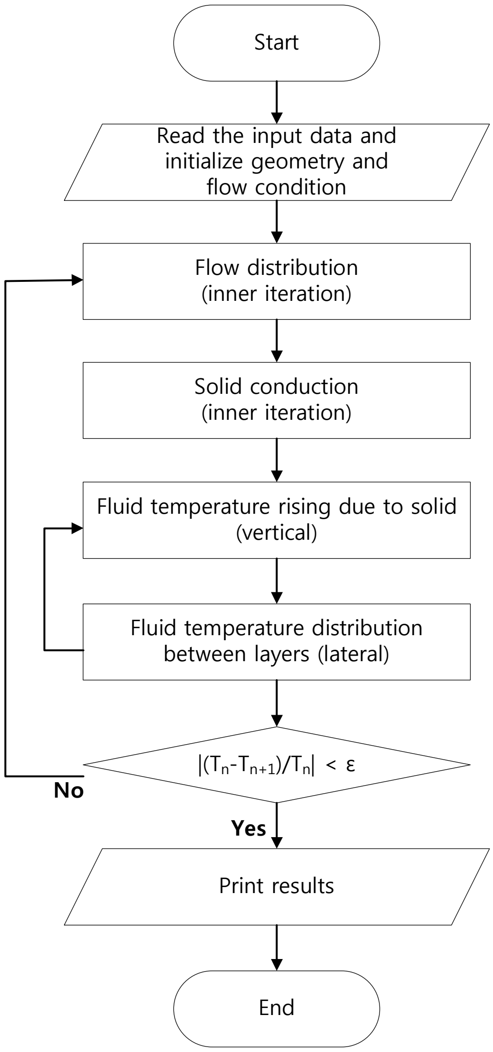

Fig. 5. Flow chart of FastNet calculation procedure

Fig. 6 shows the comparison results of bypass flow ratio between experiment and FastNet calculation. The bypass gaps are 6, 2, 4, 2 mm for each layer and cross gap is 2 mm. The slight discrepancy was from the uncertainty of the experiments such as block arrangement and gap size controlling.

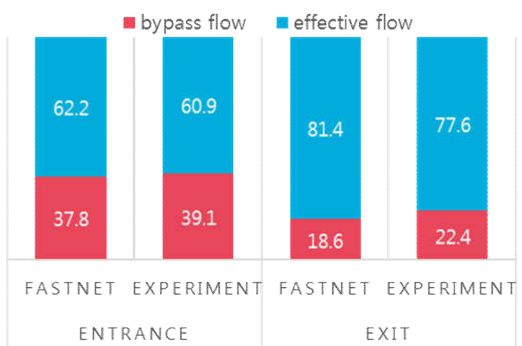

Fig. 6. Comparison results between experiment and FastNet: bypass flow ratio (BG6242-CG2)

For the pressure drop, the FastNet code slightly underestimates as seen in Fig. 7. However, considering the uncertainty of the experiment, it can be said that the FastNet code shows reasonable results.

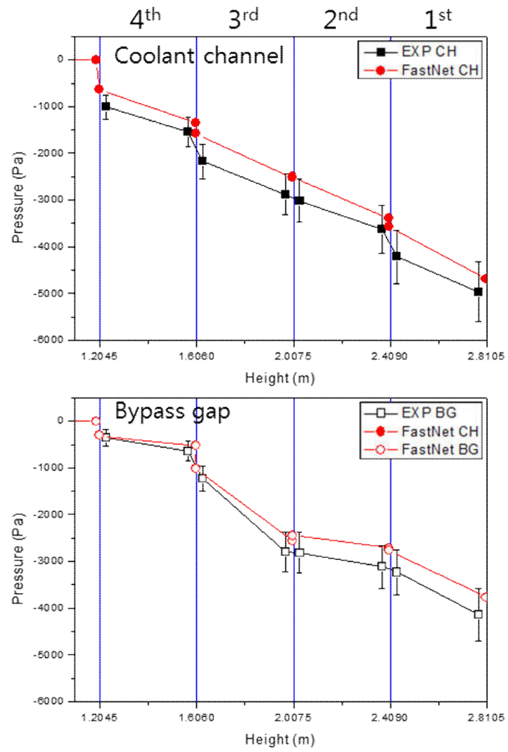

Fig. 7. Comparison results between experiment and FastNet: pressure drop (BG6242-CG2)

For verification of heat transfer analysis, simple analysis with 7 column and single fuel assembly column analysis are being carried out as presented in Fig. 8. For verification of capability of FastNet, single fuel assembly column analysis results will be compared to results of commercial CFD code and other existing codes analyses. After that, it will be extended to whole core analysis and the validation work will be conducted.

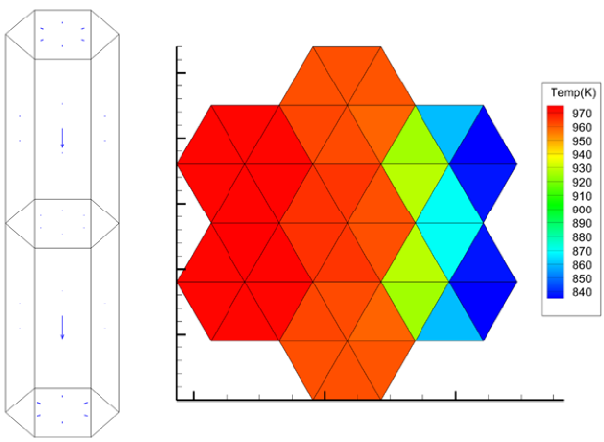

Fig. 8. FastNet single fuel assembly analysis and heat transfer analysis

5. Conclusions

Flow network analysis code, FastNet, has been developed to predict the core flow distribution and temperature distribution of the core of prismatic VHTR. The flow distribution can be predicted properly in short time and the results was compared with SNU multi-block experimental data for validation. Now the thermal analysis module is being developed. Finally, it is expected that the FastNet code can analyze whole core analysis of the Prismatic VHTR.

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