Radial Core Expansion Reactivity Model in Limited Free-Bowing Reactor Constraint System

Young-Min KWON *, Kwi-Lim LEE, Kwi-Seok HA, Hae-Yong JEONG, Won-Pyo CHANG
Korea Atomic Energy Research Institute, 1045 Daedeok St.,Yuseong, Daejeon 305-353 KOREA
**Corresponding author: ymkwon@kaeri.re.kr*

1. Introduction

The system transient analysis code, SSC-K, developed for the specific KALIMER-600 design by KAERI has a capability to calculate a radial core expansion reactivity feedback effect. Two simple radial expansion reactivity models of SSC-K [1], based on lateral uniform core dilation, have been utilized for conservatively simulating negative reactivity transients. The mechanistic radial expansion reactivity model included in the SAS4A/SASSYS code [2] has recently been transplanted into SSC-K. The main frame of the subassembly bowing model and basic assumptions of SAS4A/SASSYS are maintained in SSC-K. SSC-K incorporates a new feature to calculate detailed three-dimensional temperature and flow distributions for each subassembly over a whole core during steady-state and transient. The resultant structure temperatures including duct walls make it reasonabl to calculate the thermally induced bending moment across subassembly duct.

2. Radial Core Expansion Phenomena

The design concept of the core restraint system is categorized into two types; one is the limited free-bowing approach and another is the free-flowering one. KALIMER-600 adopts the limited free-bowing approach in which the core restraint ring (CRR) is attached to the core barrel at the level of the top load pads of assemblies. The core restraint ring provides a solid boundary for the subassemblies. This type core restraint system has been adopted in the FFTF, CRBRP, and PRISM. While PHENIX and EBR-II adopt the free-flowering approach for its core restraint system, in which such a restraint ring does not exist, instead stiff reflector/shield assemblies surrounding the fuel driver and blanket assemblies act as the solid core boundary. Figure 1 illustrates the core restraint system of KALIMER-600, in which locations of the top load pad (TLP) and above core load pad (ACLP) are shown.

As the core power-to-flow (P/F) ratio increases, radial thermal gradients across subassembly ducts are established, which cause the subassembly bending in the mode of convex to the core centerline. The available gap between the top-end of the subassembly and TLP is narrowed by the deflected displacement of the subassembly and the increased size of the load pads, which is represented as deflection shape (a) in Fig 2. As the core power increase further, the subassembly bowing and the thermal expansion of the load pads sufficiently increase enough to close the gaps at the ACLP and TLP as shown in deflection shape (b).

When the assembly bowing is sufficiently large the CRR prevents further radial expansion at the TLP elevation. and which causes compaction of the core at the ACLP elevation. It is said that the core restraint system becomes 'locked-up'. It should be noted that the active core region moves partially inward the core centerline, which results in a positive reactivity feedback. It has been known the locked-up normally occurs at P/F of between 0.5 and 0.8.

Further increase in the P/F ratio causes more thermal bowing of the subassemblies but the ACLP and TLP contact states do not change. The ACLP plane stays compacted and the TLP plane remains expanded up to the CRR. The additional thermal bow is accommodated by elastic bowing of the subassembly which results in an s-shape deflection as shown in deflection shape (c). The subassembly between the grid plate and the ACLP expands while the portion between the ACLP and TLP bows inward, which causes a negative reactivity feedback into the core.

Although the detailed determination of when lock-up occurs is very difficult, the salient feature of the core restraint design is that the locked-up must occur. This is because the thermal bow increases monotonically with P/F and the available space is restricted by CRR. After locked-up occurs, the calculation of the position of the core subassembly is greatly simplified.

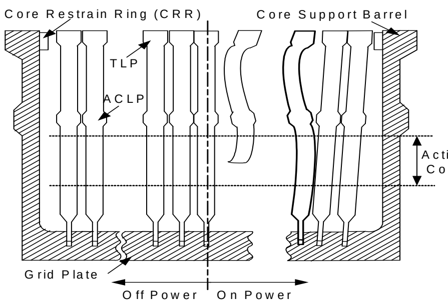

Fig. 1 KALIMER-600 Core Restraint system

3. Mechanistic Radial Expansion Reactivity Model

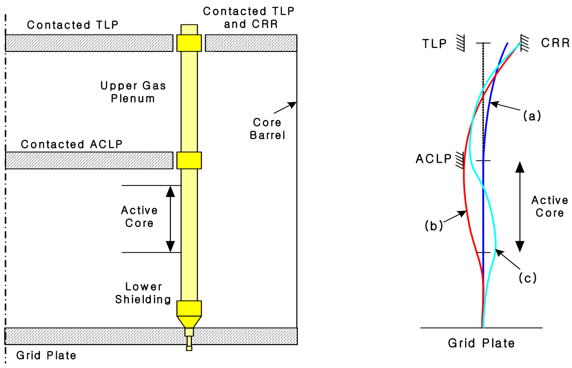

Fig.2 Schematic of Single Subassembly Model and Defection Shapes under Various P/F Condition

The major assumption of this model relies on that a single subassembly located in the outermost row of the fuel drivers region can represent the axial profile of the core radius. Detailed core restraint analysis results indicated that the hottest subassembly was found in the row of fuel driver region, and the coldest subassembly was the next outer rows. Thus, the largest thermal gradients occur at the outer edge of the fuel driver region, and consequently the greatest radial displacements are observed at the same region. The outermost region of the fuel driver region also has a large reactivity worth as a result of the large neutron flux gradient.

The single subassembly at the outer edge is treated as a simple elastic beam subjected to radial temperature gradient under various structural restraint conditions, as discussed in section 2. Therefore the axial profile of the core radius is obtained from the shape behavior of the selected single subassembly. The shapes of the subassembly at steady state and at transient conditions are determined by bending motion due to thermal gradient across the subassembly cross-section in conjunction with the relative locations of the grid plate, load pads, and CRR. The shape changes in the axial dimension during transients are used to calculate the radial core expansion reactivity.

Using a beam-theory model, the radial displacement of the subassembly can be expressed by the differential equation in the x-y plane.

$$EI\frac{d^2y}{dx^2} = M_{Tc}\left(\frac{x-L_c}{L_a-L_c}\right) + M_{Tt} \tag{1}$$

$$M_T = \frac{\alpha \Delta T}{D} \tag{2}$$

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

A number of algebraic equations representing the

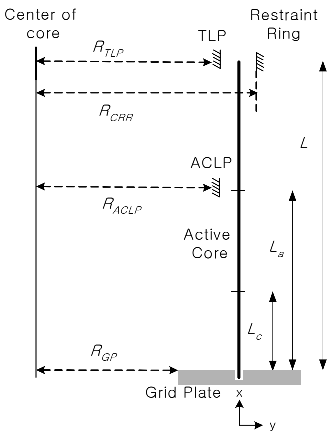

Fig. 3 Schematic of Subassembly Beam Model

shape of the subassembly can be obtained by solving Eq. (1) for the various core loading conditions. Since quantities of particular interest in this model are the resulting lateral deflections required to calculate the radial core expansion reactivity, the forces and moments are not explicitly expressed in equations and their values are not evaluated.

The term of 'contact' in the subassembly behavior relative to the core restraint structures implies one of the following situations. The outward motion is sufficient for the CRR to apply a force preventing further outward motion, or there is sufficient inward motion such that all of the intra-subassembly gaps in the load pad regions are eliminated, thus generating a force preventing further inward motion. The deflection shape equation is valid only for $L_c \le x \le L_a$..

(a) No contact at the ACLP, TLP, or CRR

$$y(x) = \frac{M_{Tc}}{6EI\,(L_a-L_c)}(x-L_c)^3 \tag{3}$$

(b) No contact at the ACLP, contact at the CRR (4)

$$y(x) = \frac{M_{Tc}}{6EI\,(L_a-L_c)}(x-L_c)^3 + \left\{R_{ACLP} - \frac{M_{Tc}}{EI}\left[\frac{(L_a-L_c)(L-L_a)}{2} + \frac{(L_a-L_c)^2}{6}\right] - \frac{M_{Tt}}{EI}\frac{(L-L_a)^2}{2}\right\}\frac{x}{L}$$

(c) No contact at the ACLP, contact at the CRR (5)

$$y(x) = \frac{M_{Tc}}{6EI\,(L_a-L_c)}(x-L_c)^3 + \left\{R_{TLP} - \frac{M_{Tc}}{EI}\left[\frac{(L_a-L_c)(L-L_a)}{2} + \frac{(L_a-L_c)^2}{6}\right] - \frac{M_{Tt}}{EI}\frac{(L-L_a)^2}{2}\right\}\frac{x}{L}$$

(d) Contact at the ACLP, no contact at the TLP or CRR

$$y(x) = \frac{M_{Tc}}{6EI\,(L_a-L_c)}(x-L_c)^3 + \left\{R_{ACLP} - \frac{M_{Tc}}{EI}\left[\frac{(L_a-L_c)(L-L_a)}{2} + \frac{(L_a-L_c)^2}{6}\right] - \frac{M_{Tt}}{EI}\frac{(L-L_a)^2}{2}\right\}\frac{x}{L} \tag{6}$$

(e) Contact at the ACLP, CRR, no contact at the TLP

$$y(x) = \frac{M_{Tc}}{6EI\,(L_a-L_c)}(x-L_c)^3 - \frac{V_{GP}}{EI}\frac{x^3}{6} - \frac{C\,x}{EI} \tag{7}$$

$$\frac{V_{GP}}{EI} = \frac{P}{EI}\left(1-\frac{L_a}{L}\right)$$

$$\frac{P}{EI} = \left\{\frac{R_{ACLP}L}{L_a} - R_{CRR} + \frac{M_{Tc}}{EI}\left[\frac{L_a{}^3}{3} - \frac{L_cL_a{}^2}{2} + \frac{L_c{}^3}{6}\right]\left[\frac{L}{L_a}-1\right]\frac{1}{(L_a-L_c)} + \frac{M_{Tt}}{EI}\frac{(L-L_a)^2}{2}\right\}\frac{3}{\left(L_a{}^3-2L_a{}^2L+L_aL^2\right)}$$

$$\frac{C}{EI} = -\frac{R_{ACLP}}{L_a} + \frac{M_{Tc}}{EI}\left[\frac{L_a{}^2}{6} - \frac{L_cL_a}{2} - \frac{L_c{}^3}{6L_a}\right]\frac{1}{(L_a-L_c)} - \frac{V_{GP}}{EI}\left(\frac{L_a{}^2}{6}\right) + \frac{M_{Tc}}{EI}\frac{L_c{}^2}{2(L_a-L_c)}$$

REFERENCES

[1] Y. M. Kwon et al., "SSC-K Code Users Manual, Rev.1," KAERI/TR-2014/2002, (2002).
[2] Argon National Laboratory, "The SAS4A/SASSYS-1 LMR Analysis Code System," ANL-FRA-1996-3, Volumes 1, 2, and 3, August (1996).