Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 24-25, 2013

One-Dimensional Flow Network Model for Thermo-Fluid Analysis of Prismatic Gas-Cooled Reactor Core

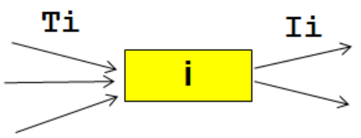
Nam-il Tak*, Sung Nam Lee, Min-Hwan Kim, and Hong Sik Lim
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon 305-353, Korea
**Corresponding author: takni@kaeri.re.kr*

1. Introduction

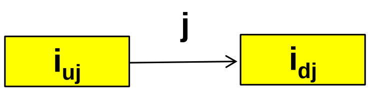
In a prismatic gas-cooled reactor core, most of the helium coolant flows through the coolant channels within the fuel block and a small fraction of the coolant bypasses the fuel block and flows through the bypass gap or the control hole. There is no flow mixing among these flows at the active region of the core except the narrow space between horizontal faces of fuel blocks (named crossflow gap). As like the previous CORONA calculations [1], lots of preliminary design and core survey calculations often neglected the crossflow effect in the thermo-fluid analyses of a prismatic-gas cooled reactor core [2]. In order to improve the accuracy of the CORONA prediction, a one-dimensional fluid flow network model has been implemented into the CORONA code by the consideration of the crossflow. This paper presents the theory of the adopted fluid flow model and a validation result of the CORONA prediction.

2. Theory

A fluid flow network model implemented into the CORONA code is based on the pressure correction method [3~5]. Fig. 1 shows the concept of node and junction to derive the mathematical formulation for arbitrary network of one-dimensional fluid flow.



(a) fluid node with initiating and terminating junctions



(b) junction between upstream and downstream nodes

Fig. 1. Concept of node and junction for fluid network.

At first, the continuity equation is applied at a one-dimensional fluid node (i) having arbitrary number of initiating junction (I_i) and terminating junction (T_i) shown in Fig. 1(a).

$$\sum_{j\in T_i}\rho_j Q_j - \sum_{j\in I_i}\rho_j Q_j = 0 \qquad (1)$$

For a junction (j) having upstream fluid node (i_{uj}) and downstream fluid node (i_{dj}) shown in Fig 1(b), the pressure drop relationship can be expressed as:

$$P_{i,dj} - P_{i,uj} + \frac{1}{2} f_j \frac{\Delta x_j}{D_j} \rho_j \frac{Q_j|Q_j|}{A_j^2} = 0 \qquad (2)$$

The first step to solve Eqs. (1) and (2) is to guess pressures at all nodes. These values are treated as preliminary values and donated by $\overline{P}$. The correction δP is defined as the difference between the correct pressure field P and the guessed pressure field $\overline{P}$.

$$P = \overline{P} + \delta P \qquad (3)$$

Similarly, volumetric flow rate correction δQ and density correction $\delta\rho$ are defined as:

$$Q = \overline{Q} + \delta Q \qquad (4)$$

$$\rho = \overline{\rho} + \delta\rho \qquad (5)$$

The density of gas can be obtained using the ideal gas law.

$$\rho = \frac{P}{RT} \qquad (6)$$

Substitution of Eqs. (3)~(6) into the momentum equation (i.e., Eq. (2)) and neglecting the terms involving products of corrections yield the following equation for the volumetric flow rate correction.

$$\delta Q_j = \frac{1}{2C_j\overline{\rho}_j|\overline{Q}_j|}\times \left\{(1-G_j)\delta P_{i,uj} - (1+G_j)\delta P_{i,dj} + \overline{P}_{i,uj} - \overline{P}_{i,dj} - C_j\overline{\rho}_j\overline{Q}_j|\overline{Q}_j|\right\} \qquad (7)$$

Where

$$C_j = \frac{1}{2} f_j \frac{\Delta x_j}{D_j}\frac{1}{A_j^2} \qquad (8)$$

$$G_j = \frac{C_j\overline{Q}_j|\overline{Q}_j|}{2RT_j} \qquad (9)$$

Finally, substitution of Eqs. (4), (5) and (7) into the continuity equation (i.e., Eq. (1)) yields the following equation for the pressure correction.

$$\left[\sum_{j\in T_i} a_j + \sum_{j\in I_i} b_j\right]\delta P_i + \sum_{j\in T_i} c_j \delta P_{i,uj} + \sum_{j\in I_i} d_j \delta P_{i,dj} = s_j \quad (10)$$

In the case of a single pipeline, Eq. (10) can be solved with the tri-diagonal matrix algorithm (TDMA) while sparse matrix techniques can be employed in the case of complex flow networks.

With the known field of δP_i, δQ_i can be obtained using Eq. (7). Then new values for P_i, Q_i, ρ_i are determined using Eqs. (3), (4), and (6). The newly updated values are now considered as the preliminary values for the next iteration and the whole process is repeated until the converged values are obtained.

3. Validation

In order to validate the one-dimensional fluid flow network model implemented in CORONA, a crossflow experimental data measured by Kaburaki and Takizuka [6] was used. Fig. 2 shows the schematic of their experimental apparatus. Four graphite blocks were stacked up in a column (total height = 2.281 m) and were surrounded by the steel shroud to simulate the bypass gap (~1.2mm) between fuel columns. The hexagonal fuel block has 12 coolant holes with 20 mm in diameter. One artificial cross flow gap (~1 mm) was created in the middle of the column to simulate a crossflow gap between fuel blocks.

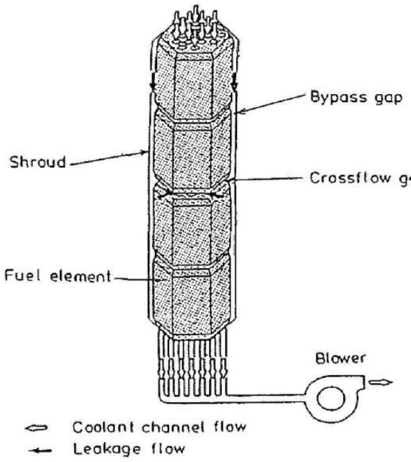


Fig. 2. Schematic of Kaburaki and Takizuka experimental apparatus for crossflow [6].

Fig. 3 shows the comparison of the CORONA prediction results with the measured pressures. A good agreement can be seen along the whole stacks. It means that the described one-dimensional fluid flow model is correctly implemented into the CORONA code and enough to consider the crossflow gap effect.

4. Conclusions

In this work, the one-dimensional fluid flow network model was implemented into the CORONA code and the implementation was validated using the Kaburaki and Takizuka experiment. Further verification study using CFD results is presented in the companion paper [8]. The verification and validation studies show that the adopted model is efficient and accurate for the prediction of fluid flow in a prismatic gas-cooled reactor core.

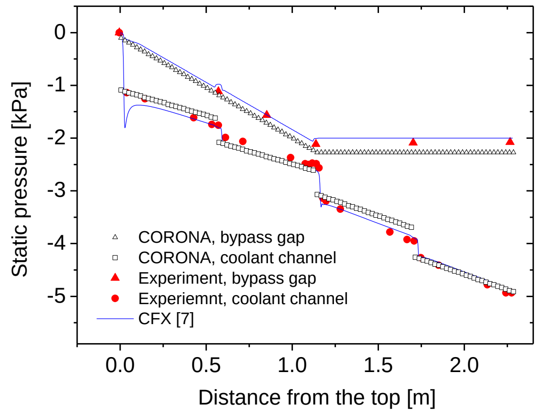


Fig. 3. Validation result of the CORONA calculation using the fluid flow network model.

Acknowledgements

This work was supported by Nuclear R&D Program of the NRF of Korea grant funded by the Korean government (Grant code: NRF-2012M2A8A2025679).

REFERENCES

[1] N.I. Tak, M.H. Kim, H.S. Lim, and J.M. Noh, "A Practical Method for Whole Core Thermal Analysis of Prismatic Gas-Cooled Reactor," *Nucl. Technol.*, **Vol. 177**, p. 352, 2012.
[2] G. Melese and R. Katz, Thermal and Flow Design of Helium-Cooled Reactors, American Nuclear Society, Illinois USA (1984).
[3] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere, New York, 1980.
[4] G.P. Greyvenstein and D.P. Laurie, "A Segregated CFD Approach to Pipe Network Analysis," Int. J. Numer. Meth. Engng , **Vol. 37**, p. 3685, 1994.
[5] G.P. Greyvenstein, "An Implicit Method for the Analysis of Transient Flows in Pipe Networks," Int. J. Numer. Meth. Engng, **Vol. 53**, p. 1127, 2002.
[6] H. Kaburaki and T. Takizuka, "Effect of Crossflow on Flow Distribution in HTGR Core Column," J. Nuclear Science & Tech., **Vol. 24**(7), p. 516, 1987.
[7] N.I. Tak, M. H. Kim, and W.J. Lee, "A Benchmark CFD Calculation for a Cross Flow between Fuel Blocks of a Prismatic VHTR," Transactions of the KNS Spring Meeting, Jeju, Korea, May 22, 2009.
[8] S.N. Lee, N.I. Tak, M.H. Kim, and J.M. Noh, "Thermo-Fluid Verification of Fuel Column with Crossflow Gap," Transactions of the KNS Autumn Meeting, Gyeongju, Korea, October 24-25, 2013.