Measurement of Weight of Kernels in a Simulated Cylindrical Fuel Compact for HTGR

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1. Introduction

The TRISO-coated fuel particle for the high temperature gas-cooled reactor (HTGR) is composed of a nuclear fuel kernel and outer coating layers. The coated particles are mixed with graphite matrix to make HTGR fuel element.

The weight of fuel kernels in an element is generally measured by the chemical analysis or a gamma-ray spectrometer [1-4]. Although it is accurate to measure the weight of kernels by the chemical analysis, the samples used in the analysis cannot be put again in the fabrication process. Furthermore, radioactive wastes are generated during the inspection procedure. The gamma-ray spectrometer requires an elaborate reference sample to reduce measurement errors induced from the different geometric shape of test sample from that of reference sample. X-ray computed tomography (CT) is an alternative to measure the weight of kernels in a compact nondestructively [5].

In this study, X-ray CT is applied to measure the weight of kernels in a cylindrical compact containing simulated TRISO-coated particles with ZrO_2 kernels. The volume of kernels as well as the number of kernels in the simulated compact is measured from the 3-D density information. The weight of kernels was calculated from the volume of kernels or the number of kernels. Also, the weight of kernels was measured by extracting the kernels from a compact to review the result of the X-ray CT application.

2. Nondestructive measurement by X-ray computed tomography

2.1 Measurement of the weight of kernels

The diameter of the simulated compacts was 12 mm and their length was 20 mm. Simulated TRISO-coated particles with ZrO_2 surrogate with a density of 6.07 g/cm^3 as a kernel were distributed in the simulated compact. 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 of a compact and the 3-D volumetric image for kernels are acquired by X-ray CT technique as shown in Fig. 1. The volume of kernels, V_k, as well as the number of kernels, N_k was analyzed for the area of the separated kernels from the CT data.

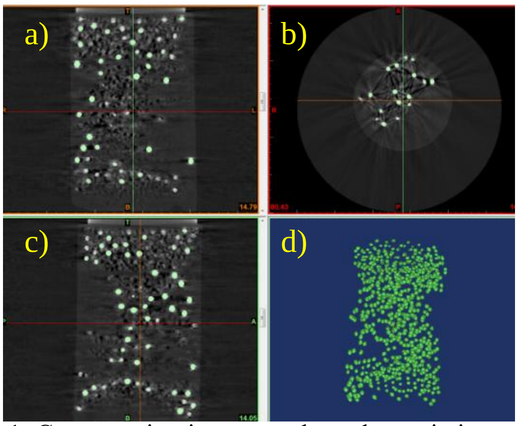

Fig. 1. Cross-section images and a volumetric image for a compact, a) a cross-section image on the coronal plane, b) a cross-section image on the axial plane, c) a cross-section image on the sagittal plane, and d) a 3D image for the extracted kernels.

The weight of kernels, W_k, was calculated by equation (1).

$$W_k = V_k \times d_k \quad , \qquad (1)$$

where, d_k is the average density of ZrO_2 kernels, 6.07 g/c m^3.

The weight of kernels W_d, can be also calculated by equation (2).

$$W_d = N_k \times w_{k1} \quad , \qquad (2)$$

where, w_{k1} is the average weight of ZrO_2 kernels, 0.445 mg.

2.2 Reliability of the measurement

The average density of ZrO_2 kernels is 6.07 g/cm^3, and the standard deviation is 0.0004 g/cm^3. Because the standard deviation of the density is very small, there will be some measurement errors for the volume of kernels due to the resolution of the X-ray detector, some artifacts in the reconstruction images, and the uncertainty in the threshold for extracting kernels in the compact.

For the number of kernels, the measurement error is not dependent on artifacts in the reconstruction images or the threshold. The standard deviation of the weight of kernels, S_W , was 0.049 mg. S_W is not so small compared with the average weight of ZrO_2 kernels, 0.445 mg. The number of kernels is often larger than 1000 in a compact. It is assumed that the number of samples, n, is 1000. The standard error, E_s, can be stochastically calculated by equation (3) under the assumption that the distribution of weight of kernels follows the normal distribution. In case of 0.95 (=1-α) of confidence coefficient, $z_{0.025}$ is 1.96 [6]. So, the standard error was 0.003 mg by the equation (3). It can be estimated that the confidence interval of the average weight of kernels ranges from 0.442 mg to 0.448 mg, and the error for the average weight of kernels is less than ±0.7 %.

$$E_s = z_{\alpha/2} \times \frac{S_W}{\sqrt{n}}, \quad (3)$$

3. Measurement by a destructive method

In order to estimate the error rates for the calculated weight of kernels, the true weight of kernels, W_t, in the compact was measured from the kernels extracted by a series of chemical process and mechanical process. Polyester resin was removed from a simulated compact to get coated particles using N,N-Dimethylformamide solution, after the X-ray CT processes. Then, kernels were extracted by a mechanical cracking for removing coating layers from coated particles. The weight of the extracted kernels, W_t, was measured by a micro-balance. E_k, the error rate of W_k, is calculated by equation (4). E_N, the error rate of W_N, is calculated by equation (5).

$$E_k = \frac{|W_k - W_t|}{W_t} \times 100(\%), \quad (4)$$

$$E_N = \frac{|W_N - W_t|}{W_t} \times 100(\%). \quad (5)$$

Table 1 shows the experimental results for 2 simulated compacts, sample A and sample B. In this experiment, the error rates were 7.5 % and 0.0 % for the measurements of the volume of kernels for sample A and sample B, respectively. The error rates were 0.2 % and 3.1 % for the measurements of the number of kernels for sample A and sample B, respectively.

Table 1. Weight of kernels for the simulated cylindrical compacts.

Sample name	A	B
V_k, mm^3	77.87	73.43
W_k, g	0.473	0.446
N_k	992	970
W_N, g	0.441	0.432
W_t, g	0.440	0.446
E_k, %	7.5	0.0
E_N, %	0.2	3.1

4. Conclusion

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

- The volume of kernels as well as the number of kernels was measured for the separated kernels in a compact from X-ray CT information.
- The weight of kernels was calculated by using the volume of the kernels and an average density of kernels. It was also calculated by using the number of kernels and an average weight of kernels.
- The weight of kernels was destructively measured by extracting the kernels from a compact.
- The validity of the X-ray tomography was verified by the average error rate less than 3.1 % for the number of kernels when compared with the true weight of kernels acquired by destructive method.

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