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New analytical approach for neutron beam-hardening correction

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HIGHLIGHTS

- Energy shift of neutron spectrum transmitted through strong absorbing materials was studied.
- A new approach was proposed for beam-hardening correction in neutron tomography.
- MCNP simulated projection was adjusted for a correct tomographic reconstruction.
- FBP method was used for two-dimensional (2D) image reconstruction.

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ABSTRACT

In neutron imaging, the beam-hardening effect has a significant effect on quantitative and qualitative image interpretation. This study aims to propose a linearization method for beam-hardening correction. The proposed method is based on a new analytical approach establishing the attenuation coefficient as a function of neutron energy. Spectrum energy shift due to beam hardening is studied on the basis of Monte Carlo N-Particle (MCNP) simulated data and the analytical data. Good agreement between MCNP and analytical values has been found. Indeed, the beam-hardening effect is well supported in the proposed method. A correction procedure is developed to correct the errors of beam-hardening effect in neutron transmission, and therefore for projection data correction. The effectiveness of this procedure is determined by its application in correcting reconstructed images.

1. Introduction

This study is a continuation of a previous one: *Characterization and MCNP simulation of neutron energy spectrum shift after transmission through strong absorbing materials and its impact on tomography reconstructed image*, where it has been clearly shown that the neutron beam-hardening (BH) effect has a significant effect on the interpretation of the reconstructed image (Hachouf et al., 2012). This can be observed when a polychromatic beam is used for tomography, where the neutron energy spectrum becomes harder when it crosses a strong absorbing material (i.e., elevated contribution of high neutron energies). This is due to the fact that low-energy neutrons are preferably absorbed in the first layers of the material. Thus, this effect can be defined by neutron spectrum shifting to the higher energy region after passing through a strong neutron-absorbing material. This effect is the main cause for the increase of the neutron transmission through this kind of material (Bastürk, 2003; Bastürk et al., 2005; Zawisky et al., 2004a).

The BH effect has been studied widely (Ay et al., 2013; Bastürk et al., 2005; Hachouf et al., 2012; Thomsen et al., 2015; Zawisky et al., 2004a). The results of these studies converge to the fact that the average energy of the transmitted beam increases with the crossed thickness. Hence, the gray level in the projection image of a given material is not strictly proportional to its thickness. BH causes artifacts (observable errors) in the reconstructed volume (Bastürk, 2003; Bastürk et al., 2005; Hachouf et al., 2012). Therefore, it needs to be considered with caution during the analysis of tomographic images.

The importance of this effect in the correction of transmission data for X-ray or neutron tomography was demonstrated in several studies (Brabant et al., 2012; Hassanein, 2006; Kasperl and Vontobel, 2005; Zawisky et al., 2004b). Indeed, there are three categories of the BH correction methods: the physical filtration; the dual energy system; and the algorithmic correction, which is also known as the linearization method (Brabant et al., 2012; Gao et al., 2007; Kasperl and Vontobel, 2005; Ramakrishna et al., 2006; Van de Casteele et al., 2004). The last method is the most suitable method for neutron tomography (Hachouf et al., 2012; Zawisky et al., 2004b), but, it is limited by the choice of the approximation

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conditions and the results of the treatment procedure. For a neutron beam approximated by a normalized Gaussian distribution of the neutrons energy, Zawisky (Zawisky et al., 2004b) shows that the best approximation for the effective cross section is obtained with the linear model but in a limited thickness range.

A linearization method based on the analytical determination of the neutron spectrum energy shift versus thickness was developed for correcting the BH effect. An analytical approach based on the approximation of the dependence of macroscopic cross section (Σ) on energy (E) has been proposed in our previous study, where Σ was considered inversely proportional to the energy ($1/E$) (Hachouf et al., 2012).

In this study, another approach based on the widely considered theoretical dependence between Σ and the energy E, commonly known as $1/\sqrt{E}$ dependence, is proposed. This dependence particularly exists for thermal neutrons energies range; it is applicable for thermal neutron transmission tomography, like in this case. The results of the proposed correction method are quantitatively compared with those of the aforementioned methods.

2. Methodology

On the basis of the analytical calculation results of spectrum energy shift, an effective procedure was developed for the correction of measurement errors related to BH, allowing the generation of new and valid data to be used for correct tomography reconstruction of the object. The effectiveness of this procedure is demonstrated by its application to correct phantom reconstructed images. The studied phantom has a favorable composition and geometry, allowing the observation of BH effect. In this study, the Monte Carlo N-Particle (MCNP) code, an efficient tool for simulating experimental data (set-up), is used to perform some comparison and for the generation of projection data (Briesmeister, 2003). A comparison of the results obtained from this new approach and our previous one is presented in this study.

2.1. Neutron transmission characterization

For a monochromatic neutron beam, a transmission image obeys exactly the universal Beer–Lambert law and decays exponentially with the object's linear attenuation coefficient and thickness, as expressed by

$$Tr = \frac{I_m}{I_{0m}} = exp\left(- \int_l \mu(x, y)ds \right), \quad (1)$$

where $\mu(x, y)$ is the material linear attenuation coefficient at a point (x, y), which is also denoted by $\Sigma(x, y)$, ds is the differential element in the path l, I_{0m} and I_m are the incident and transmitted monochromatic beam intensities, respectively.

There are several reasons for the nonverification of this evolution for the strong neutron-absorbing materials, in the case of a polychromatic beam. The main reason is the BH effect (Bastürk, 2003; Bastürk et al., 2005; Zawisky et al., 2004b), where the attenuation coefficient $\mu(x, y, E)$ depends on the incident neutron energy (E). The transmission image can be estimated by a complicated integral (Hachouf et al., 2012; Ramakrishna et al., 2006):

$$Tr = \frac{I_p}{I_{0p}} = \int_0^{\infty} P(E) exp\left(- \int_l \mu(x, y, E)ds \right) dE, \quad (2)$$

where I_{0p} and I_p are the incident and transmitted polychromatic beam intensities, respectively, and $P(E)$ is the probability that the detected ray has an energy E.

The dependence of neutron transmission on sample thickness was examined (Hachouf et al., 2012). A total of 20 borated stainless steel plates (1.88 wt% B-natural), with a standard thickness (0.137 cm), were prepared and used. The thickness is increased by adding one plate each time. Thus, the thickness ranges from 0.137 to 2.74 cm with a step increment of 0.137 cm. The experimental and MCNP simulated results are published in Hachouf et al. (2012).

In the MCNP simulation, the background effect was not considered in the incident and transmitted beam intensities (I_{0p} and I_p), which are counted by point detectors (Tally F5) for 1E+7 histories on neutron mode. Neutron transmission simulation is performed for the same plates. In addition, the natural boron containing the two isotopes (B-10 and B-11) with abundances of 18.5 and 81.5 wt%, respectively, was considered (Bastürk, 2003). The experimental and simulated neutron transmission data were used to analytically determine the energy shift as a function of thickness, and to estimate the evolution of effective macroscopic cross section.

2.2. Projection data and 2D reconstructed image

The two-dimensional (2D) images are reconstructed by the filtered back projection (FBP) method using MATLAB software, without BH effect correction. These images are compared with those reconstructed using the projection data calculated in the ideal case of a monochromatic beam.

For the projection data and 2D reconstructed image, a cylindrical phantom is considered in the MCNP simulation. It consists of two embedded cylinders as shown in Fig. 1. The inner cylinder is made of borated stainless steel (1.88 wt% natural boron) with a diameter of 1 cm. The outer cylinder is also made of borated stainless steel, containing only half the boron concentration of the inner cylinder (0.94 wt% natural boron), with a diameter of 2 cm. Fig. 1 shows a three-dimensional (3D) MCNP image of the studied cylindrical phantom geometrical configuration using the dynamic method “3D display.”

The projection data must be collected on many angles by rotating the studied sample through 180°. As our sample is symmetrical, all projection data are similar with the same profile.

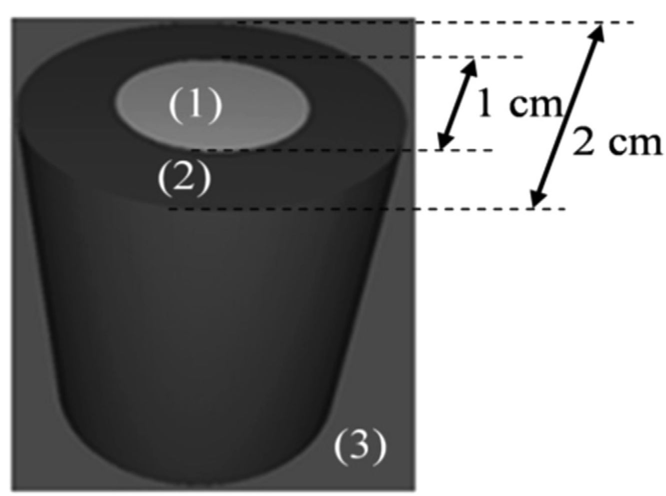

Fig. 1. Three-dimensional (3D) MCNP visualization of the geometrical configuration of the cylindrical phantom. (1): 1.88 wt% B-natural boron stainless steel cell (Σ_{th}=7.3 cm^{-1}); (2): 0.94 wt% B-natural boron stainless steel cell (Σ_{th}=4.26 cm^{-1}); and (3): the air cell.