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Neutron transport in anisotropic random media

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ABSTRACT

Assessing the impact of random media for eigenvalue problems plays a central role in nuclear reactor physics and criticality safety. In a recent work (Larmier et al., 2018a), we have applied a probabilistic model based on stochastic tessellations in order to describe fuel degradation following severe accidents with partial melting and re-arrangement of the resulting debris. The distribution of the multiplication factor and of the kinetics parameters as a function of the mixing statistics model and of the typical correlation length of the tessellation were examined in detail for a benchmark configuration consisting in a fuel assembly with UOX or MOX fuel pins. In this paper, we extend our previous findings by including in the stochastic tessellation model the effects of anisotropy that might result from gravity and material stratification: for this purpose, we adopt the broad class of anisotropic Poisson geometries. We discuss the behaviour of the key observables of interest for eigenvalue problems in anisotropic tessellations by revisiting the fuel assembly benchmark calculations proposed in (Larmier et al., 2018a). The effects of anisotropic random media on the multiplication factor, on the kinetics parameters and on the flux spectrum will be carefully examined.

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1. Introduction

Random media of interest in reactor physics typically belong to two families: stochastic inclusions of fissile chunks within a background matrix (Murata et al., 1996; Liang et al., 2013; Brown and Martin, 2004) and stochastic tessellations composed of a collection of fissile and non-fissile volumes obeying a given mixing statistics (Pomraning, 1991a), such as those resulting from fuel degradation in Three Mile Island unit 2 (Broughton et al., 1989; Hagen and Hofmann, 1987; Hofmann, 1999) and at the Fukushima Daiichi power plant (Tonoike et al., 2013; Gunji et al., 2017). Other applications of random media for criticality safety concern for instance the analysis of the impact of poison grains for neutron absorbers (Doub, 1961) or Pu grains in MOX fuels (Yamamoto, 2010), and safety margins evaluation (Pomraning, 1999; Williams, 2000; Williams and Larsen, 2001; Williams, 2013), especially for waste storage (Williams, 2003).

Two distinct strategies can be adopted in order to describe neutron multiplication in random media (Pomraning, 1991a), namely, quenched disorder and annealed disorder. The goal of the annealed disorder approach is to develop effective equations for the ensemble-averaged observables, such as the celebrated Levermore-Pomraning model (Pomraning, 1991a). When particle transport is solved by Monte Carlo simulation, the annealed disorder approach is implemented by introducing disorder-averaged neutron displacement laws that are supposed to 'mimic' the effects of the spatial heterogeneities on neutron trajectories: this is for instance the case of the Chord Length Sampling (CLS) algorithm, inspired by the Levermore-Pomraning equations (Zimmerman, 1990; Zimmerman and Adams, 1991; Donovan and Danon, 2003; Donovan et al., 2003). By construction, spatial correlations are neglected by these algorithms. Generalizations of CLS including partial memory effects and spatial correlations have been also proposed (Zimmerman and Adams, 1991; Donovan and Danon, 2003; Donovan et al., 2003; Larmier et al., 2018c). In order to assess the accuracy of such approximate methods, reference solutions are mandatory (Levermore et al., 1986; Adams et al., 1989; Malvagi et al., 1992; Su and Pomraning, 1995; Zuchuat et al., 1994; Larsen and Vasques, 2011; Brantley, 2011; Donovan and Danon, 2003; Donovan et al., 2003; Brantley and Palmer, 2009; Brantley, 2009; Larmier et al., 2017a, 2018b).

In the quenched disorder approach, the random spatial configurations (with associated material compositions) are first defined based on a probabilistic model. The Boltzmann eigenvalue equation is then solved for each configuration, and the statistical moments of the multiplication factor and of the kinetics parameters are obtained by taking the ensemble averages with respect

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to the realizations (Pomraning, 1991a,b, 1999). The quenched disorder approach leads to reference solutions, because the effects of disorder-induced spatial correlations on neutron trajectories are correctly preserved. Analytical results for the ensemble averages demand huge theoretical efforts (Pomraning, 1999; Williams, 2000, 2003; Williams and Larsen, 2001; Williams, 2004): advances have been made possible by resorting to perturbation theory, but several simplifications are needed (Pomraning, 1999; Williams and Larsen, 2001; Williams, 2004). Considerable progress can be nonetheless achieved by using Monte Carlo methods in order to generate realizations taken from the sought distribution and then using a transport code to solve the eigenvalue problem for each sampled configuration. In the context of eigenvalue problems, intensive research efforts have been devoted so far to the class of stochastic inclusions (Murata et al., 1996; Liang et al., 2013; Brown and Martin, 2004; Liang and Ji, 2011; Griesheimer et al., 2010; Ji and Martin, 2011). Eigenvalue problems for stochastic tessellations have comparatively received less attention, and have been mostly confined to one-dimensional systems (Pomraning, 1999; Williams and Larsen, 2001; Williams, 2004).

In order to overcome some of these limitations, in a recent work we have adopted three-dimensional stochastic tessellations as a idealized model to investigate neutron kinetics following random fuel degradation (Larmier et al., 2018a). For this purpose, we have introduced a series of benchmark configurations consisting of a 17×17 UOX or MOX assembly, where a portion of the assembly was replaced by a Poisson, Voronoi or Box tessellation with fuel, cladding and moderator obeying ternary mixing statistics (Pomraning, 1991a). For each realization, criticality calculations were performed by using the Monte Carlo transport code TRIPOLI-4® developed at CEA (Brun et al., 2015). We assessed the behaviour of the key safety parameters, including the multiplication factor k_{eff}, the effective delayed neutron fraction β_{eff} and the effective neutron generation time Λ_{eff}, as a function of the tessellation law and of the size of the material chunks.

For real life applications, fuel degradation will generally give rise to anisotropic re-arrangements, possibly due to gravity and other material stratification phenomena (Hagen and Hofmann, 1987; Hofmann, 1999). To the best of our knowledge, neutron transport in anisotropic random media has been only considered in relation to the Levermore-Pomraning model (Pomraning, 1992). For the sake of simplicity, the stochastic tessellations investigated in Larmier et al., 2018a were isotropic (Poisson and Voronoi) or quasi-isotropic (Box). In this work, we will extend our previous results concerning reference solutions for eigenvalue problems in random media by relaxing the isotropy hypothesis.

This paper is organized as follows: in Section 2 we will revisit the fuel assembly benchmark introduced in (Larmier et al., 2018a) by introducing 3-dimensional anisotropic Poisson stochastic tessellations as a model of fuel degradation. Then, simulation results for the multiplication factor, the kinetics parameters and the flux spectrum will be analysed in Section 3. Conclusions will be finally drawn in Section 4.

2. A model of assembly with fragmented fuel pins

We begin by revisiting the simple benchmark model introduced in (Larmier et al., 2018a), which we briefly recall in the following in order for this paper to be self-contained. As a reference configuration we will consider an assembly composed of 17×17 square fuel pin-cells of side length $\delta = 1.262082$ cm in the plane O_{xy} and of height $L_z = 10$ cm. Reflective boundary conditions are imposed on all sides of the assembly. The fuel elements will be entirely either of the UOX or MOX type: the respective material compositions and temperatures, corresponding to Beginning Of Life (i.e., non-depleted) fuel, are the same as in (Larmier et al., 2018a).

In order to model a melted fuel assembly with random material fragmentation, we assume that the fuel lattice is replaced by a Poisson tessellation: the domain of the reference configuration is partitioned by randomly generated planes drawn from an underlying Poisson process (Miles, 1970; Schneider and Weil, 2008). Poisson tessellations represent an idealized mathematical model for disordered media: they demand little information content, their correlation function being exponential (Pomraning, 1991a; Torquato, 2013). The key parameters of the Poisson tessellations are the intensity ρ of the underlying Poisson process (carrying the units of an inverse length), and the distribution $H(\mathbf{n})$ of the normal vector $\mathbf{n}$ of the sampled planes (Schneider and Weil, 2008). In dimension $d = 3, \mathbf{n}$ can be characterized by assigning two angles, namely the co-latitude θ and the azimuth ϕ. We have then $dH(\mathbf{n}) = dH(\theta, \phi)$, or $dH(\mathbf{n}) = dH(\mu, \phi)$ when using the cosine $\mu = \cos(\theta)$. The explicit construction for isotropic Poisson tessellations has been provided in (Larmier et al., 2016, 2018a), where $\mathbf{n}$ was taken to be uniformly distributed on the unit half-sphere, namely,

$$H_{\text{iso}}(\theta, \phi) = \frac{1}{2\pi} \sin(\theta), \tag{1}$$

with $0 \leqslant \theta < \pi$ and $0 \leqslant \phi < \pi$. In order to probe the effects of the angular distribution on our fuel fragmentation model, we will introduce a few examples of anisotropy laws $H(\theta, \phi)$ that might mimic the effects of material stratification along the z axis. In other words, we will preferentially sample planes whose normal vector is parallel to the z axis. For the sake of simplicity, we will assume that the distribution $H(\mathbf{n})$ can be factorized with respect to the two variables, and that the distribution of ϕ is uniform (in other words, we preserve the invariance by rotation around the z axis). A quadratic anisotropy can be introduced in the form

$$H_{\text{quadratic}}(\mu, \phi) = \frac{3}{2\pi} \mu^2 \text{ for } -1 \leqslant \mu < 1, \tag{2}$$

which has its minimum in $\mu = 0$ and the maxima in $\mu = \pm 1$. A general case that might be of interest for applications is a piece-wise constant distribution, e.g.,

$$H_{\text{histogram}}(\mu, \phi) = \frac{1}{A} \times \begin{cases} 80 & \text{for } -1 \leqslant \mu < -0.95 \\ 4 & \text{for } -0.95 \leqslant \mu < -0.5 \\ 2 & \text{for } -0.5 \leqslant \mu < -0.25 \\ 1 & \text{for } -0.25 \leqslant \mu < 0, \end{cases} \tag{3}$$

and symmetric in the range $0 < \mu < 1$, which has maxima around $\mu = \pm 1$. The normalization constant for this example reads $A = 13.1$. More complex functional forms for $H(\mathbf{n})$ can be easily conceived. For the special case of Poisson-Box tessellations with three fixed orientations parallel to the orthogonal Cartesian axes we have

$$H_{\text{box}}(\theta, \phi) = \frac{1}{3} \delta(\phi) \delta\left(\theta - \frac{\pi}{2}\right) + \frac{1}{3} \delta\left(\phi - \frac{\pi}{2}\right) \delta\left(\theta - \frac{\pi}{2}\right) + \frac{1}{3} \delta(\theta) \frac{1}{\pi}. \tag{4}$$

The typical size of the fuel fragments will be imposed by setting the tessellation density ρ (Larmier et al., 2018a), which is related to the average chord length Λ within the tessellation by $\rho = 1/\Lambda$ (Larmier et al., 2016). For our benchmark, we have assumed that the assembly is composed of only three materials (fuel, cladding and moderator), which leads to a ternary stochastic mixture: each polyhedron of the Poisson tessellation is assigned a material composition by attributing a 'color', namely, '$\mathscr{F}$' for fuel, '$\mathscr{C}$' for cladding and '$\mathscr{M}$' for moderator. The corresponding coloring probabilities $p_{\mathscr{F}}, p_{\mathscr{C}}$ and $p_{\mathscr{M}} = 1 - p_{\mathscr{F}} - p_{\mathscr{C}}$ are chosen so that for each material i the ensemble-averaged volumic ratio $\langle p_i \rangle$ coincides with that of a pin-cell before fragmentation:

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