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Analysis of DR testing blind zone of spherical fuel elements for 10 MW high-temperature gas-cooled reactor

Min Yang [a,*], Rui Li [a], Jinghui Duan [b], Lihong Liang [c], Xingdong Li [d], Wenli Liu [d], Fanyong Meng [e]

[a] School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100191, China
[b] China Information Security Certification Center, Beijing 100020, China
[c] China Special Equipment Inspection and Research Institute, Beijing 100013, China
[d] National Institute of Metrology, Beijing 100013, China
[e] State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

Spherical fuel elements technology is a main innovation of high-temperature gas-cooled reactors (HTGRs), which effectively improves the safety of the reactors for higher stability at high temperature, and their quality is crucial for the safety and reliability of HTDRs. According to a spherical fuel element's structure, the coated fuel particles are not permitted to enter the fuel-free zone and the elements with escaped fuel particles must be removed during the fuel elements' quality control. In this paper, we first introduce a DR imaging system for spherical fuel elements testing applied in Chinese 10 MW high-temperature gas-cooled reactor (HTR-10). Then the blind zone where escaped particles exist is analyzed under the continuous and concrete circular scanning trajectories and the cone-beam imaging geometrical configuration. The dominant scanning parameters determining the size of the blind zone are the rotation step angle and the distance from X-ray source to the tested object. An optimal method of designing the two parameters to decrease the size of the blind zone is proposed so as to satisfy the testing requirements. Finally, the optimal method is verified by computer simulation and some practical identification results are presented.

1. Introduction

Spherical fuel elements technology is a main innovation of high-temperature gas-cooled reactors (HTGRs), which effectively improves the safety of the reactors for higher stability at high temperature, and enhances the efficient retention capability for fission products [1–3]. The Chinese 10 MW high-temperature gas-cooled reactor (HTR-10) is a modular pebble-bed type high-temperature gas-cooled reactor, which attained its first criticality on December 21, 2000, and the fabrication of the first fuel for the HTR-10 started in February 2000 at the Institute of Nuclear Energy Technology (INET), Tsinghua University. The spherical fuel element used in HTR-10 is based on that of the HTR-Module of Siemens/Interatom of Germany and meets the performance requirements of the HTR-10 [4]. According to the reactor physics design of the HTR-10, a total of 27,000 spherical fuel elements were loaded in the core of the HTR-10 in equilibrium state. The typical structure of a spherical fuel element is shown in Fig. 1. A spherical fuel element consists of a spherical fuel zone of 50-mm in diameter, in which the fissile material in the form of coated particles is embedded in a matrix of graphite material. A shell of fuel-free pure graphite matrix having a 5-mm thickness surrounds the spherical fuel zone for protection. Each spherical fuel element of 60-mm diameter contains about 8300 coated fuel particles with the diameter of 0.92 mm. The graphite matrix serves as a neutron moderator as well as a heat conductor transmitting the power generation to the coolant. During the manufacture of a spherical fuel element, the overcoated particles mixed with the resinated graphite powder are pre-molded to a 50-mm diameter spherical fuel zone under about 50 MPa pressure. The fuel zone is covered with resinated graphite powder to form an integral spherical fuel element under about 300 MPa pressure in a press line. The press line consists basically of two units, i.e. the pre-press and the high-pressure press [5]. In line with the manufacturing process requirements of a spherical fuel element, coated fuel particles are not permitted to enter the fuel-free zone, otherwise they will bring severe threats to the safety and reliability of the fuel elements. Unfortunately during the manufacture of a spherical fuel element, especially in the press line, it is inevitable that some coated fuel particles are leaked and mixed with the outer pure graphite matrix. According to a quality testing report from INET of Tsinghua University, 44 batches, totally

* Correspondence to: School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Xueyuan Road No. 37, Haidian District, Beijing 100191, China. Tel./fax: +86 10 82339481; mobile: +86 13671192469.
E-mail address: minyang.ndt@263.net (M. Yang).

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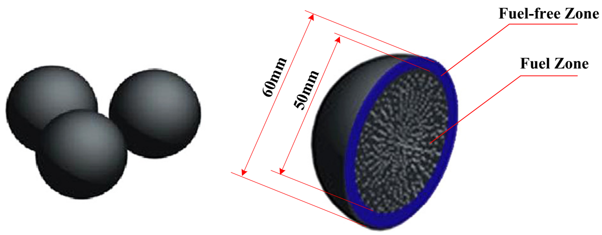

Fig. 1. Structure of a spherical fuel element.

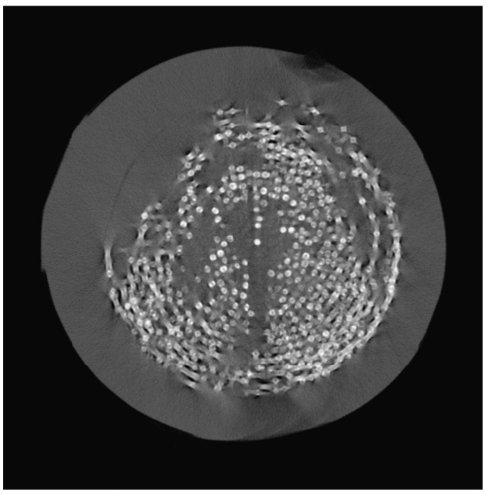

Fig. 2. Cross-sectional image of a spherical fuel element.

about 20,540 spherical fuel elements were inspected. The result was that 99% were qualified, and the rest 1% were unqualified due to the escaped coated fuel particles in the fuel-free zone [6]. Therefore, a fast and accurate non-destructive testing (NDT) method is necessary to realize zero misdetection possibility of the escaped coated fuel particles. During the existing NDT methods, X-ray imaging is the most desirable choice undoubtedly, which includes computed tomography (CT) and digital radiography (DR). CT scanning is the most accurate method because by this means all cross-sectional slices of a spherical fuel element can be reconstructed and consequently the 3D-distribution of the coated fuel particles is revealed, upon which the escaped coated fuel particles are easy to identify. Lehmann et al. applied neutron CT to investigate 3D-distribution of the coated fuel particles in the graphite matrix in order to determine its uniformity and the fuel sphere's content of fissile material [7]. We also used X-ray CT to obtain cross-sectional slices of a spherical fuel element. Because the density of the Uranium kernel of the coated fuel particle is much higher than graphite matrix's density, metal artifacts are obvious in the reconstruction image as show in Fig. 2, which resulted in interference to 3D-distribution reconstruction [8–11]. Furthermore, the time-consuming of CT technology is also a non-negligible disadvantage limiting its engineering application. DR method can provide transmission projection of a spherical fuel element in a short time and is easily implemented, so it is commonly adopted by many countries. In the experiment we captured a DR image of an unqualified spherical fuel element with escaped coated fuel particles in fuel-free zone as shown in Fig. 3, which provided very clear information of the escaped coated fuel particles so we can realize their automatic identification by software. But DR method is different from CT technology, DR image is the integration of the material's attenuation coefficient along the cone-beam X-ray [12,13], namely it is a 2D image matrix with overlapping information, so some blind

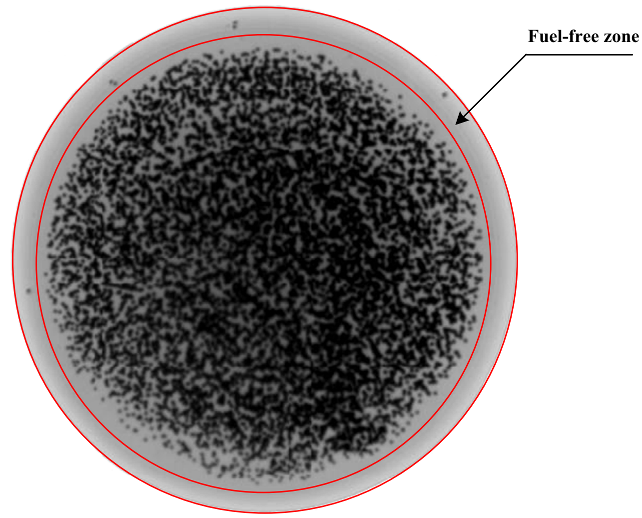

Fig. 3. DR image of a spherical fuel element with escaped coated fuel particles.

areas in the fuel-free zone will be generated inevitably, and are easy to neglect in practical application. The blind zones are the small regions in the fuel-free zone, where although there are escaped coated fuel particles existing, the DR image of the spherical fuel element shows that the escaped coated fuel particles lie in the fuel zone, which consequently brings out the error judgements of the unqualified spherical fuel elements.

In the following sections, we discuss the characteristics of the blind zones when a spherical fuel element is scanned by continuous circular trajectory and concrete circular trajectory in Section 2. Then the optimal method to design the DR scanning parameters to decrease the size of the blind zone is proposed so as to satisfy the testing requirements. In Section 3, the optimal method is verified by computer simulation and some practical identification results are presented. Finally some conclusions are drawn in Section 4.

2. Feature analysis and optimization of the blind zones

2.1. Introduction of the scanning system

Fig. 4 is the DR imaging system for spherical fuel element testing we applied. A spherical fuel element is transmitted to the rotation stage automatically and sucked by a suction cup equipped on the rotation stage. Then the fuel element rotates at the drive of the rotation stage, meanwhile, the X-ray generator is switched on and cone-beam X-rays penetrate the spherical fuel element and reach the flat panel detector. The flat panel detector collects DR projections of the fuel element at different imaging views during the rotation and transmits the projections to the host PC. According to these DR projections, the automatic identification software in the host PC evaluates the quality of the tested fuel element and sends the evaluation conclusion to the motion control terminals, which export the tested fuel element to qualified outlet or unqualified outlet finally. As mentioned above, for the circular scanning trajectory and the cone-beam imaging geometrical configuration, blind zones are inevitable. So during the design of a DR imaging system for spherical fuel elements testing, optimization control of the blind zone, namely optimizing the scanning parameters is a necessary step to ensure zero misdetection possibility of the escaped coated fuel particles. The dominant scanning parameters which decide the size of the blind zone are the distance from X-ray source to the tested object, and the rotation step angle.