Neutron shielding properties of TPX/B₄C composites based on Monte Carlo method

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Abstract. As the key and difficult point of shielding protection, many domestic and foreign scholars have carried out a lot of experimental research on neutron shielding materials. In this paper, the research progress, advantages and disadvantages of common neutron shielding materials are discussed, and the neutron shielding process of TPX/B₄C composites is simulated by Monte Carlo method, and the results are compared with the Boron polyethylene, lead boron polyethylene, aluminum based boron carbide mentioned in the literature. Based on the simulation results, it is concluded that the thermal neutron absorption rate of TPX/B₄C composites with the thickness of 1cm is 98.3%, the fast neutron shielding rate of 1MeV is 1.457, and the neutron shielding reduction factor and neutron dose reduction factor of americium beryllium neutron source are obviously better than the other three materials. The simulation results show that TPX/B₄C Composite can be used as a new kind of high temperature neutron shielding material.

1. Introduction

With the increasing demand for energy, nuclear energy has been developing rapidly with its incomparable advantages of high efficiency, cleanness and huge energy. Human beings enjoy their outstanding contributions in national defense construction, medical research, power supply and so on. At the same time, also bear the damage and unknown potential risks caused by nuclear radiation. Shielding protection is an effective and feasible way. The field of radiation protection has gradually attracted people's attention. Compared with α, β and γ rays, neutron protection is the key and difficult point of shielding protection. According to the two stages of neutron action: fast neutron deceleration and thermal neutron capture absorption, domestic and foreign scholars have carried out a large number of targeted experimental research. In this paper, the development status of main neutron shielding materials is discussed, and the neutron shielding properties of new composite material TPX/B₄C and common neutron shielding materials are simulated and compared by MCNP, which provides the basis for the development direction of new neutron shielding materials.

The common shielding materials include cement-based neutron shielding materials, high boron steel, neutron shielding fiber materials, polymer materials containing rare earth elements, boron containing composite materials and so on. Shen Zhiquiang and others tested the shielding performance of the cement-based material mixed with barite, and found that the material has a certain shielding effect on radionuclide neutron source [1]. High boron steel is often used for the storage of nuclear fuel because
of its excellent characteristics. Sumitomo Metal Industry Company added a certain amount of boron element into SUS304 stainless steel to improve the thermal neutron absorption performance to meet the shielding standard, and produced welded pipes with different specifications by special processes and methods to meet the storage requirements of nuclear fuel [2]. In Japan, a fiber material with high content of neutron absorbing particles was prepared by blending polyethylene resin with lithium and boron compound powder by melt core composite textile process. The test results show that the shielding rate of thermal neutron of nonwovens produced is 40%, and the elongation at break is also high [3]. Yang and others used the cross-linking molding method to blend gadolinium acrylate with natural rubber to prepare rare earth polymer materials with uniform dispersion and close interface bonding. With the increase of the content of rare earth elements, the radiation protection performance is also improving [4]. Boron containing composite materials refer to boron or boron compounds added into the matrix. The neutron shielding properties of materials are closely related to boron content, while other mechanical properties are mainly dominated by the matrix. Gomez prepared aluminum matrix composites by powder metallurgy method, with aluminum alloy AA6061 as the matrix, adding 10% boron carbide, the experiments show that the specific strength and friction properties of the composite have a certain improvement [5].

2. TPX/boron carbide composites

TPX usually refers to poly (4-methylpentene-1), abbreviated as PMP [6]. Most of its commercial products are the product of copolymerization of its monomer with a certain mass fraction of olefins. The original monomer on this polymer resin is easy to be replaced by olefins. However, due to its highly regular head-to-end isometric structure, the basic structure and crystallinity of the material are not greatly affected. At present, Mitsui is the only TPX manufacturer in the world [7].

Fig 1. TPX synthetic polymerization process

As the base material of neutron shielding material, TPX itself contains only C and H elements, and there are no heteroatoms easily activated by neutrons. Moreover, the ratio of C to H atoms is almost 1:2, which is the same as that of polyethylene with good neutron shielding performance. Compared with polyethylene, TPX has incomparable advantages at high temperature. In addition to the fact that the vicat softening point is between 160 °C and 170 °C and the melting point is as high as 240 °C, it is obviously higher than that of polyethylene. The experiment shows that TPX has a very good resistance and can work in high temperature environment for a long time without deformation and softening. The creep resistance, solvent cracking resistance and flexibility of the resin are improved at high temperature. Its water absorption is as low as 0.01%, and it also shows good tolerance in boiling water [8]. These excellent properties make the TPX substrate suitable for nuclear protection in some specific high temperature and high humidity sites. The TPX scrap was mixed with 10% boron carbide powder, and
then hot pressed at 300 °C to obtain a new composite with density of 1.05g/cm³. The shielding performance of the composite was simulated by Monte Carlo program.

3. Monte Carlo method

3.1. application of Monte Carlo in shielding simulation
As the first mock exam technique or statistical test method, Monte Carlo method can be used to describe the mechanism of matter and particle. It can simplify the particle process to a particle transport equation. Monte Carlo solves the transport problem by simulating and recording the movement process of a single particle one by one. Guo Liping and others used mcstas to simulate the whole physical process of tracking particles from the source to the detector, which provided a large basis for the selection of laboratory spectrometer and other instruments [9]. Russia's D.A. zakheim and others simulated the electron transport process and its derivative results in granular metal films through the Monka method, and based on the simulation results, put forward reasonable suggestions for improving the current conversion device [10].

3.2. calculation model and shielding performance representation method
In this paper, a spherical shell model is established by using MCNP code as shown in Fig.2. The spherical center is an isotropic neutron point source. The calculated single energy neutron energy ranges from 0.0253eV to 10MeV. One to two calculation points are set every other order of magnitude. In addition, the shielding effect of Am-Be neutron source is also calculated. Four thicknesses of 4cm, 8cm, 12cm and 16cm are selected to compare the neutron shielding performance of Am-Be neutron source with different thickness.

![Fig 2. plan of the Spherical shell model](image)

In order to better simulate the shielding performance of shielding materials, materials were characterized from different angles. Neutron flux reduction factor (N/N₀, N and N₀ are the neutron fluences with and without shielding materials, respectively) and the neutron dose reduction times (D/D₀, D and D₀ are the neutron doses with and without shielding materials, respectively). the thermal neutron absorption rate of 1cm thick shielding material to thermal neutron (0.0253eV) and the fast neutron shielding coefficient (1MeV) under the thickness of 4cm were calculated. The results were compared with those of the same thickness mentioned in reference [12,13]. Lead boron polyethylene (PB202, mass fraction of each component is B₄C1%, Pb80%, PE19%, density 3.42g/cm³), boron polyethylene (B201, mass fraction of each component is B₄C5%, PE95%, density 0.95 g/cm³), aluminum based boron carbide (mass fraction of each component is Al69%, B₄C31%, density 2.63g/cm³).

3.3. simulation calculation of shielding performance
As shown in the figure, Fig.3, Fig.4, Fig.5 and Fig.6 show the neutron fluence reduction factor of shielding material for single energy neutron source with different energies under the thickness of 4cm, 8cm, 12cm and 16cm. Fig.7, Fig.8, Fig.9 and Fig.10 are the corresponding neutron dose reduction times under different thicknesses. From the simulation results, the overall performance of TPX is better than
PB202, B201 and Al-B₄C. Although Al-B₄C has better shielding performance for lower energy neutrons such as thermal neutrons, its shielding effect for intermediate and high-energy neutrons is poor, which is consistent with the shielding performance of actual materials, which further confirms the feasibility of simulating the neutron shielding process by MCNP code. The other two commonly used neutron shielding materials, from 0.0253eV thermal neutrons to 10MeV fast neutrons, the neutron counts of the penetrating materials were higher than those of TPX/B₄C materials, with the increase of thickness, it is found that the neutron flux and dose reduction times of B201 are close to those of TPX/B₄C.

Fig 3. Neutron flux reduction factor of 4cm shielding material

Fig 4. Neutron flux reduction factor of 8cm shielding material
Fig 5. Neutron flux reduction factor of 12cm shielding material

Fig 6. Neutron flux reduction factor of 16cm shielding material

Fig 7. Neutron dose reduction factor of 4cm shielding material
Fig 8. Neutron dose reduction factor of 8cm shielding material

Fig 9. Neutron dose reduction factor of 12cm shielding material

Fig 10. Neutron dose reduction factor of 16cm shielding material
Fig. 11. Neutron flux reduction factor of shielding material under Am-Be neutron source

Fig. 12. Neutron dose reduction factor of shielding material under Am-Be neutron source

Fig. 11 and Fig. 12 show the shielding effect of shielding material on Am-Be neutron source at different thicknesses. The neutron fluence reduction times of composite TPX at 4cm, 8cm, 12cm and 16cm thickness are 83.3%, 55.3%, 34.3% and 20.8% respectively, and the neutron dose reduction times are 84.5%, 56.6%, 35.7% and 22.0%, which are slightly higher than that of material B201, in which the neutron flux reduction times are 85.9%, 59.2%, 38.17% and 24.0%, respectively. The neutron dose reduction times are 86.1%, 59.7%, 39.0% and 24.9%, which are obviously better than those of pb202. The neutron dose reduction times are 92.0%, 70.3%, 49.2% and 33.0% respectively, and the neutron dose reduction times are 93.0%, 70.0%, 49.2% and 33.3%. Due to the poor shielding performance of aluminum based boron carbide for fast neutrons, it does not participate in the performance comparison of Am-Be neutron source. In addition, it is found that the dose energy of gamma ray generated in the shielding process is far less than the neutron dose through simulation calculation, which will not affect the shielding result.
Table 1. related parameters

| Material | TPX | B201 | PB202 | Al-B4C |
|----------|-----|------|-------|--------|
| Thermal neutron absorption rate (%) | 98.31 | 92.59 | 83.62 | 99.12 |
| Fast neutron shielding coefficient | 1.458 | 1.374 | 1.167 | 1.01 |

It can be seen from table 1 the thermal neutron absorption rate and fast neutron shielding coefficient of TPX composite are better than those of other B201 and PB202. Although the thermal neutron absorption coefficient is slightly less than Al/B4C, its fast neutron shielding coefficient is obviously higher. Through the results, the composite material TPX/B4C has the best neutron shielding performance and is expected to be a good high temperature neutron shielding material.

4. Conclusion
In this paper, the research progress of some common neutron shielding materials is discussed, and a new high temperature resistant shielding material TPX is introduced. The neutron shielding properties of the composite material and the other three kinds of neutron shielding materials mentioned in the literature are simulated and analyzed by MCNP program.

The thermal neutron absorptivity and fast neutron shielding coefficient of TPX/B4C composites are better than PB202 and B201. The neutron fluence attenuation factor and neutron dose attenuation rate of TPX/B4C composites are lower than those of PB202 and B201. Al based boron carbide has a strong absorption capacity for thermal neutrons, but its shielding effect for fast neutrons is much lower than that of TPX/B4C composites.

Due to the epidemic situation, only preliminary experiments have been carried out, but no relevant experiments have been carried out to test the actual mechanical properties and neutron shielding properties of the composite materials. At the same time, there are some defects in TPX materials, such as expensive price (leftovers can be selected), long-term direct sunlight performance index decline and other problems, which can be improved in the future. The purpose of this paper is to provide reference for the development of new high temperature neutron shielding materials.

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