Calculation Model of Radial Core Expansion Reactivity Feedback in Sodium-cooled Fast Reactors

Young-Min KWON, Hae-Yong JEONG, Chung-Ho CHO, Su-Dong SUK, Yong-Bum LEE
Korea Atomic Energy Research Institute
ymkwon@kaeri.re.kr

1. Introduction

An inherent passive safety of pool-typed sodium-cooled fast reactors is ensured by self-regulating reactor power characteristics. The self-regulation is achieved by both negative reactivity feedback effects upon a core power excursion and large thermal inertia of a primary sodium inventory. Therefore higher fidelity analyses for the reactivity feedback effects may eliminate an unnecessary conservatism and increase safety margins by beneficial design changes. A high-accuracy reactivity feedback calculation requires mechanistic reactivity feedback models in conjunction with multi-dimensional core thermal-hydraulic models.

It has been found a radial core expansion reactivity, among various reactivity feedbacks, is dominant in view of its magnitude and response time for most postulated ATWS events in a metal-fueled core. However, the accurate calculation of its reactivity feedback effect is very difficult because of its associated complex phenomena of thermal, hydraulic, mechanistic, and neutronics. This paper discusses analytical methods to represent the radial core reactivity feedback to be employed into a system-wide safety analysis code[1].

2. Radial Core Expansion Reactivity Feedback

The radial core expansion accounts for the combined mechanisms of structures thermal expansion and subassembly(SA) bowing with constraints set by the special design of a limited free-bow core restraint system. Figure 1 illuminates the core internal structures including the core constraint system(CSS) for KALIMER-600[2].

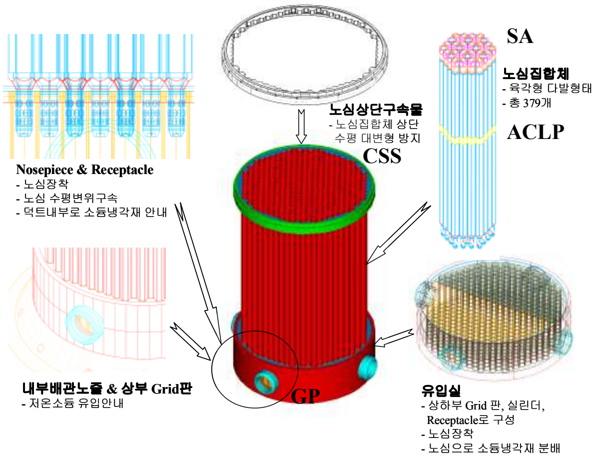

Fig.1 Core Internal Structures for KALIMER-600

The radial dimension of the core is determined by the assembly spacing, which is largely determined by the thermal expansion of the grid plate(GP) below the core and load pad above the core(ACLP). The influence of radial temperature gradients across the SA duct causes the SA to take a shape that is convex to the core centerline (core bowing) as shown in Fig.2. The radial core expansion combines the core dilation from the thermal expansion with the outward bowing of the core periphery. The effect of this growth in volume and outer surface area of the core is to increase the loss of neutrons from the core region through the surface area. This causes a reduction in core reactivity.

The ACLP thermal expansion and the SA bowing rapidly happen within a few seconds when the coolant temperature increases because the duct region is thin and has a small heat capacity. While the thermal expansions of the GP and CSS have a large time scale of about hundred seconds. It should be noted that the limited free bow constraint system in KALIMER-600 is designed in such a manner as to assure a negative contribution during power production.

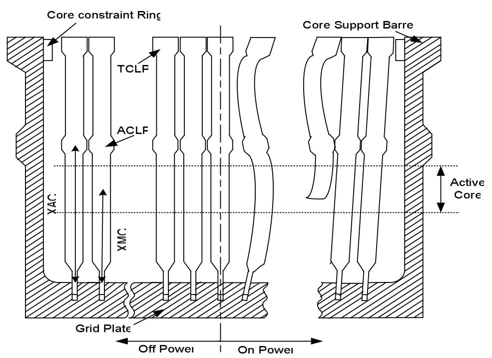

Fig.2 Schematic of Radial Core Expansion

3. Computational Methods

(a) Simple Calculation Model

The CSS and SA load pads must be designed that the core bowing always inserts a negative reactivity during any portion of the postulated power excursion transients. The total worth of the core bowing carries significant uncertainties; hence neglecting the effect makes it simple to account for the radial core expansion with ensuring conservatism for system safety analyses.

In a simple calculation that no credit is given for the SA bowing, the radial core expansion feedback is determined from thermal expansion only by tracking the structure temperatures at the ACLP and at the GP. It is noted that the ACLP and GP respond to the sodium temperatures at the core outlet and inlet locations, respectively. The radii of the ACLP and the GP are calculated at every time step and compared to their steady state values. The effective radius of the active core is determined by weighing each component with respect to geometrical consideration.

In the SSC-K code[1], the radial expansion reactivity coefficient, dk/dr, is defined as:

$$\frac{dk}{dr} = \frac{C_{rad}}{r} \tag{1}$$

where C_{rad} is a radial expansion coefficient calculated using a uniform increase over the core radius.

Equation (1) can be integrated to yield the radial expansion reactivity change due to the effective change in core radius, $\Delta\rho$ as:

$$\begin{aligned} \Delta\rho &= C_{rad} \ln(1 + \omega_{GP}\xi_{GP} + \omega_{ACLP}\xi_{ACLP}) - \rho_o \\ \xi_{GP} &= \alpha_{GP}\left(T_{GP} - T_{GP,o}\right) \\ \xi_{ACLP} &= \alpha_{ACLP}\left(T_{ACLP} - T_{ACLP,o}\right) \end{aligned} \tag{2}$$

where ξ is an effective strain, $(r - r_o)/r$, and α is the thermal expansion coefficient. ω is the geometrical weighting factor for the GP and the ACLP. The subscript o means the steady state value. The set of Eq.(2) is calculated for each channel representing the subassembly across the core and summed up.

Another simple expression for determining the radial core expansion reactivity feedback is the one included in the SAS4A code[3]. The equation is given as follows:

$$\Delta\rho = \alpha^{rad}(T)\left[\Delta T_{in} + \frac{XMC}{XAC}\left(\Delta T_{out} - \Delta T_{in}\right)\right] \tag{3}$$

where ΔT_{in} and ΔT_{out} are temperature changes at the core inlet and outlet locations, respectively. XMC and XAC are distance from the nozzle support at the bottom of the SA to the core mid-plane and to the ACLP, respectively, as shown in Fig.2. The factor XMC/XAC is the geometric relationship between the ACLP and the core mid-plane with respect to the GP.

The main drawback of the two simple methods expressed in Eqs.(2) and (3) is that they do not calculate an actual core displacement and as a result is unable to account for changes in core loading states. It also only includes the reactivity feedback from load pad thermal expansion since the reactivity feedback coefficient is based on a uniform dilation of the core. NUBOW-3D results indicate a 30~40% more feedback due to additional SA bowing caused by interaction wit the core constraint.

(b) Detailed Calculation Model

A more detailed model for calculating the reactivity feedback from radial core expansion is being developed by authors. The model will be included in SSC-K. The radius of the core periphery is calculated in this model by the bending deformation of the outer row of the core. Basically a single SA is selected form a row with a high worth for radial motion and is treated as a simple beam. A schematic representation for this model is shown in Fig.3. This SA is then subjected to an appropriate radial temperature gradient, along with clearances to the various parts of the CSS and neighboring SAs, to determine its shape at steady state and at any time during the transient.

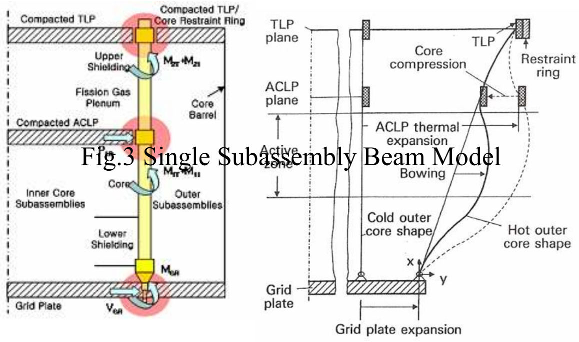

Fig.3 Single Subassembly Beam Model

The SA deflection from the vertical can be given by the following equations:

$$EI\frac{d^2y}{dx^2} = M_x \tag{4}$$

$$\frac{M_T}{EI} = \alpha\Delta T / D \tag{5}$$

where E is modulus of elasticity(N/m^2), I is moment of inertia of the SA cross-sectional area(m^4), M_x (M_T) is thermal bending moment(N-m), x and y are distance along and perpendicular to the SA as defined in Fig.3. ΔT is flat-to-flat temperature difference of the SA and D is flat-to-flat dimension of the SA(m).

Since only the displacement is required from above equations, and the boundaries are solid, the solution is independent of EI. The bending moment is the result of forces at the GP or the ACLP, or the flat-to-flat temperature difference of opposite sides of the SA hexcan. The irradiation effects are converted into an equivalent bending moment and calculated by NUBOW algorithm.

4. Conclusion

The detailed model takes accounts for the change in the equivalent radius of the core, represented as a function of axial position. This assumption makes it possible to perform a considerable simplification over the involved complex calculations, while retaining some of the basic structural modeling such as the SA bowing and the interaction between SA and CSS.

REFERENCES

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