Annals of Nuclear Energy 91 (2016) 59–64

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Technical note

Supercritical kinetic analysis in simplified system of fuel debris using integral kinetic model

Delgersaikhan Tuya [a], Toru Obara [b,*]

[a] Department of Nuclear Engineering, Tokyo Institute of Technology, 2-12-1-N1-19 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[b] Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-19 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form 21 December 2015
Accepted 5 January 2016
Available online 16 January 2016

Keywords:
Fuel debris
Criticality accident
Integral kinetic model
Weakly coupled system
Fukushima Daiichi NPP accident

ABSTRACT

Preliminary prompt supercritical kinetic analyses in a simplified coupled system of fuel debris designed to roughly resemble a melted core of a nuclear reactor were performed using an integral kinetic model. The integral kinetic model, which can describe region- and time-dependent fission rate in a coupled system of arbitrary geometry, was used because the fuel debris system is weakly coupled in terms of neutronics. The results revealed some important characteristics of coupled systems, such as the coupling between debris regions and the effect of the coupling on the fission rate and released energy in each debris region during the simulated criticality accident. In brief, this study showed that the integral kinetic model can be applied to supercritical kinetic analysis in fuel debris systems and also that it can be a useful tool for investigating the effect of the coupling on consequences of a supercritical accident.

1. Introduction

The study of nuclear criticality safety is one of the important fields in nuclear engineering. It deals with the possible scenario of a nuclear criticality accident and its undesirable consequences. In fact, approximately 60 nuclear criticality accidents have previously occurred (McLaughlin et al., 2000). One feature of the criticality accident is that it usually happens unexpectedly, and therefore poses a potential harm via radiation exposure to individuals working nearby. Hence, safety measures against such accidents are essential. These may include a safe design, criticality alarm system, and preparation of emergency response procedures. At the same time, it is equally important to model criticality accidents and predict their consequences, including transient behavior, total energy release, and radiation dose.

In 2011, a severe accident occurred in the Fukushima Daiichi nuclear power plant. It is now thought that the some parts of the reactor cores melted, interacted with the water (Tanabe, 2012), and possibly formed fuel debris. It is possible that fuel debris of various geometries in the water are neutronically weakly coupled and could become critical during the removal process due to changes in geometry, such as a fuel/moderator volume ratio or a distance from other debris. Therefore, it is necessary to study possible criticality accident scenarios using an appropriate method. Use of the conventional point-reactor kinetics model is limited because of the weak coupling between debris regions. The integral kinetic model (IKM), which has previously been used for the kinetic analysis of several weakly coupled fuel solution tank systems (Kikuchi and Obara, 2016), is more appropriate for the analysis of such debris systems.

The current study is intended as a preliminary analysis for criticality accident scenarios in such debris systems. Accordingly, the purpose of this study is to show the applicability of the IKM to the supercritical kinetic analysis of weakly coupled simplified fuel debris systems and furthermore investigate the effect of the coupling due to surrounding debris on the consequence of the criticality accident.

2. Methodology

2.1. Integral kinetic model

In this section, we provide a brief description of the IKM. The detailed theory behind the IKM has been described elsewhere (Gulevich and Kukharchuk, 2004; Takezawa and Obara, 2012). The IKM describes time- and region-dependent fission rate by considering fission contributions from all other regions in a time range from past to present. The general form of the IKM for a system consisting of n fissile regions is:

$$N_i(t) = \sum_{j=1}^{n}\left(\int_{-\infty}^{t} \alpha_{ij}^{p}(t-t')N_j(t')dt' + \int_{-\infty}^{t} \alpha_{ij}^{d}(t-t')N_j(t')dt'\right) \quad (1)$$

* Corresponding author.
E-mail address: tobara@nr.titech.ac.jp (T. Obara).

http://dx.doi.org/10.1016/j.anucene.2016.01.003
0306-4549/

where $N_i(t)$ is total fission rate in region i at time t (fissions/s); $\alpha_{ij}^{p}(\tau)$ and $\alpha_{ij}^{d}(\tau)$ are secondary prompt-fission and delayed-fission probability density functions in region i provided by the first fission in the source region j, respectively, with the time difference τ (fissions in $i\cdot s^{-1}$/source fission in j).

As a prompt supercritical excursion is considered in the current study, Eq. (1) is rewritten by ignoring the delayed neutrons as:

$$N_i(t) = \sum_{j=1}^{n} \int_{t-t_c^p}^{t} \alpha_{ij}^{p}(t-t')N_j(t')dt', \tag{2}$$

where t_c^p is the time satisfying $\alpha_{ij}^{p}(\tau > t_c^p) = 0$.

Next, using the probability density function $\alpha_{ij}^{p}(\tau)$ (note that the superscript p for prompt neutron will be omitted in further notations), the cumulative distribution function is defined as:

$$C_{ij}(\tau) = \int_0^{\tau} \alpha_{ij}(\tau')d\tau'. \tag{3}$$

This cumulative distribution function $C_{ij}(\tau)$ is the ratio between the number of source fissions in the region j and the number of secondary fissions in region i resulting from these source fissions; it is the key parameter of the IKM. Obtaining the $C_{ij}(\tau)$ functions is an essential part of using the IKM.

2.2. Method for obtaining the kinetic parameter

The Monte Carlo method is an effective way to obtain a $C_{ij}(\tau)$ function in a coupled system of arbitrary geometry, as illustrated in Fig. 1. In Fig. 1(a), S is a source point in fissile region j, where a neutron starts its random walk with initial weight W_0. The black dots indicate the point at which the neutron collides with a nuclide. P is a collision point in another fissile region i at time $\tau = \tau'$. In Fig. 1(b), a non-analog collision of an incoming neutron with weight W_{ij}^{in} and energy E_{in} at point P in region i with nuclide x is shown. In the non-analog Monte Carlo simulation of neutron transport, incoming neutrons are partially absorbed. In this way, the fission contribution can be calculated as:

$$W_{fij\tau'} = \frac{\sigma_{fx}(E_{in})}{\sigma_{tx}(E_{in})} W_{ij}^{in}, \tag{4}$$

where σ_{fx} and σ_{tx} are microscopic fission and total cross sections of nuclide x, respectively; and W_{ij}^{in} is a weight of the incoming neutron. $W_{fij\tau'}$ itself is a fission weight of neutron created by a source neutron from region j at a collision point in region i at time τ'.

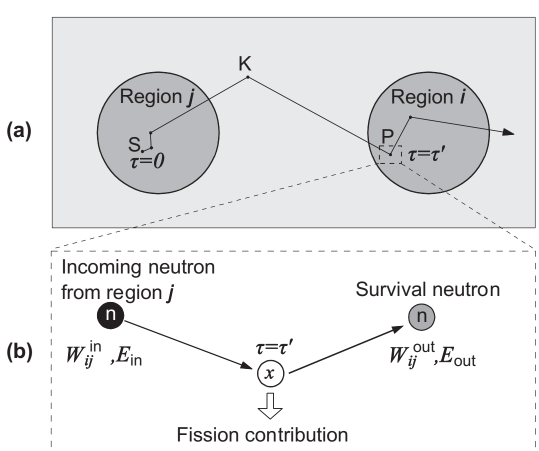

Fig. 1. Illustration of (a) a neutron random walk from region j to i; (b) a collision at point P.

Then, the $C_{ij}(\tau)$ function for tally batch L is obtained as (Takezawa and Obara, 2010):

$$C_{ij}(\tau) = \frac{\sum_{0\le\tau'\le\tau} W_{fij\tau'}}{\sum_{\text{batch}} \frac{W_{0jx'}}{\nu_{px'}(E_{in})}}, \tag{5}$$

where $W_{0jx'}$ is a weight of a source neutron in region j from nuclide x'; and $\nu_{px'}(E_{in})$ is a number of prompt neutrons produced from nuclide x' by the incoming mother neutron with energy E_{in}.

Then $C_{ij}(\tau)$ in Eq. (5) is obtained for each tally to give an average $\bar{C}_{ij}\tau$ over all the tally batches (Eq. (6)) with statistical uncertainty in the form of standard deviation (Eq. (7)).

$$\bar{C}_{ij}(\tau) = \frac{1}{N_{\text{tally}}} \sum_{L=1}^{N_{\text{tally}}} C_{ijL}(\tau) \tag{6}$$

$$\sigma_{\bar{C}_{ij}}(\tau) = \sqrt{\frac{1}{N_{\text{tally}}-1} \sum_{L=1}^{N_{\text{tally}}} \left(C_{ijL}(\tau) - \bar{C}_{ij}(\tau)\right)^2}. \tag{7}$$

The continuous-energy Monte Carlo neutron transport code MVP2.0 (Nagaya et al., 2005) was modified and used to calculate the kinetic parameters based on Eqs. (4)–(6). When using the obtained parameters, their statistical uncertainties propagate through the IKM. The estimation of such uncertainty propagation is given elsewhere (Takezawa and Obara, 2012).

Finally, another parameter useful for representing the coupling is defined as follows, considering the same fissile material composition of the system.

$$k_{ij} = \int_0^{\infty} \alpha_{ij}(\tau')d\tau' \equiv C_{ij}(\infty). \tag{8}$$

In general, this parameter is called a coupling coefficient for $i \neq j$ and a neutron multiplication coefficient otherwise (Avery, 1958).

3. System characteristics and initial conditions

3.1. System geometry and composition

The simplified fuel debris system consisted of spherical single or two units (i.e., debris regions) in the center of a rectangular prism of light water. An XY cross-sectional view of the two-unit system is illustrated in Fig. 2. Each unit was composed of 1-mm-radius spherical UO_2 particles submerged in light water. The size of the UO_2 particle was based loosely on the results of FARO experiments involving the interaction between molten UO_2 and water

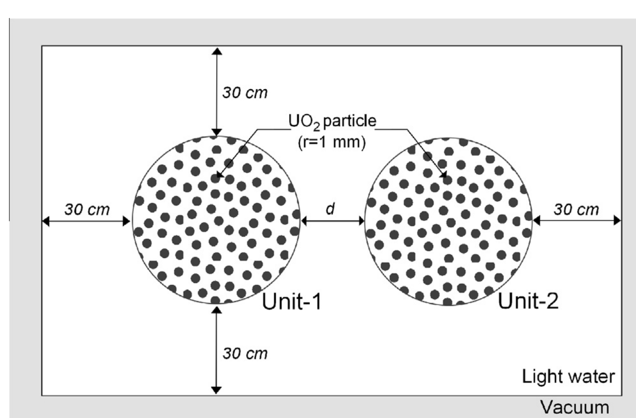

Fig. 2. Illustration of XY cross-sectional view of two-unit system (*not to scale*).