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Measurement of Weight of Kernels in a Simulated Cylindrical Compact for HTGR Using X-ray Computed Tomography

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1. Introduction

The TRISO-coated fuel particle for the HTGR (high temperature gas-cooled reactor) is composed of a nuclear fuel kernel and outer coating layers [1, 2]. The coated particles are mixed with graphite matrix to make HTGR fuel element. There are two types of fuel elements, a spherical fuel element and a cylindrical fuel compact. The spherical fuel element is burned in a PBR (pebble bed reactor), such as HTR-10 in China and PBMR in South Africa. The cylindrical fuel compact is burned in a PMR (prismatic block modular reactor), such as GT-MHR (Gas turbine modular helium reactor) in the U.S.A. and HTTR in Japan. Fig. 1 shows a model of the cylindrical fuel compact. Weight of fuel kernels in an element is one of the most important properties for evaluating the characteristics of fuel element [3, 4]. Generally, the weight of fuel kernels in an element is measured by using chemical analysis or gamma-ray spectrometer. Chemical analysis is a destructive method, and a reference sample is required to keep accuracy for a gamma-ray spectrometer. Measurement error can be induced because geometric shape of test sample is a little different from that of a reference sample for a gamma-ray spectrometer. In this study, the weight of kernels in a compact is measured on the three-dimensional (3-D) information acquired by X-ray computed tomography (CT) for a cylindrical compact. The volume of kernels as well as the number of kernels is calculated from the 3-D density information. The weight of kernels will be measured form the volume of kernels or the number of kernels in a compact.

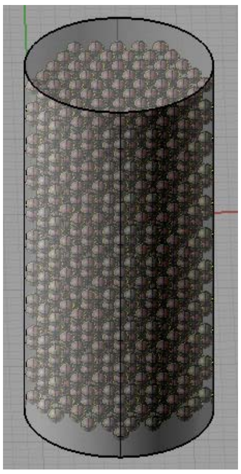

Fig.1. A model of a cylindrical compact.

2. X-ray computed tomography for a compact

The reconstructed cross-section images as well as three dimensional density information of an object can be acquired by X-ray computed tomography (CT) technology. The X-ray CT technology is widely used in medical and industrial field. The technology is also applied to analyze the fuel compact characteristics, such as the distribution of coated particles or the coating layer status of coated particles in a fuel compact for HTGR [5]. In this study, the weight of kernels in a fuel compact was measured from the volumetric density information acquired by the X-ray CT.

The X-ray CT system captures radiographic images as forward projection data for a compact according to the rotation angles over 360°, where, the object or an X-ray source and detector system should be rotated. The cross-section images are reconstructed by the captured radiographic images which are processed by the FBP (filtered back-projection) algorithm. The FBP is a powerful CT algorithm to reconstruct cross-section images by back-projecting the forward projection images as shown in Fig. 2. FBP algorithm is represented by equation (1) [6, 7].

$$f(x,y) = \int_0^{\pi} \int_{-\infty}^{\infty} P(\omega,\theta)|\omega|\, e^{j2\pi\omega(x\cos\theta + y\sin\theta)}\, d\omega\, d\theta \,, \quad (1)$$

where f(x,y) is the reconstructed image, P(ω,θ) is the X-ray projected data for the object and ω is the spatial frequency on the image plane. P(ω,θ)|ω| means the high pass filtered projection information. The filtered projection profile is projected backward (back-projected) to the object image plane to reconstruct the original cross-sectional image.

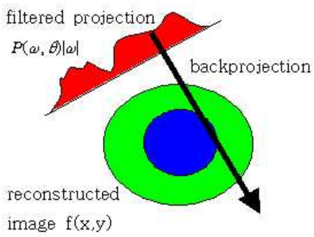

Fig. 2. Image reconstruction by filtered back-projection

In this study, The X-ray CT system captures 400 radiographic images for a simulated cylindrical compact according to the rotation angle with a step of 0.9° degree over 360°. The diameter of the simulated compacts was 12 mm and their length ranged from 10 mm to 20 mm as shown in Table 1. Simulated TRISO-coated particles with ZrO_2 surrogate with a density of 6.07 g/cm^3 as a kernel instead of UO_2 were distributed in the simulated compact. The average diameter of the simulated coated particles is 997 µm, and the average diameter of ZrO_2 kernels is 531 µm. The simulated compacts used in this study were fabricated with the simulated TRISO-coated particles mixed with polyester resin. The designed packing fraction is 20 %. The cross-section images with DICOM (digital imaging and communications in medicine) format have been reconstructed for the captured radiographic images with a resolution of 1024 × 1024 pixels × 4096 grey levels by CT reconstruction software MCT 4.1.06 of DRGEM Corp. Three-dimensional information was formed by combining the reconstructed DICOM images in a 3-D graphic software, Mimics 64bit version, V13.1.

Table 1. Parameters of simulated compacts

Compact diameter	12 mm
Compact length	10~20 mm
Coated particle diameter	997 µ m
Kernel diameter	531 µ m
Kernel substrate (density)	ZrO_2 (6.07 g/c m^3)
Designed Packing fraction	20 %

3. Measurement of weight of kernels in a compact

It is not difficult to separate the kernels from the other materials, such as coating and matrix because the density of the kernels is much higher than that of the other materials in the compact. The volume of kernels, V_k, was calculated by the volume measurement tool of Mimics for the area of the separated kernels. The number of kernels, N_k, was analyzed by the 3D design software, Rhino3D version 4.0. The weight of kernels, W_k, was calculated by equation (2).

$$W_k = V_k \times d_k \quad , \qquad (2)$$

where, d_k is the average density of a ZrO_2 kernel, 6.07 g/c m^3. The weight of kernels W_d, can be also calculated by equation (3).

$$W_d = N_k \times w_{k1} \quad , \qquad (3)$$

where, w_{k1} is the average weight of a ZrO_2 kernel, 0.445 mg, measured by micro-balance with an accuracy of 0.001 mg. The difference rate between W_k and W_d, D_W, was calculated by equation (4).

$$D_W = \frac{|W_k - W_d|}{W_d} \times 100\,(\%) \qquad (4)$$

Table 2 shows the experimental results for 4 simulated compacts. The difference rate ranged from 0.5 to 8.1 % in this experiment.

Table 2. Weight of kernels in the simulated compacts.

Sample name	A	B	C	D
V_k, mm^3	36.57	73.43	77.87	59.41
W_k, g	0.222	0.446	0.473	0.361
Number of kernels	496	950	992	750
W_d, g	0.221	0.423	0.441	0.334
D_W, %	0.5	5.4	7.3	8.1

4. Conclusion

In this study, the weight of kernels in the simulated cylindrical compacts for HTGR was measured by an X-ray CT technology. The experimental results are as follows.

- X-ray CT system was developed to acquire 3-D density information of a fuel compact for HTGR.
- The three-dimensional density information was generated by the reconstruction software and the 3-D graphic software.
- The kernel area was separated from the other materials in the compact.
- The weight of kernels was measured by using the volume of the separated kernels. It was also measured by using the number of kernels in a compact.
- The measurement skill will be applied to evaluate the weight of UO_2 kernels in a compact.

Acknowledgement

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REFERENCES

[1] K. Sawa, S. Suzuki and S. Shiozawa, “Safety Criteria and Quality Control of HTTR Fuel,” Nuclear Engineering and Design, 208, pp.305-313, 2001.
[2] K. Sawa and S. Ueta, “Research and Development on HTGR Fuel in the HTTR Project,” Nuclear Engineering and Design, 233, pp.163-172, 2004.
[3] C. Tang, et al., “Research and Development of Fuel Element for Chinese 10 MW High Temperature Gas-cooled Reactor,” Journal of Nuclear Science and Technology, Vol.37, No.9, pp.802-806, 2000.
[4] S. H Na, et al., Study on the Inspection Item and Inspection Method of HTGR Fuel, KAERI/AR-757/2006, 2006.
[5] David Tisseur, Julien Banchet, Pierre-Guy Duny, Magali Mahe and Marie-Pierre Vitali, “Quality Control of High Temperature Reactors (HTR) Compacts via X-ray Tomography,” Proceeding of HTR2006, 2006.
[6] Jiang Hsieh, Computed Tomography, SPIE Press, 2003
[7] W.K.Kim, et al., “Simulation of an X-ray Computed Tomography for the Coating Thickness Measurement in the TRISO-coated Fuel Particle,” Transactions of the KNS Autumn Meeting, 2005.