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Two-Point Reactor Kinetics for Large D_2O Reflected Systems

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다량의 중수반사체 계통에 대한 2-점노 운동방정식

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Abstract

Two-point kinetic equations for a compact-core-with-bulky-D_2O-reflector system were developed. A unique feature of the system is that certain fission gammas create retarded photoneutrons in the D_2O reflector by (γ, n) reaction.

Coupling effect between the core and the reflector was invetigated by simulating power transients with various ramp reactivity insertions. Special attention was paid to the phenomenon associated with spatial separation of photoneutrons and their precursors.

Simulations show that accuracy of the two-point model is comparable with that of space-dependent approach. Also it is found that the explicily expressed photoneutron terms in the reflector equation slow down the power transient compared to non-photoneutron expressions. Detectors for reactor power control purpose prefer to be deployed in the core zone to be able to accurately perdict transient power.

요 약

다량의 중수반사체를 가진 조밀한 노심에서는 핵분열시 발생하는 γ선과 중수소와의(γ, n) 반응에 의해 지발 광중성자가 다량 생성되므로 이러한 계통을 기술하기 위하여 광중성자와 그 모핵종의 공간적 분리에 역점을 두어 2-점노 운동방정식을 정립하였다.

여러 반응도를 주입하여 출력 천이를 모사계산하므로써 노심과 반사체사이의 관련 효과를 조사하였다.

이 모델에 의한 모사계산 결과와 공간 종속 운동방정식에 의한 계산결과를 비교하였다. 반사체 영역에서의 광중성자 효과가 포함되므로써, 이를 포함하지 않은 모델에 비해 출력 천이현상을 감소시켰다. 실제로 출력을 측정하는 계측기는 이러한 공간적 분리영향을 제거하기 위하여 노심 내부에 위치하여야 한다.

I. Introduction

Compact core with volumetric D_2O reflector is deemed to be one of promising high flux research reactor concepts with respect to broad application of intensive steady neutron source. Dynamic behaviour of such reactor systems has been analyzed using conventional single point reactor kinetics (1)~(3) or space-time-dependent diffusion equations (4)~(5). However the difficulties imposed here are how such approaches correctly describe photoneutrons produced in D_2O reflector from their precursor in the core and what is the significance of their retarded effect on the time behaviour of the integral system.

The present work is an attempt to investigate the kinetics of the KMRR(Korea Multipurpose Research Reactor) mainly from aspects of delayed photoneutron transient. The kinetic equations derived for coupled reactor systems have been applied to develop the mathematical model (6) ~(8). Feedback and controller action are not included in the present study.

II. Reactor Model

II. 1. KMRR Desciptions

The 30MWt KMRR is the first of a new generation of research reactors in Korea specifically designed for broad but intensive nuclear research. The reactor provides in this instance faulities for fuel test, radiation damage by high energy neutrons, production of isotopes and research with neutron beams.

The reactor core design incorporates a compact, modular, H_2O-cooled and moderated, central region(inner core) partly surrounded by a H_2O-cooled flow channels(outer core). The D_2O acts as the primary reflector for the inner core and the moderator for the outer core. The D_2O tank is sufficiently large that the outer core is also D_2O reflected. The core-reflector assembly is installed in an H_2O-filled pool. Plane view of the reactor tank is given in Figure 1.

The inner core consists of 23 sites of hexagonal zircaloy flow tubes and 8 sites of circular flow tubes on an uniform hexagonal pitch. The hexagonal flow tubes are separated from each other by a 3.5-mm H_2O gap. The 36-element

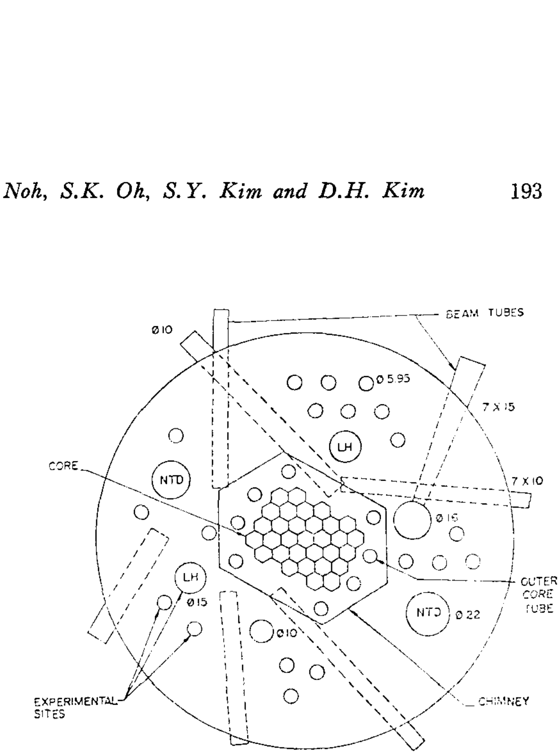

Fig. 1. KMRR Structure Plane View

driver fuel assemblies may be placed in any of hexagonal flow tubes and the 18-element shim fuel assemblies occupy the circular flow tubes. The shutoff and reactivity control H_f shrouds slip on/off the circular flow tubes from outside.

All the fuel assemblies are made from fuel pencils of an extruded uranium-aluminum-silicon dispersion. The intermetallic compound U_3Si-Al contains 58.6w/o U, 2.4w/o Si and 39.0w/o Al. The density of fuel meat is 5.29g/cm^3. The uranium loading of a 6.35mm diameter, 70cm length fuel rod is thus 68.72g. Initial enrichment is 20w/o ^{235}U.

II. 2. Two-Point Kinetic Equations

Let us consider the reactor system composed of the subcritical core, i.e., the prompt and delayed neutron source, and the D_2O reflector, i.e., the photoneutron source whose intensity is proportional to the averaged neutron flux over the core. Neutron leakage and slowing down are also considered to have influence on the neutron density in reflector and core.

Taking as a model two homogenous component reactor and applying approximately a time dependent one group diffusion equation for the system, kinetic equations may be derived to

$$\frac{d}{dt}n_c(t)=\frac{\{\rho(t)-\beta-\gamma\}}{l_c}n_c(t)+\sum_{i=1}^{I}\lambda_{ci}\mathcal{C}_i(t)+\frac{\alpha_{CR}}{l_C}n_R(t-\tau_{CR}),$$

$$\frac{d}{dt}\mathcal{C}_i(t)=\frac{\beta_i}{l_C}n_c(t)-\lambda_{Ci}\mathcal{C}_i(t),\quad i=1,2,\cdots,I$$

$$\frac{d}{dt}n_R(t)=\alpha_{RR}n_R(t)+\sum_{j=1}^{J}\lambda_{Dj}\mathcal{D}_j(t)+\frac{\alpha_{RC}}{l_C}n_C(t-\tau_{RC}),$$

$$\frac{d}{dt}\mathcal{D}_j(t)=\frac{\gamma_j}{l_C}n_C(t)-\lambda_{Dj}\mathcal{D}_j(t),\quad j=1,2,\cdots,J \tag{1}$$

where

$n_C(t)$: averaged neutron density of the core

$\mathcal{C}_i(t)$: i-th group delayed fission neutron precursor density

$n_R(t)$: averaged neutron density of the reflector

$\mathcal{D}_j(t)$: j-th group photoneutron precursor density

$\rho(t)$: reactivity of the system

β_i : yield fraction of i-th group delayed fission neutron precursor, $\beta=\sum_i\beta_i$

γ_j : yield fraction of j-th group photoneutron precursor, $\gamma=\sum_j\gamma_j$

λ_{Ci} : decay constant for the i-th precursor

λ_{Dj} : decay constant for the j-th photoneutron precursor

l_C : neutron generation time in the core

α_{CR}, α_{RC} : coefficients of cross-coupling between core and reflector

τ_{CR}, τ_{RC} : time lags for neutron transport

α_{RR} : coefficient of auto-coupling in reflector

Normalizing the state variables, $n_c(t)$, $\mathcal{C}_i(t)$, $n_R(t)$ and $D_j(t)$ to their steady state values, applying the criticality condition and linearizing with the first order approximation, Eqs. (1) become

$$\frac{d}{dt}N_C(t)=\frac{\{\delta\rho(t)-\beta\}}{l_C}N_C(t)+\sum_{i=1}^{I}\frac{\beta_i}{l_C}C_i(t)-\omega\frac{\alpha_{CR}}{l_C}(1-\tau_{CR})\{N_C(t)-N_R(t)\},$$

$$\frac{d}{dt}C_i(t)=\lambda_{Ci}\{N_C(t)-C_i(t)\},\quad i=1,2,\cdots,I$$

$$\frac{d}{dt}N_R(t)=\frac{1}{\omega}\sum_{j=1}^{J}\frac{\gamma_j}{l_C}D_j(t)+\frac{1}{\omega}\frac{\alpha_{RC}}{l_C}(1-\tau_{RC})\{N_C(t)-N_R(t)\},$$

$$\frac{d}{dt}D_j(t)=\lambda_{Dj}\{N_C(t)-D_j(t)\},\quad j=1,2,\cdots,J \tag{2}$$

where

$\delta\rho(t)\equiv\rho(t)-\rho(\infty)$,

$N_C(t)\equiv n_C(t)/n_C(\infty)$,

$C_i(t)\equiv\mathcal{C}_i(t)/C_i(\infty)$, $i=1,2,\cdots,I$

$N_R(t)\equiv n_R(t)/n_R(\infty)$,

$D_j(t)\equiv\mathcal{D}_j(t)/\mathcal{D}_j(\infty)$, $j=1,2,\cdots,J$

$\omega\equiv n_R(\infty)/n_C(\infty)$

and $\rho(\infty)$: criticality condition for the steady state. Linearized form of time-delayed state variables $N_C(t-\tau_{CR})$ and $N_R(t-\tau_{RC})$ were approximated to $(1-\tau_{CR})N_C(t)$ and $(1-\tau_{CR})N_R(t)$.

II. 3. Numerical Evaluation of Coupling Coefficients

The determination of coupling coefficients, α_{CR} and α_{RC} was studied using the HEXKIN code[9] HEXKIN simulation of various reactivity insertions for the KMRR system provided associated time behaviours of neutron density in core and reflector for the system of without-photoneutron-in-reflector. Reconstructed form of Eqs. (2), which represents the without-photoneu tron system, simulates the variation of $N_C(t)$ and $N_R(t)$ as a function of α_{CR} and α_{RC} for the same $\delta\rho(t)$ as the HEXKIN's.

Typical kinetics parameters evaluated for the KMRR are given in Table 1. Simulations showed that, if $\alpha_{CR}=\alpha_{RC}=0.01$ was taken,

Table 1. Kinetics Parameters of the KMRR

Parameters	Values	
Neutron Generation Time (sec)	1.1785×10^{-4}	
Delayed Neutron Data		
Group	Yield Fraction	Decay Constant (sec)
1	0.24747×10^{-3}	0.12709×10^{-1}
2	0.14148×10^{-2}	0.31677×10^{-1}
3	0.12057×10^{-2}	0.11591
4	0.26959×10^{-2}	0.31261
5	0.86875×10^{-3}	0.13995×10^{1}
6	0.18280×10^{-3}	0.38578×10^{1}
Total	0.66605×10^{-2}	—
Photoneutron Data		
Group	Yield Fraction	Decay Constant (sec)
1	4.0×10^{-7}	6.26×10^{-7}
2	8.0×10^{-7}	3.63×10^{-6}
3	2.7×10^{-6}	4.37×10^{-5}
4	1.97×10^{-5}	1.17×10^{-4}
5	1.74×10^{-5}	4.28×10^{-4}
6	2.84×10^{-5}	1.50×10^{-3}
7	5.92×10^{-5}	4.81×10^{-3}
8	1.727×10^{-4}	1.69×10^{-2}
9	5.512×10^{-4}	2.27×10^{-1}
Total	8.53×10^{-4}	—

discrepancy between HEXKIN and Eqs. (2) became negligible and computing time was also significantly reduced.

III. Simulations

Eqs. (2) were built in the FORSIM code[10] the automated solution of aibitrarily defined partial and/or ordinary differential equation systems. Objective of simulations is to investigate time delay of the reactor power transient, induced by photoneutron production in D_2O reflector.

0.1, 0.33 and 0.5mk/sec ramp insertions of reactivity in the core were tested. Figures 2 and 3 give neutron responses in the KMRR core and reflector with and with out photoneutron yield for cases of negative and positive insertions, respectively. Without photoneutrons, neutron densites predicted by Eqs. (2) are close to those simulated by the 2-dimensional code HEXKIN. However, with photoneutrons explicitly introduced in the reflector equation, transients were significantly slowed down. Also neutron density transient in the reflector zone is slower than that in the core.

Physical interpretation of the transient slowdown is that the core-reflector coupling term has an important role on transient especially after the neutron population balance between core and reflector becomes broken.

It is also found in the figures that neutron population in the reflector zone varies more slowly than that in the core zone regardless of

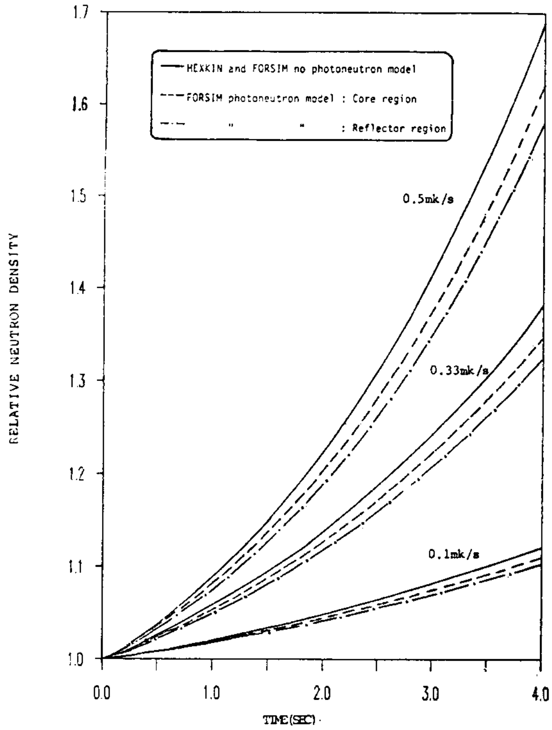

Fig. 2. Neutron Density Transients with Various Ramp Insertions of Positive Reactivity

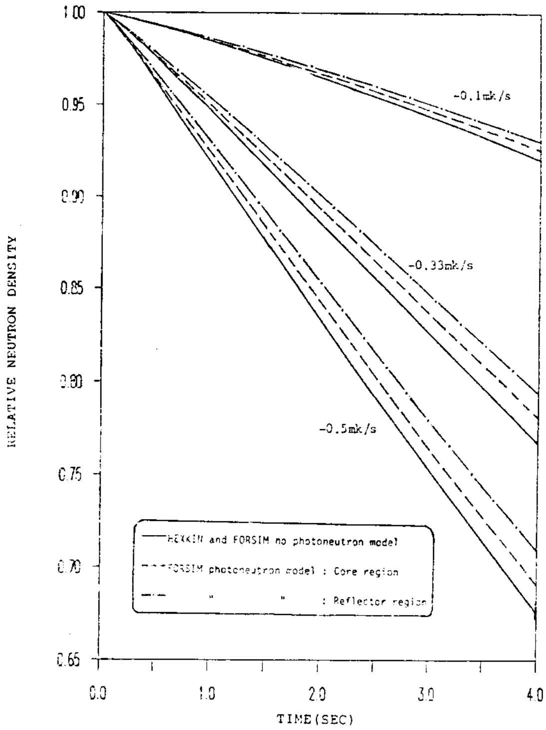

Fig. 3. Neutron Density Transients with Various Ramp Insertions of Negative Reactivity

type and magitude of inserted reactivity. For the reactor design aspect, neutron detectors for control purpose had better be deployed in the core rather than in the reflector to accurately predict the actual reactor power.

IV. Conclusion

Two-point kinetic equations for a compact core with bulky D_2O reflector system was developed. The numerical results indicate that

(1) The two-point model improves the accuracy close to the space dependent approach.

(2) The explicitly represented photoneutron term in D_2O reflector zone significantly slows down the power transient compared to non-photoneutron expressions

(3) Detectors to measure the actual reactor power prefer to be deployed in the core zone.

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