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Development of a Detailed Sub-channel Model For the Safety Analysis of Liquid Sodium-Cooled Reactor

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1. Introduction

KALIMER-600 (Korea Advanced LIquid MEtal Reactor) is a pool type advanced liquid metal reactor of 600 MWe, which is being developed in KAERI (Korea Atomic Energy Research Institute). The SSC-K Code [1] is developed for the safety analysis of KALIMER based on The SSC-L code, which is a safety analysis code for the loop type LMR(Liquid Metal Reactor) by BNL. These Codes calculate the core thermo-hydraulic using channels.

In the SSC-K Code, the core is divided into several channels and each channel represents driver fuel, Reflector, B4C Shield, IVS, etc. The number of core channels is limited to seven channels in the SSC-K code and is not enough for the detailed analysis of a core thermo-hydraulic. In this study, the detail sub-channel thermo-hydraulic model for the SSC-K code is developed and the calculation is performed for the steady-state flow and temperature distributions in test loop.

2. Detailed Sub-channel Model

2.1. Model Features

The model uses a coolant sub-channel treatment similar to that used by COBRA [2] and SUPERENERGY-2 [3]. There is an option either to use one channel for each coolant sub-channel, as figure 1, or to combine sub-channels to groups. The advantage of the combined channel option is that it uses significantly fewer channels, requires considerably less computing time, and requires considerably less storage. On the other hand, the individual channel option may be necessary in order to obtain sufficient accuracy.

The sub-channel treatment includes axial coolant flow parallel to the pins and cross flow between coolant sub-channels driven by pressure differences and wire wrap sweeping. Heat flow between adjacent coolant sub-channels is calculated, including effects of turbulent mixing. The channel treatment includes the whole length of the subassembly, with the detailed sub-channel treatment in the pin section and with a simpler treatment above and below the pins. The model couples with loop calculation model for the treatment of the coolant loops beyond the subassemblies.

2.2. Basic Equations

The basic continuity equation for the coolant in an axial node of a sub-channel is

$$\frac{d}{dt}\left(\bar{\rho}_{ji}A_{ji}\Delta z_j\right) = w_{ji} - w_{j+1,i} - \sum_k w_{Ljik} \quad . \quad (1)$$

The momentum equation is

$$\frac{1}{2}\left(\frac{\Delta z_j}{A_{ji}} + \frac{\Delta z_{j-1}}{A_{j-1,i}}\right)\frac{dw_{ji}}{dt} = \bar{p}_{j-1,i} - \bar{p}_{ji} - \Delta p_{frji} - \frac{w_{ji}\,|w_{ji}|\,K_{orji}}{2\rho_{ji}A_{ji}^2} - \rho_{ji}g(\Delta z_j + \Delta z_{j-1})/2$$
$$- \frac{\bar{w}_{ji}^2}{\bar{\rho}_{ji}A_{ji}^2} + \frac{w_{ji}^2}{\rho_{ji}A_{ji}^2} - \frac{w_{ji}^2}{\rho_{ji}A_{j-1,i}^2} + \frac{\bar{w}_{j-1,i}^2}{\bar{\rho}_{j-1,i}A_{j-1,i}^2} - \frac{1}{2}\sum_k \{S_{wjik}\frac{w_{Ljik}w_{ji}}{\bar{\rho}_{ji}A_{ji}^2} \quad (2)$$
$$-(1-S_{wjik})\frac{w_{Ljik}w_{jk}}{\bar{\rho}_{jk}A_{jk}A_{ji}} + S_{wj-1,ik}\frac{w_{Lj-1,ik}w_{j-1,i}}{\bar{\rho}_{j-1,i}A_{j-1,i}^2} - (1-S_{wj-1,ik})\frac{w_{Lj-1,ik}w_{j-1,k}}{\bar{\rho}_{j-1,k}A_{j-1,k}A_{j-1,i}}\}$$

The energy equation for the coolant is

$$V_{cji}C_{prefji}\frac{d}{dt}[\bar{\rho}_{ji}(\bar{T}_{ji} - T_r)] = \sum_{in} w_{inji}(T_{inji} - T_r)C_{prefji}$$
$$-\sum_{out} w_{outji}(T_{out} - T_r)C_{prefji} + Q_{ji} \quad (3)$$

The energy equation in the fuel is

$$\rho_f C_f \frac{dT_f}{dt} = \frac{1}{r}\frac{d}{dr}(k_f r\frac{dT_f}{dr}) + Q \quad (4)$$

A similar equation is used for the cladding, and a bond gap conductance is used between the fuel outer surface and the cladding inner surface.

2.3. Numerical Procedures

For the steady-state calculations an initial approximation to the steady-state coolant temperatures, pressures and flow rates for each subassembly is made. Then a null transient for each subassembly separately is run, neglecting subassembly-to-subassembly heat transfer. Finally, a null transient with subassembly-to-subassembly heat transfer is run for all subassemblies. In the null transient the powers and subassembly coolant inlet flows are constant. For the steady-state coolant calculations the heat flux from the fuel pins to the coolant is determined by the steady-state pin power. After the coolant conditions are calculated, the fuel pin and structure temperatures are calculated.

A time step approach is used both for the steady-state null transient and for the regular transient. Conditions are known at the beginning of the time step, and the main computational task is to determine the conditions at the end of the step. The equations are linearized about values at the beginning of the time step, and fully implicit finite differencing in time is used for the basic

conservation equations. This leads to N linear equations in N unknowns. The unknowns are solved for by iteration. Explicit time differencing is used for the subassembly-to-subassembly heat transfer, so the calculations for one time step for each subassembly can be done independently.

For a transient time step the heat flux from the fuel pins and structure to the coolant is approximated as

$$\phi_{cji} = \phi_{c1\,ji} + \phi_{c2\,ji}\Delta\overline{T}_{ji} \qquad (8)$$

for the coolant calculations. The coefficients ϕ_{c1} and ϕ_{c2} are calculated in the fuel pin heat transfer routines. In this equation ΔT is the change in coolant temperature during the time step. After the coolant temperatures are calculated, the fuel pin and structure temperatures are calculated for the time step.

If the core subassembly calculations are coupled with a detailed treatment for the primary loop, then for a time step the subassembly coolant inlet and outlet flows are approximated as

$$w_{sain}(t+\Delta t) = c_1 + c_2\Delta p_{in} + c_3\Delta p_x \qquad (9)$$

and

$$w_{sax}(t+\Delta t) = c_4 + c_5\Delta p_{in} + c_6\Delta p_x \qquad (10)$$

where Δp_{in} and Δp_x are change in inlet and outlet pressure during the time step, respectively. The coefficients $c_1 \ldots c_6$ are calculated in the subassembly coolant calculations for each time step.

3. Test Calculation

To validate the detailed sub-channel model, steady-state calculation is performed for the ORNL test. The test facility has two subassemblies and an assembly has 19 pins. The physical and test parameters are summaries in Table 1 and the arrangements of pins and sub-channels are shown in Figure 2.

One result of steady-state calculation using detailed sub-channel model is shown in Figures 2 and 3. It shows the coolant temperature distribution in a subassembly of the ORNL test section. It was certain that new model is applicable to the detailed sub-channel analysis and three-dimensional core hydrodynamic calculation.

Table 1. Test parameters

Parameter	Value
Thermal Power, MWth	6.6
No. of subassemblies	2
No. of Pin per S-A	19
Flow rate, kg/s	15.027
No. of sub-channels per SA	42

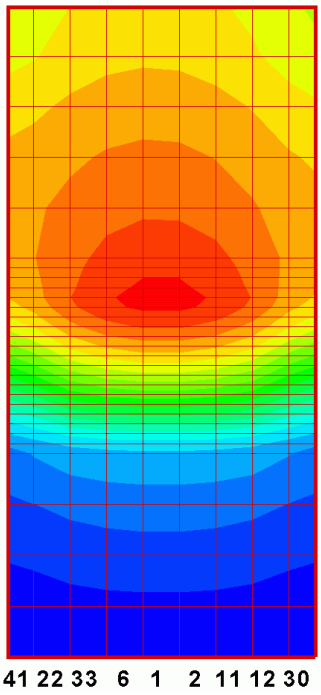

Figure 2 Temperature distribution (Vertical view)

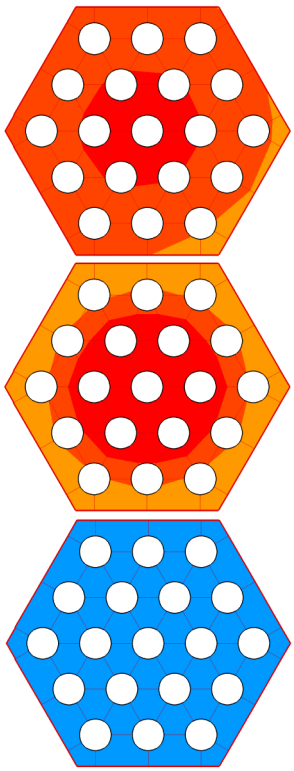
Figure 3 Temperature distribution (Horizontal view)

4. Conclusions

The detailed sub-channel thermo-hydraulic model for the SSC-K code is developed and tested through the steady-state calculation. To apply this model to the general cases of LMR safety analysis, this model will be coupled with other model, such as, loop model, reactivity model, etc. Further efforts are needed to verify the new model

REFERENCES

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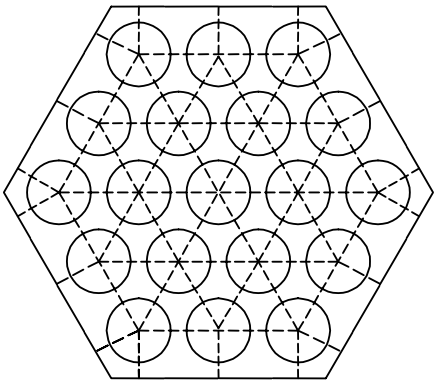

Figure 1. Layout of ORNL test section