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A Subchannel Analysis Code for LMR Core Subassembly Thermal Hydraulic Analysis: The MATRA-LMR

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Abstract — The MATRA-LMR code has been developed based on a subchannel analysis method for LMR (Liquid Metal Reactor) core subassembly thermal hydraulic design and analysis. The code was improved to allow a seven assembly calculation and can account for inter-assembly heat transfer based on a lumped parameter model. This paper describes the main modifications and improvements of the code and shows reference calculation results which compared single assembly calculation with seven assembly calculation cases for driver and blanket subassemblies of the KALIMER 150 MWe breakeven conceptual design core. KALIMER is a pool-type sodium cooled reactor with a thermal output of 392.0 MWth, which have inherently safe, environmentally friendly, proliferation-resistant and economically viable reactor concepts.

1. Introduction

Thermal hydraulic design of the core in liquid metal reactors is generally limited to the maximum temperatures of claddings and fuel pins to ensure the core safety criteria, which are somewhat conservative design requirements. Most of these requirements are related to fuel, cladding and coolant temperatures for steady-state and transient conditions. For instance, the sodium temperature must be maintained under the boiling limit, cladding temperature against corrosion considerations, core subassembly mixed mean outlet coolant temperature against the thermal striping potential temperature, etc. (Tang, 1978).

Design and analysis studies of Korea Advanced Liquid Metal Reactor (KALIMER), a pool-type sodium cooled reactor with a thermal output of 392.0 MWth (Park, 1998), have been a performed and proliferation resistance core of 600 MWe is under conceptual design at KAERI.

At the conceptual design stage of KALIMER, development of a detailed thermal hydraulic code was required because the existing codes for light water reactor (LWR) were unsuitable for the modeling of the sodium, helical wire-wrapped pin and duct walls in LMR core. The MATRA-LMR, a detailed subchannel analysis code, was developed as an analysis code to predict flow and temperature fields in LMR subassemblies. The code was based on a subchannel analysis method and used in the beginning only for single assembly analysis (Kim, 2002).

The current version of the MATRA-LMR code has been improved from a single subassembly to a seven subassemblies model and can account for the inter-assembly heat transfer effect using a lumped parameter approach method. Thus, the code can predict either temperature distribution of a single subassembly or seven subassemblies with the inter-assembly heat transfer effect.

This paper describes the main modifications and improvements of the MATRA-LMR code and summarizes the calculation results of the temperature profiles of the KALIMER 150 MWe breakeven concep- tual core subassemblies with the options of a single subassembly and seven subassemblies with a lumped parameter inter-assembly heat transfer model. Calculation references were the DR0302 driver subassembly, IB0503 and RB0704 blanket subassemblies (Lim, 2002). DR0302 is a driver fuel subassembly of maximum thermal power in the core and IB0503 and RB0704 are internal and radial blanket subassemblies, respectively.

2. MATRA-LMR Code

2-1. Description of MATRA-LMR Code

The subchannel analysis is the most widely used in rod-bundle thermal hydraulic design and analysis to

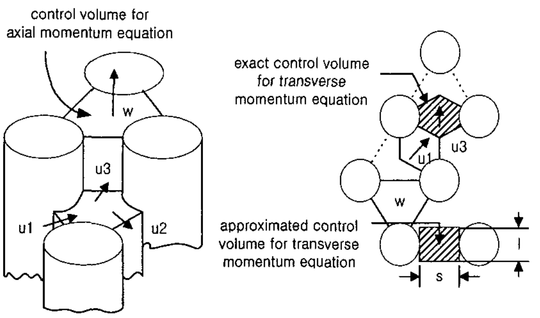


Fig. 1. Control volumes for axial and transverse momentum equation.

date. It explicitly assumes that one of the velocity components is dominant, compared to components in the other directions. Thus, a simplified model can be applied to the transverse momentum equations. A typical triangular subchannel arrangement, a control volume for an axial momentum equation and the control volumes for axial and transverse momentum equations are shown in Fig. 1.

Development of the MATRA-LMR code was based on COBRA-IV-I (Wheeler, 1976) and MATRA (Yoo, 1997). MATRA is a subchannel analysis code, which was developed in KAERI for fuel element analysis of LWR. Thus, governing equations for conservation of mass, momentum, and energy for the subchannels are identical in MATRA and COBRA-IV-I.

2-2. Basic Equations

The basic equations of the mathematical model are derived by applying the general equations of continuity, energy and momentum to a subchannel control volume. The following are the basic equations to be solved within the MTATRA-LMR code for a single phase flow.

· Continuity

$$A\frac{\partial \rho}{\partial t}+\frac{\partial m}{\partial x}+[DC]^{T}w=0 \qquad (1)$$

· Energy

$$\frac{\partial \rho h}{\partial t}+\frac{\partial mh}{\partial x}+[DC]^{T}hw=q' \qquad (2)$$

· Axial Momentum

$$\frac{\partial m}{\partial t}+\frac{\partial mu}{\partial x}+[DC]^{T}uw+A\frac{\partial P}{\partial x}=F \qquad (3)$$

· Transverse Momentum

$$\frac{\partial m}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}-[DC]P=C \qquad (4)$$

In addition to the conservation equations, the following fluid properties correlation is required.

$$\rho=\rho(h,P^{*}) \qquad (5)$$

where,

A : Subcahnnel area (ft^2)
ρ : Fluid density (lbm/ft^3)
t : time (sec)
m : Mass flow rate for axial direction (lbm/sec)
w : Mass flow rate for radial direction (lbm/sec)
x : Radial position (ft)
y : Axial position (ft)
h : Enthalpy (Btu/lbm)
q' : Heat transfer from all sources (Btu/sec-ft)
u : Fluid velocity for axial direction (ft/sec)
v : Fluid velocity for radial direction (ft/sec)
P : Pressure (Lb$_f$/ft^2)
F : Axial friction and gravity force (lbm/ft^2)
C : Lateral friction (lbm/ft^2)
[DC], [DC]^T : The matrix operator and its transpose
p* : Reference pressure

2-3. Single Subassembly Analysis Model

Based on subchannel analysis, the main improvements in the MATRA-LMR code for single subassembly calculation are as follows;

· Physical properties correlations of sodium
· Heat transfer coefficients correlations
· Geometry model for a wire-wrapped fuel pin
· Subchannel friction factor and a pressure drop model for a wire-wrapped subassembly

2-3-1. Heat Transfer Coefficient

Because of high thermal conductivity, heat transfer coefficients of liquid metals in turbulent flow were used. They were a little different from the heat transfer correlation with the Nusselt number. For liquid metals, the behavior of the Nusselt number (Nu) is as follows:

$$Nu=A+B(Pe)^{C} \qquad (6)$$

where Pe is the Peclet number, i.e., Pe=RePr. A, B, C are constants that depend on the geometry and the

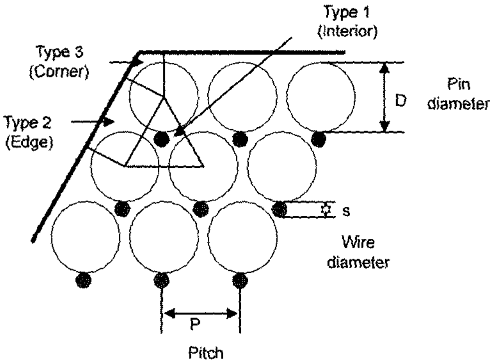


Fig. 2. Geometry of subchannels and wire wraps.

boundary conditions. In the MATRA-LMR code, Lyon-Martinelli, Westinghouse, and Schad-Modified correlations are used for heat transfer coefficients.

2-3-2. Pressure Drop Model

Figure 2 shows the geometry of the subchannels and wire wraps used to space the fuel pins in the hexagonal assembly duct in the KALIMER core. Because of the complex geometry caused by the wire wraps, simple friction factors for smooth pipes with equivalent diameter techniques are not sufficient to predict accurately the pressure drop in the fuel pin bundle region. Thus an accurate prediction of the pressure drop is required.

In the MATRA-LMR code, Novendstern (Novendstern, 1972), Chiu-Rohsenow-Todreas (Chiu, 1978) and Cheng-Todreas (Cheng, 1986) models are used to predict the pressure drop more accurately in wire-wrapped subassembly.

2-4. Lumped Parameter Inter-assembly Heat Transfer Model

Due to the high thermal conductivity of sodium, a single subassembly analysis is not sufficient since the heat transfer from the adjacent assemblies through the duct walls and sodium gaps can be significant, particularly for heterogeneous cores (George, 1980). Therefore, inter-assembly heat transfer should be considered for the LMR core thermal hydraulic design and analysis.

The primary purpose of the inter-assembly heat transfer model is to predict the temperature profile of the central subassembly considering the heat transfer effect between the adjacent subassemblies through the duct walls and sodium gaps.

The current version of the MATRA-LMR code has been improved from a single subassembly to a seven assembly model and can account for the inter-assembly heat transfer effect using a lumped parameter approach method.

Assumptions for the lumped parameter model to simplify the calculation of inter-assembly heat transfer are as follows:

· There are two types of subassemblies. One is a real standard subassembly in the center, the other is a lumped seven pin subassembly.

· Axial nodes are equally divided and the same duct wall thickness is applied to all the subassemblies.

· The code is limited to a single phase flow.

The cross sectional view for the heat transfer model in the sodium-filled gap and duct walls between the inter-assemblies is given Fig. 3. At the boundary, the convective film heat transfer coefficient between the edge subchannel and duct wall is derived from the Lyon-Martinelli correlation with the assumption of a fully developed flow. The sodium flow in the gaps between the duct walls is modified to a conductive resistance on the assumption it is stagnant. Thus, the energy balance of the wall region is modeled by a combination of the conductive resistance, heat capacitance of the fluid and gamma heating in the duct walls.

The finite difference form of the energy balance in the wall region is as follows:

$$(\rho_w C_{pw} t_w)\frac{(T_w - T_w^n)}{\Delta t} = -U_i(T_w - T_i) - U_j(T_w - T_j) + q_w''' t_w' \quad (7)$$

$$\begin{bmatrix}\text{energy}\\ \text{storage}\end{bmatrix} = \begin{bmatrix}\text{heat transfer}\\ \text{from channel i}\end{bmatrix} + \begin{bmatrix}\text{heat transfer}\\ \text{from channel j}\end{bmatrix} + \begin{bmatrix}\text{heat generation}\\ \text{in duct wall}\end{bmatrix}$$

where the temperatures and thermal properties in the wall node are denoted by a subscript w and the effective heat transfer coefficients for the subchannels i, j are expressed by U_i and U_j respectively.

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{t_d}{k_d} + \frac{t_n}{2k_n} \quad (8a)$$

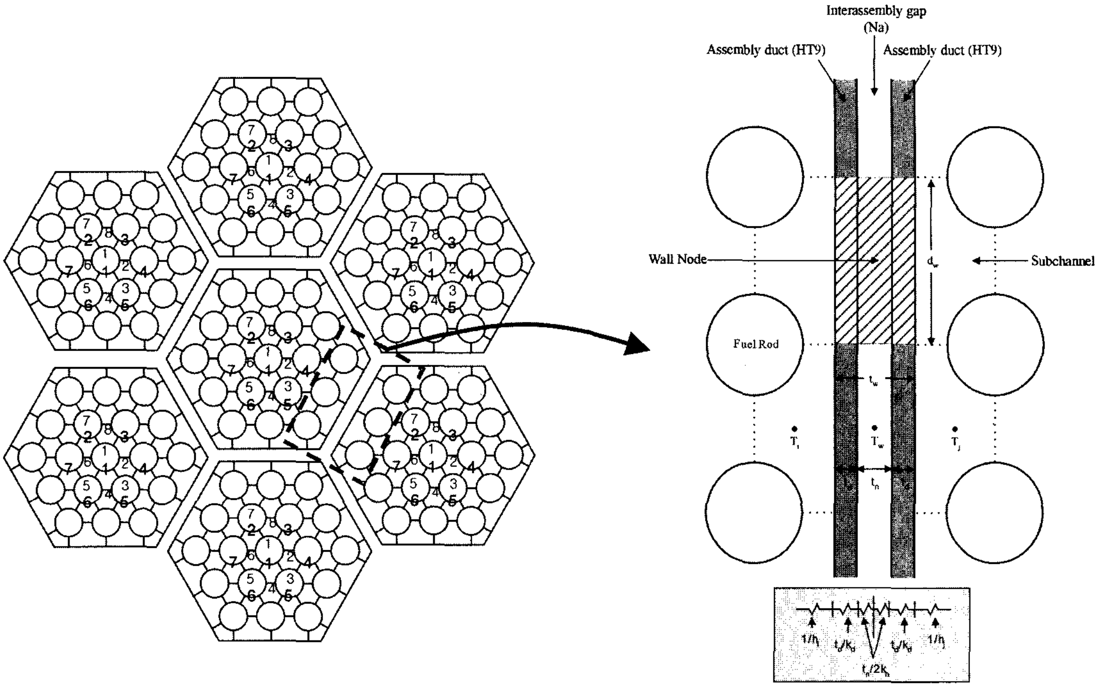


Fig. 3. Inter-assembly heat transfer model for duct wall node.

$$\frac{1}{U_j}=\frac{1}{h_j}+\frac{t_d}{k_d}+\frac{t_n}{2k_n} \tag{8b}$$

where,

h_i, h_j : subchannel heat transfer coefficient
k_d : conductivity of duct
k_n : conductivity of sodium
Re : Reynolds number
Pr : Prandtl number
D_h : hydraulic diameter ($4 \cdot A/P_w$)
t_d/k_d : heat conduction for the duct wall
$t_n/2k_n$: heat conduction for the inter-assembly sodium gap
$\rho_w C_{pw} t_w$: wall heat capacity $=2\cdot(\rho_d C_{pd} t_d)+\rho_n C_{pn} t_n$
t_w : wall node thickness ($2t_d+t_n$)
t'_w : wall thickness for heat generation

Equation (7) is rewritten for T_w in the following form.

$$\left[\frac{(\rho_w C_{pw} t_w)}{\Delta t}+U_i+U_j\right]T_w = U_i T_i+U_j T_j+(\rho_w C_{pw} t_w)\frac{T_w^n}{\Delta t}+q_w''' t'_w \tag{9}$$

The coolant temperatures in the wall heat transfer equations are transformed using a different definition for specific heat in the form of;

$$C_p=\frac{h-\tilde{h}}{T-\tilde{T}} \text{ : Specific heat} \tag{10a}$$

$$U_i T_i=U_i\left(\frac{h_i}{C_p}+\tilde{T}_i-\frac{\tilde{h}_i}{C_p}\right)=\frac{U_i}{C_p}h_i+U_i\left(\tilde{T}_i-\frac{\tilde{h}_i}{C_p}\right) \tag{10b}$$

$$U_j T_j=U_j\left(\frac{h_j}{C_p}+\tilde{T}_j-\frac{\tilde{h}_j}{C_p}\right)=\frac{U_j}{C_p}h_j+U_j\left(\tilde{T}_j-\frac{\tilde{h}_j}{C_p}\right) \tag{10c}$$

where,

superscript n : previous time step
superscript ~ : present time step but previous iteration

Equation (9) is rewritten again for the wall temperature (T_w) and subchannel enthalpy (h_i) using the above forms.

$$\left[\frac{(\rho_w C_{pw} t_w)}{\Delta t}+U_i+U_j\right]T_w=\frac{U_i}{C_p}h_i+\frac{U_j}{C_p}h_j +U_i\left(\tilde{T}_i-\frac{\tilde{h}_i}{C_p}\right)+U_j\left(\tilde{T}_j-\frac{\tilde{h}_j}{C_p}\right)+(\rho_w C_{pw} t_w)\frac{T_w^n}{\Delta t}+q_w''' t'_w \tag{11}$$

Equation (11) is combined with subchannel energy equations to produce a set of composite matrices.

This form is solved by the Gauss-Seidel iterative procedure for the unknown coolant enthalpy and wall temperature distributions.

3. Reference Calculations

Conceptual design and analysis studies of Korea Advanced Liquid Metal Reactor (KALIMER), a pool-type sodium cooled reactor, have been performed at KAERI. The main objective of these studies is to acquire the design and analysis technologies of LMR cores. A present KALIMER core is a 150 MWe (392 MWth) heterogeneous breakeven core fueled with U-TRU-Zr ternary alloy.

3-1. Descriptions of KALIMER Breakeven Core

Figure 4 shows the configuration of the KALIMER breakeven core. The core consists of nine flow groups: three in the driver fuel subassemblies, two in the internal blanket and four in the radial blanket subassemblies. Basic design data of the core are given in Table 1.

3-2. Calculations and Analyses

Calculations and analyses to predict the coolant temperature distributions in the subassemblies were performed using MATRA-LMR code with the options of a single and lumped seven pin inter-assembly heat transfer model. Three states were used as calculation references: equilibrium, BOC1 (Beginning of Cycle 1) and EOC1 (End of Cycle 1) of the KALIMER breakeven core design.

Table 1. Design data of KALIMER breakeven core.

Core thermal output (MWth)	392.2
Electric power (MWe)	150.0
Net plant thermal efficiency (%)	38.2
Core inlet/outlet temp. (℃)	386.2/530.0
Total flow rate (kg/s)	2143
Active core height (cm)	100
Core diameter (cm)	344.3
Core configuration	Heterogeneous
Refueling interval (month)	18
Refueling batches (Driver/IB/RB)	3/3/6
Pins per assembly	271/127
Total axial height (mm)	3970.7
Rod outer diameter (mm)	7.45/12.08
Rod pitch (mm)	8.95/13.07
Wire wrap diameter (mm)	1.41/0.96
Wire wrap lead (mm)	206.2/301.9
Cladding thickness (mm)	0.55/0.54
Duct wall thickness (mm)	3.72
Duct flat-to-flat distance (mm)	150.4

DR0302 is a 271 pin driver fuel subassembly with 6.55 MW thermal power and a coolant flow rate of 35 kg/sec. IB0503 and RB0704 are 127 pin blanket subassemblies with thermal powers of 1.55 and 0.99 MW and coolant flow rates of 9.40 and 2.90 kg/sec, respectively. The coolant inlet temperature is 386.2℃ and the average temperature for the coolant property evaluation is 458.1℃. The height of the assembly is 3.534 m and the axial length was divided into 354 equal meshes.

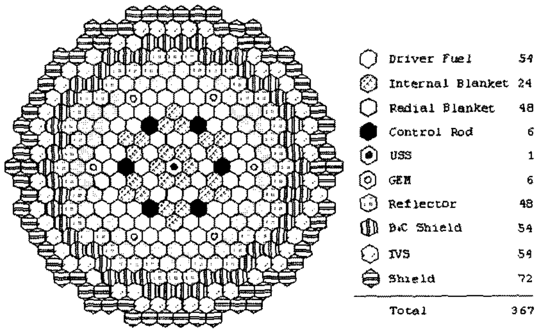


Fig. 4. Configuration of the KALIMER breakeven core.

3-2-1. DR0302 Subassembly

Figure 5 shows the number of pins, subassembly

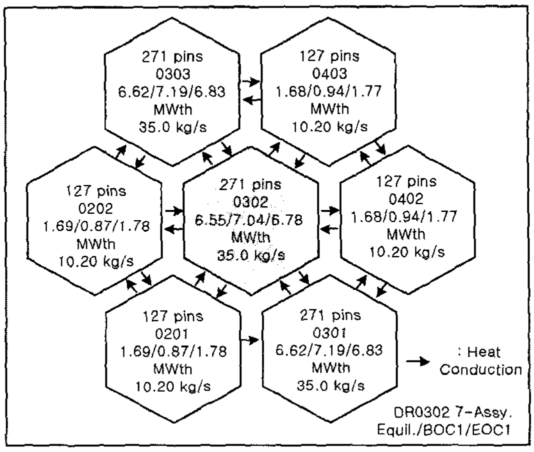
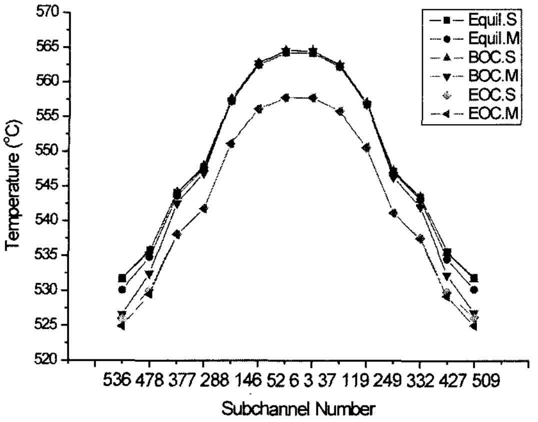
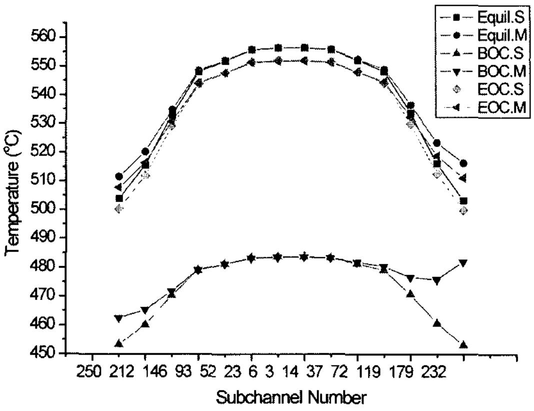


Fig. 5. DR0302 Seven-assemly model.



[S : Single assembly calculation /M : Inter-Assembly Calculation]

Fig. 6. Outlet tempertuare distribution of DR0302.



[S : Single assembly calculation /M : Inter-Assembly Calculation]

Fig. 8. Outlet tempertuare distribution of IB0503.

position, subassembly power and flow in each subassembly, DR0302 and adjacent seven subassemblies. DR0302 is the central subassembly of 271 pins with rod diameter of 7.45 mm and wire wrap spacers of 1.41 mm in diameter.

The outlet temperature distributions of DR0302 subassembly for equilibrium, BOC1 and EOC1 cores are given in Fig. 6. The maximum coolant outlet temperature is predicted at 564.3°C. In case of inter-assembly calculation, the temperature of the edge subchannel is about 1.8°C lower than that of single subassembly, which means that there are no considerable heat transfer effects with adjacent subassemblies, IB0202 and IB0402.

3-2-2. IB0503 and RB0704 Subassemblies

Seven-assembly models for the IB0503 and RB0704 subassemblies are given in Figs. 7 and 9. Those are blanket subassemblies of 127 pins with a rod diameter of 1.208 mm and wire wrap spacers of 0.96 mm in diameter.

Figures 8 and 10 show the comparison of outlet temperature distributions between single and inter-assembly calculation results with equilibrium, BOC1 and EOC1 cores. As shown in Figs. 7 and 9, the IB0503 and RB0704 subassemblies have low power-to-flow ratio compared to the adjacent driver subassemblies. Therefore, the heat is transferred from driver assemblies to central blanket assembly.

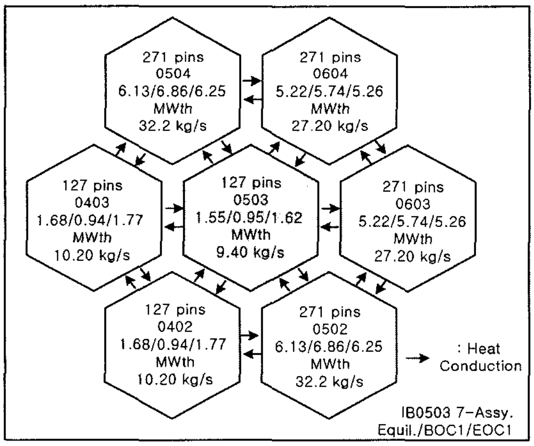


Fig. 7. IB0503 Seven-assemly model.

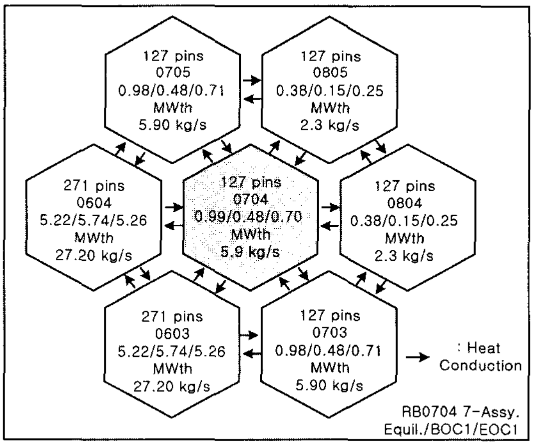
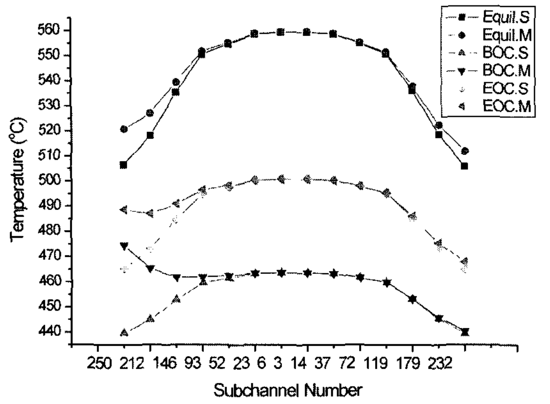


Fig. 9. RB0704 Seven-assemly model.



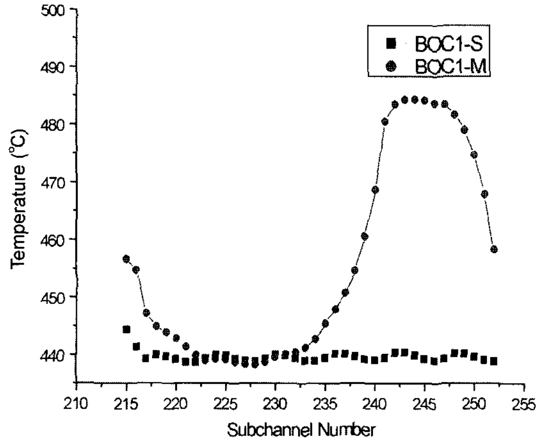
[S : Single assembly calculation /M : Inter-Assembly Calculation]

Fig. 10. Outlet tempertuare distribution of RB0704.

The maximum temperature differences between single and inter-assembly are found in the BOC1 core. Calculation results shows that the maximum coolant outlet temperatures of the IB0503 and RB0704 subassemblies are predicted at 556.5°C and 559.7°C, respectively. And the inter-assembly heat transfer effect, the maximum temperature difference in the edge subchannels are 29°C and 35°C higher than those of single assembly cases.

3-3. Calculation Results

The peak outlet temperature of the KALIMER breakeven core is predicted at 564.3°C in the DR0302 subassembly. In cases of the BOC1 core, there are considerable temperature distribution differences between single and inter-assembly calculation results. Figure 11 shows the temperature distribution in the peripheral subchannels of the RB0704 subassembly with option of single subassembly and inter-assembly calculation. The temperature distribution of inter-assembly case is considerably higher than single assembly with a range of 35°C.



[S : Single assembly calculation /M : Inter-Assembly Calculation]

Fig. 11. Peripheral subchannel temperature distribution in RB0704 (BOC1).

As calculation results, the MATRA-LMR code is capable of inter-assembly heat transfer and shows that single subassembly analysis is not sufficient for LMR core thermal hydraulic analysis and design.

4. Conclusions and Recommendations

The MATRA-LMR is a subchannel thermal hydraulic analysis code which was developed to predict flow and temperature profiles in the LMR core subassemblies. This code has been improved from single assembly analysis to multi-assembly analysis with inter-assembly model in order to calculate the inter-assembly heat transfer. From the development and analysis studies, this code is evaluated to be capable of predicting the temperature profiles in the subassemblies with the inter-assembly heat transfer effect.

The lumped parameter inter-assembly heat transfer model in the MATRA-LMR code was described in this paper and references calculations were performed with driver and blanket subassemblies in the KALIMER breakeven core. Calculation results showed that the peak outlet temperature of breakeven core was predicted at 564.3°C, and the edge subchannel temperatures were predicted higher than single subassembly by the range of 35°C.

For the future work, a number of modeling and verification works under various conditions will be needed for a further extension of the code and the MATRA-LMR will be used a basic tool for development of the LMR whole core thermal hydraulic design and analysis code.

Acknowledgement

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