Preliminary study of neutron tomography performance tested by a standard specimen

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Abstract. The performance of neutron tomography facility at the Thai Research Reactor TRR-1/M1 is studied. Thermal neutron beams with a flux of \(10^6\) n/cm\(^2\)/s are employed to radiate on a standard sample, so-called Strip B, in the test. The neutron irradiating on samples were detected by a neutron-to-photon conversion plate. After that, the low-energy photons were guided to a charge coupled device (CCD) to obtain a digital image. During the experiment, a rotation stage was used to rotate the sample in order to measure the attenuated/scatted neutrons at different angles with respect to the sample geometry. The angle-varied images were then processed via a reconstruction software to create a 3-dimension (3D) image (tomography). The result shows that an image of 0.5 mm-diameter cadmium wire could be observed by employing our facility, but the sharpness of the 3D image is still needed to be further improved.

1. Introduction
Neutron imaging is a non-destructive technique to give complementary information on the structural characterization together with X-ray imaging. Since it is impossible to detect neutrons via a conventional ionization-based detector, a neutron-to-photon/charged-particle material is used to change as well as amplify the detected neutrons to photons or charged particles, which can be detected via a conventional detector such as a CCD camera. The photons created by such a conversion plate are needed to be focused via optical components to guide as much as possible intensity of focused photon beam to a photodetector. The sensitivity and readout become other issues for the optimization of high signal-to-noise ratio in order to achieve a high-quality image such as high spatial resolution \([1]\). In recent years, due to a well-developed digital data acquisition and image processing, neutron radiography (so-called a 2D imaging) has been employed to implement neutron tomography (3D imaging). The underlying principle of neutron tomography is based on a collection of angle-varied 2D images as well as the reconstruction of all projections. In particular, a set of slices for each 2D image, stored in a digital format, are transformed via Fourier transformation method to create a 3D image \([2]\). The reconstruction process is commonly carried out by an image processing software, which is based on the same method to obtain a 3D photograph. This technique is useful for non-destructive investigation on internal structure of materials, possessing a different neutron cross section in different positions \([3]\).

After the neutron beam collides with the sample, neutrons may be scattered or attenuated, depending on the interaction cross section which is independent on the atomic number. It is versatile to use neutron imaging for distinguishable characterization of nearby elements in the periodic table as well as isotopes.
[4]. The interaction cross section of neutrons and target nuclei is based on the strong-nuclear force, where some isotopes, e.g. Li-6, B-10, Gd-157 and Cd-113, show higher cross section compared to the others [5]. The neutrons interacting with the sample will travel in different directions before being incident on the conversion plate, which is used to record and convert the number of neutrons to photons.

Neutron tomography (NT) system in Thailand has recently been established at the Thai Research Reactor TRR-1/M1, Thailand Institute of Nuclear Technology (Public Organization). During the establishment phase, several specimens were measured to reveal a spatial resolution for our facility. In this work, a standard sample, named Strip B [6], was employed to test the capability of neutron tomography system.

2. Experimental Setup
Thermal neutrons were generated by the 1.2 MW TRR-1/M1 research reactor at the Thailand Institute of Nuclear Technology [7]. At the reactor core, multi-energy neutrons were generated from the reactor core. The velocity of fast neutrons is decreased by a graphite cylindrical chunk used for decreasing the neutron energy down to a range of meV, called thermal neutrons. A tangential beam port was used to guide the thermal neutrons to the experimental area. The Bi-aperture with a diameter of 8.2 cm together with a boral cone was used to focus the neutron beam [8]. A 16×16 cm² beam-aperture is located at the exit of the beam port, where the mechanical slider can move the beam shutter to allow the neutron beam to the experimental area.

The collimated neutron beam collides with a sample, located on a rotation stage which is able to rotate the sample around the vertical axis, perpendicular to the incident beam. The sample holder is composed of the in-house rotation stage, made from a used compact disc, equipped with a stepper motor, which can be controlled by a computer software.

Figure 1 shows a schematic diagram for the neutron imaging facility at Thailand Institute of Nuclear Technology. The neutron beam will travel to the neutron-to-photon conversion plate made of lithium fluoride zinc sulfide (LiF/ZnS). The neutrons are captured by Li, producing He-3 and alpha particles, where the latter further interacts with ZnS, resulting in photon emission. The emitted photons are then guided by a 45°-mirror to a CCD, located at the upper part of the detection system. It is noted that a Nikkor 50-mm f/1.2 lens is used to focus the incoming light located in front of the CCD. The CCD camera contains 2048×2048 photosite arrays (pixels) with an individual size of 7.4×7.4 µm², covering a field-of-view (FOV) of about 20×20 cm². In order to reduce electronic noise, the CCD camera was operated at -10 °C, cooled by a Peltier device.

Figure 1. The (a) diagram and (b) schematic of neutron imaging facility at the Thai Research Reactor TRR-1/M1.

2.1. Data Acquisition
For neutron radiography test, a standard sample, called Strip B, was mounted at the conversion plate in order to observe the internal structure and also obtain a resolution as well as dynamic range of our setup. The exposure time was varied from 30 to 150 seconds, limited by the maximum value of 16-bit greyscale.
data. The sample Strip B, provided by Argonne National Laboratory, USA [6], was also used for testing the capability of neutron tomography. This sample is an aluminum plate, containing a cadmium plate, cadmium wires and plastic wires. The cadmium plate consists of several holes in sizes, ranging from 0.25 to 2.0 mm, while plastic and cadmium wires are in diameters of 0.10 – 2.5 mm. The individual projections of this sample were recorded at the exposure time of 30 seconds. 101 images were recorded at the angle interval of 1.8°, resulting in an overall projection of 180°. The open beam and also dark images were recorded at the same exposure time for image normalization. After that, all images were then reconstructed for creating a 3D image, using Octopus software [9]. The diagram of data acquisition is shown in figure 2 including (a) a rotation stage, (b) in-house software used for controlling the acquisition system, and (c) the neutron imaging system containing a neutron-to-photon conversion plate, optical components and a Peltier-cooled CCD camera.

2. Standard Sample

Figure 3 shows (a) an appearance of a standard sample, test Strip B, which is an aluminum plate with a size of 15×60 mm² and (b) its internal structure containing several cadmium holes and wires as well as plastic wires with different sizes. Based on our previous work [10], the neutron image recorded for 30 seconds showed that the smallest sizes of the cadmium hole and wire were 0.25 and 0.1 mm, respectively, and the smallest size of plastic wire is 0.07 mm. It is found that the contrast between the cadmium matrix (dark area) and the aluminum plate (pale area) was clearly separated.

3. Results and Discussion

The standard sample was placed on the rotation stage in front of the conversion plate with a distance of 10 cm. Figure 4 shows five projections of the sample Strip B record for 30 seconds at different angles.
with respect to the incoming neutron beam. It is seen that the images of Cd wires are distorted in a horizontal plane, compared to the radiograph image recorded at the beginning (0°) or the end (180°) of the group. Although the smallest Cd and Al objects inside the aluminum plate are observed, the sharpness of the zero-degree and also 180-degree images is much blurred compared to the radiograph one. Moreover, the contrast between the plastic and cadmium wire becomes lower for individual images.

Figure 4. The 2D neutron images of the sample located on the rotation stage, were taken at several rotational angles including 0°, 45°, 90°, 135° and 180° with respect to the incident neutron beam.

The 2D images were taken and then reconstructed by using Octopus software. Figure 5 shows the reconstructed images of sample Strip B, revealed by different image processing algorithms [11] including (a) summed projection, (b) maximum projection, and (c) volume rendering. Figure 5 (a) shows the minimum size of observable Cd wire in the size of 0.5 mm, while the plastic one is 1.0 mm. In figure 5(b) and (c), the cloudiness found in the reconstructed images were reduced, improving the image quality (sharpness and contrast); however, the detail of the rendered images was less observed than the non-processed image.

Figure 5. reconstructed images of sample Strip B in different 3D image processing algorithms.

In order to determine the sharpness and spatial resolution of tomography images, the radiography and tomography images were compared. The same standard sample was employed, where the data for the radiography image was obtained from ref. [10]. Since the tomography system needs the rotation stage, the sample have to be located at the distance of 10 cm from the conversion plate. Figure 6 shows the plot of greyscale values as a function of spatial position of radiography and tomography images of the standard sample. The greyscale value shown in the figure was obtained from the line drawn across the cadmium matrix through the aluminum gap and the plastic absorber (see the red line in figure 2).
The areas for cadmium and plastic absorbers are marked in the figure. Although the plot is obtained from the same area and angular position of the standard sample, the distance between the standard sample and the conversion plate for the tomography image is larger than the one for the radiography image. It is clearly seen that the full width at half-maximum (FWHM) of the peak, representing the aluminum gap between the cadmium plate and the plastic absorber, for the radiography image is 1.4 mm, while the one for the tomography image is 2.2 mm (see inset).

![Figure 6](image)

**Figure 6.** Greyscale value of radiography (dashed line) and tomography (solid line) images plotted as a function of distance, obtained from the same area. The greyscale value for the area between the cadmium and the plastic absorber is shown in the inset.

It is clearly seen that the field of view for our neutron imaging system is rather large compared to the L/D ratio. This number leads to a low resolution of the image, where a small object, in particular, plastic wire becomes blurred. The 2D neutron image confirms that cadmium shows better contrast and sharpness compared to plastic and also aluminum, resulting from a high absorption of neutron beam (dark area). This result proves that the images is affected by gamma rays, since the attenuation of heavy elements would have been larger than the one of lighter element. In addition, the distance between the sample and the conversion plate also influences the sharpness and contrast of the image, possibly due to the divergence of scattered neutron beams as well as the thickness of the sample.

Reconstructed images are built by a transformation of slices of 2D images. As seen in figure 4, the wires were not aligned on the same plane due to the offset of the sample position and also the rotational axis with respect to the direction of the neutron beam. The neutron beam is probably diverged, since the open-beam image depicts a ring-feature on the image, resulting from scattering and divergence of the beam. This effect gives rise to a shift in the spatial and temporal positions for the same object point, recorded at the CCD camera. These problems can be overcome by an installation of in-shutter collimator, reducing the divergence of neutron beam as well as the reduction of high-energy photons. The smallest cadmium wire of 0.5 mm-diameter could be observed in the reconstructed image, however, the image should further be improved to get better neutron tomographic image quality. The alignment of the facility and also the stability of the rotation stage should be further improved.

In figure 6, it seems that the distance between the conversion plate to the sample position influences the spatial resolution of the tomography image, where the resolution is dropped by 30%. Neutron scattering may take place at the sample and contribute to the distribution of scattered beam at the conversion plate. The distance between the sample and the conversion plate does increase the transverse direction for the scattered beam, giving rise to lower contrast image. Based on the difference in the greyscale value for cadmium and plastic, it can be described that the neutron beam is attenuated,
depending on the difference in the interaction cross section, where cadmium shows much higher cross section (about 2 order of magnitudes) compared to plastic material, containing hydrogen.

4. Conclusion
We successfully obtain a 3D image by a reconstruction of 2D-projection slices. The preliminary image of neutron tomography for a standard sample was obtained by using a compact neutron imaging system. It is found that our facility can probe a cadmium-based object down to 0.5 mm, while plastic material shows a poorer spatial resolution. The image of the standard specimen with known internal structure can provide information on the sensitivity of the neutron imaging system and guidelines for adjusting an image to display a reconstructed result. Sample alignment, data acquisition and image processing are the influential variables that affect the image quality. Although the L/D ratio is difficult to be increased due to the restriction of the policy on modification of the experimental area, the quality of the image could be improved by employing the well-collimated neutron beam and high-resolution optical detection components. The sharpness of a tomography image may be increased via an optimization of optical detection system to compensate the scattering of neutron beam.

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