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Equivalent Pre-Xenon-Oscillation Method for Core Transient Simulation

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등가제논진동법을 이용한 노심천이현상의 모사계산

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Abstract

The initial condition of a core transient should be consistent with real core state for the simulation of the core transient. The initial xenon distribution, which can not be measured in the core, has a significant effect on the transient with xenon dynamics. In the simulation of the transient starting from non-equilibrium xenon state, the accurate initialization of the non-equilibrium xenon distribution is essential for the prediction of the core transient behavior. In this study, a xenon initialization method to predict the core transient more accurately was developed through the equivalent pre-xenon-oscillation which represents the xenon oscillation before the transient and verified by the application of the simulation for a startup test of Yonggwang Unit 3.

요 약

노심천이현상의 모사계산을 위해서는 노심상태의 초기조건을 실제노심과 일치시켜야 하는데 특히, 제논동특성이 관심의 대상이 되는 천이현상에 있어서는 직접적인 측정이 불가능한 노심내 제논분포의 초기상태가 천이현상의 해석결과에 커다란 영향을 미치게 된다. 초기상태의 노심이 정확히 제논 평형상태에 있지 않는 경우 노심의 시간에 따른 변화를 잘 예측하기 위해서는 비평형 제논분포를 모사하는 초기화가 필수적이다. 본 연구에서는 천이현상 이전에 관측된 비평형 제논진동을 등가 제논진동으로 모사하여 천이현상을 보다 정확히 예측할 수 있는 제논 초기화 기법을 개발하였으며 영광 3, 4호기 시운전 시험에서 입수된 실측자료를 통하여 그 적용성을 입증 하였다.

1. Introduction

The purpose of PWR core transient simulation is to predict the variation of the core behavior with xenon dynamics time scale due to the change of operating conditions such as power, control rod position and moderator temperature. The simulation of the core transients requires initial core conditions, not only measurable parameters (e.g. core burnup, control rod position, power distribution, moderator temperature etc.) but also non-measurable parameters (e.g. fuel temperature, xenon distributions etc.). Difficulties in the core transient simulation or prediction are originated from the uncertainties in the parameters related with the initial conditions. An adaptive technique, such as ONED series [1, 2], had been developed to remove the prediction errors due to the uncertainties of the initial condition.

The adaptive core simulation requires adjustments of several parameters which affect the core behavior. One of the most important and difficult parameters adjusted for the initialization is the xenon distribution, since it may affect the core behavior sustainedly. Furthermore, since the reactor may have a xenon oscillation, the exact prediction of the initial xenon distribution is almost impossible. In the indirect initialization approach tried by S.H. Lee [3], the existence of xenon oscillation was characterized by axial power shape variation and it has been found that the initial xenon distribution has a dominant effect on the prediction of core transient behavior. Lee's method solves first order perturbation equation for initial iodine and xenon distributions with the assumption of a linear relationship between the axial power shape and the xenon distribution. The initial iodine and xenon distributions are linearly adjusted by the least square method which minimizes the difference between measured and predicted axial power shape. This method, however, is a kind of trial and error approach so that much more efforts are required to determine the initial xenon distribution.

In this study, an equivalent pre-xenon-oscillation approach, which can determine the initial xenon distribution more straightforwardly, is discussed for the core transient analysis. A core transient behavior starting with xenon oscillation depends on the direction of the xenon distribution change as well as xenon distribution itself. If the slight pre-xenon-oscillation before the transient exists in the core without any significant change of core condition, the pre-xenon-oscillation can be characterized by the variation of the core axial power shape. This pre-xenon-oscillation can be represented by an equivalent pre-xenon-oscillation which reproduces the core behavior before the transient. Determining the equivalent pre-xenon-oscillation using axial power shape variation before the transient, the simulation of core transient estimates the core transient behavior with resonable accuracy as discussed later.

2. Determination of Equivalent Pre-Xenon-Oscillation

The xenon oscillation is characterized by the axial power shape variation. For the simple representation of the axial power shape variation, a parameter ASI (Axial Shape Index) is defined by

$$ASI = \frac{P_B - P_T}{P_B + P_T}, \tag{1}$$

where P_B and P_T are the power of the bottom and top half of the core, respectively. During the xenon oscillation, the ASI variation can be represented by

$$ASI(t) = C \cos(\omega t)\, e^{Bt} + ESI, \tag{2}$$

where C is the initial amplitude, ω is the frequency, B is the damping factor of the ASI oscillation and ESI is the ASI of the equilibrium state. The frequency can be written as

$$\omega = \frac{2\pi}{T}, \tag{3}$$

where T is the oscillation period. The period of the xenon oscillation can be determined from the reference core calculation or actual core measurement. The xenon oscillation within any single oscillatory cycle can be represented by an equivalent oscillation whose time domain is only on a period. If the equivalent oscillation is the n-th original oscillation, the equivalent amplitude C_e is

$$C_e = Ce^{BT_n}, \tag{4}$$

where, T_n is the starting time of cycle n.

Since the time span to be considered is only a per iod of the oscillation, the equilivalent amplitude C_e is approximately a constant in the period for the relatively small amplitude. Let the difference between

ASI and ESI be D at time t after an impulse perturbation which leads to a pre-xenon-oscillation is then

$$D(t) = C_e \cos(\frac{2\pi}{T} t). \quad (5)$$

Now, assume that a transient starts time ϕ after the impulse perturbation which leads to an equivalent oscillation. Eq.(5) is in a time domain that the impulse perturbation occurs at $t=0$. Transforming Eq. (5) into a time domain that the transient starts at $t=0$ and the impulse perturbation is given at $-\phi$ introduces

$$D(t) = C_e \cos[\frac{2\pi}{T}(t+\phi)].$$

This pre-xenon-osciallation before the transient can be determined by the estimation of equivalent amplitude C_e and pre-oscillation time ϕ using least square fitting from the core measurement data, i.e., ASI measurements before the transient.

If N measurement data points are given before a certain transient, C_e and ϕ can be determined to minimize the sum of the squares of errors, e_r,

$$e_r = \sum_{i=1}^{N}\left\{D_i - C_e \cos[\frac{2\pi}{T}(t_i+\phi)]\right\}^2. \quad (7)$$

so that

$$\frac{\partial e_r}{\partial C_e} = \frac{\partial}{\partial C_e} \sum_{i=1}^{N}\left\{D_i - C_e \cos[\frac{2\pi}{T}(t_i+\phi)]\right\}^2 = 0 \quad (8)$$

and

$$\frac{\partial e_r}{\partial \phi} = \frac{\partial}{\partial \phi} \sum_{i=1}^{N}\left\{D_i - C_e \cos[\frac{2\pi}{T}(t_i+\phi)]\right\}^2 = 0. \quad (9)$$

Equations (8) and (9) can be rewritten as

$$2\sum_{i=1}^{N} \cos[\frac{2\pi}{T}(t_i+\phi)] \left\{D_i - C_e \cos[\frac{2\pi}{T}(t_i+\phi)]\right\} = 0 \quad (10)$$

and

$$\frac{T}{\pi}\sum_{i=1}^{N} \sin[\frac{2\pi}{T}(t_i+\phi)] \left\{D_i - C_e \cos[\frac{2\pi}{T}(t_i+\phi)]\right\} = 0, \quad (11)$$

respectively. Equations (10) and (11) can be solved with conditions of $C_e \geq 0$ and $0 \leq \phi \leq T$. The Elemination of C_e in equations (10) and (11) introduces

$$\frac{\sum_{i=1}^{N} D_i \cos[\frac{2\pi}{T}(t_i+\phi)]}{\sum_{i=1}^{N} \cos^2[\frac{2\pi}{T}(t_i+\phi)]} = \frac{\sum_{i=1}^{N} D_i \sin[\frac{2\pi}{T}(t_i+\phi)]}{\sum_{i=1}^{N} \cos[\frac{2\pi}{T}(t_i+\phi)] \cdot \sin[\frac{2\pi}{T}(t_i+\phi)]} \quad (12)$$

Let

$$a_i = \cos(\frac{2\pi}{T} t_i), \qquad b_i = \sin(\frac{2\pi}{T} t_i),$$

and

$$\alpha = \cos(\frac{2\pi}{T}\phi), \qquad \beta = \sin(\frac{2\pi}{T}\phi),$$

then Equation (12) can be rewritten as a third order polinomial equation for $\frac{\beta}{\alpha}$,

$$A(\frac{\beta}{\alpha})^3 + B(\frac{\beta}{\alpha})^2 + A(\frac{\beta}{\alpha}) + B = 0, \quad (13)$$

where

$$A = \sum_{i=1}^{N}(D_i b_i)\sum_{i=1}^{N}(a_i^2) - \sum_{i=1}^{N}(D_i a_i)\sum_{i=1}^{N}(a_i b_i)$$

and

$$B = \sum_{i=1}^{N}(D_i a_i)\sum_{i=1}^{N}(b_i^2) - \sum_{i=1}^{N}(D_i b_i)\sum_{i=1}^{N}(a_i b_i)$$

Equation (13) can be factorized by

$$\left\{(\frac{\beta}{\alpha})^2 + 1\right\}(A\frac{\beta}{\alpha} + B) = 0, \quad (14)$$

and we can get

$$\frac{\beta}{\alpha} = -\frac{B}{A}. \quad (15)$$

Since $\frac{\beta}{\alpha} = \tan(\frac{2x}{T}\phi)$, ϕ is then

$$\phi = \frac{T}{2\pi}\tan^{-1}(\frac{\beta}{\alpha}), \quad (16)$$

and C_e can directly be obtained from Equation (10) as

$$C_e = \frac{\sum_{i=1}^{N} D_i \cos[\frac{2\pi}{T}(t_i+\phi)]}{\sum_{i=1}^{N} \cos^2[\frac{2\pi}{T}(t_i+\phi)]} \tag{17}$$

Note that, however, ϕ solved by Equation (16) always has two roots within the range of $0 \leq \phi \leq T$, and that one leads to positive C_e and the other leads to negative C_e by Equation (17). It is obvious that we should select only positive C_e and relevant ϕ.

Thus, obtaining C_e and ϕ means that we can reconstruct an equivalent pre-xenon-oscillation which represents the core behavior before the transient. Any initial impulse perturbation which leads to positive ASI perturbation can be used for the reconstruction.

3. Application for Unit Load Transient Test in YGN-3 Cycle 1

A core transient had been tested in Yonggwang Unit 3 Cycle 1 startup to verify the core power change capability to concur with turbine power change. The test was performed at 1900 MWD/MTU and started from ARO 95% power level with a step power change to 85%. About two and half hour later the core power was decreased to 70% by the ramp rate of -5% per minute. Then, three hours after, the core power increased to 70% by the ramp rate of 5% per minute. After another three hours core power returned to 95% by step change. Figure 1 shows the core power change in the transient. The boron concentration during the test was kept between 745 to 785 PPM. The major power control was performed by lead bank insertion and withdrawal. The boron concentration and the lead bank movement during the test are shown in Figures 2 and 3. ASI variation was measured for the whole transient from the on-line monitoring system COLSS [4].

To simulate the tested core transient, ONED94 was used. ONED94 is an updated version of ONED90 developed by KAERI [1, 2]. This code solves two group one-dimensional diffusion equation by

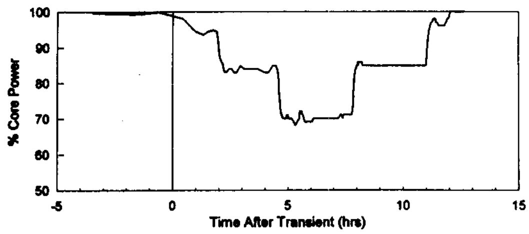

Fig. 1. Core Power Change in Transient

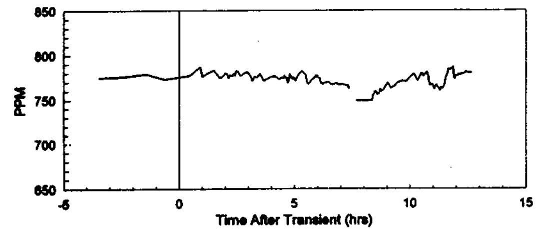

Fig. 2. PPM Change in Transient

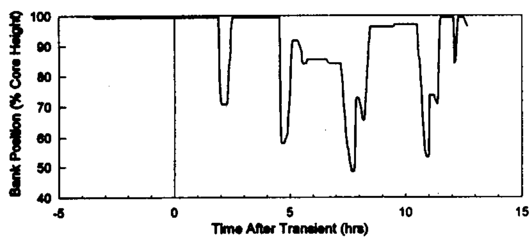

Fig. 3. Lead Bank Position in Transient

the ANM/NEM with adapted parameters which adjusts the steady state ONED94 model [5] to be consistent with those of three-dimensional nuclear design code ROCS [6].

Figure 4 shows the comparison of measured ASI's with the ONED94 simulation results assuming the transient starts from the equilibrium xenon state i.e., it was assumed that there is no pre-xenon-oscillation before the transient. As shown in this figure, the simulation neglect ASI variation before the transient and thus, the difference between measured ASI and ONED94 results increases as the transient proceeds with RMS difference of 1.8% in ASI predictions versus measurements. It can be seen that the four ASI measurement data before the transient of which pow

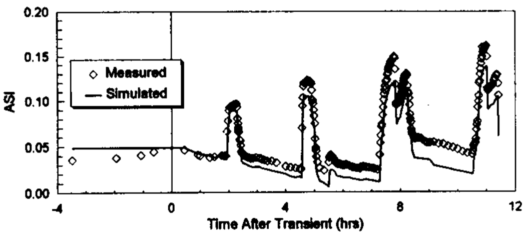

Fig. 4. ASI Simulation of Transient with Eq. Xenon

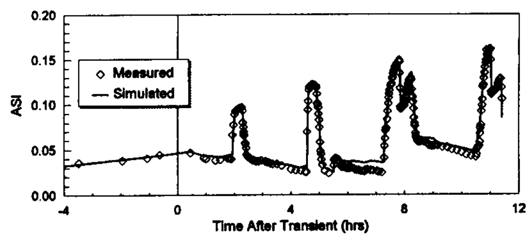

Fig. 6. ASI Simulation of Transient with Pre-Xenon-Oscillation

er level is greater than 99%, were increasing slightly. It implies that the core has the xenon oscillation before the transient and the effect on transient core behavior appears by the difference between measured and simulated ASI's in Figure 4.

In order to consider the xenon oscillation before the transient, an equivalent pre-xenon-oscillation discussed in Section 2 was determined from four ASI measurement data before the transient. As a result of least square fitting, the equivalent pre-xenon-oscillation was characterized by

$$D(t) = 0.0177 \cos[\frac{2\pi}{30.5}(t+22.18)],$$

where 30.5 is the free xenon oscillation period estimated by the equilibrium ONED94 simulation and t is the time in hour from the start of transient. Figure 5 shows the equivalent pre-xenon-oscillation determined using the four ASI measurement data before the transient.

The equivalent pre-xenon-oscillation can be generated by one hour impulse lead bank movement of which insertion step leads to the amplitude of 0.0177. The insertion step can easily be determined

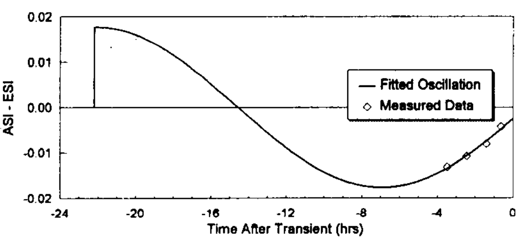

Fig. 5. Cosine Fitting of Equivalent Pre-Xenon-Oscillation

by a few simulations of the impulse perturbation followed by free xenon oscillation. In this case, the insertion step was determined by 28% core height. The result of the transient simulation preceeded by the 22.18 hours xenon oscillation after one hour lead bank insertion of 28%, is shown in Figure 6. It can be seen that the simulated ASI variation well agrees with measured data. The RMS difference in ASI predictions versus measurements is 0.7%.

4. Conclusions

A straightforward xenon initialization method was discussed in this study, which is based on the core behavior before the transient. The core behavior represents the xenon status in the core as ASI variation. Though the xenon distribution itself can not directly be reproduced, the equivalent pre-xenon-oscillation, which represents the core behavior, provides an implicit initial xenon distribution for the core transient simulation. The efficiency of the equivalent pre-xenon-oscillation depends on the confidence of the core measurement data before the transient. Since the equivalent pre-xenon-oscillation considers only a single period of oscillation, the core ASI variation data which covers a quarter of single period of xenon oscillation (about 8 hours for typical PWR) is sufficient to determine the pre-xenon-oscillation. In the application of this study, only 4 hours data give a good prediction of the core transient simulation. It should be noted that, however, all of the ASI variation data in this case are within a quarter of an oscillation period. Therefore, it is concluded that the necessary ASI variation data required to generate the equivalent pre-xenon-oscillation is at least 4 hours of data of which the ASI's are between ESI and any one peak value in the positive or negative direction.

In conclusion, the equivalent pre-xenon-oscillation approach to initialize the xenon distribution in the core using pre-measurement core data enables accurate estimation of the core transient. Because the equivalent pre-xenon-oscillation can be generated straightfowardly by the least square fitting, this method can easily be programmed and applicable to the core simulator.

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