Transactions of the Korean Nuclear Society Spring Meeting
Chuncheon, Korea, May 25-26 2006

Modeling of a Porous Blockage in a Liquid Metal-Cooled Reactor Subassembly

Hae-yong Jeong, Kwi-seok Ha, Young-min Kwon, Won-pyo Chang, and Yong-bum Lee
Korea Atomic Energy Research Institute, 150 Dugjin-dong, Yusong-gu, Daejon, 305-353 Korea
hyjeong@kaeri.re.kr

1. Introduction

The occurrence of a blockage in a core flow path could be one of the major accident scenarios threatening the safety of a liquid metal-cooled reactor (LMR). This is because the fuel rods are configured compactly to take advantage of the high heat capacity and the large heat transfer coefficient of a liquid metal coolant. In addition, the heat flux from the fuel rods is usually higher than other type of nuclear reactors. Therefore, it is important to maintain the integrity of the fuel rod configuration without any obstacle in the flow path for a continuous operation of a liquid metal-cooled reactor. The flow blockage can be formed either by the introduction of foreign material remaining in the primary coolant system or by the degraded fuel itself.

When there occurs a blockage in the flow path, the axial flow rate decreases drastically up to a certain distance downstream from the blockage and a re-circulating wake is formed. This re-circulating wake is characterized by a reverse flow and a large lateral cross flow and it is accompanied by an increase of the local temperatures of the coolant and the fuel rod surface, which threatens the integrity of the fuel clad.

In the design of an LMR, the consequence of the blockage formation in a fuel assembly is deliberately analyzed with an appropriate tool. Since the blockage disturbs the normal flow field it is important to simulate the flow and temperature field correctly in the analysis. The analysis code requires a proper numerical scheme and thermal-hydraulic model to deal with the re-circulating flow.

Most experimental studies on flow blockage have been performed with an impermeable and planar type of blockage. However, some experiments to investigate the mode of the blockage buildup suggested that the most possible type of blockage in a wire-wrapped bundle is a thick porous one formed by the agglomeration of small particles at some part of the wire-wrap and the pin bundle. Therefore, it is essential to include a porous blockage model in a computer code to describe the thermal-hydraulic phenomenon in and around a porous type of blockage.

For the analysis of blockage accident, the Korea Atomic Energy Research Institute (KAERI) has developed the MATRA-LMR-FB code by modifying some models in the MATRA-LMR code [1], which has been developed based on the COBRA-IV [2] and the MATRA code [3] for the thermal-hydraulic design of the KALIMER core. The MATRA-LMR code has two numerical schemes. One is the fully implicit method using a marching scheme solving sequentially in axial direction, and the other is the explicit method using an ICE with an upwind scheme. The fully implicit method has a limitation to model the reverse flow in the downstream of the blockage due to the characteristics of a marching scheme. Thus, based on the explicit method, some models, which are essential for the description of flow blockage, have been implemented into the MATRA-LMR-FB. The MATRA-LMR-FB code has been applied successfully for the prediction of some planar impermeable blockages. However, it does not equip any model for a porous blockage.

2. Porous Blockage Modeling

The MATRA-LMR-FB code uses the distributed resistance model (DRM) [4] to describe the sweeping flow formed by the wire-wrap around the fuel rods and to model the re-circulation flow after a blockage. The hybrid difference scheme is also adopted for the description of the convective terms in the re-circulating wake region of a low velocity. Some state-of-the-art turbulent mixing models are implemented in the code as an effort to describe correctly the mixing phenomena after a blockage.

For the modeling of a porous type blockage, a suitable pressure drop model is implemented. When a porous type of blockage is formed in a flow path, the highest temperature usually occurs at some part in a blockage. Therefore, it is required to model the axial flow rate and transverse flow rate in the narrow paths formed by the porous particles. Summarizing the various experimental and analytical studies on porous blockage,[16] the most important model for the accurate velocity and flow rate in a blockage would be a correct pressure drop model which calculates accurately the pressure distribution in a porous blockage. For the modeling of the pressure drop in a blockage, the following correlation, suggested by Ergun [5], is implemented in the MATRA-LMR-FB code:

$$\frac{\Delta p}{\Delta z} = 150 \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu u_s}{d_p^2} + 1.75 \cdot \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho u_s \left| u_s \right|}{d_p}, \qquad (1)$$

where u_s is the superficial velocity of fluids. The Eq. (1) should be implemented cautiously in a computer code with a correct definition of the variable u_s .

3. Model Assessments

The predictability of the MATRA-LMR-FB code for the porous blockage was analyzed for the SCARLET-II experiment [6]. In the experiment, 19 pins of 8.5 mm diameter were located in a triangular array with 9.79 mm of pin pitch. The pitch of the wire-wrap was 180 mm. Each pin was rated at 45 kW and the heated length was 1 m. The central 6-subchannel blockage was 60 mm long between 587 mm and 647 mm downstream of the beginning of the heated length. The porous blockage was composed of spherical particles of 0.5 mm diameter. For the code calculation, the axial flow path of 1,457 mm in length has been divided into total 103 axial nodes, which were categorized into 10 groups of axial region depending on the mesh size used for the nodalization. As a result, the mesh size near the blockage was fine and the other parts were nodalized with relatively coarse mesh.

In Fig. 4, the experimental data of SCARLET-II and the results predicted with the CAFCA code are compared with the prediction by MATRA-LMR-FB. The experimental results are not for a fixed subchannel but a merged one for three different subchannel locations. The porosity affects considerably to the temperature profile in the blockage, therefore, it is the most important parameter for the analysis of blockage of porous type. As shown in Fig. 5, the MATRA-LMR-FB code best predicts the maximum temperature of the experimental data with the porosity of 0.4. It should be noted that the minimum porosity attainable with the spherical particles with the same diameter is about 0.38, therefore, the porosity of 0.4 is actually the lowest porosity for real situation.

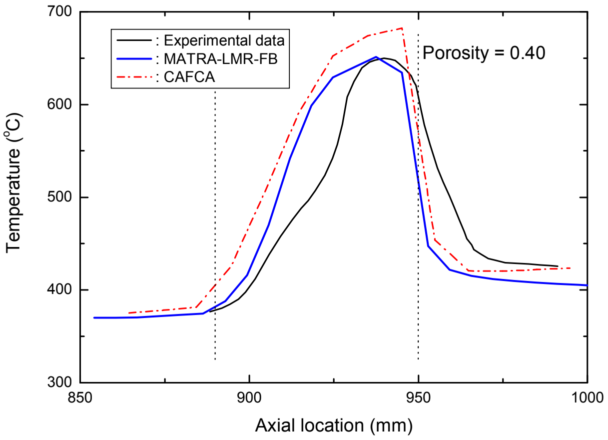

Figure 1. MATRA-LMR-FB prediction for SCARLET-II test

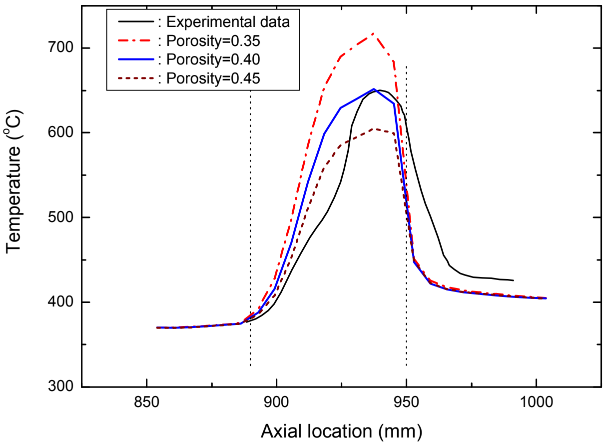

Figure 2. Temperature profiles with different porosity

4. Conclusion

A porous blockage model for the MATRA-LMR-FB code has been developed based on the Ergun's pressure drop correlation in a porous medium. The model has been successfully implemented in the MATRA-LMR-FB code. It has been shown that the model predicts the temperature distribution of SCARLET-II experiment, which includes a porous blockage in a flow path, quite accurately when a proper porosity is selected. The accurate prediction results also imply that the other models included in the codes are appropriate for the modeling of porous blockage. It is noted that the accurate prediction of pressure drop in a porous medium is the most important factor in the modeling of a porous blockage.

Acknowledgements This work has been performed under the nuclear R&D Program supported by the Ministry of Science and Technology of the Korean Government.

REFERENCES

[1] W. S. Kim, Y. G. Kim and Y. J. Kim, A subchannel analysis code MATRA-LMR for wire-wrapped LMR subassembly, Ann. Nucl. Energy, Vol.29, p.303, 2002.
[2] C. W. Stewart, C. L. Wheeler, R. J. Cena, C. A. McMonagle, J. M. Cuta, and D. S. Trent, COBRA-IV: The Model and the Method, BNWL-2214, Pacific Northwest Laboratories, 1977.
[3] Y. J. Yoo, D. H. Hwang, and D. H. Sohn, Development of a Subchannel Analysis Code MATRA applicable to PWRs and ALWRs, J. Korean Nucl. Soc., Vol.31, p.314, 1999.
[4] H. Ninokata, A. Efthimiadis and N. E. Todreas, Distributed Resistance Modeling of wire-wrapped Rod Bundles, Nucl. Eng. Des., Vol.104, p.93, 1987.
[5] S. Ergun, Fluid Flow Through Packed Columns, Chem. Eng. Prog., Vol.48 (2), p.89, 1952.
[6] J. Olive and P. Jolas, Internal Blockage in a Fissile Super-Phenix Type Subassembly: The SCARLET experiments and their Interpretation by the CAFCA-NA3 code, Nucl. Energy, Vol.29 (4), p.287, 1990.