Calculation of Doppler Reactivity Effect in the Metal-Fueled KALIMER Reactor

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1. Introduction

In the fast reactors, the most serious adverse consequence would be compaction of molten fuel in a postulated unprotected transient either by gravity or external pressure forces. The fuel compaction under sodium loss condition has the potential to make the reactor super-prompt critical. Conventional control rods driven by mechanical action is too slow after prompt criticality is reached. A Doppler effect is very important for fast reactors because it provides a prompt negative reactivity feedback that reverses a power transient if the reactor becomes prompt critical.

The existence of the Doppler effect in fast oxide-fueled reactors and the prediction method of its feedback effect on transients with reactivities above prompt critical was fully demonstrated in the late 1960s. Two analytical methods to predict the Doppler effect in the fast reactor with metal-fueled core are suggested in the present paper.

2. Doppler Coefficient

Doppler is the direct result of the laws of nature. As the fuel temperature rises, more neutrons are parasitically absorbed in the resonance energy range. This has the effect of removing active neutrons from the core and reducing reactivity. Doppler feedback is the fastest acting feedback mechanism. Doppler feedback removes the reactivity as the temperature rises and can thus help limit the extent of the power-increase excursion.

Metal-fueled reactors have a hard neutron spectrum because it has no moderator in the fuel matrix. The flux in the principal Doppler resonance region for the metal-fueled reactors is appreciably less than for the oxide-fueled reactors (0.1~10keV). Since most of the Doppler effect comes from the fertile atomic nuclei, the fissile plutonium contribute little to the Doppler effect.

The fuel temperature coefficient or the Doppler coefficient(dk/dT), defined to estimate the Doppler reactivity resulting from the change in fuel temperature, is expressed by

$$\frac{dk}{dT} = \frac{K_D}{T^m} \tag{1}$$

where, K_D is a constant(called Doppler constant) and the exponent m is spectrum-dependent. The value of m is 0.5 for thermal reactors, 0.9~1.1 for large fast oxide-fueled reactors, and 1.5 for small fast metal-fueled reactors [1].

3. Computational Methods

For a uniform change in fuel temperature from the initial T_o to T, the Doppler reactivity effect can be calculated from Eq.(1) as follows:

$$\rho^{DOP} = \int_{T_0}^{T} \frac{dk}{dT} dT = \int_{T_0}^{T} \frac{K_D}{T^m} dT \tag{2}$$

The total Doppler reactivity for the reactor at any time is then given by

$$\rho^{DOP} = \sum_{J,K} \frac{K_D(J,K)}{1-m} \left[\overline{T}(J,K)^{1-m} - \overline{T}_o(J,K)^{1-m} \right] \tag{3}$$

where $T(J,K)$ is the local, volume-averaged fuel temperature over the Jth axial segment in channel K. $K_D(J,K)$ is the local Doppler coefficient. Eq.(3) is used at each axial location where a fuel temperature is calculated. The K_D is adjusted linearly between the with and without sodium values to correct for the effect of coolant voiding on neutron leakage. The local Doppler coefficient K_D can be approximated by

$$K_D(J,K) = A_D(J,K)\left[1-\alpha(J,K)\right] + B_D(J,K)\alpha(J,K) \tag{4}$$

where $\alpha(J,K)$ is a local equivalent sodium-void fraction at time t

$$\alpha(J,K) = \frac{\rho_0^{Na}(J,K) - \rho^{Na}(J,K)}{\rho_0^{Na}(J,K)} \tag{5}$$

and $A_D(J,K)$ and $B_D(J,K)$ are the Doppler constants with and without sodium present at the (J,K) node, respectively. The subscript o refers to the node conditions at the initial time.

The Doppler reactivity effects due to fuel temperature change for KALIMER at the beginning of equilibrium cycle are expressed by $-1302.2T^{-1.12}$ (pcm) for with sodium and $-1132.0T^{-1.15}$ for without sodium, respectively. The above temperature correlations are defined by a least-square fitting of reactivities at different fuel temperatures [1]. It is shown that the Doppler coefficient for the sodium voided case is less negative compared with the flooded case because of spectrum hardening due to sodium voiding.

The Doppler coefficients for KALIMER are on the basis of about $T^{-1.12}$ variation, which shows the temperature variation of dk/dT for the present core design is not much deviated from the oxide-fueled core. The Doppler reactivity for KALIMER could be calculated using the model basis for the oxide-fueled core because the local Doppler constants(K_D) are generated by a well established oxide-fueled reactor method. The Doppler reactivity effect for the case of m=1can be calculated as follows:

$$\rho^{DOP} = \sum_{J,K} \rho^{DOP}_{J,K} = \sum_{J,K} K_D(J,K) \ln\left(\frac{\bar{T}(J,K)}{\bar{T}_0(J,K)}\right) \quad (6)$$

The fuel temperature used in above equations is the volume-averaged one, which is defined by

$$\bar{T}(J,K) = \frac{\sum_i V_i(J,K) T_i(J,K)}{\sum_i V_i(J,K)} \quad (7)$$

where $V_i(J,K)$ is a local volume at the i-th radial node at the (J,K) position. In the reactor there is a fuel temperature distribution that must be taken into account in calculating the reactivity effect. The temperature variations are often accounted for by the weighting factor $W(J,K)$ that is a normalized spatial variation of the Doppler effect, such that

$$\frac{1}{V_i}\int_{Vi} W(J,K)\, dV_i = 1 \quad (8)$$

where the summation is over the fuel regions for the channel K. Since the Doppler effect is reduced as the fuel temperature increases by reduction of number of atoms, another correction factor for K_D is introduced by the time-dependent ratio of fuel mass at time t and at initial mass. Then the total Doppler reactivity for the reactor is given by

$$\rho^{DOP} = \sum_K \sum_J W(J,K) \frac{M_f(J,K)}{M_{fo}(J,K)} K_D(J,K) \ln \frac{\bar{T}(J,K)}{\bar{T}_o(J,K)} \quad (9)$$

The A_D and B_D are practically given by the representative value for each channel by

$$K_D(J,K) = A_D(K)\left[1-\alpha(J,K)\right] + B_D(K)\alpha(J,K) \quad (10)$$

The coefficients of A_D and B_D for each channel as well as the axial weighting factor $W(J,K)$ are determined from a separate diffusion or transport calculation and specified in the problem input.

4. Code Analysis

The Doppler effect in the KALIMER reactor for the unprotected transient overpower (UTOP) has been calculated using the SSC-K code [2] in which two methods described in Section 3 are employed. The method 1 based on Eq.(3) utilizes the Doppler coefficients expressed in the temperature correlation with the exponent m. The fuel temperature in the method 1 must represent the whole core. The Doppler effect can be calculated by directly integrating the temperature correlations. Method 2 based on Eq. (9) follows the traditional calculation process for the oxide-fueled reactor.

The UTOP event results when a positive reactivity is inadvertently inserted into the core and there is a complete failure of the reactor protection system. It is assumed to insert 2 cents per second for 15 seconds in this analysis.

Figures 1 and 2 show comparison of the reactivity components predicted by two methods employed in SSC-K. The peak Doppler reactivities calculated by the method 1 and method 2 are -14.7 and -13.2 cents, respectively. The complicated method 2 predicts higher negative peak than the simple method 1, but the overall trend of the Doppler reactivity transient is very similar. As shown in the figures the other reactivity components during UTOP are slightly different in the magnitude due to the discrepancy of Doppler reactivities predicted by the different methods.

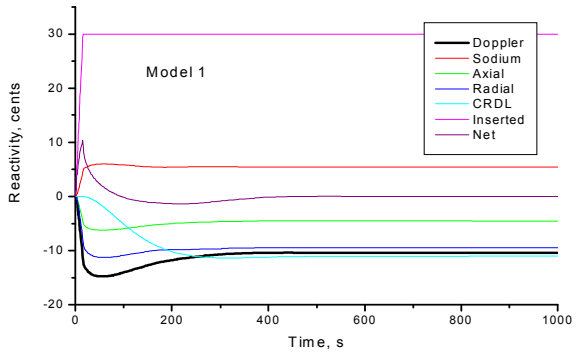

Fig.1 Doppler Reactivity calculated by Method 1

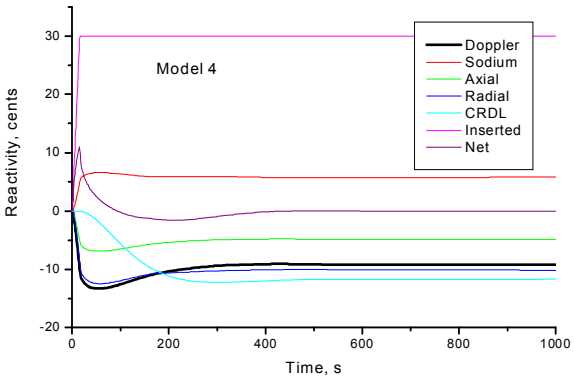

Fig.2 Doppler Reactivity calculated by Method 2

5. Conclusion

The results of the SSC-K analysis indicate that the calculation of the Doppler effect in the fuel by the simple method 1 agrees well in general with the more complex prediction method 2. Most of differences between the two calculations may result from differences in the calculation method. It can be stated that the Doppler feedback of reactivity calculated by two methods introduced in this paper may be reasonably usable for the conservative design purpose. The comparison of results also indicates that the thermal-hydraulic behaviors calculated by two methods during the UTOP event show good agreements.

REFERENCES

[1] D. Hahn et al., KALIMER-600 Conceptual Design Report, KAERI/TR-3381/2007, Korea Atomic Energy Research Institute, 2007.
[2] Y. M. Kwon et al., SSC-K Code Users Manual, Rev.1, KAERI/TR-2014/2002, Korea Atomic Energy Research Institute, 2002.