Annals of Nuclear Energy 68 (2014) 146–156

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Effects of fuel particle size distributions on neutron transport in stochastic media

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 5 January 2014
Accepted 7 January 2014
Available online 2 February 2014

Keywords:
Size distribution effects
Eigenvalue problem
Radiation transport
Monte Carlo method
Stochastic media

ABSTRACT

This paper presents a study of the fuel particle size distribution effects on neutron transport in three-dimensional stochastic media. Particle fuel is used in gas-cooled nuclear reactor designs and innovative light water reactor designs loaded with accident tolerant fuel. Due to the design requirements and fuel fabrication limits, the size of fuel particles may not be perfectly constant but instead follows a certain distribution. This brings a fundamental question to the radiation transport computation community: how does the fuel particle size distribution affect the neutron transport in particle fuel systems? To answer this question, size distribution effects and their physical interpretations are investigated by performing a series of neutron transport simulations at different fuel particle size distributions. An eigenvalue problem is simulated in a cylindrical container consisting of fissile fuel particles with five different size distributions: constant, uniform, power, exponential and Gaussian. A total of 15 parametric cases are constructed by altering the fissile particle volume packing fraction and its optical thickness, but keeping the mean chord length of the spherical fuel particle the same at different size distributions. The tallied effective multiplication factor (k_{eff}) and the spatial distribution of fission power density along axial and radial directions are compared between different size distributions. At low packing fraction and low optical thickness, the size distribution shows a noticeable effect on neutron transport. As high as 1.00% relative difference in k_{eff} and $\sim$1.50% relative difference in peak fission power density are observed. As the packing fraction and optical thickness increase, the effect gradually dissipates. Neutron channeling between fuel particles is identified as the effect most responsible for the different neutronic results. Different size distributions result in the difference in the average number of fuel particles and their average size. As a result, different degrees of neutron channeling are produced. The size effect in realistic reactor unit cells is also studied and, from the predicted values of infinite multiplication factors, it is concluded that the fuel particle size distribution effects are not negligible.

1. Introduction

3-D particle systems, characterized by the stochastic distribution of spherical inclusions in a background material, are typical radiation transport media encountered in many scientific and engineering fields. For example, in the area of atmospheric science, solar radiation transports through clouds consisting of tiny water droplets, ice crystals and dust aerosols. These cloud particles have sizes ranging from 10^{-5} m to 10^{-3} m and their distribution in the cloud can influence the solar energy radiative transfer to the surface of the earth (Breon et al., 2002). In the area of nuclear engineering, some advanced nuclear reactor designs, such as the Very High Temperature Gas-Cooled Reactors (VHTR) (Ji et al., 2005), the Fort Saint Vrain (FSV) reactor (Pavlou et al., 2012) or innovative light water reactor designs (LWRs) loaded with fully ceramic microencapsulated (FCM) fuel (Brown et al., 2013; Liang and Ji, 2013; Sen et al., 2013; Snead et al., 2011), utilize unique fuel elements called TRISO fuel particles that are fabricated to different fuel types (fissile or fertile) and different sizes (to achieve high packing fractions). These fuel particles are randomly packed in the reactor core at volume packing fractions ranging from 5% to 60%. To provide reliable predictions of solar energy transfer through the atmosphere or neutronic safety analysis in nuclear reactors, one needs to model not only the stochastic distribution of particles but also the size distribution of each type of particle in the system, which presents a significant computational challenge to the study of radiation transport in 3-D particle systems. Although radiation transport computation in stochastic media, specifically in 3-D particle systems, has been an actively researched topic for a long time (Donovan and Danon, 2003; Ji et al., 2005; Ji and Martin, 2007, 2008; Liang and Ji, 2011; Liang et al., 2013, 2012; Murata et al., 1996, 1997; Reinert et al., 2010), much of the focus is on the methodology development that

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http://dx.doi.org/10.1016/j.anucene.2014.01.005

accounts for the spatial and size distribution of particles in the media. Less attention has been given to the study of particle spatial or size distribution effects on radiation transport, especially the size distribution effects. Recently, Brantley and Martos (2011) have studied a general radiation transport problem to calculate reflection, transmission and absorption rates when radiation penetrates a cubic 3-D particle system, consisting of optically thick spherical particles and an optically thin background at the particle volume packing fractions ranging from 5% to 30%. Spherical particles were assumed to follow three different distributions in radius: constant, uniform and exponential. They found a weak dependence of the predicted radiation transport rates on particle size distribution, provided different distribution functions give the same mean chord length of spherical particles. Earlier work by Olson (Olson, 2007) studied photon transport in 2-D disk and 3-D spherical particle systems and found that very different disk/sphere sizes produced similar predictions of photon transport as long as the total volume packing fractions were the same. Recent work by the University of Michigan (Burke et al., 2012; Pavlou et al., 2012) on the Fort Saint Vrain reactor has shown the effects of six different distribution functions on the multiplication factors in a densely packed particle system. The radius size distribution range was fixed and different distributions were applied to generate a fuel compact consisting of fuel particles in a packing range of 58% to 60%. No significant differences in multiplication factor were found.

Previous studies primarily focused on how the particle size distribution affects the integral physical quantities that depend on the global distribution of particles, such as total absorption rate or multiplication factor. Computational results at different particle size distributions were reported. Little or no physical interpretation, however, was provided to explain differences in the simulation results. The lack of theoretical analysis makes such research remain incomplete. Also, quantities that depend on the local properties of particle distributions, such as fission density distribution, have not yet been studied. The fission density distribution is important in reactor analysis because it can be used to identify a hot spot location in the reactor fuel pins that are filled with TRISO fuel particles. In this paper, we first study the size distribution effect on a simplified cylindrical fission system that consists of randomly distributed fissile fuel particles in one-group eigenvalue problems. Five different size distributions are assumed for the fissile particles and their impacts on the multiplication factor, volume-average flux in fuel particles and background media, and spatial distribution of fission density in the system are studied. To ensure that the size distribution is the only parametric effect, the parameters of each distribution function are optimized to produce exactly the same mean chord length in the spherical particles. Physical interpretations are provided to explain the differences in the above calculated quantities at different particle size distributions. Then, we pack the same fuel particles used in the simplified system in three realistic reactor design unit cells. Continuous energy neutronic analysis for eigenvalue problems is performed at different particle size distributions.

Although our study focuses specifically on neutron transport in 3-D particle systems, it may be of interest to the general radiation transport community. First, it can provide a more insightful understanding of the radiation transport phenomenon in stochastic media by quantifying the uncertainties in the radiation transport computation due to the uncertainties in particle size. This is fundamental to radiation transport research. Second, from a more practical perspective, it can provide pragmatic guidelines on how to simplify the realistic physical model for routine basis analysis by understanding the size distribution effects. For example, an equivalent single size particle can be used in modeling systems that consist of poly-dispersed particles. This equivalent size is determined by finding an optimal size that produces similar solutions as poly-dispersed distributions with acceptable errors in practice. Fuel particles with a single size in a reactor system are easy to model and efficient to simulate. These considerations have motivated our present work.

The remainder of the paper is outlined as follows: In Section 2, the geometry and material configurations of a simplified 3-D particle fission system are described. Specifically, the size distribution of fuel particles and the determination of distribution functions are thoroughly addressed. In Section 3, one-group eigenvalue problems are solved in the simplified system. Numerical solutions of effective multiplication factor, volume-average flux in fuel particles and background material, and spatial distributions of fission density along axial/radial directions are presented for each studied scenario. Comparisons and interpretations of the results are provided. A thorough investigation of the size distribution effect on the neutronic behavior is performed and physical reasons for the effect are identified. In Section 4, fissile fuel particles with the same distributions as in the simplified system are loaded into unit cells of three types of reactor designs. Realistic material composition and density are applied and continuous energy eigenvalue problems are solved for infinite multiplication factors. The size distribution effect is shown. In Section 5, final conclusions and possible future work are presented.

2. Configurations of simplified 3-D particle fission systems

2.1. Geometric configuration

We construct a series of simplified 3-D particle fission systems in a cylindrical container of radius 2 cm and height 4 cm. Fissile fuel particles are randomly packed in the cylindrical container with five different radii distributions: constant, uniform, power, exponential and Gaussian. In each distribution, the fuel particle radius is distributed over the same range (except for the constant distribution) and the mean chord length in fuel particles, denoted as $\langle l \rangle$, is fixed at 0.05 cm by adjusting distribution function parameters. Monte Carlo neutron transport simulations are performed in the system assuming vacuum boundary conditions for each size distribution and for five different fuel particle volume packing fractions, denoted as *frac*, of 5%, 15%, 30%, 45% and 60%. A total of 25 geometric configurations are constructed for the study. Fig. 1 shows one physical realization of the stochastic packing of fuel particles with constant size in a cylindrical container at *frac* = 45%. Once a geometric realization of a 3-D particle system is generated, Monte Carlo radiation transport simulations are performed in the system. How the fuel particle size distribution affects the neutronic behavior in a stochastic medium system, such as the reaction rates

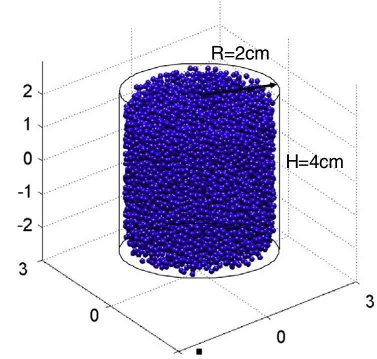

Fig. 1. One physical realization of a 3-D particle fission system. Fuel particles with 0.075 cm diameter are randomly packed in a cylinder at the volume packing fraction of 45%. The cylinder is 4 cm high and has a diameter of 4 cm.