Comparative Studies of Core Thermal Hydraulic Design Methods for the Prototype Sodium Cooled Fast Reactor

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1. Introduction

The Korea Atomic energy Research Institute (KAERI) has performed a conceptual SFR design with the final goal of constructing a prototype plant by 2028. The main objective of the SFR prototype plant is to verify the TRU metal fuel performance, reactor operation, and transmutation ability of high-level wastes.

The core thermal-hydraulic design is used to ensure the safe fuel performance during the whole plant operation. Compared to the critical heat flux in typical light water reactors, nuclear fuel damages in SFR subassemblies are arisen from a creep induced failure. The creep limit is evaluated based on both the maximum cladding temperature and the uncertainties of the design parameters. Therefore, the core thermal-hydraulic design method, which eventually determines the cladding temperature, is highly important to assure a safe and reliable operation of the reactor systems.

In this work, various core thermal-hydraulic design methods, which have arisen during the development of a prototype SFR, are compared to establish a proper design procedure.

2. Core T/H Design Code

The current core thermal-hydraulic design is performed using the SLTHEN (Steady-State LMR Thermal-Hydraulic Analysis Code Based on the ENERGY Model) code, which calculates the temperature distribution based on the ENERGY model [1]. The SLTHEN code employs two region approximations.

The resulting energy transport equations for the two regions are then calculated by

$$\rho C_p U_{zI} \frac{\partial T}{\partial z} = (\rho C_p \varepsilon_I + \zeta k)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + Q \qquad (1)$$

$$\rho C_p U_s \frac{\partial T}{\partial s} + \rho C_p U_{zII} \frac{\partial T}{\partial z} = (\rho C_p \varepsilon_n + \zeta k)\frac{\partial^2 T}{\partial n^2} + (\rho C_p \varepsilon_s + \zeta k)\frac{\partial^2 T}{\partial s^2} + Q \qquad (2)$$

where the left and right terms represent the convective heat transfer and conduction by the enhanced eddy diffusivity, respectively. Q, k, and ζ are the volumetric heat source, coolant thermal conductivity coolant and conductivity enhancement ratio from the geometrical factor.

3. Design Methods

3.1 Design Principle

The basic principle of the core T/H design is to protect a thermal failure in the fuel pins. In order to that, fuel assembly grouping and flow rate can be determined by a way of maintaining the mixed outlet temperature for each orifice zone equal to the outlet temperature. On the other hand, the maximum cladding mid-wall temperatures including uncertainties can be equalized over the whole core, which is utilized with both the flow-grouping program and the iteration of the flow-rate allocations.

3.2 Flow Rate Determination

To maintain the mixed outlet temperature for each orifice zone, the flow rate for each flow group is calculated as follows:

$$m = \frac{P_{sum}}{C_p (T_{out} - T_{in})} \qquad (3)$$

where P_{sum}, C_p, T_{out}, and T_{in} represent power summation of each group, heat capacity, core outlet temperature, and core inlet temperature, respectively. Flow distribution for each subassembly is conducted by installing orifice plates through flow path within the subassembly receptacle.

Iteration is also conducted to determine the flow rate. In general, the flow rate is calculated to meet the design limit of the cladding mid-wall temperature, which is the minimum value to ensure the thermal safety including parameter uncertainties. Therefore, it only gives a minimum core flow to fulfill the thermal safety. To allocate all of the core flow and increase the thermal margin, two loop iterations are currently conducted for the core T/H design.

3.3 Flow Grouping Strategy

Flow grouping was performed to collect similar flow rates into a single value, which reduces the fabrication cost and the possibility of operating errors. A trial /error method to minimize the maximum power difference within each flow group is generally utilized. KAERI recently developed a programmatic approach that provides an optimum configuration of flow grouping.

Table I : Design method comparison

Design method	Fixed 2σ mid-wall temperature	Fixed flow-rate*	Fixed outlet temperature	Minimization of 2σ mid-wall temperature
Explanation	Initial conceptual design in KAERI	Total flow allocation after the conceptual design	Heat balance from inlet/outlet temperature	Present design
Maximum 2σ mid-wall temperature [ºC]	644.9	636.4	639.4	636.3
Flow Rate [kg/sec]	1906	1977	1977	1977
Bundle Pressure Drop [MPa]	0.443	0.472	0.466	0.472

* Flow rates in the fixed 2σ mid-wall temperature is multiplied by a constant ratio, which reveals the same total flow-rate with the fixed outlet temperature.

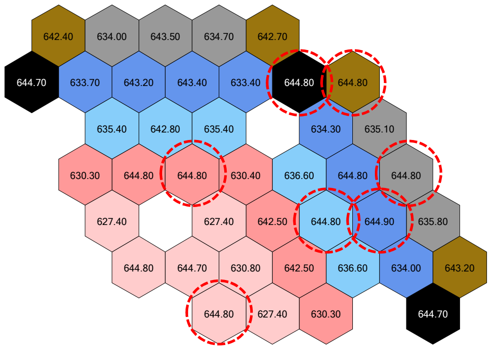

Fig. 1. Fixed 2σ mid-wall temperature

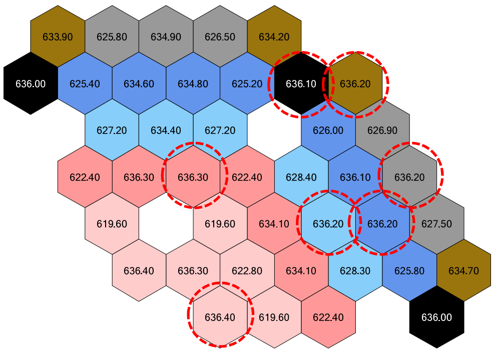

Fig. 2. Fixed flow-rate

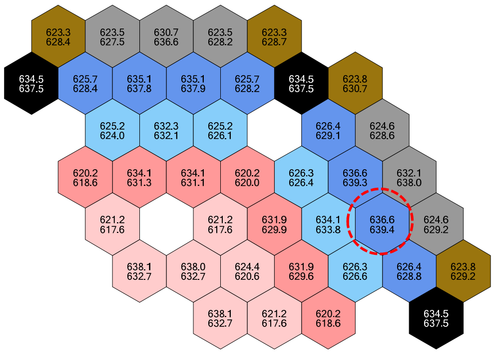

Fig. 3. Fixed outlet temperature

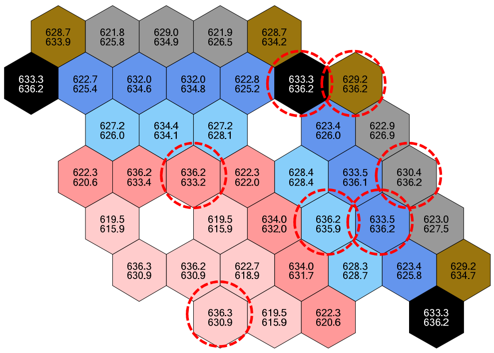

Fig. 4. Minimization of 2σ mid-wall temperature

4. Results and Discussions

The design results are presented in Table I and Fig.1-4. The red circles in the figures represent assemblies with the maximum mid-wall temperature over the whole core. The initial conceptual design in KAERI equalizes the maximum cladding temperature, which is fixed and equals the minimum temperature to ensure the thermal integrality of the fuel pins [2]. Therefore, the fixed 2σ mid-wall temperature method has a higher temperature and lower total flow rate compared to other methods. After allocating the same flow rate, the temperature distribution is similar with that of the minimization method of the 2σ mid-wall temperature as shown in Figs. 2 and 4. Allocating the same flow rate, the fixed outlet temperature method shows the highest maximum cladding midwall temperature, showing the peak assembly in the outer core region. Therefore, the simple heat balance method results in the least safety margin for a thermal failure of the fuel pins.

5. Conclusions

Comparative studies have been performed to determine the appropriate design method for the prototype SFR. The results show that the minimization method show a lower cladding midwall temperature than the fixed outlet temperature methods and superior thermal safety margin with the same coolant flow.

REFERENCES

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[2] S. R. Choi, Conceptual Core Thermal-Hydraulic Design of the Prototype SFR, SFR-DR111-WR-13-2012Rev.00, KAERI, 2012.