Simulation design of the moderator and collimator of a thermal neutron radiography system based on reactors

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Abstract

Neutron imaging technology is an important non-destructive testing technique widely applied in fields such as nuclear energy, military, and medicine. However, the development period of neutron imaging technology has been relatively short, and further research is still required in many aspects. In neutron imaging equipment, the quality of the neutron moderator-collimator affects imaging resolution, and exposure time also has a significant impact. Therefore, the development and research of neutron collimation systems are crucial for the advancement of neutron imaging technology.

Based on the deficiencies of currently commonly used collimator structures, this paper proposes a new collimator structure composed of a circular tube collimator and a divergent collimator. Using a reactor as the neutron source, the Geant4 program was utilized to study and design the new neutron collimation system, and research and design were conducted on neutron moderation, collimation, and the improvement of the neutron-to-gamma ratio under this structure. The optimal selection and design of materials and structural dimensions for each part were completed.

The designed device was compared with traditional devices, and simple thermal neutron radiography (TNR) experiments were performed. Simulation results show that the device has a collimation ratio of 62, a normalized thermal neutron flux at the exit of 2.07×10^{-6} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, an n/γ ratio of 4.01×10^{11} $\mathrm{cm}^{-2} \cdot \mathrm{Sv}^{-1}$, and a radial neutron distribution non-uniformity of 7.5%. The neutron beam passing through the new collimator exhibits a higher average thermal neutron flux and thermal neutron fraction compared to those passing through traditional cylindrical and divergent collimators. The thermal neutron imaging simulation results of Image Quality Indicators verify the importance of this research, providing a reference for the design optimization of TNR devices and offering theoretical support for subsequent experiments.

Full Text

Preamble

Simulation design of the moderator and collimator of a thermal neutron radiography system based on reactors∗ Yang Liu,1, 2, † Zhi Luo,1 Teng-Fei Zhu,1 and Xiao-Ping OuYang1, 3

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Neutron imaging technology is a crucial nondestructive testing technique widely used in nuclear, military, medical, and other fields. However, the development time of neutron imaging technology is relatively short, warranting further investigations in many aspects. In neutron imaging devices, the neutron-slowing collimator is good or bad in terms of imaging resolution, and the exposure time has a significant impact. Hence, developing and investigating neutron collimation systems are essential for the development of neutron imaging technology.

Based on the shortcomings of the current common collimator structure, we propose a new collimator structure consisting of a circular tube-type collimator and an evanescent collimator. Taking the reactor as the neutron source, a new neutron collimator system is studied and designed using the Geant4 program, and neutron slowing, collimation, and neutron gamma ratio improvement are studied and designed under this structure. The optimal selection and design of materials and structural dimensions of each part are completed. The designed device is compared with a conventional device, and simple thermal neutron radiography (TNR) is conducted. The simulation results show that the device has a collimation ratio of 62, a normalized thermal neutron flux of 2.07 × 10−6 cm−2 ·s−1 at the exit, an n/γ ratio of 4.01 × 1011 cm−2 ·Sv−1 , and the inhomogeneity of the radial distribution of neutrons is 7.5%. The neutron beams passing through the new collimator have higher average thermal neutron fluxes and thermal neutron ratios than those passing through conventional cylindrical and divergent collimators. The thermal neutron imaging simulation results of the Image Quality Indicators validate the significance of this study by providing a reference for the design optimization of TNR devices and theoretical support for subsequent experiments.

Keywords

Geant4 simulation, Moderator, Collimator, Reactor, Thermal neutron radiography

INTRODUCTION

Neutron radiography (NR) is a significant nondestructive testing technique that complements gamma and X-ray radiography. Neutrons and X-rays interact differently with the materials, resulting in significant differences in the images. The attenuation coefficients of X-rays and gamma rays increase with an increase in atomic number. However, in NR, the nuclear cross-section of the material and the incident neutron energy determine the attenuation coefficient. Neutrons decay more in light elements (e.g., carbon, hydrogen, oxygen, etc.) and some elements (e.g., cadmium, gadolinium, lithium, and boron) than in other elements and readily pass through most metals [1]. Additionally, they can be used for isotopic discrimination [2]. These unique advantages make NR more effective than other radiographic techniques for the detection of light elemental compounds such as water and hydrocarbons. Therefore, neutron imaging technology has significant potential applications in materials science [3, 4], aerospace [5–7], cultural heritage preservation [8, 9], geological exploration [10, 11], and industrial and military applications [12–14]. Currently, many research institutes in China and abroad, such as the Chinese Academy of Engineering Physics [15, 16], the National Institute of Standards and Technology in the United States [17], the University of Munich in Germany [18], Kyoto University in Japan [19], and the Paul Scherrer Institute in Switzerland [20], are involved in the research in the field of NR. NR can be classified into thermal neutron radiography (TNR) and fast neutron radiography (FNR) based on neutron energy. TNR is used in an extensive range of areas owing to its high image resolution and advanced technology [21, 22].

The basic components of a TNR system include a neutron source, moderator, collimator, aperture, flight tube, sample table, and imaging detector, all of which have a significant impact on the penetration capability, resolution, and sensitivity of the TNR system. TNR systems typically use various types of neutron sources such as nuclear reactors, accelerators, and radioisotope sources. Currently, most TNR equipment are built using reactors as the neutron source.

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Nuclear reactors can provide high neutron flux [23] and are usually considered the best neutron source for TNR [24]. However, reactor neutron sources must be moderated and collimated before they can be used for TNR; therefore, high-performance moderators and collimators are essential for a TNR system.

This study aims to design a novel moderator collimator sys-

tem with an imaging surface that has a low γ dose rate, low hot neutron content, and high thermal neutron flux (i.e., high cadmium ratio) to obtain the desired imaging quality. In this study, the investigation and design of moderators and collimators for a TNR system with a reactor as a neutron source were carried out using the Geant4 [25, 26] program. An improved structure of the collimator is proposed based on the deficiencies of the current common collimator structure, which expands the single-configuration collimator structure into a combination of cylindrical and divergent structures. Compared with the conventional collimator structure, the neutron beam acquired by this structure has a greater difference in the neutron injection rate inside and outside the field of view (FOV) range and can acquire a higher collimation ratio and thermal neutron flux, which is more favorable for neutron imaging. Neutron slowing and improvement in the collimation and neutron gamma ratios are investigated and designed in this structure. The optimal design of the TNR system moderator and collimator is obtained, and the designed device is compared with a conventional cylindrical collimator and divergent collimator, as well as a simple thermal neutron photography simulation of the designed device.

reactor neutrons into thermal neutrons, and the second part is the reflection layer, which reflects the slowed neutrons to the outlet end. The third part is an absorption layer used to reduce neutron leakage, and the fourth part is a collimation-shielding layer. The main function is to constrain the neutron beam into a uniform parallel-collimated neutron beam and shield the interfering neutrons to reduce their interference outside the FOV. Finally, the outermost part is the γ absorption layer, which reduces the γ-ray leakage.

B. Neutron source

The neutron source used in this study is a reference Xi' an Pulse Reactor [27, 28]. The simulation of the neutron source is simplified to a planar neutron source with a diameter of 5 cm, and only neutron emission from the source is considered.

The neutron flux density is 5 × 1010 cm−2 · s−1 . Neutrons are emitted in the direction of the cosine distribution along the radial direction. The energy follows the Maxwell distribution, and its energy spectrum is shown in Fig. 2 [Figure 2: see original paper].

II. MATERIALS AND METHODS A. Moderated shield collimation system

The moderated collimation-shielding device is one of the key devices of the TNR system, which plays a decisive role in the imaging performance of the TNR system. Its functions are as follows: (1) slow down reactor neutrons with an average energy of 2 MeV to the thermal neutron energy region, thereby providing sufficient thermal neutrons for photography. (2) Ensure neutron beams with high thermal neutron ratios and fluxes, and decrease the effects of γ rays and highenergy neutrons. (3) Shield the neutron source to a certain extent, reduce the environmental radiation dose. Obtaining better-quality TNR images.

The conceptual design of the moderated collimationshielding device based on the reactor neutron source is shown in Fig. 1 [Figure 1: see original paper]. The first part is the moderator layer, which slows the

Simulation design of the moderator

Elastic and inelastic scattering with the nuclei of the moderator material is the main way in which fast neutrons are moderated to thermal neutrons. Therefore, when choosing a neutron moderator, materials with a small thermal neutron absorption cross-section and a large fast neutron scattering cross-section should be selected. Light materials such as water and polyethylene (PE) are better fast neutron moderators [29]. Therefore, thermal neutron moderators include water, PE, paraffin, and graphite.

To obtain a suitable neutron beam, simulation calculations are conducted based on constraints and available materials.

The structural model used for the moderator design was cylindrical. The material dimensions were optimized mainly for

the axial and radial lengths. Water, PE, and paraffin are used as the moderators in the simulation. The radial thickness remains unchanged during the simulation, and the axial thicknesses are 5 cm, 10 cm, 15 cm, and 20 cm. The average neutron flux after slowing is determined. The simulation results are presented in Table 1 . Similarly, the average neutron fluxes at axial thicknesses of 30 cm, 40 cm, 50 cm, and 60 cm were simulated using graphite as the moderator; the results are listed in Table 2 . All simulation results listed in this paper, unless otherwise specified, are normalized data, that is, the counting position of the counting position when the neutron source emits a particle. The energy range of thermal neutrons is set to 5 × 10−9 MeV 5 × 10−7 MeV during the simulation. According to the simulation results, the axial thicknesses of water, paraffin, and PE reached 20 cm, and the thermal neutron ratio exceeded 65%. The average thermal neutron flux of the PE is the highest. However, graphite requires a thickness of SI60cm to achieve the same thermal neutron ratio, and the corresponding average thermal neutron flux is also lower. PE is selected as the moderator material via comprehensive comparisons.

According to the simulation results, the axial thicknesses of water, paraffin, and PE reached 20 cm, and the thermal neutron ratio exceeded 65%. The average thermal neutron flux of the PE is the highest. However, graphite requires a thickness of SI60cm to achieve the same thermal neutron ratio, and the corresponding average thermal neutron flux is also lower. PE is selected as the moderator material through comprehensive comparisons.

Once a moderator material is selected, its specific size must be determined. The results in Table 1 indicate that the proportion of thermal neutrons reached 65% when the axial thickness of the moderator is 10 cm 20 cm. Therefore, the radial and axial thicknesses of the moderator in the range of 65% of the thermal neutrons can be obtained through simulation calculations, and the results are listed in Table 3 . A reasonable moderator size should ensure that the moderated neutron beam exhibits a high thermal neutron ratio and thermal neutron flux density. Based on the simulation results, the final size of the moderator is set to 13 cm for the axial thickness and 11 cm for the radial thickness.

Adding a neutron-reflecting layer to the periphery of the moderator enables neutrons scattered outside the moderator during the moderation process to be reflected into the moderator, reducing neutron leakage and allowing more neutrons to slow down along the imaging direction, thus improving the reaction efficiency and increasing neutron utilization.

Graphite is selected as the reflector material in this study [30]. A reflective layer is added to the periphery of the moderated body to simulate thickness variation. The variability in the neutron flux and thermal neutron ratios with the graphite thickness is shown in Fig. 3 [Figure 3: see original paper]. Based on the simulation results, when the thickness of the graphite reflective layer reaches 5 cm, its thickness increases, and the flux density of the neutron beam and the thermal neutron ratios change less. Finally, the thickness of the graphite material is set to 5 cm.

Considering the minimization of neutron leakage and reduction in radiation dose to the surrounding environment,

neutron ratios with graphite thickness.

the thickness of BPE material.

the setting of neutron-absorbing layers is necessary. Thus, neutron-absorbing materials typically comprise materials with high neutron absorption cross-sections, such as gadolinium, europium, cadmium, boron, indium, and dysprosium.

In this study, boron-containing PE (BPE) is selected as the neutron-absorbing material, as boron is capable of absorbing neutrons with a wide range of energies while emitting lower γ energies. A neutron-absorbing layer composed of BPE is added to the periphery of the reflecting layer and different thicknesses are simulated. Figure 4 [Figure 4: see original paper] shows the effect of variability in the thickness of the BPE material on the leakage neutron flux. According to the simulation results, when the thickness of the absorber layer reaches 10 cm, increasing the thickness minimally influences the reduction in the leakage neutron flux density. The final material thickness is 10 cm.

D. Simulation design of the collimator

The collimator has two main functions, one is to constrain the neutron beam flow, is the neutron beam flow into a uniform parallel collimated neutron beam, and the second is to

10 cm 15 cm 20 cm thermal thermal thermal thermal thermal thermal thermal thermal material neutron neutron neutron neutron neutron neutron neutron neutron flux (cm−2) rate (%) flux (cm−2) rate (%) flux (cm−2) rate (%) flux (cm−2) rate (%) water 1.06 × 10−3 19.74 7.17 × 10−4 47.46 2.82 × 10−4 61.64 9.14 × 10−5 65.63 PE 1.45 × 10−3 27.61 7.42 × 10−4 57.39 2.24 × 10−4 68.16 6.52 × 10−5 70.33 paraffin 1.49 × 10−3 28.32 7.31 × 10−4 57.77 2.11 × 10−4 67.84 5.86 × 10−5 68.25

30 cm 40 cm 50 cm 60 cm thermal thermal thermal thermal thermal thermal thermal thermal material neutron neutron neutron neutron neutron neutron neutron neutron flux (cm−2) rate (%) flux (cm−2) rate (%) flux (cm−2) rate (%) flux (cm−2) rate (%) graphite 3.21 × 10−5 20.90 2.16 × 10−5 45.70 8.91 × 10−6 53.03 4.49 × 10−6 68.63

axial thickness radial thickness thermal neutron ratio average thermal neutron flux (cm−2) 5.30 × 10−4 3.82 × 10−4 2.81 × 10−4 2.05 × 10−4 1.35 × 10−4 9.75 × 10−5 7.74 × 10−5 6.95 × 10−5 4.69 × 10−5

shield the interfering neutrons, to reduce the interference of the neutrons outside the FOV range.

The structure of the collimator is key to constraining the neutron beam flow. Common neutron collimators include round tubes, multibeam round tubes, multibeam flat plates, and divergent collimators. The round tube-type collimator has a simple structure and is easy to process; however, this collimator provides a smaller neutron beam and crosssectional area, and the collimation is poor. The collimation ratio of multibeam circular tube-type and multibeam flat plate-type collimators is equal to the collimation ratio between each small circular tube or flat plate; therefore, their collimation ratios can be very large. When applying this type of collimator in neutron imaging devices, the neutron injection rate at the entrance of the collimator needs to be distributed uniformly. However, the intensity loss of this type of collimator’ s neutron beams is very serious, and it produces a circle-shaped or line-like background in the neutron imaging image. A collimator can produce a circular or linear background interference in neutron imaging images. In addition, multibeam flat collimators can only collimate neutron beams in one direction. Divergent collimators are the most widely used collimators.

To shield interfering neutrons, materials with large neutron absorption cross sections should be selected. Simultaneously, secondary rays and particles produced by the reaction of neu-

trons with the material should be as small as possible or easily shielded. In this study, the main requirement is to absorb high-energy neutrons, for which a slowing down is required before absorption. Hydrogen-containing materials are ideal for slowing down neutrons, whereas boron-containing materials can effectively absorb slowed-down neutrons, and together, they can achieve neutron shielding.

The collimator collimation ratio L/D is another significant parameter for measuring the performance of the collimator, according to the definition of TNR geometric unsharpness Eq. (1), the collimation ratio has a direct effect on TNR geometric unsharpness.

(L t)

where t is the length of the object in the image plane, D is the diameter of the aperture, and L indicates the distance between the aperture and the specimen [31]. A large collimation ratio and short object-to-image plane distance reduce geometric ambiguity and increase the resolution of the TNR system.

The collimator collimation ratios typically range from 20 to 100 [32].

A contradiction exists between the collimation ratio and neutron injection rate at the measurement object. Increasing the collimation ratio decreases the neutron injection rate, with thermal neutrons decreasing faster than fast neutrons, requiring a balance between these parameters.

thickness of thickness of neutron flux in percentage of thermal neutron flux outside PE (cm) B4 C (cm) the FOV (cm−2) neutrons in the FOV (%) the FOV (cm−2) 5.07 × 10−6 4.78 × 10−7 5.14 × 10 4.78 × 10−7 5.10 × 10−6 4.98 × 10−7 5.07 × 10 5.12 × 10−7 5.14 × 10 5.00 × 10−7 5.21 × 10 5.12 × 10−7 5.42 × 10−6 5.23 × 10−7 5.70 × 10 5.00 × 10−7

collimator neutron flux in the percentage of thermal neutron flux outside structures FOV (cm−2) neutrons in the FOV (%) the FOV (cm−2) cylindrical 2.04 × 10−6 1.48 × 10−7 diverging 2.39 × 10 1.33 × 10−8

The design of collimators for small reactors or microreactors should follow the following principles: 1. The collimation ratio exceeded 25.

2. The neutron injection rate at the object to be measured

is higher than 105 cm−2 ·s−1 . 3. The neutron flux outside the FOV is one order of magnitude lower than that inside the FOV.

Considering common collimator structures and based on the principles that should be followed in shield design, a new shield structure is proposed in this study, as shown in Fig. 5 [Figure 5: see original paper].

The collimator structure combines a circular tube collimator and a divergent collimator. In this structure, the moderator is a 13 cm-thick PE, the neutron source is surrounded by the PE, and the collimator has a length of 60 cm and an entrance diameter of 1 cm. The internal cavity consists of three parts: a small truncated cone with top and bottom diameters of 1 cm and 10 cm and a thickness of 2 cm; a cylindrical body with a diameter of 10 cm and a thickness of 18 cm; and a large truncated cone with top and bottom diameters of 10 cm and 5 cm and a thickness of 40 cm. A large truncated cone forms a shield at the rear end of the collimator. This structure makes the collimation ratio very large, and the rear end of the colli-

mator can shield the neutrons outside the FOV in the direction of the neutron exit. The rear end of the collimator shields neutrons along the direction of neutron emission and outside the FOV. Theoretically, compared with the traditional collimator structure, the neutron beam obtained by this structure has a larger difference in the neutron injection rate inside and outside the FOV, which is more favorable for neutron imaging.

A combination of PE and boron carbide (B4 C) is selected as the backend shield. In the simulation, counting grid elements are set up in the FOV and outside the FOV, and the average neutron fluxes of the two counting grid elements are simulated for different combinations of the thicknesses of PE and B4 C in the back-end shielding structure; the simulation data are shown in Table 4 .

From the information in Table 4, when the thickness of PE and B4 C is 21 cm and 19 cm respectively, the total neutron flux within the FOV is 5.07 × 10−6 cm−2 , and thermal neutrons account for 59.72% of the total average neutron flux, and at this time, the average neutron flux outside the FOV is 5.12 × 10−7 cm−2 , which is one order of magnitude lower than that within the FOV, and can meet the requirements of neutron imaging technology. Therefore, the combination of a PE thickness of 21 cm and a B4 C thickness of 19 cm is the optimal choice for the shield design.

The thicknesses of the PE and B4 C at the rear end were 21 cm and 19 cm, respectively, to simulate the average neutron flux inside and outside the imaging FOV of the cylindrical and diverging collimators. Figure 6 [Figure 6: see original paper] illustrates two collimator configurations: the internal cavity of the cylindrical collimator is a cylinder and the internal cavity of the divergent collimator is a truncated cone. The simulation results of the two collimator structures are shown in Table 5 .

Comparing Tables 4 and 5, we observe that the average thermal neutron flux through the divergent collimator is lower and has a lower thermal neutron ratio compared to the improved collimator structure, demonstrating the improved structure’ s advantage in enhancing thermal neutron flux and proportion.

E. Shielding of gamma rays

For the neutron imaging device of the reactor neutron source, two γ-ray sources exist: neutrons generated during slowing down and absorption, and γ-rays emitted inside the reactor with neutrons. For γ-rays from neutron slowing and absorption, their energy and quantity are low, requiring only 1 2 cm-thick lead outside the collimator for shielding. The γ-rays emitted inside the reactor with neutrons along the collimator aperture have high energy and complex spectra, significantly impacting sample detection, necessitating specific shielding structures. To measure γ-ray influence on the neutron beam, the parameter n/γ

(ratio of neutron injection rate to γ-ray dose) is used; A larger n/γ indicates higher thermal neutron ratio, enabling better image quality.

Lead and bismuth have high γ absorption and small thermal neutron absorption cross-sections, without producing secondary γ sources after neutron irradiation. These materials are selected for γ shielding in the imaging system [33, 34].

A 2 cm-thick lead layer surrounds the moderator and collimator to reduce γ ray leakage from neutron moderation and absorption. A γ-shield at the collimator aperture exit shields accompanying γ-rays. The collimator structure is shown in with thickness varied from 2 cm to 6 cm. The γ-ray dose rate and neutron injection rate in the FOV for different bismuth thicknesses are simulated and shown in Table 6 .

Typically, the ratio of the neutron injection rate to the γray intensity must be greater than 3 × 1011 cm−2 · Sv−1 [35].

According to the data in Table 6, as the thickness of bismuth increases, the neutron injection rate and γ dose rate decrease, and the n/γ reaches the required value. Considering n/γ, the neutron injection rate, and the thermal neutron ratio, the optimum thickness of the bismuth layer is 4 cm.

the four parts of the neutron-moderated body, reflecting layer, absorbing layer, and γ shielding body. The structure, materials, and size of the final collimation system are shown in

III. RESULTS AND DISCUSSION

The design of the moderated collimation system for the TNR device is completed through Geant4 simulation calculations, including the design of the structure and material of

In this device, the PE is surrounded by a neutron source as a moderator, and the thickness of the PE moderator is 13 cm.

A 5-cm-thick neutron reflecting layer made of graphite and

thickness of thermal neutron total neutron thermal neutron γ dose rate bismuth (cm) injection rate (cm−2 · s−1) injection rate (cm−2 · s−1) ratio (%) (Sv · s−1) (cm−2 · Sv−1) 1.59 × 10−6 2.83 × 10−6 6.68 × 10−18 4.23 × 1011 1.39 × 10 2.31 × 10 6.32 × 10−18 3.65 × 1011 1.35 × 10−6 2.07 × 10−6 5.16 × 10−18 4.01 × 1011 1.07 × 10−6 1.75 × 10−6 4.66 × 10−18 3.75 × 1011 8.76 × 10 1.55 × 10 4.39 × 10−18 3.54 × 1011

10-cm-thick neutron absorbing layer made of BPE are installed at the periphery of the moderator, which had an overall length of 62 cm and an inlet diameter of 1 cm; the FOV diameter is 5 cm; the collimator wall was made of PE, B4 C; the lead three-layer composition was PE can be slowed down to deviate from the direction of neutron emission, and B4 C will be slowed down after the absorption of neutrons, slowing down the process of absorption of γ-rays generated by the outermost layer of the lead shielding. The collimated aperture consists of a small truncated cone, a cylinder, and a large truncated cone, and the cylinder and the large truncated cone form a shielding structure at the rear end of the aperture, which is 40 cm thick, of which the PE is 21 cm thick, and the B4 C is 19 cm thick, and it shields neutrons outside the FOV along the emitting direction.

The neutrons of the designed moderately collimated system are simulated to obtain properties such as the neutron beam energy spectrum, the inhomogeneity of the radial distribution of neutrons, and the spatial distribution of the neutron Based on the outlet neutron energy spectrum of the collimated system shown in Fig. 9 [Figure 9: see original paper], the thermal neutron flux and thermal neutron ratio in the outlet neutron beam are higher than those in the superthermal and upper neutrons. This demonstrates that the designed collimation system can perform its intended functions.

neutron flux at the outlet of the designed moderated collimator device, with an irradiated FOV of 5 cm in diameter. According to Fig. 10 Figure 10: see original paper, the exit neutron flux is uniformly distributed over the FOV, with thermal neutron flux outside the FOV significantly lower than inside, differing by one order of magnitude, showing sufficient attenuation at the beam boundary.

The inhomogeneity of the collimated neutron beam appears in the radial distribution of the neutron flux and masks image information, affecting contrast and resolution. According to the American Society for Testing and Materials (ASTM) [36], neutron flux inhomogeneity is the ratio of the difference between maximum and minimum neutron fluxes to the maximum neutron flux in the FOV. The radial distribution at the outlet is shown in Fig. 10(b).

According to calculations, the inhomogeneity of the neutron radial distribution in the FOV with 5 cm diameter is 7.5%, meeting the basic requirement of 8% [37].

Figures 11 and 12 show the neutron and γ dose rates in the designed collimation device. In Fig. 11 [Figure 11: see original paper], the largest neutron dose rate occurs in the slowing body, where fast neutrons are converted to thermal neutrons with significant energy loss.

The collimator shapes the slowed neutrons and removes stray neutrons, with relatively small neutron dose rates. According to Fig. 12 [Figure 12: see original paper], the γ dose rate distribution resembles that of neutrons, with γ rays generated from neutron-material reactions, peaking near the slowed body and reflection layer. The higher γ dose rate at the collimator exit results from the γ shielding layer, which filters γ rays and improves the n/γ ratio for better imaging quality. parameter items parameter value maximum neutron injection rate (cm−2 · s−1) 2.07 × 106 thermal neutron ratio (%) n/γ (cm−2 · Sv−1) 4.01 × 1011 collimation ratio

collimator.

The designed moderate collimation system is installed in a neutron source with a neutron injection rate of 5 × 1010 cm−2 ·s−1 and a diameter of 5 cm in a planar reactor.

The simulation yielded relevant values for the neutron beam at the exit of the device, as listed in Table 7 . According to the simulation results, the designed device satisfied the TNR requirements.

A thermal neutron imaging system is introduced to perform relevant neutron imaging tests for the designed collimation

system. Thermal neutron projection imaging technology generally uses an instantaneous light-emitting screen [38] whose mechanism is to convert neutrons, which are difficult to detect directly, into particles such as X-rays, γ-rays, and visible photons, which can be recorded by film or CCD cameras.

Ideal materials for thermal neutron image conversion screens should be characterized by a large thermal neutron reaction cross-section, low sensitivity to γ-rays, and high light conversion efficiency. Among these materials, 3He and 6Li have relatively large thermal neutron reaction cross-sections, emit charged particles after nuclear reactions with neutrons [39],

and do not produce secondary γ-rays. Compared with the He material, 6Li can be easily combined with scintillator materials for the preparation of scintillator materials for thermal neutron measurements, although the neutron absorption reaction cross section is low. Thermal neutron detection materials based on 6Li such as lithium glass, LiF(ZnS), and LiF(GOS) have been widely used.

Thermal neutrons interact with 6Li scintillator-containing materials to generate charged particles by the 6Li(n,α) 3H reaction, and the charged particles deposit energy to excite the luminescent materials such as ZnS and Gd2 O2 S to emit

light with wavelengths in the range of 450 − 600 nm, which can be directly recorded by a CCD camera. The imaging detector simulated in this study consists of a 0.2 mm-thick LiF:ZnS(Ag) scintillator screen and CCD camera with a scintillator size of 25 mm × 25 mm and 512$×$512 pixels.

The accuracy of radiographs showing defects in the examined area can be determined based on the quality of the radiographs. The ASTM standard enables determination of the grade of radiographic equipment and provides a method for comparing the quality of different neutron radiographic equipment [40, 41]. Among these standards, the radiographic

method uses thermal neutrons to examine components and materials [42–44].

According to ASTM E 545 standards, Image Quality Indicators (IQI) are important tools for measuring the quality level of a TNR system. IQI includes a sensitivity indicator (SI) and beam purity indicator (BPI), the structures and shapes of which are shown in Fig. 13 Figure 13: see original paper and Fig. 14 Figure 14: see original paper). The BPI is composed of a combination of PTFE, lead discs, cadmium rods, and boron nitride discs. BPI is a combination of neutron beams that can be exposed to the neutron beam to obtain information on many parameters of the neutron beams

related to the quality of the image. The designed system was used to simulate the neutron beam irradiation of the BPI and SI to obtain thermal neutron images of the BPI (Fig. 13(b)) and SI (Fig. 14(b)). The images of cadmium rods on the BPI in Fig. 13(b) shows no significant difference in sharpness and the boron nitride portion is visible, indicating that the collimation ratio of the neutron beam is sufficiently high. The metal-lead part is not observed, indicating a low γ content or low electron pair content in the neutron beam. Gaps V and W are clearly distinguished in Fig. 14(b)).

IV. CONCLUSION

In this study, numerical simulations were conducted using Geant4 software to design a moderator and collimator device for TNR equipment based on a reactor neutron source. The materials of the moderator and collimator are analyzed and selected to achieve a higher thermal neutron flux. In addition, the collimator structure and shielding of gamma rays

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were carefully designed and optimized. Finally, TNR was performed on the designed device. The specifications are as follows. The moderator material is PE with a thickness of SI13cm, and the neutron-reflecting layer material is graphite with a thickness of 5 cm. The BPE is set up as a 10 cm-thick neutron-absorbing layer, which has a transverse thickness of 62 cm and contains materials such as PE, B4 C, and lead with thicknesses of 21 cm, 19 cm, and 2 cm. The collimator outlet is set as 4 cm-thick bismuth. The simulation results show that the device has a collimation ratio of 62, a normalized thermal neutron flux within a 5-cm diameter of the field of view at the exit of 2.07 × 10−6 cm−2 ·s−1 , an n/γ ratio of 4.01 × 1011 cm−2 ·Sv−1 , and an inhomogeneity in the radial distribution of the neutrons of 7.5%. The new collimator has a higher thermal neutron ratio and thermal neutron flux than the conventional cylindrical and dispersive collimators. The thermal neutron imaging simulation results of the Image Quality Indicators validate the significance of this study by providing a reference for the design optimization of TNR devices and theoretical support for subsequent experiments.

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