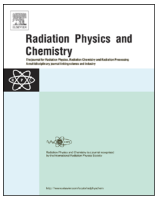
Radiation Physics and Chemistry 122 (2016) 100–107

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem



Deterministic simulation of thermal neutron radiography and tomography

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HIGHLIGHTS

- Thermal neutron interactions in a highly scattering medium have been modeled.
- A scatter model has been developed using forward scattering and a convolution method.
- Deterministic approach has been used which is much faster than Monte Carlo methods.

ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form
21 January 2016
Accepted 26 January 2016
Available online 27 January 2016

Keywords:
Deterministic simulation
Neutron radiography and tomography
Noise
Scatter

ABSTRACT

In recent years, thermal neutron radiography and tomography have gained much attention as one of the nondestructive testing methods. However, the application of thermal neutron radiography and tomography is hindered by their technical complexity, radiation shielding, and time-consuming data collection processes. Monte Carlo simulations have been developed in the past to improve the neutron imaging facility's ability. In this paper, a new deterministic simulation approach has been proposed and demonstrated to simulate neutron radiographs numerically using a ray tracing algorithm. This approach has made the simulation of neutron radiographs much faster than by previously used stochastic methods (i.e., Monte Carlo methods). The major problem with neutron radiography and tomography simulation is finding a suitable scatter model. In this paper, an analytic scatter model has been proposed that is validated by a Monte Carlo simulation.

1. Introduction

Thermal neutron imaging, including radiography and tomography, has been used in industry as an important nondestructive testing (NDT) method (Heller and Brenizer, 2010). The interaction between thermal neutron and matter demonstrates that it is a complimentary technique to X-ray imaging. While an X-ray passes easily through light materials, such as water, and is significantly attenuated by heavier materials, such as lead, the attenuation of thermal neutrons is not directly proportional to the atomic number of materials. Thermal neutrons easily penetrate metal materials, such as steel, lead, and zirconium, but are heavily attenuated by materials like hydrogen, boron, cadmium, samarium, gadolinium etc. This property of thermal neutrons makes them useful in thermal neutron imaging for industrial nondestructive testing (Winch et al., 2014; Mishra et al., 2006; Lehmann et al., 2005; Craft et al., 2014; Putra et al., 2015), especially for detecting oil or water within large metal objects.

Compared to low energy X-ray imaging, thermal neutron imaging is quite complex due to the nature of available neutron sources and their complex shielding requirements. Neutron imaging facilities generally utilize one of the following three sources: nuclear reactors, accelerators, or radioactive isotopes (Chankow, 2012). It may take a long exposure time to obtain one radiograph if the source strength is low (Shu-Quan, 2013). To generate a tomographic image, many (depending on resolution requirements) of these measurements need to be taken. Therefore, the capability to accurately simulate the performance of a thermal neutron radiography or tomography setup can improve a neutron imaging facility's ability to design experiments and optimize the imaging quality (Sogbadji et al., 2014). Monte Carlo simulation has often been used to simulate neutron radiography (Tharwat et al., 2014). However, the use of stochastic codes, such as MCNP5 (X-5 Monte Carlo Team, 2003) to simulate neutron tomography is hindered by the expensive computation time and resource consumption.

This drawback can be overcome if a deterministic simulation is used in place of a stochastic simulation to generate neutron images. Use of a deterministic simulation in the case of X-ray imaging

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http://dx.doi.org/10.1016/j.radphyschem.2016.01.036
0969-806X/

is a common practice. In 1982, Siddon developed an algorithm, known as the 'ray-tracing algorithm' that minimizes the time and resource consumption in the case of X-ray imaging with photons (Siddon, 1985). Later, the works of Zhao et al. (2007), Freud et al. (2004) and Li et al. (2007) greatly improved the efficiency of this algorithm, thereby reducing the time required to simulate images.

Thermal neutron imaging is very similar to X-ray imaging in that neutrons are not charged and can travel significant distances in matter without interacting. Therefore, many of the concepts and methodologies of X-ray imaging can be used in neutron imaging. However, thermal neutron imaging differs from X-ray imaging in that the interaction of neutrons with electrons is very weak. Neutrons interact directly with the atomic nucleus, rather than the outer electric field of an atom. Also, scattering is the major source of attenuation in thermal neutron transport. In our present work, we have modified the ray-tracing algorithm in terms of neutron interaction with matter to simulate neutron imaging. This deterministic simulation reduces the computation time to less than 5 s, compared to a 10-h simulation using MCNP5 with five million particle histories on an eight core i7-3770K central processing unit (CPU).

2. Method

2.1. Physics model

The physics model for the ray tracing algorithm is described by the following equation,

$$I(\beta) = I_o(\beta)\exp\left(-\sum_i \mu_i \rho_i d_i\right) + I_{sc}(\beta) + I_n(\beta) \quad , \tag{1}$$

where $I(\beta)$ is the number of neutrons (or the neutron intensity) detected at the detector with source fan angle β, and $I_o(\beta)$ is the source intensity. β denotes the angular position of a ray in the neutron beam. μ_i, ρ_i and d_i are respectively the mass attenuation coefficient, density, and path length of the ray which travels in material i, and the sum extends over all regions and materials through which the neutron passes on the way to a particular detector element. $I_{sc}(\beta)$ and $I_n(\beta)$ are the contributions to the detected neutron intensity from scattered neutrons and noise. A typical ray tracing algorithm includes the following steps:

1. Ray casting from the source to a particular pixel of the detector system.
2. Tracing the primary ray as it penetrates the object volume and calculating its attenuation.
3. Computing the scattered ray contribution with appropriate physics model and cross sections.
4. Computing the statistical noise and scatter contribution with suitable physics models.
5. Accumulating the neutron intensity recorded by each detector pixel.

Steps 1–5 simulate neutron radiographic imaging. To simulate neutron tomography, the object volume is rotated to the next view angle and steps 1–5 are repeated.

For most common materials in NDT, the types of thermal neutron interaction are absorption, elastic scattering, and inelastic scattering. Microscopic cross section data for these interactions for different materials can be found in data libraries, such as ENDF/B VII.1 (Chadwick et al., 2011). In this work, we have created a neutron mass-attenuation coefficient data library for elements from hydrogen to zinc using the following equation,

$$\mu = \frac{N_A}{M}\left(\sigma_a + \sigma_s + \sigma_{in}\right) , \tag{2}$$

where, μ is the total mass attenuation coefficient, N_A is the Avogadro's number, M is the atomic mass. σ_a, σ_s, and σ_{in} are the absorption, elastic scattering, and inelastic scattering microscopic cross sections, respectively. The calculation of the contributions of scattering and noise to the detected neutron intensity are described in the following sections.

2.2. Noise model

As with X-ray imaging, neutron imaging also suffers from inherent statistical noise. This noise is random and is generated due to effects like Poisson statistics on the detected number of neutrons, fluctuation of energy that each neutron deposits in the detector, and electronic readout noise, etc. (Lewandowski et al., 2012). In this paper we have modeled the neutron noise with a Poisson noise approximation. The neutron noise is estimated using a Poisson distribution, as shown in the following equation,

$$\Pr(N = k) = \frac{e^{-\lambda t}(\lambda t)^k}{k!} , \tag{3}$$

where N is the number of neutrons measured by a given detector element over a time interval t, and λ is the expected number of neutrons per unit time interval. The uncertainty described by this distribution is known as the statistical noise.

Because the incident neutron count follows Poisson distribution, it has the property that its variance is equal to its expectation, as shown in Eq. (4).

$$E(N) = Var(N) = \lambda t \tag{4}$$

In the case of neutron imaging, the neutron noise is modeled as the Poisson noise σ (i.e., square root of the mean number of neutrons detected) randomly fluctuates around the mean number of neutrons detected. Mathematically, it is expressed by the following equation,

$$\sigma(\beta) = \sqrt{I_o(\beta)\exp\left(-\sum_i \mu_i \rho_i d_i\right)}. \tag{5}$$

2.3. Scatter model

To simulate the contribution of scattered neutron to the detected intensity Kardijlov et al. (2005), Hassanein et al. (2006), and later Hai-Feng and Bin (2011) have modeled a point scatter function by creating an image formed by a point source and a homogenous phantom using MCNP5. A scatter distribution function was developed which is dependent on the geometry of the phantom, the distance of the image grid from the phantom, and the fan beam angle of the source. The simulated data are processed with MATLAB (MATLAB and Statistics Toolbox Release, 2012) to form an analytic representation of the scatter distribution. The point scatter function depends on the size and shape of the object being imaged, as well as the distance between the object and the source. The main disadvantage of this method is that it is not a generalized method and needs a Monte Carlo simulation to be carried out to generate the scatter data.

In the present work, we have developed an approximate model of neutron scatter, which depends only on the incident neutron intensity and the neutron intensity distribution over the detector. The foundation of this algorithm lies in the work of Hangartner (1987), who formulated a forward scatter function for X-ray imaging, with later improvement of the work by Ohnesorge et al. (1999). The interactions between neutrons and matter create