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Research Article
Simulation Design of Thermal Neutron Collimators for Neutron Capture Studies at The Dalat Research Reactor

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Abstract

Background and Objective: The neutron beams at the Dalat nuclear research reactor have been utilized for experimental researches based on the neutron capture reaction (n,γ) and prompt gamma neutron activation analysis. In recent years, a national project has been carried out for extending and improving the physical characteristics of the beam facilities. The objective of this study is to improve the thermal and epithermal neutron fluxes at the horizontal beamlines of the Dalat reactor. **Materials and Methods:** The new design of collimators and neutron filter selections has been made with optimal parameters for alternative applications. For validation of the simulation models, the values of neutron flux and gamma dose rate were measured and compared with the simulated values. **Results:** The simulation of the new collimator system shows that for a crystal filter composition of 60 cm Si and 6 cm Bi, the thermal neutron flux at the beam port is 4.0×10^7 n/cm^2/s. The selection of crystal filters of 20 cm Si and 3 cm Bi is proposed with higher thermal neutron fluxes of 1.74×10^8 n/cm^2/s, that the thermal neutron component will be improved with a factor of 7.67. **Conclusion:** A newly designed model of the conical collimator with a filter combination of 20 cm silicon and 3 cm bismuth, in crystal formations, is proposed for the experimental study of the in-phantom boron neutron capture measurements.

Key words: Thermal, epithermal, neutron, beam port, collimator, neutron filter, simulation

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

A reactor based thermal neutron beam can be used for basic research and education on the nuclear reaction of neutrons with nuclei and important applications such as Prompt Gamma Neutron Activation Analysis (PGNAA) and Boron Neutron Capture Therapy (BNCT). In the case of the BNCT application, the supporting studies with phantom and beam collimation structure are necessary to be performed to define the characteristics of neutron flux distribution and the behavior of radiation dose rate inside the phantom. This method is based on the nuclear reaction $^{10}B(n, \alpha)\,^{7}Li$ occurring when stable isotopes of ^{10}B are irradiated with a slow neutron beam to produce high energy α-particles and ^{7}Li nuclei inside the targeted tumor cells[1,2]. The 2.3 MeV kinetic energy of the α-particles and ^{7}Li nuclei are almost deposited within about 1 cell diameter and selectively destroy those tumor cells and spare the normal cells around[3].

The effective neutron sources for BNCT are mainly based on neutron beams from thermal nuclear research reactors[4]. In which, the spectrum filter technique using Si and Bi single crystals as filter materials are applied to eliminate the fast neutrons and gamma components from the reactor core and to provide a proper beam of thermal or epithermal neutron flux at the irradiation position in the reactor building[5,6].

A pure thermal neutron beam with a flux of 1.6×10^{6} n/cm^{2}/s has been developed at the horizontal channel No. 2 of the Dalat nuclear research reactor for neutron capture experiments[7] and prompt gamma neutron activation analysis[8]. However, to extend the use of the channel, the beam structure needed to be upgraded with a new design of neutron filters and collimators for a higher value of neutron flux within the acceptable range for neutron capture therapy studies and related applications. The expected neutron parameters have been estimated by simulation using the MCNP5 code[9]. The purpose of this study is to provide a proposal design of a collimator system for upgrading the neutron beam with higher values of thermal and epithermal neutron fluxes.

MATERIALS AND METHODS

Study area: The study was carried out at the Dalat Nuclear Research Institute, Vietnam in 2019.

Collimator models: The current cylindrical collimator has a total length of 240.3 cm consisting of two parts. The first part

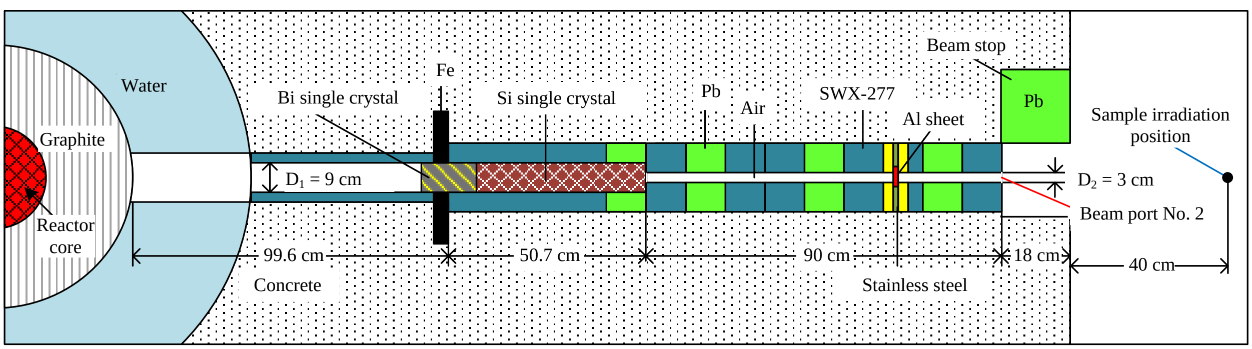

Fig. 1: The current collimator at the radial channel No. 2 of the Dalat research reactor

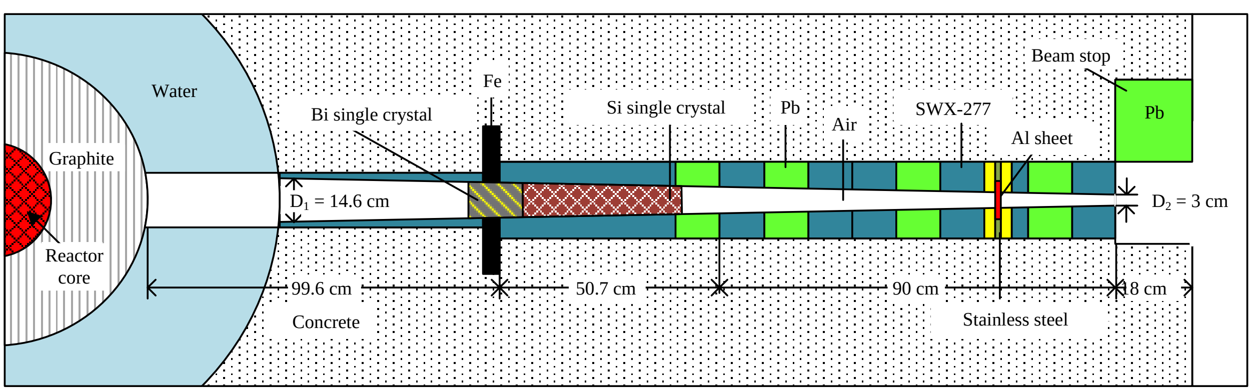

Fig. 2: The new proposal neutron cone-collimator

is 150.3 cm in length and 9 cm in diameter for installing neutron filters made of bismuth and silicon crystals with alternative thickness. The second part is 90 cm in length with the outer diameter of 20.1 cm and the collimated diameter is 3 cm. The lining layers, surrounding the collimator, are made of Pb and SWX-277 (Neutron Shielding-Shieldwerx) as gamma and neutron absorbent materials and an aluminum plate for prevention in the case of leaking water, as shown in Fig. 1. This cylindrical collimator is currently installed into the radial channel No. 2 of the Dalat research reactor for prompt gamma neutron activation analysis. The thermal neutron flux is 1.6×10^{6} n/cm^{2}/s at the collimated beam port for the case of 6 cm Bi and 80 cm Si crystals. The neutron intensity can be higher corresponding to a shorter Si filter, but for optimal neutron flux, a new conical design of collimator is also considering and proposed in this work. The new design model has specified with 14.6 cm inlet diameter and 3 cm outlet diameter as shown in Fig. 2.

RESULTS AND DISCUSSION

The current and new design collimator systems were simulated by using the MCNP5 code[9]. The measured and simulated results of thermal neutron flux and gamma dose rate for the first collimator system with 20 cm Si and 3 cm Bi are shown in Table 1. The simulated result of neutron flux delivered by the cone collimator is improvable by a factor of 7.67 as shown in Table 2. For the second collimator system, the simulation model has been performed with alternative filter thickness and the calculated values of thermal and epithermal neutron fluxes at the collimators outlet are shown in Table 3.

Table 1: Measured and simulated results of the thermal neutron flux and gamma dose rate for the cylindrical collimator with filters thickness of 20 cm Si and 3 cm Bi

Parameters	Simulation results	Experimental values
Thermal neutron flux (n/cm^{2}/s)	2.27×10^{7}	$(2.13\pm0.04)\times10^{7}$
Gamma dose rate (Gy/h)	3.33×10^{-3}	$(3.01\pm0.90)\times10^{-3}$

Table 2: Simulated results of the thermal neutron flux and gamma dose rate for the cylindrical and conical collimators

Type of collimator	Thermal neutron flux (n/cm^{2}/s)	Gamma dose rate (Gy/h)	Filter thickness (cm)	
			Si	Bi
Cylindrical collimator (A)	2.27×10^{7}	3.06×10^{-3}	20	3
Conical collimator (B)	1.74×10^{8}	2.09×10^{-2}	20	3
Ratio B/A	7.67	6.83		

Table 3: Simulated results of the thermal and epithermal neutron fluxes for the conical collimator model with alternative filter thickness

Filter (cm)		Neutron flux			
Si	Bi	Thermal neutron $\times10^{8}$ (n/cm^{2}/s)	Epithermal neutron $\times10^{7}$ (n/cm^{2}/s)	Thermal/Total (%)	Epithermal/Total (%)
0	0	4.68	16.92	73.43	26.57
5	1	3.46	8.49	80.30	19.70
5	2	2.95	6.58	81.79	18.21
5	3	2.53	5.12	83.17	16.83
5	4	2.18	3.99	84.53	15.47
5	5	1.88	3.04	86.10	13.90
5	6	1.63	2.36	87.33	12.67
10	1	3.02	5.51	84.56	15.44
10	2	2.58	4.27	85.77	14.23
10	3	2.21	3.32	86.96	13.04
10	4	1.91	2.59	88.09	11.91
10	5	1.64	1.97	89.31	10.69
10	6	1.42	1.52	90.36	9.64
15	1	2.64	3.65	87.84	12.16
15	2	2.26	2.87	88.74	11.26
15	3	1.94	2.19	89.86	10.14
15	4	1.67	1.74	90.58	9.42
15	5	1.44	1.35	91.42	8.58
15	6	1.25	1.01	92.50	7.50
20	1	2.32	2.42	90.57	9.43
20	2	1.99	1.91	91.24	8.76
20	3	1.74	1.46	92.24	7.76
20	4	1.47	1.12	92.89	7.11
20	5	1.26	0.90	93.36	6.64
20	6	1.09	0.73	93.72	6.28
30	1	1.79	1.12	94.08	5.92
30	2	1.53	0.90	94.46	5.54
30	3	1.31	0.67	95.11	4.89

Table 3: Continue

Filter (cm)		Neutron flux			
Si	Bi	Thermal neutron $\times 10^8$ (n/cm^2/s)	Epithermal neutron $\times 10^7$ (n/cm^2/s)	Thermal/Total (%)	Epithermal/Total (%)
30	4	1.14	0.56	95.29	4.71
30	5	0.98	0.43	95.82	4.18
30	6	0.84	0.34	96.13	3.87
40	1	1.37	0.56	96.07	3.93
40	2	1.19	0.45	96.34	3.66
40	3	1.03	0.34	96.82	3.18
40	4	0.88	0.28	96.92	3.08
40	5	0.76	0.22	97.12	2.88
40	6	0.66	0.17	97.52	2.48
60	1	0.82	0.18	97.84	2.16
60	2	0.71	0.14	98.05	1.95
60	3	0.62	0.13	97.93	2.07
60	4	0.54	0.10	98.14	1.86
60	5	0.46	0.09	98.18	1.82
60	6	0.40	0.07	98.33	1.67

For a crystal filter composition of 60 cm Si and 6 cm Bi, the thermal neutron flux at the outlet becomes the dominant component with 4.0×10^7 n/cm^2/s (account for 98.33% of total neutron flux) and the epithermal is almost depleted with only 7.0×10^5 n/cm^2/s (account for 1.67% of the total neutron flux). This selection of the filter lengths is proposed for a pure thermal neutron beamline for neutron capture experiments and applications such as prompt gamma neutron activation analysis. For the BNCT study, a selection of crystal filters of 20 cm Si and 3 cm Bi is possible with higher thermal and epithermal neutron fluxes of 1.74×10^8 n/cm^2/s and 1.46×10^7 n/cm^2/s, respectively and the gamma dose rate is about 0.03 cGy/min. The simulated result of thermal neutron flux is about 10 times lower than the published values of Jun and Lee[10] and Brockman *et al.*[4], but our results are reasonable in the category of low power nuclear research reactor. These simulated results are estimated to be useful for in-phantom boron neutron capture therapy study, application of prompt gamma neutron activation analysis and for providing an essential facility for educational research.

CONCLUSIONS

The filtered neutron collimator modes at the radial channel No. 2 of the Dalat nuclear research reactor have been simulated for neutron-induced prompt gamma activation analysis and related applications such as the in-phantom study of boron neutron capture therapy. Thermal neutron flux delivered by the conical collimator model proposed in this work is expected to be improved by a factor of 7.67 in comparison with the cylinder collimator model. For the BNCT study, a silicon filter of 20 cm and a bismuth filter of 3 cm in length are proposed. The expected thermal and epithermal neutron fluxes at the collimated beam port are 1.74×10^8 and 1.46×10^7 (n/cm^2/s), respectively. The simulated results in this work are expected to be useful for upgrading the neutron beam facility at the Dalat research reactor for in-phantom boron neutron capture therapy study and alternative application of prompt gamma neutron activation analysis.

SIGNIFICANCE STATEMENT

The present study provides the neutron beam parameters and neutron characteristics that can be beneficial for experimental researches and relevant applications, which are carried out based on the neutron beams of the Dalat nuclear research reactor. This study will help the researcher to uncover the critical areas of neutron beam collimator at the Dalat nuclear research reactor. Thus a new theory on design simulation of reactor-based neutron beam may be arrived at.

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