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Thermal-Hydraulic Analysis of Internal Flow Blockage within Fuel Assembly of Nuclear Liquid-Metal Fast Reactor

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액체금속원자로 핵연료집합체의 내부 유로폐쇄 열수력 해석

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Abstract

The numerical simulation of a 271-rod fuel assembly of nuclear Liquid-Metal Fast Reactor (LMFR) with an internal blockage has been carried out. Internal blockage within a subassembly is addressed in the safety assessment because it potentially has very serious consequences for the reactor as a whole. Three dimensional calculations were performed using the SABRE4 computer code for the range of blockage positions and sizes to investigate the seriousness and detectability of the internal blockage. The magnitude and location of the peak temperatures together with the temperature distribution at the subassembly exit were calculated in order to look at the potential for damage within the subassembly, and the possibility of blockage detection. The analysis result shows that the 6-subchannel blockage causes large temperature rise within a assembly with practically no change in mixed mean temperature at the assembly exit.

1. Introduction

The fuel driver assembly of nuclear Liquid-Metal Fast Reactor (LMFR) consists of a cluster of cylindrical fuel pins, surrounded by an outer duct. The sodium coolant flows outside the fuel pins and inside the duct. The fuel pins are held apart from one another by a wire-wrapped spacer.

Events such as fuel pin failures or debris ingress and accumulation could lead to formation of the internal blockage within the fuel subassembly. The internal blockages are of particular importance because of the LMFR design characteristics; tight package of the fuel bundle and the high power density. The blockage phenomenon has to be addressed in the safety assessment because it is considered as a potential whole core accident initiator. The worst consequences of blockage may be extensive fuel and clad melting. Within the design basis of the LMFR, the blockage resulting in unacceptable consequences must be precluded by means of the engineering design features and the adequate performance of detection systems.

This paper presents the numerical results obtained using the SABRE4 [1] computer code to simulate a 271-rod fuel assembly in a hexagonal duct with various planar blockages located within the highest power density section.

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2. Problem Statement

A local blockage in LMFR assembly can progress to a whole core incident, because a local blockage is a necessary precursor to more serious events. Therefore the purpose of flow blockage analysis is to investigate the potential for damage within the subassembly and to investigate the possibility of blockage detection. It is very important to know which types of blockages are of most concern to the safety of the subassembly and whether or not any signals would be detected by the reactor instrumentation. In the LMFBR design concept, thermocouples installed at the subassembly exit detected the blockage before the occurrence of pin failure. The seriousness and detectability of the internal blockage are two major concerns with respect to the LMFR subassembly design.

The fuel subassembly under consideration is the one used in the Korea Advanced Liquid Metal Reactor (KALIMER) [2] core. The assembly is located at the center of the core, rated at 6.11 MW (thermal) with a flow of 27.2 kg/s giving a coolant temperature rise from 386 °C to 548 °C. The drawings of driver fuel assembly and fuel pin are presented in Fig.1. The driver fuel assembly contains 271 7.45 mm diameter fuel pins held on a 8.95 mm pitch by the wire-wrapped spacer. The fuel bundle is in the vertical position and the flow of sodium enters from the bottom. The 1.41 mm diameter wire spacers are wrapped around the

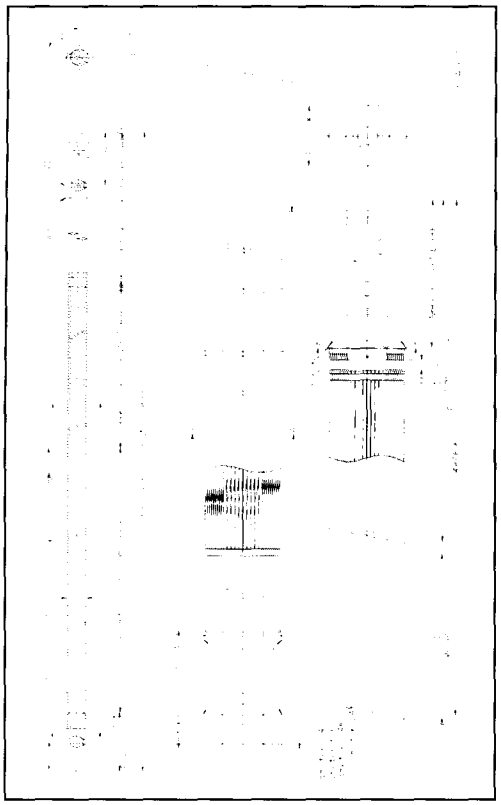

Fig. 1 KALIMER fuel assembly and pin

rods in a counter-clockwise fashion as one moves up the rod as shown in Fig. 2. The z-axis is aligned axially along the duct. The 353.4 cm overall length is partitioned into 103 axial partitions. Nuclear fission power is generated along the 105 cm active fuel slug region with a cosine shape of power distribution. The 34.4 mm thick planar blockages are located at the 47th axial level (161.5 cm) which has the highest power density.

Fig. 3 shows a cross section of the fuel assembly and the flow area blocked by the planar blockage. The figure shows the numbering system of subchannel and fuel pin for SABRE4 calculation. A whole assembly is evenly divided into 103 meshes in axial direction, and 40 and 21 meshes in x and y direction, respectively. Total 271 pins and 600

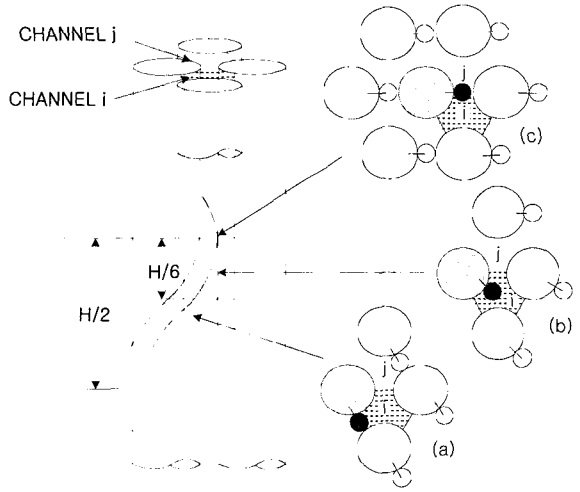

Fig. 2 Configuration of wire-wrapped fuel bundle

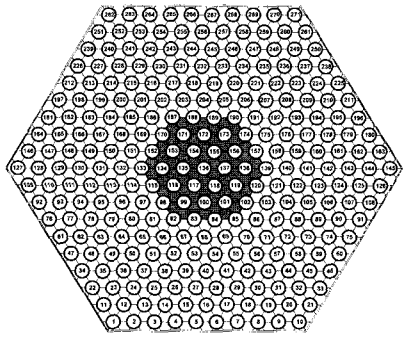

Fig. 3 Cross section of fuel assembly with central 24-subchannel blockage

subchannels have their unique numbers as shown in Fig. 3. The subassembly calculation has to encompass the whole bundle if the swirl effects generated by the wire wraps are to be properly taken into account. The flow area of the fuel rod bundle consisting of a triangular array of pins is divided into "subchannels" which is defined by the surfaces of three surrounding pins and the lines joining their nominal centers, as shown in Fig. 4. The subchannels are divided axially into discrete control volumes.

3. Flow Blockage Analysis

The SABRE4 code is a general purpose thermo hydraulic code for calculating the flows and temperatures in rod bundles, using a subchannel representation of the geometry. The subchannel analysis technique gives accurate practical representation of the pin bundles. The geometrical representation in SABRE4 is based on a regular mesh of pins. The layout of nods and control volumes in triangular geometry are defined as shown in Fig. 4. The main variables are the flow velocity components u, v, and w, the static pressure p, and the energy I, The axial direction is that of z coordinate. The main nodes (i,j,k) are taken at the centers of the subchannels. The nominal pin centers lie on a uniform triangular mesh. The velocity nodes are taken at the mid points between the main nodes.

In subchannel analysis, two different control volumes are used: one for the axial momentum equation, and the other for the transverse momentum equation. The reason for that is primarily due to the subchannel arrangement. For the axial velocity w, the control volume is a section of subchannel, but lying between adjacent main nodes. For the transverse velocities u and v the control volume is taken as the volume bounded by the lines joining the two adjacent

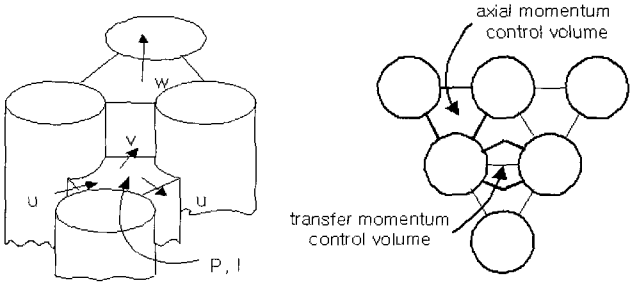

Fig. 4 Control volumes of SABRE4

nominal pin and subchannel centers, the adjacent pins and the adjacent axial velocity planes.

These subchannels communicate laterally through narrow gaps. It is assumed that any lateral flow is directed by the gap through which it flows and loses its sense of direction after leaving the gap region. Since cross flow may exist only between two adjacent channels, no specific boundary conditions are required.

The governing equations for mass, momentum, and energy conservation for a subchannel are derived in a finite-difference form directly from control volume balances. The basic thermo-hydraulic equations for a continuum is written as:

Conservation of Mass

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{u} \tag{1}$$

Conservation of Momentum

$$\frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot \rho \mathbf{u}\mathbf{u} + \mu \nabla^2 \mathbf{u} - \nabla P + R \tag{2}$$

Conservation of Energy

$$\frac{\partial \rho I}{\partial t} = -\nabla \cdot \rho \mathbf{u} I + \Gamma \nabla^2 I - P \nabla \cdot \mathbf{u} + S \tag{3}$$

Equation of State

$$\rho = \rho(I, P) \tag{4}$$

where the effects of viscosity, heat conduction and turbulence have been approximated by the diffusive terms of $\mu \nabla^2 \mathbf{u}$ and $\Gamma \nabla^2 I$, μ being an effective viscosity and Γ an effective heat exchange coefficient. **R** and **S** represent external body forces and heat sources respectively.

A key feature of the code is its ability to recognize the elliptic character of the conservation equations. The solution method in SABRE4 allows the code to deal with recirculating wakes, which requires reverse flows and strong cross-flows. In SABRE4 there are various solution options such as SIMPLE, MAC, ICE and IMSL, so either a fully implicit method or a semi-implicit scheme is available. The method used in SABRE4 to reduce numerical diffusion is the use of vector upwind difference scheme for the energy equation and the use of a hybrid scheme for the momentum equations

The turbulence model allows for turbulence production by shear between adjacent subchannels, and at the pin, turbulence transport by convection and diffusion and finally turbulent dissipation. The parameters used to close the system of equations were derived from experimental and detailed CFD calculations.

4. Numerical Analysis Results

The primary important parameters in the blockage calculations are the location and magnitude of the peak temperature and the effects seen at the subassembly outlet. The peak temperature is obviously vital for determining the seriousness of the blockage, and the location of it provides information for purpose of blockage detectability analysis. The peak temperature region may be located in the blockage itself or may appear within a recirculating wake. The safety objective of the flow blockage in the design bases event is to maintain coolability of the incident subassembly. The coolability will be maintained if extensive clad damage is avoided.

According to the various blockage experiments [3], the shape of blockage within the wire wrapped bundles is known to be long and narrow. Therefore, the majority of blockages considered in the LMFR design bases event are for 6-subchannel blockage in which all subchannels surrounding a particular pin are completely blocked. No recirculation zone was seen behind the 6-subchannel blockages except edge positions. These results serve to illustrate the importance of the wire wrap model in the SABRE4. The SABRE4 predicted swirl flow around the peripheral subchannels caused by the helical wire wrap as expected. Large cross flow occurs near the blockage, both upstream and downstream. It is noted that small internal blockages caused large temperature rises within a assembly with practically no change in mixed mean temperature at the assembly exit.

Fig. 5 is the analysis result of peak temperatures for 6-subchannel blockage cases at central and edge locations, respectively. The calculated temperatures are represented as function of blockage depth which is defined as the number of wire lead. For the 6-subchannel blockage, the SABRE4 calculations indicate that the peak temperatures were found within the blockage themselves in all cases. The peak temperature variation with the blockage position is shown in Fig. 5. The temperature rise in any position is insufficient to bring the sodium temperature to the boiling point (1153 K). It was found that the position of the blockage seemed to have little effect on the results unless the blockage was actually adjacent to the assembly duct. Calculations of the 6-subchannel blockages in six corners of the hexagon show higher temperature rise than central blockage case.

Since no significant temperature rise was calculated by SABRE4 for the 6-subchannel blockage case as shown in Fig. 5, 24-subchannel blockage was additionally analyzed. Fig. 6 shows the temperature contours in x-y plane at the blockage location and at the assembly outlet, for the central 24-subchannel blockage case. Fig. 7 shows the temperature distribution in x-z plane. The highest temperature of 954 K

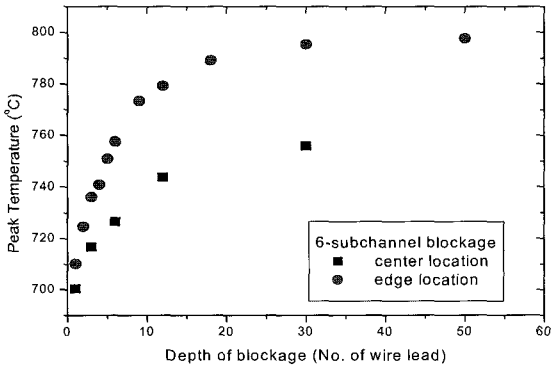

Fig. 5 Peak temperatures of 6-subchannel blockages

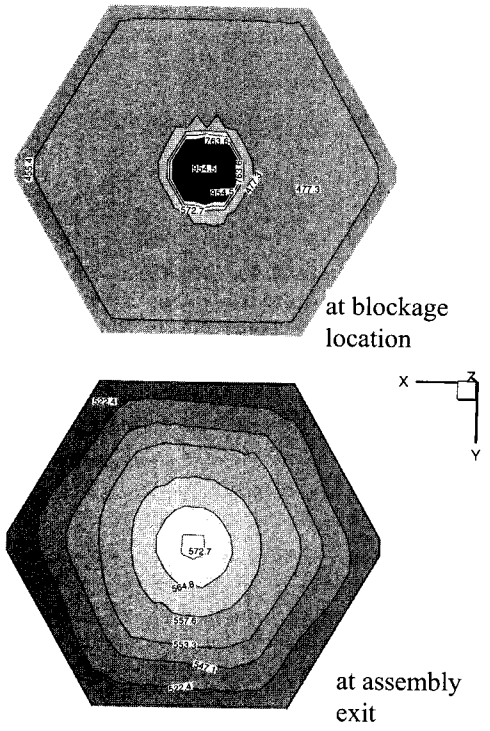

Fig. 6 Temperature contour for central 24-subchannel blockage

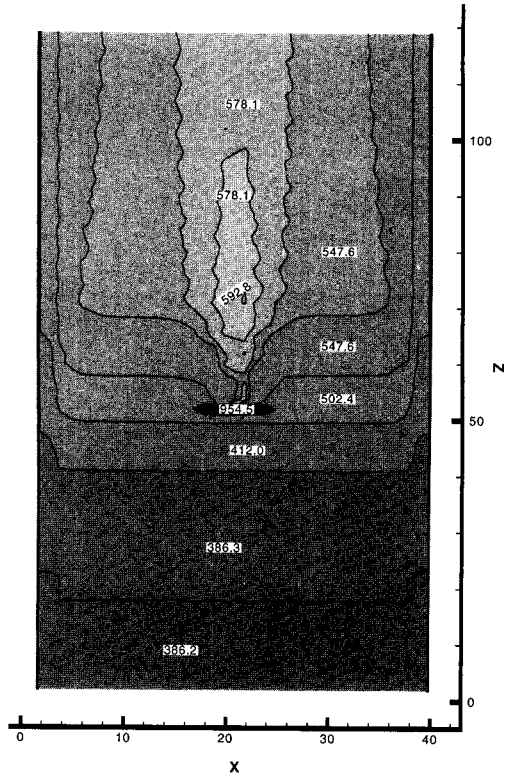

Fig. 7 Temperature contour in x-z plane for central 24-subchannel blockage

occurs within the blockage itself, which satisfies the safety criteria. Therefore no melting of fuel clad occurs and coolability of fuel bundle is maintained. The temperature at the assembly exit for 24-central blockage is about 572 K in contrast with 555 K at steady state. The temperature difference at the exit is only 17 K which seems not enough for thermal sensor installed at the top of assembly to detect the abnormality. The calculated peak temperature for the 24-central blockage does not exceeds the boiling point also.

It is noted that the SABRE4 predicted flow reversal in the wake of the blockage for 54-central subchannel blockage case and the peak temperature was situated in the wake. The results for the larger blockages investigated suffered from relatively poor solution convergence and unacceptable temperature spikes. These phenomena are present because of the discretization scheme used in the calculations and cannot easily be overcome without increasing the amount of numerical diffusion in the solution.

5. Conclusion

The blockage calculation shows that the 6-subchannel blockage, which is design bases event of KALIMER core, causes large temperature rise within a assembly. It is also shown that the 6-subchannel blockages doesn't have a substantial change to the overall coolant mass flow rate through the assembly, therefore they make little difference to its mixed mean temperature at the subassembly exit.

Therefore, it doesn't seem to be reliable to try to detect such a case with a single thermocouple located at the top of each assembly. However the local formation of high temperature regions may be severe if it remains unseen outside of the incident assembly.

For the 6-subchannel blockages, high temperature region is located in the blockage itself and the rise is insufficient to bring the sodium temperature anywhere near its boiling point. The calculated results for the peak exit temperature appear to be a function of blockage size alone and not of blockage position.

Acknowledgement

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References

[1] G. P. Dobson and J. M. O'Neill, "SABRE, User Guide for Version 4," AEA Technology.

[2] D. Hahn, Y. M. Kwon et al., "KALIMER Conceptual Design Report" KAERI/TR-2204/2002, Korea Atomic Energy Research Institute (2002).

[3] Y. M. Kwon et al., "Analysis of Local Subassembly Accident in KALIMER," KAERI/TR-1659/2000, Korea Atomic Energy Research Institute (2000).