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A Detailed Radial Core Expansion Reactivity Feedback Model for Advanced LMFRs

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1. Introduction

Advanced Liquid Metal Fast Reactor (LMFR) design highly emphasizes inherent safety, which maintains the core power reactivity coefficient to be negative under accidental conditions. It was found that the radial core expansion of the reactor core provides the dominant negative reactivity feedback among all the reactivity components during KALIMER-150 ATWS events [1]. A theoretical model to accurately predict the core deformation phenomena has been developed with the purpose of implementation into the system safety analysis code of SSC-K [2].

2. Analytical Model

The radial core expansion means any change in the radial dimensions of the reactor core due to thermal expansion and bowing of the subassembly duct. A change in the dimension of the core results in reactivity feedback of the core.

2.1 Fundamental Phenomena

The driving force of the radial core expansion is temperature. As schematically shown in Figure 1, when the coolant temperature rises, the reactor core expands by the results of thermal expansion and bowing of the core, and the mechanical interaction between the adjacent sub-assemblies at the location of load pads. Thermal expansion of the core structures is a result of both the laws of nature and the particular core design.

The subassembly is vertically held at the grid plate (GP) but it is free to pivot or tilt. KALIMER subassembly has two load pads, one at the top (TLP) and one just above the top of the core (ACLP), which is typical design for limiting the free bow of the subassembly. The core restraint ring (CRR) limits excessive outward deformation of the core.

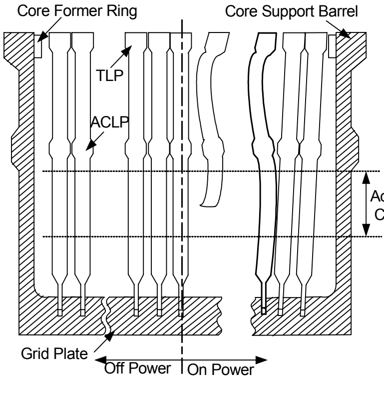

Figure 1. Schematic description of radial core deformation mechanism

The differential thermal expansion of the duct in conjunction with interactions between adjacent subassemblies and the core restraint boundaries force tends to cause the subassembly to take a certain shape dependent on the core condition.

2.2 Analytical Mode for Core Deformation

In the current SSC-K model, the radial deformation of the core is determined solely by the thermal expansion of the GP and load pad regions. The displacement of the core mid-plane is used to estimate the reactivity feedback from the radial core expansion. The model can not explicitly account for subassembly bowing with these assumptions. The main drawback of the current model is that it is unable to calculate an actual core displacement and changes in core loading states.

In order to realistically predict the radial core expansion reactivity feedback, and to provide a framework for more detailed modeling as required, a detailed model [3] has been developed based on the results from NUBOW-2D [4] and SASSYS/SAS4A [5]. Insight from the NUBOW-2D calculations was used to define the important fundamental phenomena.

The proposed model is intended to combine the best features of the current simple model and the complicated NUBOW-2D models. The model focuses on a single averaged subassembly in the outermost row of drivers, in which the radial reactivity worth is highest in the core. The selected subassembly is considered as a simple beam as shown in Figure 2 and its displacement from the vertical is expressed by the following differential equation.

$$EI\frac{d^2y}{dx^2} = M_x \qquad (1)$$

Where E is a modulus of elasticity and I is a moment of inertia of the subassembly cross-section area. The bending moment, M_x is the result of forces at the GP or load pads, or temperature differences of opposite hexcan walls within the subassembly.

The equation (1) is solved subject to various loads and moments, depending on the state of the core. The subassembly deflections at the ACLP and TLP are determined from the bending moments, M_1 in the core region and M_2 in the above core region, by the following equations.

$$y_a = M_1\left(a - x_1\right)^2 / 6EI \qquad (2)$$

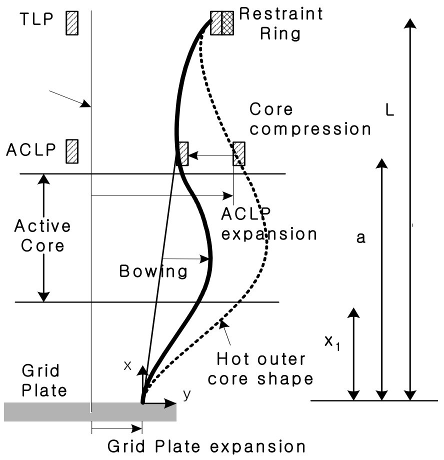

Figure 2. Schematic description of assembly duct deflection at the outer edge of the active core

$$y_L = \frac{M_1}{6EI}\left[3(L-a)(a-x_1)+(a-x_1)^2\right]+\frac{M_2}{2EI}(L-a)^2 \quad (3)$$

The existence of clearance between grid plate and subassembly bottom nozzle allows the subassembly to tilt. When the clearance is exceeded due to the GP thermal expansion, a moment is applied to the subassembly at the nozzle. With the KALIMER core restraint design, there are many possible core loading configurations. The cases with maintaining the clearance at the GP is presented in this paper. The analytical equation to represent the subassembly shapes with no clearance at the GP is more complicated.

For the case that the gaps at either the ACLP or TLP is not closed, the subassembly shape is determined by

$$y(x) = \frac{M_1}{6EI(a-x_1)}(x-x_1)^3 \quad (4)$$

For the case the subassembly contacts at the CRR

$$y(x) = \frac{M_1}{6EI(a-x_1)}(x-x_1)^3 + \frac{(R_3-y_L)x}{L} \quad (5)$$

For the case the subassembly contacts at the TLP

$$y(x) = \frac{M_1}{6EI(a-x_1)}(x-x_1)^3 + \frac{(R_2-y_L)x}{L} \quad (6)$$

For the case the subassembly contacts at the ACLP

$$y(x) = \frac{M_1}{6EI(a-x_1)}(x-x_1)^3 + \frac{(R_1-y_a)}{a} \quad (7)$$

For the case the subassembly contacts at the ACLP and CRR

$$y(x) = \frac{M_1}{6EI(a-x_1)}(x-x_1)^3 - \frac{P}{EI}\left(1-\frac{a}{L}\right)\frac{x^3}{6} - \left[\frac{C_3}{EI}+\frac{M_1}{EI}\left(\frac{x_1^2}{2(a-x_1)}\right)\right]x \quad (8)$$

$$\frac{P}{EI} = \left[\begin{array}{l}\dfrac{R_1L}{a}-R_3+\dfrac{M_1}{EI}\left[\dfrac{a^3}{3}-\dfrac{x_1a^2}{2}+\dfrac{x_1^3}{6}\right]\left[\dfrac{L}{a}-1\right]/(a-x_1)\\ +\dfrac{M_2}{EI}\dfrac{(L-a)^2}{2}\end{array}\right] / \left[(a^3-2a^2L+aL^2)/3\right] \quad (9)$$

$$\frac{C_3}{EI} = -\frac{R_1}{a}+\frac{M_1}{EI}\left[\frac{a^2}{6}-\frac{x_1a}{2}-\frac{x_1^3}{6a}\right]/(a-x_1)-\frac{P}{EI}\left(1-\frac{a}{L}\right)\left[\frac{a^2}{6}\right] \quad (10)$$

R_1 and R_2 mean the minimum core radius at the ACLP and TLP, respectively. R_3 means the maximum core radius at the CRR

2.3 Reactivity Coefficient

The reactivity worth curve for radial core expansion is obtained from a uniform dilation of the core. The radial expansion coefficient is then proportioned among the axial fuel nodes according to the axial power shape. The reactivity coefficient based on the uniform core dilation is the same assumption used for the core radius change calculation in which the core material is uniformly distributed. This assumption implies that all of the subassemblies are moving in proportion to their distance from the core centerline.

When the core radial displacement at each axial node is determined, the reactivity coefficient in the unit of $/m is multiplied by the each displacement to calculate the reactivity change. The total reactivity feedback is the sum over all of the axial nodes.

2.4 Implementation into SSC-K

The detailed radial core reactivity feedback model developed herein will be implemented into the system safety analysis code of SSC-K. It is expected that the proposed model will enhance the passive safety of the KALIMER design. The validation of the proposed model against some experimental data is necessary; however, since no experimental data is available at the present time the calculation result by the model will be compared with the one by the well proven code.

Acknowledgement

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