Annals of Nuclear Energy 120 (2018) 178–185

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A stylized 3D Advanced High Temperature Reactor (AHTR) benchmark problem

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ARTICLE INFO

Article history:
Received 2 April 2018
Accepted 8 May 2018

Keywords:
Benchmark problem description
Advanced High Temperature Reactor (AHTR)
Fluoride Salt Cooled High Temperature Reactor (FHR)

ABSTRACT

A set of Stylized 3D Advanced High Temperature Reactor (AHTR) benchmark problems in full core and single fuel assembly configurations is developed in this paper. The configurations include the lower support plate, the bottom reflector, the fuel zone (AHTR assemblies), the top reflector, and the upper support plate. The benchmark problems retain the multiple heterogeneities and other important neutronics features such as the detailed geometric and material distributions of the Tristructural-Isotropic (TRISO) fuel and burnable poison particles, the fluoride salt coolant, the graphite moderator, and the reflectors. Monte Carlo results are presented for the benchmark problem in both the uncontrolled and controlled single assembly configurations. These benchmark problems can be used for evaluating the performance of neutronics codes.

1. Introduction

The Advanced High Temperature Reactor (AHTR) (Varma et al., 2012, and Holcomb et al., 2011) is a fluoride-salt-cooled high-temperature reactor (FHR) concept that provides inherent safety through passive safety systems and improved economics through higher operating temperatures. One of the challenges that remain before the commercialization and deployment of this class of reactors is the verification and validation (V&V) of neutronics tools and methodologies for design optimization and safety analysis in support of licensing this type of reactors. To verify neutronics tools, it is necessary to create new heterogeneous benchmark problems that retain the important neutronic characteristics of the AHTR such as the detailed geometric and material configurations of the Tristructural-Isotropic (TRISO) fuel and burnable poison particles, fluoride salt coolant, graphite moderator, and reflectors. However, the structural details and the randomness of the fuel particles distribution are simplified for ease of modeling and the lack of the capability of existing codes (including stochastic transport) to model random particle distributions in large systems (e.g., AHTR). These simplifications have relatively small neutronic effects as compared to that of the multiple heterogeneity. This stylized benchmark problem set facilitates numerical verification of deterministic transport and diffusion methods in which the multigroup approximation is a common practice, cross section sensitivity analysis, and evaluation of various approximations used in neutronic modeling at both lattice (fuel assembly) and core levels.

The paper is organized as follows. The assumptions and simplifications used to develop the stylized AHTR benchmark problems are summarized in Section 2. Then, the specification of the AHTR full core problems is presented in Section 3. The description of the assembly configuration and the reflectors as well as support plates is given in Sections 4 and 5, respectively. Reference solutions for controlled and uncontrolled single assembly benchmark problems are presented in Section 6. The paper is summarized in Section 7. The isotopic composition of the materials in the core are given in the appendix.

2. Assumptions and simplifications

In developing any benchmark problem, it is desirable to simplify as much as possible without compromising the underlying physics (neutronic characteristics). The benchmark problem presented in the paper is based on the description of the AHTR conceptual design found in Varma et al. (2012) and Holcomb et al. (2011). In addition to the usual simplifications, assumptions had to be made to fill gaps and resolve inconsistency in the data found in these references.

The assumptions and simplifications that were made to the original AHTR design specification are enumerated below.

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https://doi.org/10.1016/j.anucene.2018.05.019
0306-4549/

(1) TRISO fuel isotopic composition

It was specified that the advanced gas reactor (AGR) fuel AGR-5 or AGR-6 with a 9 wt% enrichment can be used in the AHTR core design. However, the isotopic composition was not found in the open literature. Instead, the material composition of the AGR-2 fuel given in Philips et al. (2010) was used.

(2) TRISO particle distribution and the fuel stripe dimension

In Varma et al. (2012), the fuel plate dimensions are given as in Fig. 1 and the TRISO particles are assumed to be randomly distributed over two fuel stripes with a "limited" volumetric packing fraction of 40%. However, the thickness of the fuel plate calculated from the dimension of individual regions is inconsistent with the specified total thickness of 2.55 cm as shown Fig. 1. Moreover, the total fuel stripe volume is also inconsistent with the specified total heavy metal mass (17.48 Mt) in the core and the desired packing fraction that is assumed to be 40%. (Using the specified reference stripe dimensions $(22.5 \times 0.62 \times 550) \times 36$ (stripes per assembly) $\times$ 252 (fuel assemblies) and the fuel density of 10.9 g/cm^3, the packing fraction is estimated to be close to 20%.) For modeling simplicity, instead of random, a body-centered rectangular lattice is used to represent the fuel particle distribution. A 40% packing fraction leads to a lattice pitch of 0.09406-cm, 0.09128-cm, and 0.09266-cm in the x, y, z-directions, respectively. To conserve the total heavy metal mass in the core, the total number of particles must therefore be 808 in the transverse direction. Choosing 4 layers of particles in the y-direction leads to 19.00012-cm $\times$ 0.36512-cm as the transverse dimension of each fuel stripe in the benchmark problem. We note that this choice is not unique but convenient (the simplest) to model in stochastic transport codes. And further, modelling fuel particle distributions randomly in large systems such as the AHTR by any existing codes is impractical given the huge number of fuel particles ($\sim$40 billion).

(3) SiC-SiC composite and radial reflector mass density

The mass densities of the SiC-SiC composite and the radial reflector are not reported in Varma et al. (2012). In this paper, the SiC-SiC mass density is assumed to be 3.1 g/cm^3 (Kohyama and Kishimoto, 2013), while the density of the reflector is the same as that of the graphite matrix (1.75 g/cm^3) in Varma et al. (2012).

(4) Simplifications in the axial direction

In the AHTR conceptual design, the reactor consists of 7 axial zones: lower plenum, lower support plate zone, core zone, upper support plate zone, upper plenum zone, argon plenum zone and top flange zone. The lower plenum, upper plenum zone, argon plenum zone and top flange zone are not modeled in this paper since they are far away from the active reactor core and their neutronics impact is negligible. The coupling holes and guides in the lower support are replaced with the supporting structure material C-C composite and the structures beyond the control blade hole of the upper support plate are homogenized by conserving mass, leading to 78.9% FLiBe and 21.1% graphite, by volume. These simplifications are expected to have negligible neutronic effect.

(5) Simplification in the radial direction

The AHTR reactor concept consists of 6 radial zones: reactor core, boron layer, barrel, downcomer, N-liner and Vessel. The zones beyond the reactor core are replaced by a surrounding infinite absorber. This significantly simplifies geometric modeling while having negligible neutronic effect.

(6) Simplification of temperature distribution

The fuel temperature distribution was not found in the literature and as a result was taken to be the maximum fuel temperature (837 °C) in the "average assembly" in the steady-state condition (Varma et al., 2012). Note that the variation in the maximum fuel temperature as a function of the radial peaking factor (RPF) is relatively small; it ranges from 818 °C to 890 °C as the RPF changes from 1.2 to 2.3 (Varma et al., 2012). The same temperature is also used for all the other components in the fuel plates since they should be in thermal equilibrium with the fuel. The temperature of the coolant and the channel box is assumed to be 675 °C, the average of the FLiBe inlet temperature (650 °C) and outlet temperature (700 °C). The temperature of the spacers is taken to be the average of the fuel and coolant temperatures (756 °C). The lower support and the bottom reflector are assumed to be at 650 °C while the top reflector and the upper support plate are assumed to be at 700 °C.

(7) Graphite material

The graphite form is not specified in Varma et al., 2012) or Holcomb, et al. (2011). For simplicity, it is assumed to be natural carbon. Its density depends on the location in the core and can be found in the relevant tables in Section 4.

(8) Burnable poison particles

The burnable poison particles are sintered grains of Eu_2O_3 powder that are over-coated by pyrocarbon. However, the over-coating thickness and density are not specified in Varma et al. (2012). For simplicity, the over-coating is assumed to be natural carbon and therefore is blended in the fuel plate graphite matrix.

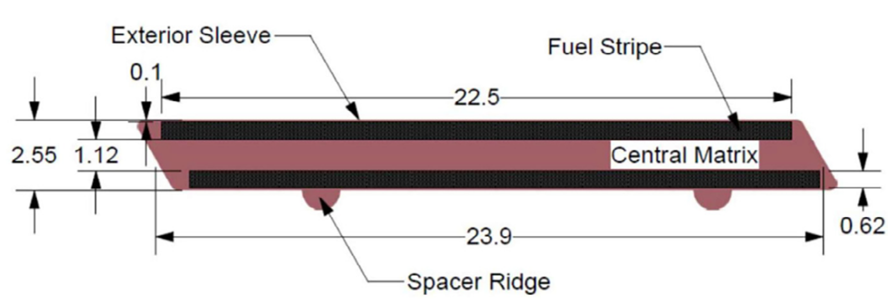

Fig. 1. Transverse cross section of a fuel plate (Taken from Varma et al., 2012).