Monte Carlo simulation of low energy neutron reflection characteristic of Al/B₄C composite material

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Abstract. To systematically analyze the neutron reflection characteristics of boron carbide reinforced with aluminium (Al/B₄C) composite material, the neutron shielding calculation model of Al/B₄C was established. Monte Carlo method had been used to simulate the low energy neutron transmission and reflection coefficients of Al/B₄C composite with different mass content of B₄C and different thickness of composite material. The results show that the neutron reflection coefficient of Al/B₄C increases rapidly with the increase of composite shielding thickness and then tends to saturate when the shielding thickness increases to a certain value. The neutron saturation reflection coefficient and the corresponding saturation reflection thickness both decreases with the increase of B₄C mass content in the composite material. The smaller the interaction cross section of the neutron with the material is, the greater the neutron saturation reflection coefficient of the material is, and the greater the saturation thickness required reaching the saturation reflection. In the energy range of 200 eV-20 keV, in addition to the resonance energy point, the neutron reflection coefficient increases with the increase of the neutron energy. The increase of the neutron reflection coefficient per unit of energy increases firstly and then decreases with the increase of energy. When the B₄C mass content in the composite material is at the range of 10%-40%, the 100 eV neutron reflection coefficients are below 10%, and the 10 keV neutron reflection coefficients are above 25%.

1. Introduction
With the rapid development of nuclear technology and its application research, the neutron shielding materials are becoming more and more important, and the requirement for shielding performance of neutron shielding materials is getting higher and higher[1-2]. For neutron shielding, we usually add some neutron moderator and absorbent to the main materials such as ordinary concrete, polyethylene or metal to get good shielding performance [3-5]. Researchers have carried out a lot of researches on many new shielding materials to meet the growing demands of neutron shielding applications. Aluminum reinforced with boron carbide (Al/B₄C) composite is a promising neutron shielding material [6-7]. Many experiments and simulation studies have been carried out on the preparation technology, structural mechanical properties and neutron transmission coefficient of Al/B₄C composite materials at home and abroad [8-9]. These research results provide important references for the application of Al/B₄C composite materials to neutron shielding. However, the neutron reflection characteristic of Al/B₄C composite materials has not yet been reported.

In addition to neutron transmission characteristics of the shielding material, the neutron reflection characteristics of the shielding material must also be taken into account in some situations when neutron shielding materials is used [10-13]. For example, in pulsed reactor research, the reflected...
neutrons produced by neutron shield, hall walls, floors or ceilings will make the pulse waveform broadened and lost symmetry, which will have a great impact on the fission yield of the pulsed reactor. Even in some extreme cases, the reflected neutrons may affect the safe operation of the pulse reactor when the shield is not set properly [14-15]. Therefore, it is necessary to study the neutron reflection characteristics of the new neutron shielding material of Al/B\textsubscript{4}C composite.

In this paper, Monte Carlo method is used to simulate the neutron transmission and reflection coefficients of Al/B\textsubscript{4}C composite material. The influences of neutron energy, thickness of composite material, and mass content of B\textsubscript{4}C on neutron reflection characteristics are simulated systematically. Considering that the nuclide of \textsuperscript{10}B has good absorption effect on thermal neutrons and slow neutrons, the simulated neutron energy range is chosen to be in low energy range of 100eV-20keV. The research results can provide a theoretical reference for better design and utilization of Al/B\textsubscript{4}C composite as neutron shielding material.

2. Calculation model and method
A shielding calculation model was developed as shown in figure 1. The mono-energetic narrow beam neutron source is injected perpendicularly to the Al/B\textsubscript{4}C composite shield. The distance between the neutron source and the shield body is 10 cm. The shielding body is a circular plate, with the radius \( R \) is 25 m, and with the thickness \( T \) is in the range of 0.5 cm to 35 cm. The entire system is set in the air. As shown in figure 1, the incident surface is the side of the shield near the neutron source, and the transmission surface is the other side opposite to the incident surface.

![Figure 1. Sketch of the calculation model.](image)

According to the isotope abundance ratio of natural boron, the ratio of \textsuperscript{10}B and \textsuperscript{11}B in B\textsubscript{4}C materials is set up in the model, that is, the ratio of the atomic number of \textsuperscript{10}B to \textsuperscript{11}B in B\textsubscript{4}C materials is set to be 1:4. The density of Al and B\textsubscript{4}C are 2.7 g/cm\(^3\) and 2.5 g/cm\(^3\), respectively. The density of Al/B\textsubscript{4}C is obtained according to the mass ratio of Al and B\textsubscript{4}C. For a mono-energetic energy narrow beam neutron source, the neutron reflection coefficient \( I_0 \) on the incident surface and the transmission coefficient \( I_t \) on the transmission surface are respectively expressed as

\[
I_t = \frac{N_t}{N_0} \quad (1)
\]

\[
I_i = \frac{N_i}{N_0} \quad (2)
\]

Where, \( N_0 \) is the number of injected neutrons, \( N_i \) is the number of neutrons reflected from the incident surface, and \( N_t \) is the number of neutrons that penetrate the shield. The general Monte Carlo program MCNP4B [16] is used to simulate the joint transport of neutron and photon. The transmission and the reflection coefficients of different energy neutrons penetrating Al/B\textsubscript{4}C with different thickness are calculated. The number of the simulated neutrons is set to be \( 10^7 \), which can make the statistical errors of all the simulation results less than 10%.

3. Simulation results and discussion
According to the established model, the incident neutron energy is set to be the typical value between 100 eV and 20 keV, and the thickness of Al/B\textsubscript{4}C composite material is taken from 0.5 cm to 35 cm.
The neutron transmission and reflection coefficients of Al/B₄C composite material under different conditions are investigated.

3.1. Effect of material thickness on neutron reflection coefficient

The simulated relationship between neutron reflection coefficient and the thickness of Al/B₄C composite material is shown in figure 2(a) and figure 3(a) for two neutron energies, 100 eV and 10 keV, respectively. It can be seen from figure 2(a) and figure 3(a) that the variation law of reflection coefficient with thickness is obviously different from that of transmission coefficient decaying exponentially with thickness increasing. The neutron reflection coefficient of Al/B₄C composite material firstly increases rapidly with the increase of the thickness of Al/B₄C, and then increases slowly when the thickness increases to a certain value. The increase of the neutron reflection coefficient per unit thickness of the composite shield is getting smaller and smaller when the thickness increases to a certain value, and the neutron reflection coefficient tends to saturate with the increase of the thickness. The trend of the variation law of neutron reflection coefficient with thickness of Al/B₄C composite material obtained in this paper is basically consistent with those obtained by previous studies[17]. The calculation result in literature [17] shows that, for the concrete wall of the experiment hall, the intensity of scattering neutrons increases with the thickness of the concrete wall and then is almost no longer influenced by the increased thickness of the concrete wall when the thickness of the concrete wall is more than 60 cm. When the B₄C mass content is 10%-40%, the 100 eV neutron reflection coefficients are below 10%, and the 10 keV neutron reflection coefficients are above 25%.

![Figure 2](image2.png)

**Figure 2.** Neutron reflection coefficients of Al/B₄C for energy of 100 eV.

![Figure 3](image3.png)

**Figure 3.** Neutron reflection coefficients of Al/B₄C for energy of 10 keV.

In order to easily understand the influence of the thickness of Al/B₄C composite shielding material on the neutron reflection characteristics, we draw the relationship between the neutron reflection coefficient change corresponding to unit thickness dI/dT and the thickness of Al/B₄C composite material, as shown in figure 2(b) and figure 3(b). The neutron reflection coefficient corresponding to
the beginning of dIr/dT less than 0.001 cm⁻¹ is defined as the neutron saturation reflection coefficient of the Al/B4C composite material, and the corresponding thickness is defined as the neutron saturation reflection thickness. The neutron saturation reflection coefficient Ir,n and corresponding neutron saturation reflection thickness Tr,n are listed in Table 1. The results of Table 1 show that the saturation reflection coefficient decreases with the increase of B4C mass content in the Al/B4C composite shielding material and the corresponding saturation reflection coefficient decreases. This is because the interaction between 10B and low energy neutron is large. The higher the boron mass content of shielding material is, the more effective the material will absorb the low energy neutron, the smaller the number of neutrons that can be reflected by the shielding, the smaller the thickness of the shielding material needed to reach the saturation reflection. When the mass content of B4C is the same, the higher the neutron energy is, the larger the saturation reflection coefficient of the material will reach, the thicker the thickness required to achieve neutron saturation reflection will be. The saturation reflection coefficient of Al/B4C composite material with a B4C mass content of 20% is 74% and 31.2% for 100 eV and 10 keV neutrons, respectively. The corresponding neutron saturation reflection thickness is 4.55 cm and 17.4 cm, respectively.

Table 1. Neutron saturation reflection coefficient and saturation thickness of Al/B4C composite.

| wB4C | Irs | Tsr/cm | Irs | Tsr/cm |
|------|-----|--------|-----|--------|
| 10   | 0.101 | 8.33   | 0.357 | 25.1 |
| 20   | 0.074 | 4.55   | 0.312 | 17.4 |
| 30   | 0.064 | 3.04   | 0.293 | 13.3 |
| 40   | 0.059 | 2.47   | 0.282 | 10.9 |

3.2. Effect of B4C mass content on neutron reflection coefficient

The neutron shielding performance of Al/B4C composite is also influenced by the mass content of B4C in the material. Take the Al/B4C composite thickness of 25 cm as an example, which has reached or exceeded the neutron saturation reflection thickness for the energy of 100eV-10keV. The relationship between neutron transmission and reflection coefficients with the mass content of B4C in the Al/B4C composite material, as shown in Figure 4, is simulated with three energies of neutrons, 100 eV, 1 keV and 10 keV. From Figure 4(a), it can be seen that in the 100 eV-10 keV range of low energy neutrons simulated in this paper, with a given thickness and energy, the neutron transmission coefficient decreases exponentially with the increase of B4C mass content wB4C. The lower the neutron energy is, the faster the rate of neutron transmission coefficient decreases with the increase of B4C mass content.

![Figure 4](image-url)
From figure 4(b), we can see that when the shielding thickness and neutron energy are given, the neutron reflection coefficient firstly decreases rapidly with the increase of B$_4$C mass content in Al/B$_4$C composite material, and then the descending rate becomes more and more gentle. The lower the neutron energy is, the smaller the mass content of B$_4$C is corresponding when the neutron reflection coefficient begins to decrease slowly. For the neutrons with energies of 100 eV, 1 keV and 10 keV, the mass content of B$_4$C corresponding to the slow decreasing trend of neutron reflection coefficient is about 15%, 25% and 30%, respectively. For example, for neutron with energy of 1 keV, when the mass content of B$_4$C in Al/B$_4$C composite material reaches 25%, if the mass content of B$_4$C continually increases to 35%, the transmission coefficient will decrease from 1.09×10$^{-3}$ to 1.05×10$^{-4}$, reduced about one order of magnitude, but the neutron reflection coefficient decreased little, only from 16.4% to 15.1%, decreased by about 1.3%

3.3. Effect of neutron energy on neutron reflection coefficient

Figure 5(a) and 5(b) show the neutron transmission and reflection coefficients of Al/B$_4$C composite material with mass content of B$_4$C of 10% and 20% when the neutron energy changes continuously in the range of 200eV−20keV, respectively. Figure 6 (a) is the total cross section of the interaction of the four typical nuclides $^{27}$Al, $^{12}$C, $^{11}$B, and $^{10}$B with low energy neutrons[18]. In the simulated energy range, when the neutron energy is 5.9 keV and 20 keV, $^{27}$Al and $^{11}$B have resonance absorption interaction with neutrons. Therefore, near the two energy points, a smaller energy interval is used for detailed simulation. The macroscopic total cross section of Al/B$_4$C composite material can be calculated by the next calculation.

$$\Sigma_i=N_i^{\sigma_{\gamma}}+N_i^{\sigma_{\tau}}+N_i^{\sigma_{\sigma}}+N_i^{\sigma_{\delta}}$$

Where, $N_i^{\sigma_{\gamma}}$, $N_i^{\sigma_{\tau}}$, $N_i^{\sigma_{\sigma}}$, and $N_i^{\sigma_{\delta}}$ are the number density of $^{27}$Al, $^{12}$C, $^{11}$B, and $^{10}$B nuclides in Al/B$_4$C composite material, respectively. $\sigma_{\gamma}$, $\sigma_{\tau}$, $\sigma_{\sigma}$, and $\sigma_{\delta}$ are the microcosmic cross sections of $^{27}$Al, $^{12}$C, $^{11}$B, and $^{10}$B nuclides, respectively. The number densities of the four atoms $^{27}$Al, $^{12}$C, $^{11}$B, and $^{10}$B in Al/B$_4$C composite with B$_4$C mass content of 10% is 5.38×10$^{22}$ cm$^{-3}$, 2.92×10$^{21}$ cm$^{-3}$, 9.35×10$^{21}$ cm$^{-3}$, and 2.34×10$^{21}$ cm$^{-3}$, respectively. The number density of the four atoms $^{27}$Al, $^{12}$C, $^{11}$B, and $^{10}$B in Al/B$_4$C composite with B$_4$C mass content of 30% is 4.12×10$^{22}$ cm$^{-3}$, 8.63×10$^{21}$ cm$^{-3}$, 2.76×10$^{21}$ cm$^{-3}$, and 6.90×10$^{21}$ cm$^{-3}$, respectively. The relationship between the macroscopic total cross section $\Sigma_i$ of Al/B$_4$C composite with B$_4$C of 30% mass content and the neutron energy is shown in figure 6 (b). It can be seen that there are resonance absorption peaks at 5.9 keV and 20 keV in the macroscopic total cross section $\Sigma_i$.

![Figure 5](image1.png)

**Figure 5.** Neutron transmission and reflection coefficients of Al/B$_4$C composite material for neutrons in the energy range of 200eV to 20keV.

From the simulation results of figure 5(a), it can be seen that when the thickness of Al/B$_4$C composite shield and B$_4$C mass content in the material are selected, the neutron transmission coefficient increases with the increase of neutron energy except for two resonance energy points...
5.9keV and 20keV. That is, the shielding performance of Al/B₄C composite material to low energy neutrons is better. The higher the neutron energy is, the worse the shielding performance is. As shown in figure 5(b), the neutron reflection coefficient increases with the increase of the neutron energy, except for the two resonant energy points, 5.9 keV and 20 keV. For Al/B₄C composite material with a thickness of 20 cm and with B₄C mass content of 30%, the neutron transmission coefficients for energy of 5.9 keV and 20 keV are 3.2×10⁻³ and 1.46×10⁻², respectively; and the neutron reflection coefficients for those two energies are 59.6% and 61.3%, respectively.

![Microscopic cross section and macroscopic cross section of neutron.](image)

**Figure 6.** Microcosmic total cross section and macroscopic total cross section of neutron.

4. Conclusions
In this paper, a calculation model for low energy neutron shielding of Al/B₄C composite material is established. The Monte Carlo method was used to simulate the reflection and transmission coefficients of Al/B₄C composite material with different mass content of B₄C and with different thickness to different energy neutrons. The results show that the change law of the neutron reflection of the Al/B₄C with thickness is obviously different with that of the neutron transmission coefficient with thickness. The reflection coefficient firstly increases rapidly with the increase of the thickness of Al/B₄C composite material, and then tends to saturate when the thickness reaches a certain value. The neutron saturation reflection coefficient and the corresponding saturation reflection thickness are related to the neutron energy and B₄C mass content in Al/B₄C composite material. The fundamental reason is determined by the interaction cross section between neutron and shielding material. Due to the large cross section between ¹⁰B and low energy neutron, the neutron saturation reflection coefficients for neutrons with energy below 20 keV decrease with the increase of B₄C mass content in Al/B₄C composite material, and the corresponding saturation reflection thickness also decreases. In the energy range of 200 eV-20 keV, in addition to several resonance energies, neutron interactions with Al/B₄C macroscopic total cross section decreases with the increase of neutron energy, the neutron reflection coefficient increases with the increase of neutron energy, and the increase of the neutron reflection coefficient per unit of energy increases firstly and then decreases with the increase of energy. For resonance energies of 5.9 keV and 20 keV, the neutron reflection coefficients of Al/B₄C composite material with the thickness of 20 cm are 59.6% and 61.3%, respectively.

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