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Coupled reactors analysis: New needs and advances using Monte Carlo methodology

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ABSTRACT

Coupled reactors and the coupling features of large or heterogeneous core reactors can be investigated with the Avery's theory; however, the complex geometries that are often encountered in association with coupled reactors, require a detailed geometry description that can be easily provided by modern Monte Carlo (MC) codes. The results presented in this paper show that the MC code SERPENT has been successfully modified in order to compute the needed quantities like coupling coefficients. Moreover, the capability for calculating sensitivities to the quantities of interest for coupling reactors has been developed and implemented in SERPENT.

1. Introduction

The idea of "coupled" reactors, i.e. reactors with e.g. two core regions with different spectra, neutronically coupled with or w/o a geometrical barrier (intermediate zone or buffer, more often without fissile material), has been originally proposed by Avery (1958). The motivation at the time was to couple a fast and a thermal assembly in order to obtain a combined system that can have the breeding ratio characteristics of an all-fast spectrum system and at the same time exhibiting a prompt neutron lifetime characteristic of a thermal neutron system, i.e. much higher than the one for an all-fast neutron system, considered at the time as a potential drawback.

The principle was experimentally tested (Toppel, 1957). Successively the fast-thermal coupling was often used to build fast neutron experimental facilities with a limited all-fast neutron zone (see for example Meister et al., 1964, and Bustraan et al., 1970); moreover that type of system was also experimentally realized e.g. in order to test the principle of specific coupled systems, as the pulse coupled reactor system consisting of fast burst reactor and a subcritical thermal module (Kukharchuk et al., 2000) or even a cluster of rocket reactors (Seale, 1964).

More recently, the potential of a coupled Fast-thermal reactor as versatile test reactor has been pointed out (Sen et al., 2016).

Theoretical methods have been developed to describe these systems both in steady and in transient conditions (see e.g. Avery, 1958; Baldwin, 1959; Komata, 1969; Abramov, 2001).

The "decoupling" of spatial regions in a reactor, is a well-recognized phenomenon that has been pointed out the early reactor physics studies. The decoupling/coupling effects are physics effects that can be found not only in the type of coupled systems mentioned above, but also in large reactors, where spatial regions can act as regions weakly or more strongly coupled. The potential flux tiltiness in the system can be associated for example to the so-called Boltzmann operator eigenvalue separation (see e.g. Abramov, 2001,) or, in case of a coupled system, the "flux tilting" between e.g. two regions, associated to the flux ratio in these regions, can be directly related to the ratio of the sub-criticality in the two regions (Seale, 1964).

In all cases, the performance analysis of these systems, both in steady or in transient conditions, requires a deep understanding of the, sometime non-conventional, physics phenomena, from the appropriate preparation of cross-sections to the evaluation of the impact of uncertainties and e.g. of the dependence of the specific coupling phenomena from nuclear data uncertainties.

Moreover, the detailed description of the geometry of typical coupled systems requires an appropriate Monte Carlo treatment; see e.g. Fig. 1 from Sen et al. (2016):

The need of using a Monte Carlo code implies its extension to the evaluation of the typical coupling parameters (see next section) and the development of a full sensitivity analysis capability. This capability should go beyond the standard reactor integral

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parameter sensitivity, but should be extended to coupling features of the system, kinetic parameters and spatial power distributions.

In this paper we will describe the theoretical formulations that have been developed for this purpose and their practical implementation together with some significant applications.

2. Short summary of some specific features of the Avery's theory

For the purpose of this paper, we will remind shortly the simplest form of the coupled reactor reactivity and criticality conditions that are given by (in the case of two coupled "regions", (see Avery, 1958)) for the coupling coefficients k_{ij}:

$$\begin{vmatrix} (k_{11}-1) & k_{12} \\ k_{21} & (k_{22}-1) \end{vmatrix} = 0, \tag{1}$$

$$k_{12}k_{21} = \Delta_1\Delta_2. \tag{2}$$

where ρ

$$\Delta_j = 1 - k_{jj} \tag{3}$$

If we indicate with S_i the power of region i, the power ratio in the two coupled regions is given by:

$$\frac{S_1}{S_2} = \frac{k_{12}}{\Delta_1} = \frac{\Delta_2}{k_{21}}. \tag{4}$$

In the general case of N regions one has to solve the following system:

$$\begin{pmatrix} k_{11}k_{12}\dots k_{1N} \\ k_{21}k_{22}\dots k_{2N} \\ \dots \\ \dots \\ \dots \\ k_{N1}k_{N2}\dots k_{NN} \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ . \\ . \\ . \\ S_N \end{pmatrix} = k \begin{pmatrix} S_1 \\ S_2 \\ . \\ . \\ . \\ S_N \end{pmatrix} \tag{5}$$

The reactivity ρ is defined as:

$$\rho \approx \sum_{i=1}^{N} \propto_i \frac{\delta v_i}{v_i}, \tag{6}$$

where

$$\propto_i = \frac{\frac{1}{\Delta_i}}{\sum_{j=1}^{N}\frac{1}{\Delta j}} \tag{7}$$

The point kinetics equations are given (using exactly the same notations as in Avery (1958)) by:

$$l_{jk}\frac{dS_{jk}}{dt} = k_{jk}(1-\beta)\sum_{m=1}^{N} S_{km} - S_{jk} + k_{jk}\sum_{i=1}^{D}\lambda_i C_{ki} \tag{8}$$

$$\frac{dC_{ki}}{dt} = \beta_i \sum_{m=1}^{N} S_{km} - \lambda_i C_{ki}. \tag{9}$$

where D is the number of delayed neutron families.

The power in region k is given by:

$$S_k = \sum_{m=1}^{N} S_{km} \tag{10}$$

In practice, the following expressions are the solution of the standard Boltzmann equations and that account for the space and energy dependence:

$$S_j = \int [v\sigma_f(r,v)]_j \varphi(r,v) dr dv. \tag{11}$$

$$S_{jk} = \frac{\int [v\sigma_f(r,v)]_j \varphi(r,v) dr dv \times \int \chi(v')\varphi^*(r,v')[v\sigma_f(r,v)]_j \varphi_k(r,v) dr dv dv'}{\int \chi(v')\varphi^*(r,v')[v\sigma_f(r,v)]_j \varphi(r,v) dr dv dv'} \tag{12}$$

$$k_{jk} = \frac{S_{jk}}{S_k} \tag{13}$$

$$k_{jk} = \frac{\int [v\sigma_f(r,v)]_j \varphi(r,v) dr, dv}{\int [v\sigma_f(r,v)]_k \varphi(r,v) dr dv} \times \frac{\int \chi(v')\varphi^*(r,v')[v\sigma_f(r,v)]_j \varphi_k(r,v) dr dv dv'}{\int \chi(v')\varphi^*(r,v')[v\sigma_f(r,v)]_j \varphi(r,v) dr dv dv'}. \tag{14}$$

Using these expressions, one can solve the kinetics equations given above accounting for the energy and the within-region space dependence.

It has been shown the overall Avery formulation as indicated above, is well suited for a rather quick analysis not only of coupled systems of the type shown in Fig. 1, but also for the analysis of a wider class of systems of current interest. This is the case of the coupling of different regions in large, potentially decoupled systems like the proposed axially heterogeneous fast reactor ASTRID (Varaine et al., 2012), as shown in a simplified model below (Fig. 2), where the fertile region in the middle of the core can induce weak coupling effects among the different core regions:

In fact the k_{ij} coefficients give a rather accurate description of the coupling mechanism between core regions and the power evolution by region gives a first quantitative indication of potential power "tiltiness" e.g. in case of asymmetrical reactivity insertion (Palmiotti and Salvatores, 2016).

3. Monte Carlo estimators for the coupled system parameters k_{ij} and l_{ij}

k_{ij} is defined as the average number of fission neutrons produced in the reactor i by a neutron born in the reactor j. Implicit Monte Carlo estimators for these quantities were implemented in several codes, in which the (spatially discretized) Fission Matrix

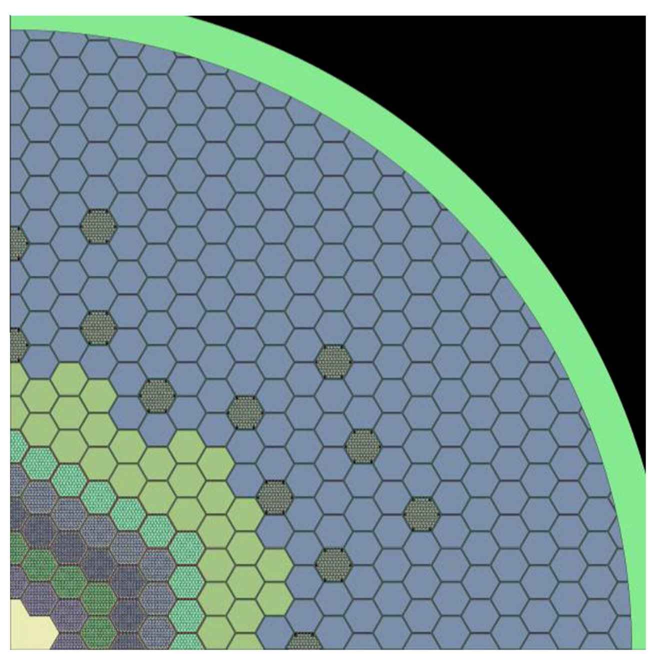

Fig. 1. XY view of a coupled thermal-fast irradiation test reactor (VCTR from Sen et al., 2016).