Design and spatial resolution analysis of a portable thermal neutron radiography system

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Date: 2026-03-25T20:05:47+00:00

Abstract

Thermal neutron radiography is extremely sensitive to materials containing specific elements, making it a powerful complement to X-ray imaging techniques. To date, portable thermal neutron radiography systems are under development but face substantial barriers to commercialization. To overcome the limitations of conventional fixed thermal neutron radiography systems in specialized application scenarios, this work designed a portable thermal neutron radiography system and evaluates its spatial resolution performance. Based on the source characteristics of the high-intensity compact D-D neutron generator at Lanzhou University, a moderation-collimation system with a total thickness of 53.3 cm was designed, using polytetrafluoroethylene and heavy water as the primary moderator materials. Monte Carlo simulations showed that the thermal neutron fluence rate could reach 2.90×10^4 n/(cm$^2 \bullet$s), with a non-uniformity of 7.6 %. The spatial resolution of the system was simulated using two methods, including a gadolinium line-pair phantom and a gadolinium plate. Among them, the results of slanted-edge method were more reliable. The spatial resolution was determined to be 2.365 lp/mm, which was mainly limited by the 167 μm detector pixel size used. The designed radiography system enables thermal neutron imaging in confined spaces and for immovable objects.

Full Text

Preamble

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Abstract

Thermal neutron radiography is extremely sensitive to materials containing specific elements, making it a powerful complement to X-ray imaging techniques. To date, portable thermal neutron radiography systems are under development but face substantial barriers to commercialization. To overcome the limitations of conventional fixed thermal neutron radiography systems in specialized application scenarios, this work designed a portable thermal neutron radiography system and evaluates its spatial resolution performance. Based on the source characteristics of the high-intensity compact D-D neutron generator at Lanzhou University, a moderation-collimation system with a total thickness of 53.3 cm was designed, using polytetrafluoroethylene and heavy water as the primary moderator materials. Monte Carlo simulations showed that the thermal neutron fluence rate could reach 2.90×10^4 n/(cm$^2 \cdot$ s), with a non-uniformity of 7.6 %. The spatial resolution of the system was simulated using two methods, including a gadolinium line-pair phantom and a gadolinium plate. Among them, the results of slanted-edge method were more reliable. The spatial resolution was determined to be 2.365 lp/mm, which was mainly limited by the 167 μm detector pixel size used. The designed radiography system enables thermal neutron imaging in confined spaces and for immovable objects.

Keywords

thermal neutron radiography, moderation-collimation system, spatial resolution, slanted-edge method

1. Introduction

Thermal neutron radiography (TNR) is recognized as a significant non-destructive testing (NDT) technique. Due to its unique physical reaction mechanism, TNR has special application prospects.

The X-ray radiography technology currently in widespread use is essentially an electromagnetic imaging method. It relies on photon interactions with atomic orbital electrons.

The interaction cross-section generally increases with atomic number. Therefore, X-ray radiography has limited ability to distinguish light elements, and it is difficult to differentiate adjacent elements. In contrast, TNR is based on the strong interaction between neutrons and atomic nuclei. Due to the unique physical properties of thermal neutrons, the interaction

cross-section is independent of the atomic number and is extremely large when compared to the interaction cross-sections of certain light elements or specific isotopes. This fundamental difference enables TNR to recognize light elements such as hydrogen (H), lithium (Li), and boron (B), as well as to differentiate isotopes. Moreover, its ability to penetrate certain high-Z shielding materials allows for the inspection of low-Z objects enclosed within them, a task where X-rays typically fail. For example, in aerospace applications, TNR is indispensable for inspecting structural defects within turbine blade cooling channels [1] and mapping the distribution of residual ceramic cores [2] after casting. In the nuclear industry, it serves as a vital tool for verifying fuel element cladding integrity and assessing uranium enrichment levels [3]. In automotive engineering and next-generation battery research, dynamic TNR allows the visualization of damper filling processes [4], and can also reveal the correlation between microstructures and lithium transport in lithium-ion anode [5, 6]. For security screening, it provides a reliable method for identifying concealed hazardous organic materials within sealed metallic containers.

TNR is a powerful complement to X-ray radiography technology [7, 8]. All of this has led to broad implementation of TNR in some challenging fields, including aerospace engineering [1, 2, 9], modern agricultural science [10, 11], nuclear energy systems [12, 13, 14], advanced materials research [15, 16], emerging energy technologies [17], and critical national defense industries [18], etc.

Currently, a large number of academic studies of thermal neutron radiography rely on neutron sources in reactors or large accelerators [19, 20]. These facilities can provide a high level of thermal neutron fluence for experimental beam, resulting in better imaging results.

However, due to high costs, bulky non-portable equipment, strict safety regulations, TNR is still at the research stage and remains difficult to meet the growing demand for on-site nondestructive testing in industrial and field environments. These have significantly hindered the further promotion of TNR. Consequently, the development of portable thermal neutron radiography systems represents a critical technological frontier. It is essential for transitioning

this powerful inspection method from controlled laboratory settings to practical industrial and in-site field applications.

In this work, a portable thermal neutron radiography system was designed. The neutron source part used the self-developed neutron generator [21] from Lanzhou University. The structure optimization of the moderation-collimation system was carried out using the Monte Carlo method. By simulating the interaction between neutrons and the structural materials as well as the moderator materials, the key parameters at the sample location were obtained, such as the relative thermal neutron fluence (relative to source neutrons), the proportion of thermal neutrons, and beam inhomogeneity. The imaging detector was designed with a structure capable of accommodating three types of conversion screens, meeting the various

experimental requirements. Furthermore, to conduct a quantitative analysis of the physical design of this system, spatial resolution was evaluated through simulated imaging experiment using two imaging schemes: a gadolinium (Gd) line-pair phantom [22] and the slanted-edge of a Gd plate [23]. By using various analysis methods, the modulation transfer function (MTF) curves corresponding to the imaging results were obtained to characterize the spatial resolution capability of the system. The spatial resolution level directly reflected the quality of the system design, which provides a reference for the subsequent optimization and experimental planning.

2. The structure of the portable thermal neutron radiography system

The architecture of the portable system consists of three parts, including a compact high-yield neutron source, a high-efficiency moderation-collimation system, and a sensitive imaging detector, as shown in Figure 1 [Figure 1: see original paper]. The overall length of the system is less than 1.5 m.

The total weight is approximately 1.27 tons. The moderation-collimation system and imaging detector are separate from the support frame. The support structure below the moderation-collimation system is designed with grooves, which facilitate the movement of moderator materials using a lightweight stacker truck. The above design meets the application requirements of industrial sites.

2.1 The D-D neutron source

The high-intensity compact D-D neutron generator has been developed at Lanzhou University. A radio-frequency (RF) ion source ignited by an internal antenna is designed with magnetic mirror fields in both axial and radial directions, which can facilitate the confinement of high-density plasma and prolong the service life of the ion source. The adsorption target is fixed at an angle of 45° with respect to the beam direction, which is beneficial to reduce the beam power density of the target. A neutron yield of 6.06×10 n/s can be achieved at the deuterium beam of 200 keV/6 mA. The successful development of this generator provides a reliable controllable neutron source foundation for the portable thermal neutron radiography

system. In order to precisely simulate the beam characteristics of the source neutrons, an accurate generator model needs to be established. The D-D source neutrons exhibit a distinct neutron angular distribution. In the direction perpendicular (90°) to the deuterium beam axis, the neutrons show favorable quasimonoenergetic characteristics with a nominal energy of approximately 2.45 MeV. To achieve a reasonable and optimized design of this key subsystem, this work adopts a simplified but physically meaningful model of the neutron generator within the Monte Carlo simulation. Figure 2 [Figure 2: see original paper] shows the structure of the high-intensity compact D-D neutron generator developed at Lanzhou University, where Fig. 2(a) displays the primary structure and Fig. 2(b) presents the corresponding simplified computational model used in the simulation.

model constructed using Monte Carlo method The fundamental emission properties of the D-D neutron source, namely its energy spectrum, angular distribution, and total yield, are intrinsically linked to the operational parameters of the deuterium beam, specifically energy and current. The neutron energy spectra, neutron angle distributions, and integrated neutron yields of the compact D-D/D -T neutron generator are calculated and evaluated by using the multi-layer computing model [24], corresponding to a thick adsorption target at incident deuterium energy of 200 keV. The

simulated D-D neutron energy spectrum is presented in Figure 3 Figure 3: see original paper, and the corresponding angular distribution in Figure 3(b). From Figure 3(a), the neutron angular distributions of the D-D neutron source are clearly anisotropic. Particularly, differential neutron yields are obviously higher at both small angles and large angles accompanied by significant energy broadening. Due to the fact that the structural material in the 90 ° direction is thin and is closest to the target, the moderation-collimation system is designed and installed in this direction. Furthermore, the center of the moderation-collimation system is aligned with the

target.

D-D neutron generator @ 200keV and 6mA The detailed neutron source properties simulated by the multi-layer computational model were imported into the program’s source definition. An accurate definition of the source can ensure that the energy, spatial position and emission direction of each initial source neutron are precisely sampled probabilistically. This is the foundation for the accuracy of neutron transport simulation. 2.2 The designed moderation-collimation system The D-D reaction produces fast neutrons (En 2.45 MeV), which is much higher than the thermal energy range for radiography. These fast neutrons must first be thermalized and collimated into a well-defined beam, and this process relies on the moderation-collimation system. The quality of the system design directly affects the beam characteristics of the emitted neutrons, including thermal fluence, energy spectrum, spatial uniformity, and divergence. These factors fundamentally determine the spatial resolution achievable by the imaging detector. Spatial resolution is the core performance of an imaging system, directly reflecting the system’ s ability to distinguish details and object boundaries. Therefore, the design of the moderation-collimation system is of crucial importance. In this study, neutrons with kinetic energy lower than 1 eV are classified as thermal neutrons.

The optimization design of the moderation-collimation system is based on the Monte Carlo method, which simulates the transport processes of neutrons, photons, etc., and evaluates the design quality by the quality of the outgoing beam.

The expected performance of the outgoing beam includes: (1) the proportion of thermal neutrons should exceed 70%, in order to reduce the impact on the imaging quality caused by scattering from the imaging detector structure materials; (2) the thermal neutron fluence rate should be higher than 10^4 n/s, to shorten the imaging time and improve the image signal-to-noise ratio; (3) the beam non-uniformity of thermal neutrons within the field of view should be lower than 8 % across to ensure imaging quality while reducing the difficulty of subsequent imaging processing caused by source neutron inhomogeneity. Based on the above

design goals, the materials and structural of the moderation-collimation system were optimized and finally determined. The system structure is shown in Figure 4 [Figure 4: see original paper]. The total mass is approximately 1.005 tons.

This moderation-collimation system adopts a layered structure, which can efficiently thermalize source neutrons and simultaneously minimize beam scattering and background radiation. Along the incident direction of the source neutron, the moderator materials are as follows. The first layer is a 6 cm-thick polytetrafluoroethylene (PTFE), which is located in the outer cavity of the generator target system. The installation of this layer does not affect the vacuum environment of the generator or its normal operation. The second layer is a 41.1 cm-thick heavy water (D_2O). D_2O has an extremely small absorption cross-section for thermal neutrons and is thus an ideal moderator. At the center of this layer, there is a cylindrical collimation channel (10 cm × 20 cm) for neutron extraction. The third layer is a 10 cm-thick boron-containing polyethylene (8 wt% B), which absorbs scattered thermal neutrons and improves the parallelism of the emitted thermal neutron beam. At the center of this layer, there is a thermal neutron beam channel (8 cm × 10 cm). The last layer is 1 cm-thick of lead, which is used to reduce the photon background of the emitted

beam. Graphite material is wrapped around the main structure. Its function is to re-scatter the neutrons back into the collimator to reduce the loss of neutrons and act as a radiation shielding material to lower the environmental dose. A conical lead homogenizer is designed at the outlet of the collimator. This component can absorb the prompt gamma rays generated during the source neutron production and moderation, and improve the uniformity of the outgoing thermal neutron beam.

2.3 The designed imaging detector

The imaging detector part converts the two-dimensional spatial distribution of transmitted neutrons into an optical signal, which is recorded by the charge coupled device (CCD) and stored as a digital signal that can be analyzed and processed. The main structural material of the detector is aluminum plate, and the total mass of the detector structure is approximately 37 kg. An ultra-black coating is applied to the inner wall of the detector to absorb stray photons and improve the imaging quality.

This imaging conversion unit adopts a modular design and is equipped with standardized interfaces. This enables it to support two detection schemes. One is the mature fluorescent screen, such as LiF (ZnS) and LiF (GOS), etc., and the other is the scheme of adding Gd -doped microchannel plate (MCP) detector to the fluorescent screen. Specific ancillary components required for the MCP detector are pre-installed on the side of the detector housing. These components include high-voltage feedthroughs, a molecular pump port, and a vacuum gauge connection. This design flexibility enables the system to be adjusted according to different experimental requirements, such as imaging quality or imaging time, etc. Scintillator screen parameters play a key role in determining spatial resolution and imaging time [25]. In previous studies, we conducted in-depth research on the thickness of the scintillator screen and the problem of the decline in spatial resolution caused by the scintillator screen, and obtained the optimal thickness of the conversion screen suitable for thermal neutron photography [26].

A first-surface mirror is placed at the center of the detector module to deflect the optical signal by 90°. This arrangement protects the sensitive CCD from direct neutron exposure, thus reducing radiation damage and associated noise. The optical lens is placed in front of the CCD camera to focus on visible light and enhance the efficiency of light collection. The F-number is the most important parameter in the selection of the optical lens. The imaging system employs a KOWA LM35HC lens with a large maximum aperture of F/1.4, coupled with a PIXIS 1024B air-cooled scientific CCD camera. To reduce radiation damage, the CCD camera is positioned directly behind the moderation-collimation system. This position also matches the focusing range of the optical lens.

The schematic diagram of the portable thermal neutron radiography system is shown in

3. Characteristics of the emitted neutron beam

The quality of the outgoing neutron beam critically determines the overall imaging performance of the system. The beam parameters at the imaging site, such as energy spectrum, fluence distribution and non-uniformity, are the basic indicators for evaluating the performance and reliability of the system. This section provides a comprehensive description of the physical characteristics of the beam stream emitted from the moderation-collimation system, analyzes whether it meets the requirements of thermal neutron radiography, and lays the foundation for the subsequent system optimization and experimental design. 3.1 Neutron fluence and uniformity in the sample plane The neutron fluence distribution and uniformity on the sample plane are critical factors affecting imaging quality. Inhomogeneous thermal neutron fluence can lead to image distortion, reduced contrast, and even artifacts. The plane 5 cm away from the edge of the lead homogenizer is defined as the standard sample plane, and the beam characteristics are evaluated at this plane. Due to the symmetrical design of the moderator material, the two-dimensional spatial distribution of the neutron fluence can be simplified to a one-dimensional radial analysis. In the simulation, multiple detection tallies are placed radially to record the relative neutron fluences of thermal, epithermal and fast neutrons at different positions. The distribution of neutron fluences of different energy levels is shown in Radial distribution data indicate that the relative fluence distribution trends of neutrons in different energy levels are similar. In the area corresponding to the aperture (80 mm) of the collimator, the distribution of neutron fluence changes relatively smoothly and has good uniformity. Within the effective field of view with a diameter of 70 mm, the non-uniformity of the thermal neutron fluence is approximately 7.6 %. This value satisfies the basic uniformity requirement of less than 8 % for most thermal neutron radiography applications.

The result confirms that the design of the moderation-collimation system and lead homogenizer achieves the intended objectives. Beyond the collimator aperture boundary, the neutron fluence drops sharply due to the shielding effects of borated polyethylene. At the edge of the shielding material, the relative neutron fluence (approximately 6.11 × 10-9 cm-2) is reduced by about three orders of magnitude compared to the neutron fluence at the center of the field of view (approximately 6.79 × 10-6 cm-2). This indicates that it has excellent shielding performance. This steep fluence gradient not only effectively suppresses the interference of scattered neutrons in the imaging area and reduces background noise, but also

helps in the compact design of the imaging detector.

3.2 Axial distribution of relative neutron fluence in collimator holes The neutron channels within the moderation-collimation system not only serve as the path for beam focusing, but also provide the possibility for in-site neutron activation analysis (NAA) or real-time irradiation experiments. To examine this potential, detectors were placed along the axial direction of the collimator channel, with the bottom of the channel defined as the coordinate origin. The detectors recorded the relative neutron fluence at different positions within different energy groups, as shown in Figure 6 Figure 6: see original paper.

The axial distribution data show that thermal neutrons dominate within the collimator channel, accounting for 75.2 %. This condition is conducive for thermal neutron–related nuclear reaction experiments such as capture reactions. As the axial distance increases, the thermal neutron fluence decreases significantly and exhibits a clear gradient. Such a gradient provides the physical basis for the analysis of axial activation experiments. At the bottom of the collimator channel (the axial coordinate origin), the relative thermal neutron fluence reaches 2.82 × 10-4 cm-2, which is about 40 times higher than the value at the sample plane (6.79 × 10-6 cm-2). This result indicates that neutrons are mainly moderated in the front region of the moderator material D2O and then undergo intense scattering and absorption within the collimator channel, thereby achieving the collimation of the thermal neutron beam.

3.3 Moderator performance of the moderation-collimation system The moderation performance is a key objective in the design of the moderation-collimation system. It directly determines the neutron energy spectrum of the outgoing beam, thus influencing imaging contrast, spatial resolution, and the required shielding thickness for the imaging detector. To quantitatively evaluate the moderation performance, a detector with a diameter of 70 mm was deployed at the sample plane to record the local neutron energy

distribution, as presented in Figure 7 [Figure 7: see original paper].

Integral analysis of the spectral data shows that the relative fluence of thermal neutrons

) is approximately 4.78 × 10-6 cm-2, accounting for 70.3 % of the

total outgoing neutron fluence. The relative fluence of epithermal neutrons (1 eV < En < 10 keV) is about 1.40 × 10-6 cm-2, accounting for 20.6 %. The relative fluence of fast neutrons (En > 10 keV) is approximately 6.17 × 10-7 cm-2, accounting for 9.1%. These results confirm that the 2.45 MeV fast neutrons generated by the D-D reaction have been effectively moderated, and thermal neutrons constitute the dominant component of the outgoing beam.

The high thermal neutron fraction not only enhances the detection sensitivity of the imaging system for light elements such as H, Li, and B, but also significantly reduces interference and radiation damage to the imaging detector from fast and epithermal neutrons. This reduces the radiation resistance capability of the imaging detector and the design requirements for surrounding protective measures, facilitating the miniaturization and weight reduction of the system.

To assess system performance from an engineering application perspective, it is necessary to convert the relative fluence data into absolute fluence rates with clear physical meaning.

Based on the high-intensity compact D-D neutron generator developed by Lanzhou University, which operates stably at deuterium beam parameters of 200 keV/6 mA, the neutron yield reaches 6.06 × 109 n/s. Combined with the relative fluence from the above simulations, the thermal neutron fluence rate at the sample plane is calculated to be 2.90$×$104 n/(cm2 ·s). This level satisfies the requirements for static neutron imaging experiments and provides a physical basis for obtaining images with sufficient signal-to-noise ratio.

4. Evaluation of spatial resolution of imaging systems

Spatial resolution serves as a pivotal parameter for evaluating imaging system performance.

It reflects the ability to distinguish fine structures and delineate boundary details. In the thermal neutron radiography system, spatial resolution is mainly limited by the size of the

neutron source, the neutron scattering during moderation and collimation process, and the inherent unsharpness of the imaging detector. Given that previous studies [26] have systematically simulated the optical response characteristics of similar imaging conversion screens, including key parameters such as neutron-to-photon conversion efficiency and inherent unsharpness, this study adopts two simulation methods to accurately assess the spatial resolution limit imposed by the neutron source and the moderation-collimation system.

One method involves using Gd line-pair phantom to simulate imaging of the model, by observing the decrease in contrast in the periodic bright and dark line pairs to analyze the spatial frequency response. The other method is to use Gd plates with slanted-edges to simulate edge response, from which the MTF of the system can be calculated, thereby precisely describing the spatial blurring effect. Both methods are widely used in experiments to evaluate the system' s resolution capability. This lays a solid foundation for evaluating the system' s resolution capability and provides theoretical support for subsequent experimental setup and verification.

For the imaging simulations, a simplified model of the complete thermal neutron radiography system is constructed. The system is divided into four main components: the neutron source, the moderation-collimation system, the sample, and the imaging detector. The neutron source and moderation-collimation system are modeled rigorously according to the physical design and parameters specified in Section 2 to ensure simulation consistency.

Depending on the evaluation method, the test sample consists of either a Gd line-pair phantom or a Gd plate. The structure of imaging detector has been simplified. A grid counter placed flush against the exit surface of the sample replaces the complex imaging chain (including a scintillator, optical lens, and CCD sensor) and directly records the two-dimensional spatial distribution of transmitted neutron fluence. This setup allows the simulation results to more purely reflect the theoretical spatial resolution limit imposed by the neutron source size and the moderation and collimation process. 4.1 Analysis of Gd line-pair phantom for imaging evaluation

The line-pair phantom is a typical resolution testing device. It was first used in the 1920s to characterize the spatial resolution capability of imaging system. In this study, seven sets of slit arrays with different line-pair widths were designed and etched on a Gd plate of 80 mm × 40 mm × 1 mm. Its schematic structure is shown in Figure 8 [Figure 8: see original paper]. Gd possesses an extremely high thermal neutron absorption cross-section of 259000 barns resulting in a much lower thermal neutron transmittance through the Gd material than through the slit regions.

This difference produces alternating bright and dark periodic fringe patterns on the imaging plane.

A model of this sample was constructed in the simulation program for imaging simulations.

The grid detector was placed in close contact with the sample and has an imaging area of 10 cm × 10 cm. To investigate the influence of simulation mesh size on imaging quality, six different meshing schemes ranging from 100 × 100 to 600 × 600 were adopted. Higher-density meshing was not performed due to computational memory limitations. The resulting two-dimensional spatial distribution of thermal neutrons is shown in Figure 9 [Figure 9: see original paper]. The results indicate that as mesh refinement increases, the visual contrast of the line-pair images is significantly improved. Under the 600 × 600 meshing scheme, line pairs with a width of 0.2 mm corresponding to a spatial frequency of 2.5 lp/mm, can be clearly discerned from the two-dimensional distribution map. This result preliminarily suggests that under the current simulation settings, the system spatial resolution is mainly limited by the sampling interval of the detector grid. Meanwhile, the spatial blurring effect introduced by the neutron source and the moderation-collimation system is less than 0.2 mm.

For further quantitative analysis, one-dimensional fluence distribution profiles along the line $y = 0$ were extracted from the two-dimensional maps, as illustrated in Figure 10 [Figure 10: see original paper]. At a mesh resolution of 500 × 500, the signal waveform corresponding to the 0.2 mm line pairs group shows distinct periodic fluctuations, indicating that the 0.2 mm line pairs can be effectively resolved.

The system MTF can be calculated from the output image contrast. The formula is given as follows:result

Where Coutput(u) denotes the contrast at spatial frequency u, and Cinput(u) is the ideal contrast

of the input image. For an ideal Gd line-pair phantom, the input contrast Cinput(u) equals 1, which simplifies Equation (1) to:

where Imax denotes the average intensity in the transmission fringes and Imin represents the average intensity in the absorption fringes. During calculation, multiple periods of maximum and minimum intensities are extracted and averaged for each line-pair group.

Based on the one-dimensional distribution data from a 600 × 600 grid division, the system's MTF curve was calculated according to Equation (2), as illustrated in Figure 11 [Figure 11: see original paper]. The

line-pair phantom imaging method can only provide discrete MTF values at spatial frequencies corresponding to the widths of different line-pair groups, and cannot yield a continuous MTF curve. The calculation results show that for the narrowest 0.2 mm line-pair group (2.5 lp/mm), the corresponding MTF value is approximately 0.45. Taking the spatial frequency at MTF = 0.1 as the system' s limiting resolution, the simulated limiting spatial resolution obtained by the line-pair phantom method far exceeds 2.5 lp/mm.

4.2 Analysis of Gd plate for imaging evaluation To validate the reliability of the Gd line-pair phantom imaging simulations and to more accurately determine the system' s limiting spatial resolution, the slanted-edge method was used to simulate imaging at the edge of a Gd plate. The sample consists of a 40 mm × 40 mm × 1 mm Gd plate. In the simulation, this plate is rotated counterclockwise by 5 degrees. The slanted-edge method is an advanced analytical approach for MTF determination. Its key advantage is that a sharp edge is tilted at a small angle, allowing each pixel row along the direction perpendicular to the edge to record data corresponding to different sub-pixel edge positions. This method effectively realizes oversampling of the edge spread function (ESF), enabling direct acquisition of the ESF with sub-pixel precision. It significantly improves data

utilization and result reliability, and avoids aliasing errors [27] that may be introduced by discrete sampling in the line-pair phantom method. meshing schemes.

A meshing grid of 600 × 600 was adopted, and the resulting two-dimensional thermal neutron fluence distribution is shown in Fig. 10(a). Geometric correction was performed using a rotation matrix in MATLAB to align the edge vertically for visual clarity, with the processed image presented in Fig. 10(b). From the corrected image, multiple rows of data were averaged to obtain a smooth, oversampled ESF curve, as illustrated in Fig. 10(c). This ESF curve shows the highest neutron fluence at X = 0 (edge position), with fluence gradually decreasing as the distance from the center increases. Notably, in regions where |X| > 4 cm, the thermal neutron fluence decreases significantly more rapidly, which is consistent with the radial neutron fluence distribution trend obtained from previous simulations (Fig. 6(a)),

confirming the self-consistency of the simulation.

Differentiation of the ESF curve yields the line spread function (LSF), as shown in Fig. 10(d). After performing Fourier transformation, modulus extraction and normalization on the LSF curve, the MTF of the system was finally obtained, as shown in Figure 12 Figure 12: see original paper. When the MTF was 0.1, the corresponding spatial resolution of the system was 2.365 lp/mm.

Rotation-corrected image (MATLAB), (c) ESF curve, (d) LSF curve, (e) MTF curve 4.3 Analysis of imaging simulation result discrepancies A comparative analysis of the spatial resolution results obtained from the two methods reveals significant discrepancies. Based on the MTF curve shown in Figure 11(e), the corresponding spatial frequency is approximately 2.365 lp/mm at MTF = 0.1. This result differs substantially from the value of "far exceeds 2.5 lp/mm" obtained from the Gd line-pair phantom simulation. The shape of the MTF curve indicates a critical issue. The line-pair phantom simulation was likely affected by significant aliasing interference, leading to an overestimation of the system resolution. Aliasing effects originate from the misrepresentation of signal components above the Nyquist frequency in discrete sampling systems. The Nyquist frequency fN of the system is determined by the pixel pitch p as follows:

In this simulation system, a 600 × 600 meshing grid was adopted, with the pixel pitch is p = 167 μm. It can be calculated that the Nyquist frequency is fN = 3 lp/mm. When the spatial frequency of the measured signal exceeds 0.5 fN (1.5 lp/mm), aliasing artifacts become

progressively pronounced and can no longer be neglected. These artifacts superimpose moiré patterns onto the actual imaging signal and introduce non-physical oscillations or anomalous peaks in the MTF curve. As observed in Figures 11 and 12(e), the MTF curves do not exhibit smooth decay; Instead, noticeable fluctuations appear in the high-frequency region. Such fluctuations are a typical hallmark of aliasing effects.

For the simulated imaging method using a Gd line-pair phantom, the input comprises periodic square-wave signals at a single frequency. Although this approach determines the MTF by measuring the contrast between bright and dark line pairs in the resulting image, it cannot distinguish whether the measured contrast arises from genuine attenuation or from moiré patterns induced by aliasing. Consequently, particularly when evaluating signals at or above the Nyquist frequency, the MTF values obtained by the line-pair method are likely to reflect the contrast of aliasing artifacts rather than the true optical transfer performance of the system. This may lead to an overestimation of the spatial resolution.

In contrast, the slanted-edge method has distinct advantages. It uses a unique and sharp slanted edge as the input. By fitting an oversampled ESF in the spatial domain, a continuous edge profile is reconstructed. Then, by differentiating this profile and performing Fourier transformation, the MTF can be derived. This method alleviates the problem of discrete sampling to a certain extent, more effectively suppresses aliasing effects, and makes the obtained MTF curve closer to the actual optical transfer function of the system. Thus, the spatial resolution of 2.365 lp/mm (at MTF = 0.1) determined by the slanted-edge method is regarded as a more reliable theoretical estimate. This analysis further indicates that the selection of the method is crucial when evaluating high-resolution imaging systems. The slanted-edge method is superior to the traditional line-pair method in avoiding sampling aliasing and achieving accurate system performance characterization.

5. Conclusion

In this work, a portable thermal neutron radiography system has been designed, which comprises

high-intensity

compact neutron source, high-efficiency moderation-collimation system, and a sensitive imaging detector. The proposed system exhibits good portability and high spatial resolution.

Based on a precise neutron source model, this study adopts thermal neutron ratio, thermal neutron fluence rate, and non-uniformity as design indices to accomplish the physical design of the moderation-collimation system. The overall dimensions of the system are 90 cm × 90 cm × 53.3 cm. The primary moderator materials include PTFE and D2O, with aluminum as the D2O containment structure, and graphite as the reflector material. At the exit of the moderation-collimation system, boron-doped polyethylene is adopted as an absorption layer to efficiently capture stray thermal neutrons that deviate from the main beam direction after moderation. This configuration substantially enhances the parallelism of the outgoing neutron beam, thus greatly reducing the beam divergence angle and neutron background. These improvements lay a crucial foundation for high spatial resolution neutron imaging by ensuring excellent beam quality. Through comprehensive characterization of the outgoing neutron field, within an effective imaging field of view with a diameter of 70 mm, the non-uniformity of the thermal neutron fluence is approximately 7.6 %, and the thermal neutron fluence rate reaches 2.90 × 104 n/(cm2 · s) (corresponding to a yield of 6.06 × 109 n/s for the high-intensity compact D-D neutron generator).

The spatial resolution of the system is evaluated using a Gd line-pair phantom and a Gd plate edge. The minimum detector cell size used in the simulation is 167 μm. The measured spatial resolutions of the designed portable thermal neutron radiography system are "far exceeds 2.5 lp/mm" and 2.365 lp/mm, respectively. The results reveal that both methods are influenced by aliasing effects to different degrees, as reflected by the fluctuations observed in the measured MTF curves. Specifically, the line-pair phantom method tends to overestimate the resolution due to aliasing interference, while the edge imaging method based on the slanted-edge method effectively suppresses aliasing artifacts and provides more reliable spatial resolution results. Accordingly, the spatial resolution of the designed portable thermal neutron radiography system is determined to be 2.365 lp/mm, which satisfies the requirements for thermal neutron imaging technology. The system can be employed for neutron transmission inspection in confined or immovable scenarios, effectively meeting the demand for field-deployable thermal neutron imaging.

Funding This work was supported by the National Natural Science Foundations of China (12435018, 12527806), the China National Nuclear Corporation-Lanzhou University National Research Institute for Nuclear Fuel Cycle and Nuclear Technology (CNNC-LCKY-2024-085), the Major Science and Technology Projects of Gansu Province (22ZD6GB020), and the

Fundamental

Research

Funds

Central

Universities

(lzujbky-2026-jdzx11,

lzujbky-2023-stlt01). Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment:

All data generated during this study are included in this published article.]

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Note: Figure translations are in progress. See original paper for figures.