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Research Article

Uniformity Assessment of TRISO Fuel Particle Distribution in Spherical HTGR Fuel Element Using Voronoi Tessellation and Delaunay Triangulation

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Nonuniform distribution of tri-structural-isotropic (TRISO) fuel particles in a spherical fuel element (SFE) may increase the failure probability of the SFE in the high-temperature gas-cooled reactor, leading to the release of fission products. To evaluate the uniformity of the TRISO particles nondestructively, 3-dimensional cone-beam computed tomography is used to image the SFE, and TRISO particles are segmented. After TRISO particle positions are identified, the Voronoi tessellation and Delaunay triangulation are used to extract several geometric metrics. Results indicate that both the Voronoi volume distribution and the nearest neighbor-distance distribution follow the log-normal distributions, which provide strong evidence that the TRISO particles are approximately randomly uniformly distributed. Further study will be focused on validating the conclusion with more SFE data.

1. Introduction

The spherical fuel element (SFE) is the key component in the Chinese high-temperature gas-cooled reactor (HTGR) project. Usually, an SFE is stuffed with about 12,000 tri-structural-isotropic (TRISO) fuel particles [1, 2]. Ideally, the TRISO particles are uniformly distributed, giving a good temperature distribution, as well as a homogeneous temperature gradient field [3, 4]. An illustration of the SFE for HTGR is shown in Figure 1. The diameter of the fuel zone is 50 mm encased with a 5 mm fuel-free outer graphite matrix. The nonuniform distribution of the TRISO particles in the SFE may lead to a nonuniform thermal expansion and excessive thermal gradients. Close clusters of particles may form local hotspots, increasing the stress on TRISO particle layers as the stress is directly dependent on the temperature in pressure vessel model of the particle [5]. Consequently, the failure probability of the TRISO particle would increase, leading to the release of fission products. Thus, it is necessary to measure and evaluate the TRISO particle distribution to ensure they are relatively uniform before operation. Monte Carlo method was used to simulate TRISO particle distributions and the distance of nearest neighbors was calculated by Nabielek [6]. In our previous research, 3D visualization of particles in an SFE was implemented and 3D volume rendering was obtained for subjective evaluation, as shown in Figure 2. The integrity of SFE, i.e., whether there were fabrication defects, was discussed in [7]. In order to assess the spatial uniformity of the particles, we propose in this study to process the TRISO particles in a 3-dimensional (3D) coordinate system and assess the uniformity of the TRISO particle distribution using the geometric metrics extracted from the Voronoi tessellation and Delaunay triangulation. The number of particles and their locations were obtained by the use of an image-processing method, after a cone-beam computed tomography (CBCT) was used for data acquisition. Then, the Voronoi tessellation and Delaunay triangulation were constructed for the assessment of the distribution uniformity of the TRISO particles.

A Voronoi tessellation, or Voronoi diagram, partitions a space into a set of mutually exclusive regions, with a number of given seeds. Each seed locates at the center of one region,

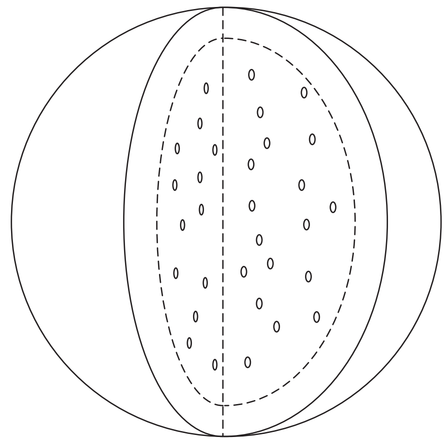

Figure 1: Sketch of a spherical fuel element used in HTGR stuffed with TRISO fuel particles.

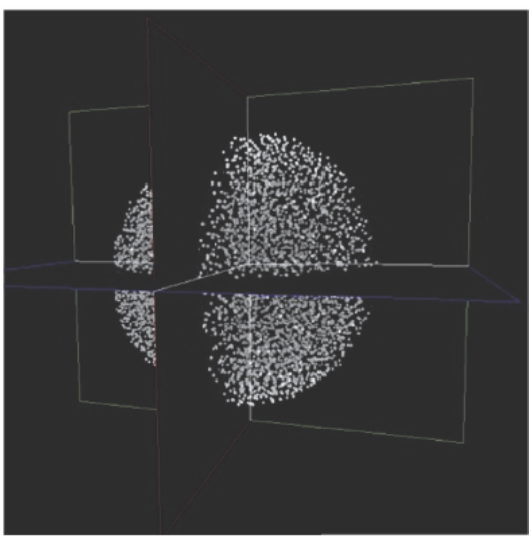

Figure 2: 3D volume rendering of TRISO particles in a spherical fuel element.

also known as a Voronoi cell. The region is composed of the set of all points that are closer to that seed than any others. A Delaunay triangulation is simply the dual graph for a Voronoi tessellation [8, 9]. The Voronoi diagram was successfully used in cylindrical particle packing by Rycroft [10]. Herein, nearest neighbor distance and Voronoi cell volume were investigated to describe the characteristics of the spatial distribution of TRISO particles.

2. Methods

2.1. Nondestructive Data Acquisition and 3D Image Reconstruction. X-ray inspection is a commonly used qualitative evaluation technique for SFEs [11]. In this paper, CBCT was employed as a powerful and quantitative tool to evaluate the TRISO particle distribution nondestructively [12–14].

The sketch and a photo of the CBCT system are shown in Figures 3(a) and 3(b), respectively. A 160 kVp micro focus X-ray generator (Philips HOMX-161) was used as the X-ray source. The tube voltage and the current were set to be 140 kV and 0.2 mA, respectively. The focal size was adjusted to 20-50 μm. A flat panel (Varian PaxScan 2520) was used as the X-ray photon detector. The effective spatial resolution (pixel size) was 80 μm [15]. As shown in Figures 3(a) and 3(b), the SFE is placed between the X-ray source and the detector. X-ray was emitted from the source and penetrated the object of interest before being detected by the flat-panel detector. Computed tomography (CT) images, or cross-section images, can be reconstructed from the projection data (attenuation of the X-ray by the object of interest). To acquire projection data at different angles, the SFE was rotated. The source-to-isocenter (rotation center) distance was 25 cm and the source-to-detector distance was 75 cm. Projection data were obtained at one-degree interval for 360°. Thus 360 sets of projection data were collected at different angles. Tomographic images were reconstructed using the fast FDK algorithm as shown in Figure 3(c) and a 3D image was generated nondestructively.

2.2. Construction of the Voronoi Tessellation and Delaunay Triangulation. We developed an image segmentation method to identify the centroids of TRISO particles in the 3D reconstructed SFE tomographic image. With the coordinates of the TRISO particle centroids, the 3D Voronoi tessellation and Delaunay triangulation were constructed [8, 9]. Note that the size of the TRISO particles was ignored hereafter to simplify the analysis. In the following steps, all TRISO particles are represented by their centroids.

We take a 2-dimensional (2D) case as an example to demonstrate how the Voronoi tessellation and Delaunay triangulation may be used to evaluate the uniformity of a group of particles. Randomly distributed particles and the corresponding Voronoi tessellation and Delaunay triangulation are shown in Figure 4. Figure 4(c) shows the dual relationship clearly. It can be imagined that the Voronoi cells

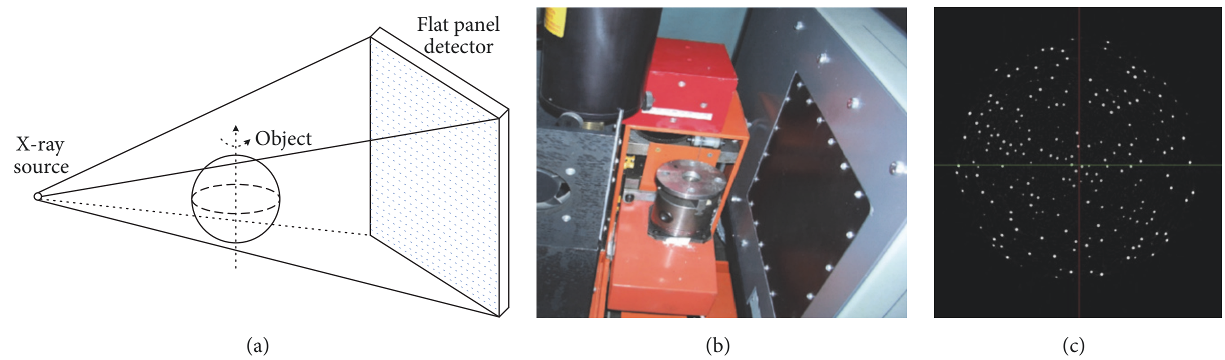

Figure 3: (a) Scheme of 3D cone-beam CT, (b) facility, and (c) a tomographic image of a spherical fuel element.

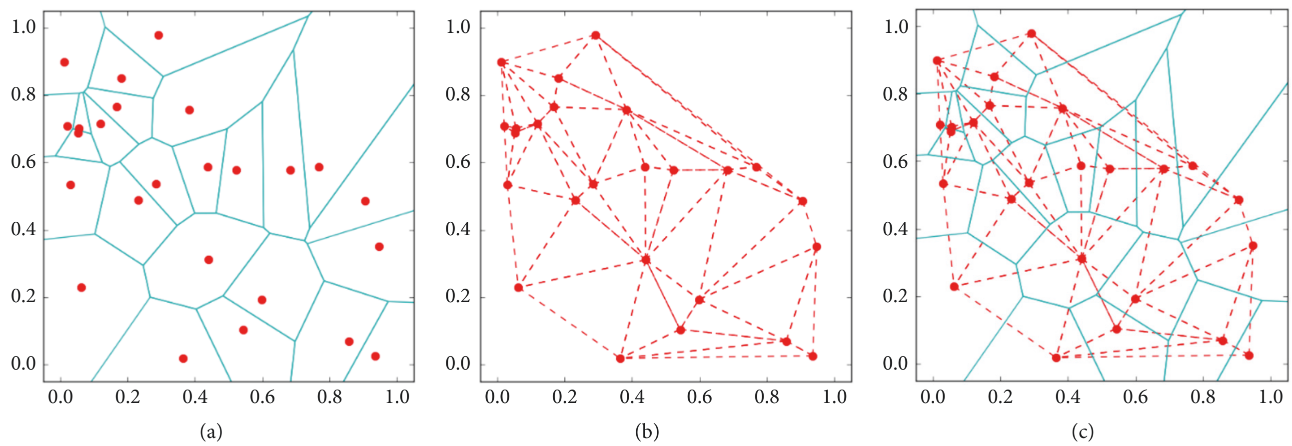

Figure 4: An example of the Voronoi tessellation (cyan solid lines, (a)), and its dual graph, the Delaunay triangulation (red dashed lines, (b)) for the same set of seed points (red solid dots). The overlap of both aforementioned graphs to illustrate the duality (c).

and the edges of the Delaunay triangles tend to be similar if the particles are uniformly distributed.

3. Metrics for Assessment of Uniformity of TRISO Particles

To investigate the relation between the local density of particles and geometric characteristics of the Voronoi tessellation, five metrics were extracted, including the volume of Voronoi cell, number of neighbors, area of Voronoi facet, volume of Delaunay simplex, and length of simplex edges [8]. Intuitively, one expects the spread of the distributions of the metrics to be narrow if particles are uniformly distributed. In other words, the uniformity of the particle is closely related to the width of the distributions. We may thus quantify the uniformity of the particles by characterizing the distributions of the metrics.

Every TRISO particle has its own Voronoi cell during the tessellation construction. The number of neighbors indicates how many TRISO particles are related/connected in the specified field. The nearest neighbor indicates how close a TRISO particle is to its neighbor. The volume of Voronoi cells indicates the mean size of a region TRISO particles control. The volume of Voronoi cells is smaller in areas where particles are more densely packed.

We use 2D examples to demonstrate how the aforementioned metrics may help us assess the uniformity of the particle distribution. As shown in Figure 5, for instance, the number of neighbors is equal to 6 for uniformly distributed particles, while the same metric tends to be different in the random example.

In Figure 6, 121 particles randomly distributed in a 2D space are shown. The distributions of the five metrics are also sketched in the same figure.

4. Experimental Results

An SFE was processed using the above methods. The number of the measured TRISO particles in the SFE was 11,603, after image segmentation and region labeling. Given that the nominal number of TRISO particles is 12,000, the relative error is approximately 3% (397/12000). Table 1 is the xyz position of each TRISO particle in orthogonal coordinate system (Cartesian). The location unit is pixel which is equal to about 80 μm. Voronoi volume distribution of all particles is shown in Figure 7, close to a log-normal distribution for randomly uniformly distributed particles in theory.

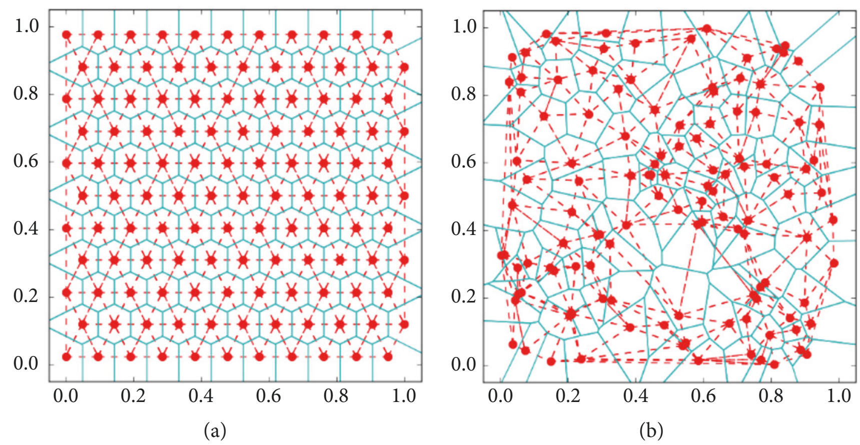

Figure 5: Examples of a uniformly distributed seed pattern (a) and a randomly distributed seed pattern (b) with both Voronoi tessellation and Delaunay triangulation.

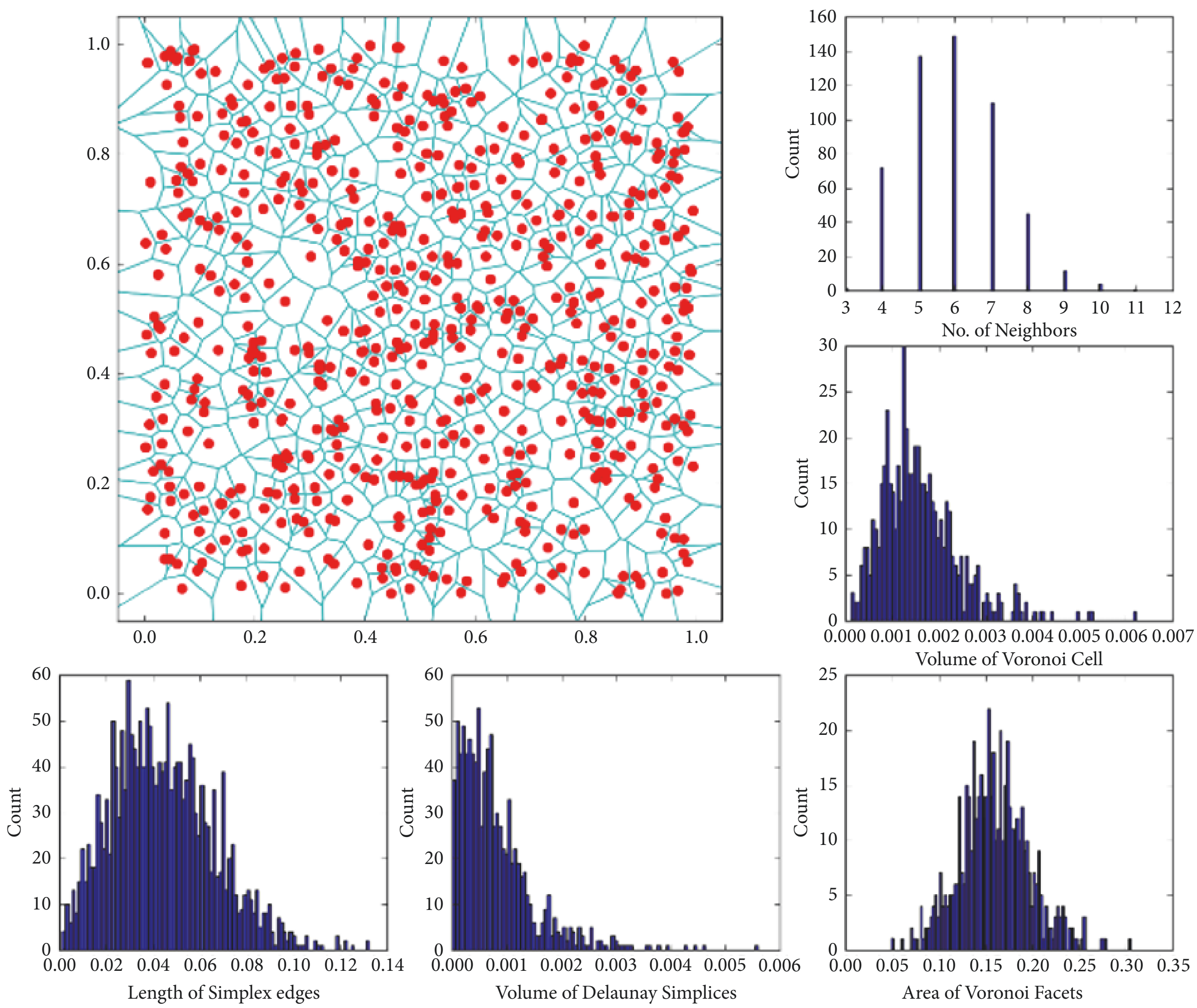

Figure 6: The distributions of the five metrics (from top to bottom, right to left): number of neighbors, volume of Voronoi cells, area of Voronoi facets, volume of Delaunay simplices, and length of simplex edges for randomly distributed particles in a 2-dimensional space.

TABLE 1: Mass center (XYZ) of every TRISO.

Index	X	Y	Z
1	925.500	817.800	6.300
2	874.204	844.408	5.633
3	934.897	850.759	2.897
4	905.167	862.333	2.000
5	935.704	885.481	2.074
6	793.854	899.902	9.073
7	865.333	922.667	5.429
8	1020.160	927.520	3.360
9	770.222	937.778	6.000
......	......	......	......
11603	1034.489	981.244	1503.200

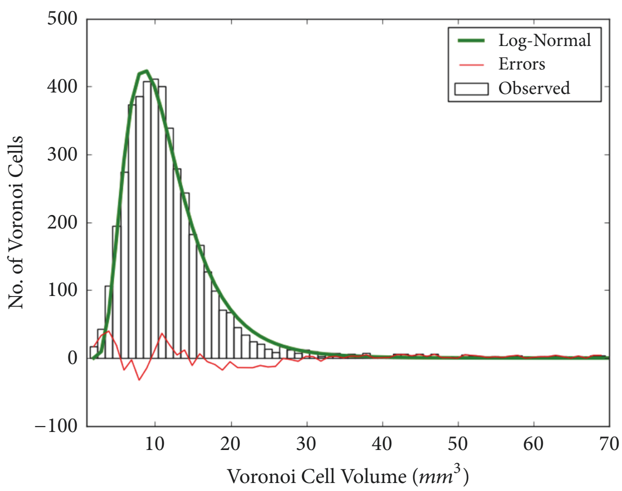

FIGURE 7: Voronoi volume distribution (Influential Zone).

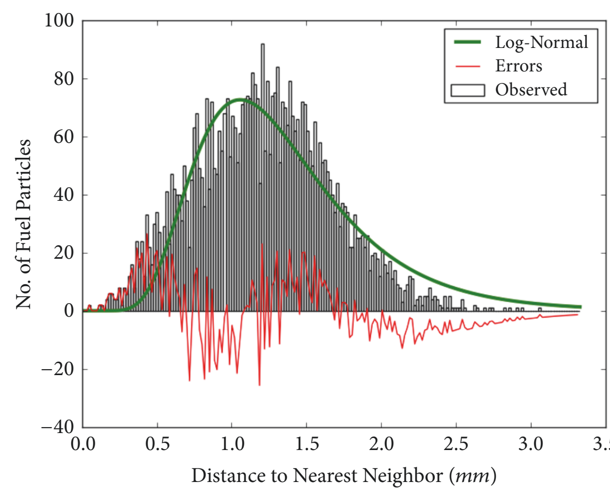

FIGURE 8: Nearest neighbor distances.

The distribution of the distance to the nearest neighbor of TRISO particles is shown in Figure 8, which is also close to a log-normal distribution for randomly uniformly distributed particles in theory [9].

The experimental results demonstrated that the distribution of the TRISO particles is highly similar to the log-normal distribution, which represents randomly uniformly distributed particles [9]. The majority of the particles had 5 or 6 neighbors, the most probable volumes of Voronoi cells were between 0.003 and 0.015, the most probable areas of Voronoi facets were between 0.2 and 0.6, the most probable Delaunay simplex volumes were less than 0.01, and the lengths of simplex edges peaked at 0.01 and roughly symmetrically distributed between 0 and 0.2.

5. Conclusion

In this study, uniformity assessment method based on the Voronoi tessellation and the Delaunay triangulation gives quantitative results in a 3D volume rendering for TRISO particles in an SFE. The metrics extracted from the Voronoi tessellation and Delaunay triangulation demonstrated that, in a real SFE, the locations of the TRISO particles closely followed a randomly uniform distribution. A more rigorous algorithm is under development, in which statistical test will be used to reach a more convincing conclusion in terms of the uniformity of the TRISO particle distribution inside a 3D spherical space.

Data Availability

The figures and experimental setup data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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