Applied Radiation and Isotopes 105 (2015) 249–256

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

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

Analyzing the effect of geometric factors on designing neutron radiography system

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H I G H L I G H T S

- The design of a neutron radiography system was investigated.
- The effect of geometric factors on the design of such systems was investigated.
- The system performance can be increased by regulating the geometric factors.

A R T I C L E I N F O

Article history:
Received 27 April 2015
Received in revised form
15 August 2015
Accepted 19 August 2015
Available online 20 August 2015

Keywords:
Neutron radiography system
Beam tube
Collimator
Beam quality
Collimation ratio

A B S T R A C T

Neutron radiography is one of the main applications of research reactors. It is a powerful tool to conduct nondestructive testing of materials. The parameters that affect the quality of a radiographic image must be considered during the design of a neutron radiography system. Hence, this study aims to investigate the effect of geometric factors on the quality of the neutron radiography system. The results show that the performance of the mentioned system can be increased by regulating the geometric factors.

1. Introduction

Radiography with neutrons was first used shortly after the neutron was discovered. The initial experiments in neutron radiography were performed in Germany by H. Kallmann and E. Kuhn in the late 1930s. This is a powerful tool to conduct nondestructive testing of materials, with several industrial and material research applications. The underlying principle of neutron radiography is similar to X-ray radiography. A beam of neutrons falls on the sample, passes through the sample, and finally leaves the sample image on a photographic plate or a detector. The neutrons in this method interact with an object's nucleus rather than its orbital electron, so the electron density, and not the elemental composition, of the object is involved. Materials with low Z such as hydrogen are easily imaged due to scattering, whereas boron and cadmium are imaged due to their strong absorption.

In general, a neutron radiography facility consists of the following three major components: a neutron source, a neutron collimator, and an image-processing system. The principal arrangement of a neutron imaging facility is relatively simple, as indicated in Fig. 1. The neutrons delivered by the source are selected and guided to the object via a collimator to the location where the neutrons interact with the sample material. The detector behind the object registers all arriving neutrons both unperturbed and interfered by the object. The detector is arranged mostly perpendicular to the beam, representing a two-dimensional array of image dots (pixels) (Jafari and Feghhi, 2012).

In this paper, the effects of the geometric factors on the system are examined, especially their individuals roles in improving the performance of the neutron radiography system. The effective parameters in neutron radiography operation are mentioned in Section 2. The studied factors and simulation methodology are described in Section 3. These factors are analyzed and discussion in Section 4, and the final conclusions are presented in Section 5.

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http://dx.doi.org/10.1016/j.apradiso.2015.08.030
0969-8043/

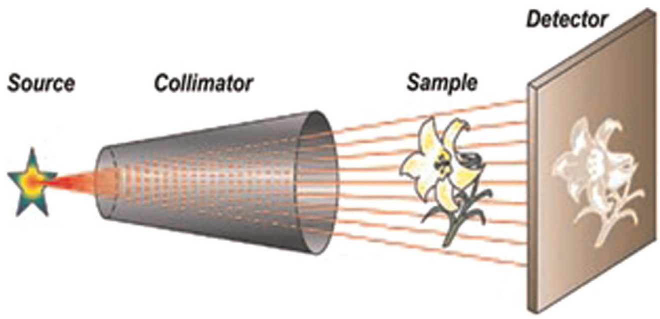

Fig. 1. Illustration of a typical neutron radiography system.

2. Effective parameters on neutron radiography operation

The quality of the neutron radiography system is dependent on several parameters. These parameters can be divided into the following general categories:

- Characterizations of neutron beam
- Neutron radiographic techniques

2.1. Characterizations of neutron beam

All parameters of the beam related to the quality of a radiographic image must be considered when characterizing a neutron beam. The parameters of the neutron beam characteristics are as follows (Morgan et al., 2013):

2.1.1. Effective collimation ratio

The effective collimation ratio of a neutron beam can also be expressed by the ratio of length to diameter (L/D). A higher L/D ratio indicates a clearer image produced by the neutron beam.

2.1.2. Beam quality

The beam quality determines the thermal neutron content, scattered neutron content, gamma content, and pair production content of a neutron beam.

2.1.3. Beam divergence

The divergence of a beam of particles describes the angle at which the beam subtends after leaving the beam port.

2.1.4. Energy spectrum

Each reactor produces a different neutron energy spectrum. These differences create various beam conditions for neutron radiography. A well-established neutron energy spectrum can be used to analyze radiographic images and compare images from different radiographic systems.

2.1.5. Flux profile

The flux across a neutron beam may not be uniform, with a tendency of tapering at the edges and peaking in the middle.

2.2. Neutron radiographic techniques

In addition to the abovementioned parameters, the quality of the neutron radiography image depends on such neutron radiographic techniques as neutron converters and the image recording media (Chankow, 2012).

After passing through the specimen, the neutrons interact with the converter screen to produce radioisotopes such as alpha particles or light, which can be recorded by film, imaging plate, optical camera, or video camera. The neutron converter and image recording media have their own characteristics. For example, for a particular density, a Gd metallic foil screen/film requires about 5.5×10^8 total thermal neutrons per square centimeter and NE-426 light emitting screen/film assemblies require 5×10^6. If the neutron flux at the specimen is about 10^6 cm^{-2} s^{-1}, the exposure time required for registering is 550 and 5 s, correspondingly. The general characteristics of these two imaging techniques are as follows:

1. Gd foil/Industrial X-ray film has the best image quality, although it requires high neutron exposure.
2. NE426/film (optical or video camera) has the fastest speed and acceptable image quality, requiring low exposure and allowing real-time or near real-time imaging.

Due to these characteristics, the geometric factors of a neutron radiography system can significantly affect parameters such as the L/D ratio and the output flux of the collimator (Kobayashi and Plaut, 2001).

3. Procedure

3.1. Simulation methodology

The Tehran research reactor was selected as a neutron source for this study, and all calculations were performed for the first operating core, which contains 14 standard fuel elements and five control fuel elements. This reactor is a 5-MW pool-type, light-water-moderated reactor with heterogeneous solid fuel, which also uses water for cooling and shielding. Its fuel assemblies contain low-enriched uranium fuel plates in the form of U_3O_8–Al alloy.

Most importantly, the neutron flux of research reactors is used for medical and industrial purposes. A beam tube (BT) facility contains the equipment required to exploit the neutron flux for different purposes (Moguiy et al., 2011). A cylindrical BT, as in Fig. 2, was used to analyze the effective parameter of the neutron radiography system. The BT is made of stainless steel, as seen in Fig. 2. The inner wall of the collimator is covered with cadmium and the outer with bismuth. At the front of the collimator, the moderator and beam filter thermalize the fast neutron and minimize the gamma intensity, respectively. These two parts are filled with air in this study.

The MCNPX 2.4 code (MCNPX, 2002) was used to simulate the Tehran first operation core and the proposed BT. The result of this simulation is shown in Fig. 2. To reduce the computation time, record data, and obtain agreement, the output of code is derived from the geometry splitting method (Moguiy et al., 2012). In the proposed process of analyzing each factor, the other factors are assumed to be fixed and only the considered factor is changed. The distributions of the thermal neutron flux, the total neutron flux, epithermal and fast neutron flux, and gamma content are calculated for each step.

3.2. Problem definition

The aim of this study is to evaluate the effect of geometric factors on the effective parameters of the neutron beam characteristics of the thermal neutron radiography system. As mentioned earlier, the BT is an indicator of the quality of the produced image, and it is affected by several parameters in the design process. The majority of the aforementioned parameters are geometric factors that affect the operation of the system. Geometric factors can change the output of the system by affecting the L/D ratio, minimum photon flux, maximum thermal neutron flux, and