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Optimization study of some neutron imaging parameters in a reactor based neutron radiography facility

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ABSTRACT

Neutron imaging technique can be used as a means of material Non-Destructive testing. One of common neutron sources for neutron radiography is nuclear research reactor. In this work, several neutron imaging parameters such as aperture distance and the radiography plane location from the neutron source as well as the aperture diameter have been computationally optimized to deliver a proposed neutron beam. According to the results, the aperture diameter of 3.5–4 cm which was located at 55–85 cm from the outer layer of reactor core and the position of image plane at 300–400 cm fulfills delivering of the suitable neutron flux and other required conditions. W, Fe and Pb walls with an identified length formed the convergent-divergent collimator and shielded the neutron and gamma out of beam path. Bi and Fluental filters with an optimal dimension were used to efficiently improve the neutron beam profile at a sample position.

1. Introduction

Neutron radiography (NR) is a powerful imaging technique for the internal evaluation of materials or components in research and industrial applications. Air–water two-phase flows in a commercial plate heat exchanger can be visualized by NR (Asano et al., 2005). Damaged concretes are studied by NR with extraordinary sensitivity to detect water penetration in concrete (Zhang et al., 2011). NR can be successfully utilized on aluminum-epoxy bonds to detect defects that are a concern in adhesively bonded joints (Michaloudaki et al., 2005). In addition, it is applied for imaging of particulate filters (PFs), porous media, the internal structure of rocks and Pressurized Water Reactor (PWR) nuclear fuel rods (Toops et al., 2013; Jasti and Fogler, 1992; Beer et al., 2004; Wei et al., 2013).

NR requires parallel or divergent beam of low energy neutrons with fluxes in the range of 10^4–10^6 (n/cm^2.s) (Jafari and Feghhi, 2012). Convergent-divergent collimators are more suitable for nuclear reactor sources because of the loss in neutron flux is less than in other configurations (Whittemore, 1991).

Many NR facilities have been installed and utilized on nuclear reactors such as the NR facility at beam hole of CIRUS reactor with neutron beam of 15 cm in diameter and ~5 × 10^8 n/cm^2.s flux at sample position (Shaikh, 2009). At BARC, thermal neutrons from the reactor were collimated by a divergent, cadmium lined aluminum collimator with a length/inner diameter (L/D) ratio of 90 which provides ~10^6 n/cm^2.s neutron flux at the sample position (Ouardi et al., 2009). Quardi carried out a preliminary study concerning the neutron imaging facility around the TRIGA reactor. The NR designed collimator had divergence angle of 1.41° and 1.61°, beam diameter of 32 and 40 cm, as well as collimation ratio (L/D) of 165 and 325 respectively (Shaikh, 2012). Turkoglu investigated a NR system for OSURR reactor. The neutron collimator of this reactor delivers the filtered thermal neutron beam with a 4 cm diameter and a thermal equivalent flux of (1.27 ± 0.03) × 10^7 n/cm^2.s at the end of the collimator (Turkoglu et al., 2011). Shaaban designed a NR facility for MNSR reactor. The facility has L/D ratio of 125 and thermal neutron flux 2.548 × 10^5 n/cm^2.s (Shaaban, 2010). A small NR system is operating at the thermal column of ENEA TRIGA research reactor. The facility is based on a neutron collimator with a measured L/D ratio of 44, circular aperture with 4 cm in diameter and neutron flux of 5 × 10^6 n/cm^2.s (Palomba and Rosa, 2007). Furthermore, Gaarbe developed a new neutron imaging instrument which is going to be built for support of the area of neutron imaging research at ANSTO. The estimated flux, for an L/D of approximately 250, was about 4.75 × 10^7 n/cm^2.s (Garbe et al., 2011).

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The aim of this work is, through the computerized modeling of a thermal neutron radiography system, to optimize neutron imaging parameters for a research reactor based NR system. In such a common system, the neutron flux and L/D parameter should be large enough for a good resolution. Moreover, the gamma and fast neutron backgrounds should be reduced as much as possible by sufficient shielding. Therefore, in this work, a computer modeling of a convergent-divergent neutron radiography system based on a hypothetical 40 MWth nuclear research reactor via MCNPX code has been proposed. Furthermore, there has been suggested a neutron collimator length optimization to provide a neutron flux in the order of 10^6 n/cm^2.s at image plane.

2. Material and methods

2.1. Bare collimator optimization

Determination of different parameters in a neutron imaging system, including the collimation ratio (L/D), neutron flux profile, neutron energy spectrum, image quality, and beam divergence is vital for producing high quality radiographic images. MCNPX 2.6 code (Pelowitz, 2008) has been used to simulate a convergent-divergent neutron radiography system as shown schematically in Fig. 1. MCNPX is a Monte Carlo particle transport code for simulating a nuclear process which includes two types of image capability: the pinhole image projection and the transmitted image projection (Pelowitz, 2008).

The radiography system design has been carried out for a hypothetical 40 MWth nuclear reactor in which total neutron flux on the outer layer of the core (heat shield layer) is 1.63×10^{11} n/cm^2.s and thermal neutron flux ($E_n < 0.1$ eV) on the layer is 9.23×10^{10} n/cm^2-s. The aperture has been located at 55–165 cm (L1) from the source plane with d1 = 15.24 cm. In this design, the image plane size (d2) has been assumed as 20–40 cm, located at two positions of 300 cm and 400 cm (L2).

The collimation ratio parameter (L/D) is a key issue in the design of any facility for neutron imaging system. The ratio directly indicates a relation between the object thickness and the image sharpness and relates the aperture flux to its value on the imaging film according to the following equation (ASTM Standards, 2008; Harms and Wyman, 1986):

$$\phi_0 \cong \frac{\phi_s}{16\left(\frac{L}{D}\right)^2} \quad (1)$$

Where, Φ_s is neutron flux in exit, Φ_0 is neutron flux in entrance, L is collimator length and D is entrance aperture diameter.

Aperture size, location and shape determine the resolution of radiographic images which can be obtained by completely-paralleled or diverged neutron beams. A convergent-divergent collimator has been used in designed NR system in present work since the performance of this collimator can lead to a high resolution image (Klann, 1996). The parameters of design were considered to obtain a thermal neutron flux of $(8–10) \times 10^5$ n/cm^2.s at the image plane and L/D ratio of 60–150 and the neutron beam divergence of 2–8°.

The aperture was located at several positions from the neutron source (L1 = 55, 70, 85, 110, 165 cm) to determine an optimal distance. The neutron beam characteristics, including neutron flux and its uniformity, have been evaluated on the image plane at L2 = 300,400 cm. Moreover, the ratio of L/D has been calculated for aperture diameters from 1 to 8 cm. Then, the optimal aperture diameter range has been determined in order to satisfy the desired neutron radiography design parameters.

The pinhole image projection option in MCNPX 2.6 has been used for all simulations. In the pinhole image projection case, a point is defined in space that acts much like the hole in a pinhole camera and is used to focus on image specially around a grid which acts much like the photographic film (Pelowitz, 2008). Therefore in this method, the scattering of the system walls is not considered and an ideal situation is regarded.

The scattering effects were involved in simulations in further steps of the collimator structure shaping. In our work, thermal, epithermal and fast neutron energy ranges were selected as <0.1 eV, 0.1 eV–100 keV and >100 keV respectively.

2.2. Optimization of the collimator neutron and gamma filters

A thermal neutron flux of $>10^6$ n/cm^2.s, n/γ intensity of $>10^6$ (n/cm^2.mR) and beam thermal neutron content (TNC) of 70–90% were considered as the basis of the collimator optimization. A composition made from tungsten, iron and lead was used as gamma and neutron shields in the converging section of the collimator. In addition, the aperture must prevent thermal neutrons from entering the beam except when they are headed toward the hole. Therefore, the material such as B4C is chosen for this case.

Filters are often used in a neutron radiography system. These filters remove gamma rays from the beam. Moreover, the neutron filters are used to reduce the more energetic neutrons from the beam for thermal neutron radiography. The materials such as Fluental and Bi were selected for fast neutron and gamma ray filtering, respectively. An optimal thickness in the range of 1–10 cm was determined for neutron and gamma filters. Neutron and gamma dose rates at the sample position were calculated for the optimized collimator.

3. Results and discussion

Fig. 2 shows the possible L/D ratios of designed neutron radiography system versus L1 for several aperture diameters and image plane at 300 cm from the source. Since the ratio of L/D > 60 was considered as a design parameter, the boundary of this value is indicated by dash-line. Therefore, it can be seen that all of L1 values satisfy the required collimation ratio condition for 1–2 cm aperture diameter. This condition is acceptable for the aperture diameter of 2.5 cm in all of L1 value except the L1 = 160 cm. In addition, the aperture diameters of 3, 3.5 and 4 cm are only acceptable for L1 values of 55–110 cm, 55–85 cm and 55 cm respectively.

The possible L/D ratios as a function of L1 for several aperture diameters and image plane at 400 cm from the source are also shown in Fig. 3. Here, all of L1 values satisfy the required collimation ratio condition for 1–4 cm aperture diameter. Moreover, the aperture diameter of 5 cm is only acceptable for L1 values of 55–110 cm.

Fig. 4 shows the thermal neutron flux at the image plane,

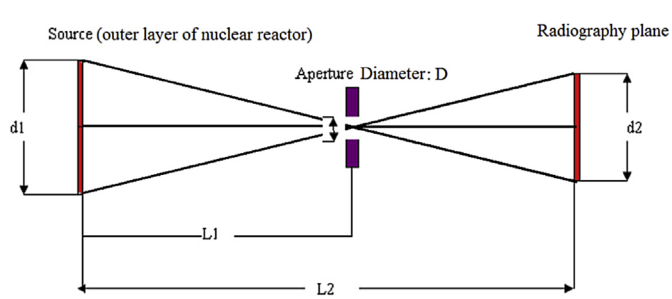

Fig. 1. Schematic view of the designed radiography system.