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Denoising method of X-ray phase contrast DR image for TRISO-coated fuel particles

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ABSTRACT

TRISO (tristructural-isotropic) fuel is a type of micro fuel particles used in high-temperature gas-cooled reactors (HTGRs). Among the quality evaluation methods for such particles, in-line phase contrast imaging technique (PCI) is more feasible for nondestructive measurement. Due to imaging hardware limitations, high noise level is a distinct feature of PCI images, and as a result, the dimensional measurement accuracy of TRISO-coated fuel particles decreases. Therefore, we propose an improved denoising hybrid model named as NL P–M model which introduces non-local theory and retains the merits of the Perona–Malik (P–M) model. The improved model is applied to numerical simulation and practical PCI images. Quantitative analysis proves that this new anisotropic diffusion model can preserve edge or texture information effectively, while ruling out noise and distinctly decreasing staircasing artifacts. Especially during the process of coating layer thickness measurement, the NL P–M model makes it easy to obtain continuous contours without noisy points or fake contour segments, thus enhancing the measurement accuracy. To address calculation complexity, a graphic processing unit (GPU) is adopted to realize the acceleration of the NL P–M denoising.

1. Introduction

TRISO-coated fuel particle 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 (Sawa & Ueta, 2004; Tang et al., 2002). A typical ball-type TRISO-coated fuel particle with a diameter of about 1 mm includes a nuclear fuel particle as a kernel, and four outer coating layers composed of buffer PyC (pyrolytic carbon), inner PyC (I-PyC), SiC, and outer PyC (O-PyC) layers, as shown in Fig. 1. The density and dimensional features, such as coating layer thickness, diameter, and roundness, are the key parameters related to fuel particle performance under irradiation (Table 1). Effective inspection and quantitative description of these parameters have a direct effect on the quality and security conditions of TRISO-coated fuel particles (Kim, Lee, Park, & Ra, 2006; Sawa, Suzuki, & Shiozawa, 2001). Among the existing non-destructive inspection means, X-ray phase contrast imaging (PCI) is a novel emerging technique to evaluate the weakly absorbing materials of the coating layers of TRISO-coated fuel particles. According to the X-ray transmission attributes, when X-rays penetrate through low-density material, its phase variation rate will be about 1000 times its amplitude attenuation rate (Wang, Zhu, & Yang, 2006). So, for the coating layers of fuel particles which contain carbon and silicon, the capture of the phase variation by PCI is more feasible than that of the attenuation contrast by traditional radiography (Peterzol, Berthier, Duvauchelle, Ferrero, & Babot, 2007; Pogany, Gao, & Wilkins, 1997; Schelokov, Weitkamp, & Snigirev, 2002; Wilkins, Gureyev, Gao, Pogany, & Stevenson, 1996; Wu & Liu, 2003, 2004). Accordingly, we applied in-line phase contrast imaging method based on a micro-focus X-ray source for quality testing of TRISO-coated fuel particles, and we obtained digital radiography (DR) images with sharper boundaries than conventional X-ray radiography images, as shown in Fig. 2.

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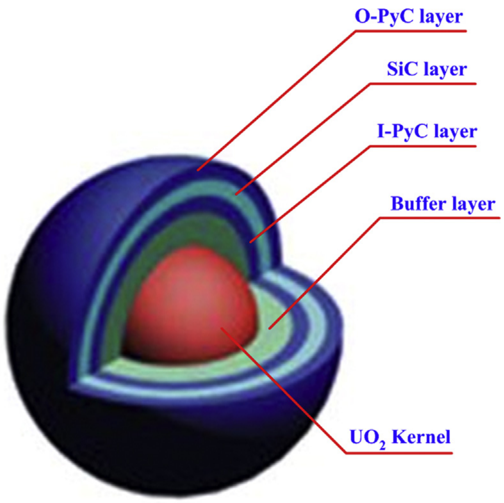

Fig. 1. Structure of a typical ball-type TRISO-coated fuel particle.

Table 1
The thickness and the density of coating layers.

Coating layer	Thickness (μm)	Density (g/cm^3)
Buffer	95	1.1
I-PyC	40	1.9
SiC	35	3.18
O-PyC	40	1.9

In our experiments, a micro-focus X-ray source is used, and the current intensity of the X-ray tube is on the microampere scale. As a result, the total number of photons that penetrate through the objects and reach the detector is very small, which causes DR images with low signal-to-noise ratio (SNR). A high level of noise in the images prevents the extraction of edge contours of the coating layers with high precision, and consequently, the accuracy of dimensional measurement decreases. As such, image denoising is an important step during the processes of dimensional measurement. The basic rule of the image denoising algorithms can be generalized as less blur in the texture region and more smooth in flat region (Nadernejad, Koohi, & Ssanpour, 2008; Rajan, Kannan, & Kaimal, 2008). Following this rule, the typical and broadly applied algorithms are partial-differential-equation-based (PDE-based) methods. Among them, the representative method is the P–M model, a nonlinear diffusion approach proposed by Perona and Malik (1990). Through anisotropic diffusion controlled by the diffusion coefficient, which is small, while the gradient of the image is large, the P–M model can effectively remove the noise as well as achieve edge enhancement simultaneously. However, PDE-based denoising algorithms have innate drawbacks, so several improved approaches were proposed. Wu and Ruan (2006) pointed out that PDEs could produce "staircasing" in processed images, and textures could not be well preserved, and they developed a hybrid denoising algorithm which combined an adaptive PDE with wavelet shrinkage to eliminate these drawbacks. Esedoglu (2001) also mentioned that the staircasing phenomenon was exacerbated by the unstable behavior of the P–M model, and investigated how the PDEs of the P–M model could be given an existence and uniqueness resolution. Shih, Rei, and Wang (2009) determined that the nonlinear diffusion model was weak in removing salt-and-pepper-type noise, they also proposed a convection-diffusion filter by adding a convection term in the modified diffusion equation as a physical interpretation for denoising.

We propose an improved Perona–Malik model based on the non-local theory, namely NL P–M model, which has been successfully used for denoising the X-ray PCI images of TRISO-coated fuel particles. In Section 2, the derivation of the NL P–M model is first

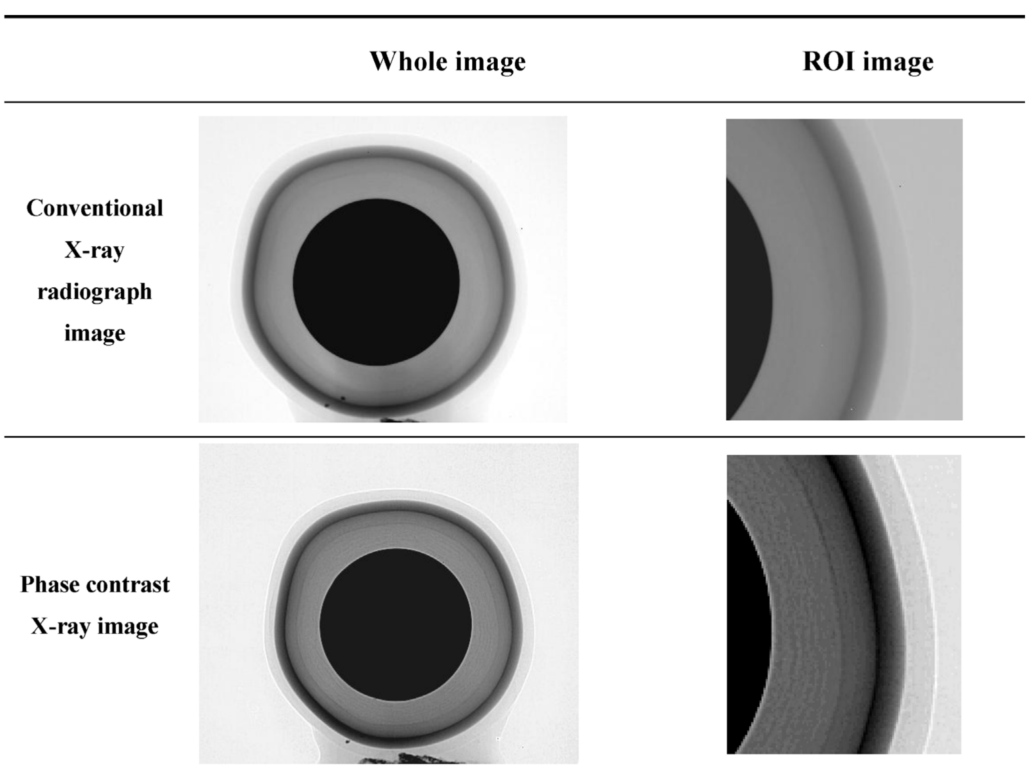

Fig. 2. Comparison of conventional and PCI X-ray radiograph images of a TRISO-coated fuel particle.