Nuclear Engineering and Technology 51 (2019) 1436–1443

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

A fast gamma-ray dose rate assessment method for complex geometries based on stylized model reconstruction

Li-qun Yang, Yong-kuo Liu*, Min-jun Peng, Meng-kun Li, Nan Chao

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, 150001, China

ARTICLE INFO

Article history:
Received 12 October 2018
Received in revised form
26 February 2019
Accepted 6 March 2019
Available online 9 March 2019

Keywords:
Dose rate assessment
3D-geometrical solid
Automatic modeling
Point-kernel method
Stylized model reconstruction

ABSTRACT

A fast gamma-ray dose rate assessment method for complex geometries based on stylized model reconstruction and point-kernel method is proposed in this paper. The complex three-dimensional (3D) geometries are imported as a 3DS format file from 3dsMax software with material and radiometric attributes. Based on 3D stylized model reconstruction of solid mesh, the 3D-geometrical solids are automatically converted into stylized models. In point-kernel calculation, the stylized source models are divided into point kernels and the mean free paths (mfp) are calculated by the intersections between shield stylized models and tracing ray. Compared with MCNP, the proposed method can implement complex 3D geometries visually, and the dose rate calculation is accurate and fast.

1. Introduction

The dose rate calculation software used in radiation environment assessment and shielding design falls into two main methods. The first kind of software is based on Monte Carlo (MC) method, such as MCNP [1] and FLUKA [2]. The MC method based on probability theory leads to perfect accuracy of the calculated values even for complex models. But MC calculations require considerable amount of computing time. Another group contains software is based on point-kernel (PK) method, such as PUTZ [3] and QAD [4]. The point-kernel method based on analytical methods is much less computationally intensive than Monte Carlo method.

The dose calculations for multiple sources and multilayered shielding could be conducted at reliable time using point-kernel method. Base on the PK method [5], presented a FORTRAN code QAD-CGPIC for neutron and gamma-ray shielding calculations. Moreover [6], proposed a PK code called SHIELD DESIGN for precise estimation of shielding thickness in gamma ray shielding designs. In this code, a technique based on inverse calculation and iterative procedures had been employed to estimate the shield thickness using the dose rate criteria as input information. To generate a non-regular mesh model and computes the dose rate in real time [7], presented an algorithm to calculate gamma dose rates for virtual reality simulation applications in nuclear safeguards and security. For calculating dose rates in scenarios with complex geometries and gamma radiation sources [8], developed a code named CIDEC by the PK method. This code uses the geometric modeling capabilities of CAD tools to construct the geometry. However, the code can't obtain the details of geometries such as the volume [9]. proposed a PK code named VTK for arbitrary geometries based on voxelization algorithm. However, the code require a long computing time in thin shield calculation.

Fast and accurate dose rate calculation for complex geometries is still a hard work. In this work, a fast gamma-ray dose equivalent rate shielding assessment method based on stylized model reconstruction has been developed for complex geometries. This method uses the geometric modeling capabilities of 3dsMax software to construct 3D geometrical solid, and the material and radiometric attributes are imported for solids based on the naming format. Based on 3D stylized model reconstruction of solid mesh, the solid models are automatically converted into stylized models. In PK calculation, the stylized source models are divided into point kernels and the mfp are calculated by the intersections between shield stylized models and tracing ray.

The rest of the paper is organized as follows: section 2 describes the implementation of the proposed method; section 3 shows the related experiments; section 4 analyzes the results of experiments. The paper is concluded in the last section.

* Corresponding author.
E-mail address: LYK08@126.com (Y.-k. Liu).

https://doi.org/10.1016/j.net.2019.03.004

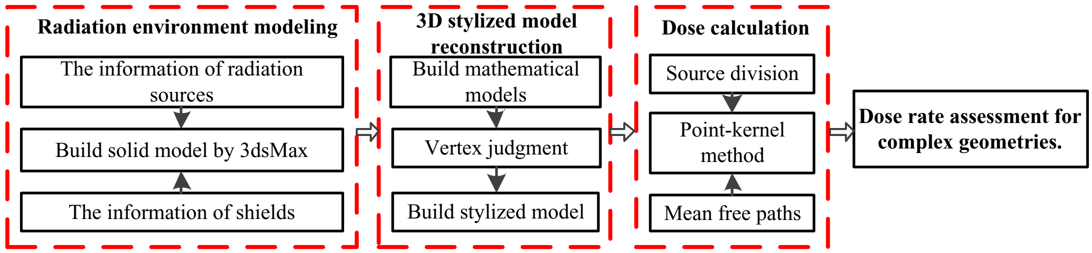


Fig. 1. The structure of gamma-ray dose rate calculation for complex geometries.

2. Methodology

The structure of gamma-ray dose rate calculation for complex geometries is shown in Fig. 1. At first, the 3D solid model of radiation environment is built by the 3dsMax software. The information of source and shield are also given directly in the solid model. By judging the vertices of the solid mesh, the solid model can be simulated as mathematical models. The stylized models of initial solid model are built by choosing the suitable mathematical model. After dividing the stylized source models to point kernels and calculating the mfp by using stylized models, the dose rates of complex radiation environment are got by PK calculation in the end. The whole process can be divided into three parts: radiation environment modeling, 3D stylized model reconstruction and dose calculation. The details of each section are described below.

2.1. Radiation environment modeling

Creating 3D geometry for radiation environment simulation and dose calculation is a very important and time consuming work. In this work, in order to simplify the modeling process of complex geometries, the solid model was established based on the exact dimensions of the radiation environment in the 3dsMax software. The solid model imports the program in a 3DS format file. The surface of the solid model is described by a curve mesh. The surface mesh consists of a series of triangular patches, each containing three vertices.

To distinguish whether the model is empty, the solid model is built using a naming format. If the model is non-empty, the object will have the keyword “NS” (non-empty source) or “NH” (non-empty shield) as the initial name of the object. For the hollow model, the keywords used in the naming format are “HS” (hollow source) and “HH” (hollow shield). At the same time, for a hollow model with a uniform shell thickness, the thickness is written directly behind the keyword. In order to store the material information and source information in a solid model, the energy distribution and intensity information is provided to the material ball used by the source in the Material Editor, and the density and atomic number information is provided to the material ball used by the shield.

2.2. 3D stylized model reconstruction

In order to solve the complex geometric description problem, converting the complex solid model into stylized model is a feasible method. The stylized model is the abstraction of the solid model, a combination of spatial surface equations, and a formulaic representation of the mathematical model. A stylized model can represent a combination of basic geometries using equation sets. The 3D stylized model reconstruction of complex geometrical solid is converting geometric objects from their complex geometric representation into the combination of several basic mathematical formulas that approximates it. The core of the stylization algorithm is selecting the suitable mathematical model/formula for solid object as stylized model.

As shown in Fig. 2, let S be a solid model with volume V. S can be described by curved mesh with n vertices. Build a mathematical model G based on the curved mesh. The volume of G is V_G and the number of vertices of curved mesh contained in G is N. If $n = N$ and $V = V_G$, then $S = G$. if $n \approx N$ and $V \approx V_G$, S can be approximated as G. Therefore, it is a feasible method to build many mathematical models based on the vertex of curved mesh and choose the mathematical model with maximum N and smaller volume as the approximated stylized model.

In experiments, it is easy to find that for certain S, the more number of vertices, the finer the simulation of the stylized model, the slower the speed of the computer calculation. Therefore, it is an effective method to improve the accuracy of simulation by adding the center point of each triangle edge to the set of vertex.

The flow of the stylization algorithm for solid model of complex radiation environment is shown in Fig. 3. First, build the minimum bounding box for each solid model and build the mathematical models based on the bounding box. Then select the appropriate mathematical model as the external stylized model. If the solid model is hollow, build the internal stylized model based on the external stylized model and solid thickness. Finally, the complex stylized models are built based on internal stylized models and external stylized models. The key steps for stylization algorithm are

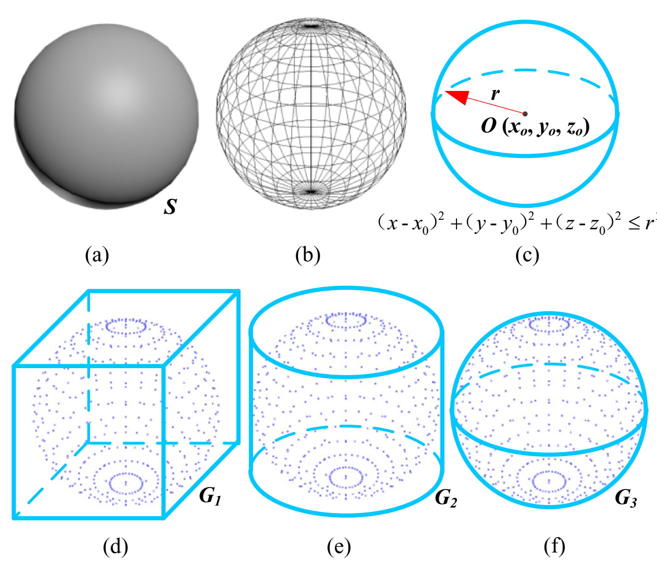


Fig. 2. Reconstruction of 3D stylized model of the solid object based on triangle mesh vertex judgment. (a) Sphere solid model S with volume V. (b) S is described by curved mesh with n vertices. (c) The stylized model of S. (d–f) Build mathematical models G1, G2 and G3 based on the curved mesh. The number of vertices of curved mesh contained in mathematical models is N1, N2 and N3 and the volume is V1, V2 and V3. Since n = N3 = N2 = N1 and V3 < V2 < V1, G3 is selected as stylized model.

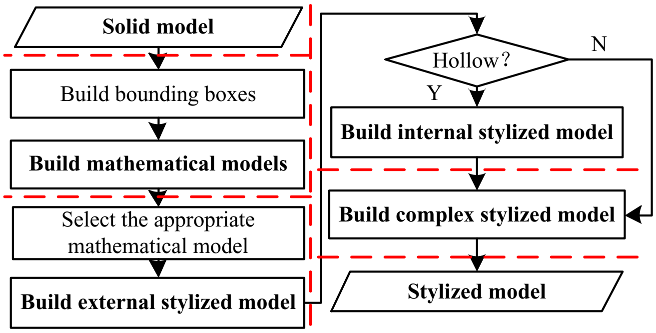


Fig. 3. Flow of solid model stylization algorithm.

given as follows.

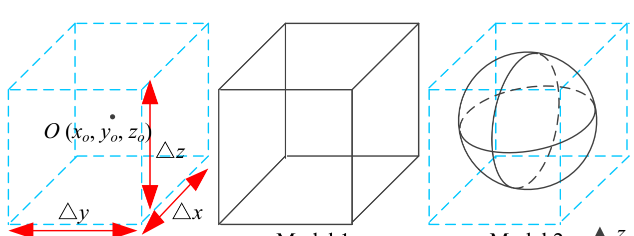
2.2.1. Build the mathematical models based on the bounding box of solid model

Build minimal bounding box *B* based on the size of solid. *O* (x_o, y_o, z_o) is the center of *B*, and $\triangle x \times \triangle y \times \triangle z$ is the size of *B* (see Bounding Box in Fig. 4.). Based on the six parameters x_o, y_o, z_o, $\triangle x$, $\triangle y$, $\triangle z$ of *B*, five kind of general mathematical models have been established, including rectangular parallelepiped, ellipsoid, elliptical cylinder, semi-ellipsoid and right-angled triangular column. These five general mathematical models can be subdivided into 23 specific mathematical models based on the direction of central axes.

The rectangular parallelepiped mathematical model is defined as Model 1 in Fig. 4. Rectangular parallelepiped model is the most basic mathematical model and only has one specific mathematical model. It is suitable for the simulation of slab in the radiation environment.

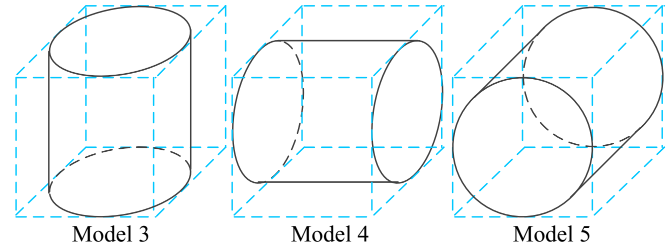
The mathematical model of ellipsoid is defined as Model 2 in Fig. 4. The ellipsoid mathematical model has one type specific model, which is suitable for the simulation of spherical radioactive source in nuclear radiation environments. When $\triangle x = \triangle y = \triangle z$, the ellipsoid is a sphere.

The mathematical models of elliptical cylinder (parallel to the coordinate axes) are defined as Fig. 5. There are three kinds of elliptical cylindrical mathematical models, which are suitable for the simulation of cylindrical tanks and straight pipes in radiation environment. For Model 3 in Fig. 5, when $\triangle x = \triangle y$, the elliptical cylinder is a circular cylinder.



$$\begin{cases} x_0 - \frac{\Delta x}{2} \le x \le x_0 + \frac{\Delta x}{2} \\ y_0 - \frac{\Delta y}{2} \le y \le y_0 + \frac{\Delta y}{2} \\ z_0 - \frac{\Delta z}{2} \le z \le z_0 + \frac{\Delta z}{2} \end{cases} \qquad \frac{(x-x_0)^2}{(\Delta x/2)^2} + \frac{(y-y_0)^2}{(\Delta y/2)^2} + \frac{(z-z_0)^2}{(\Delta z/2)^2} \le 1$$

Fig. 4. Minimum bounding box is built based on the six parameters xo, yo, zo, $\triangle$x, $\triangle$y, $\triangle$z. Model 1 is the mathematical model of rectangular parallelepiped and Model 2 is the mathematical model of ellipsoid. The mathematical formulations are given under the figure.

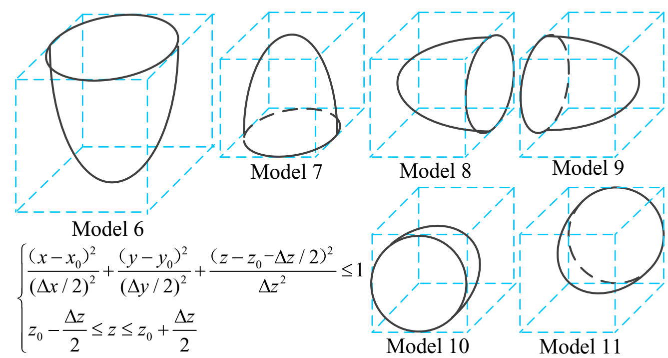


$$\begin{cases} \frac{(x-x_0)^2}{(\Delta x/2)^2} + \frac{(y-y_0)^2}{(\Delta y/2)^2} \le 1 \\ z_0 - \frac{\Delta z}{2} \le z \le z_0 + \frac{\Delta z}{2} \end{cases} \quad \begin{cases} \frac{(x-x_0)^2}{(\Delta x/2)^2} + \frac{(z-z_0)^2}{(\Delta z/2)^2} \le 1 \\ y_0 - \frac{\Delta y}{2} \le y \le y_0 + \frac{\Delta y}{2} \end{cases} \quad \begin{cases} \frac{(y-y_0)^2}{(\Delta y/2)^2} + \frac{(z-z_0)^2}{(\Delta z/2)^2} \le 1 \\ x_0 - \frac{\Delta x}{2} \le x \le x_0 + \frac{\Delta x}{2} \end{cases}$$

Fig. 5. Model 3~Model 5 are mathematical models of elliptical cylinder parallel to the coordinate axes. The mathematical formulations are given under the figure.

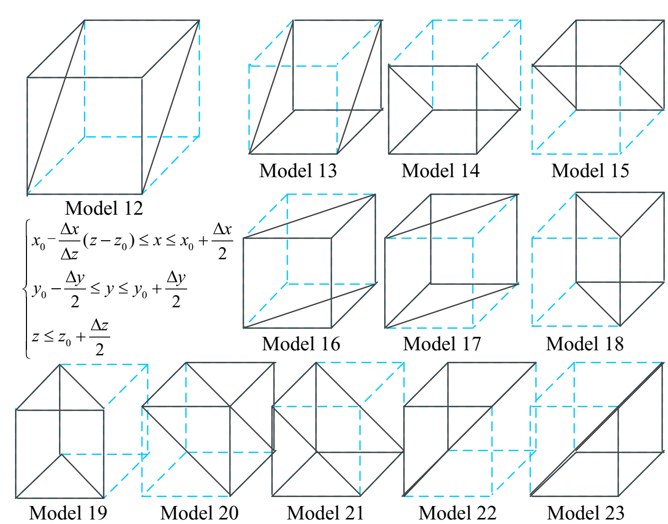
The mathematical models of semi-ellipsoid (parallel to coordinate axis) are defined as Fig. 6. There are six kinds of elliptical parabolic mathematical models, which are suitable for the simulation of the top cover of various pressure vessels in the nuclear radiation environment.

The mathematical models of right-angled triangular column (parallel to the coordinate axes) are defined as Fig. 7. This model has



$$\begin{cases} \frac{(x-x_0)^2}{(\Delta x/2)^2} + \frac{(y-y_0)^2}{(\Delta y/2)^2} + \frac{(z-z_0-\Delta z/2)^2}{\Delta z^2} \le 1 \\ z_0 - \frac{\Delta z}{2} \le z \le z_0 + \frac{\Delta z}{2} \end{cases}$$

Fig. 6. Model 6~Model 11 are mathematical models of semi-ellipsoid parallel to coordinate axis. The formulations of Model 6 are given under the figure.



$$\begin{cases} x_0 - \frac{\Delta x}{\Delta z}(z-z_0) \le x \le x_0 + \frac{\Delta x}{2} \\ y_0 - \frac{\Delta y}{2} \le y \le y_0 + \frac{\Delta y}{2} \\ z \le z_0 + \frac{\Delta z}{2} \end{cases}$$

Fig. 7. Model 12~Model 23 are mathematical models of right-angled triangular column parallel to the coordinate axes. The formulations of Model 12 are given under the figure.

a total of 12 specific models, which is suitable for the simulation of models such as L-walls, bends in the radiation environment.

2.2.2. Build complex stylized model

The procedure for build complex stylized model is shown in Fig. 8. According to definition, the key to select the appropriate stylized model is to judge the N of 23 mathematical models. Since the rectangular parallelepiped is the same size as the bounding box ($N = n$), the N of a rectangular parallelepiped mathematical model which little smaller than bounding box is calculated. As shown in Fig. 9, if $N = 0$, the bounding box can be used as external stylized model directly. Otherwise the algorithm is simplified to select the mathematical model that contains the maximum N from Model 2 to Model 23 as the external stylized model. If there is more than one mathematical model that has same maximum N, the smallest volume mathematical model is selected as external stylized model. In program, the priority of choice is: right-angled triangular column first, semi-ellipsoid second, ellipsoid third and elliptical cylinder last.

For a non-empty solid model, the selected mathematical model is used directly as the stylized model. When the model is hollow, it is necessary to establish the internal stylized model. As shown in Fig. 10, for a hollow model with a uniform shell thickness, the internal stylized model is built by adjusting the formula of the external stylized model with the thickness of the shell. For models with uneven shell thickness, the bounding box of the internal model needs to be re-established according to the vertices of the hollow part of the model, and the appropriate stylized model is selected as the internal stylized model.

For the complex geometries, the area described by the external stylized model is completely contained within the external stylized model, whereas the area described by the internal stylized model is completely external to the internal stylized model. As shown in Fig. 11, the complex stylized model is built based on the external stylized model and the internal stylized model.

2.3. Gamma-ray shielding calculation

The procedure of PK method used for stylized models is shown in Fig. 12. For gamma-ray shielding calculations, this method uses the ray tracing technique. In this technique, the fundamental assumption is that the radioactive sources can be regarded as consisting of differential isotropic point sources and the effect of

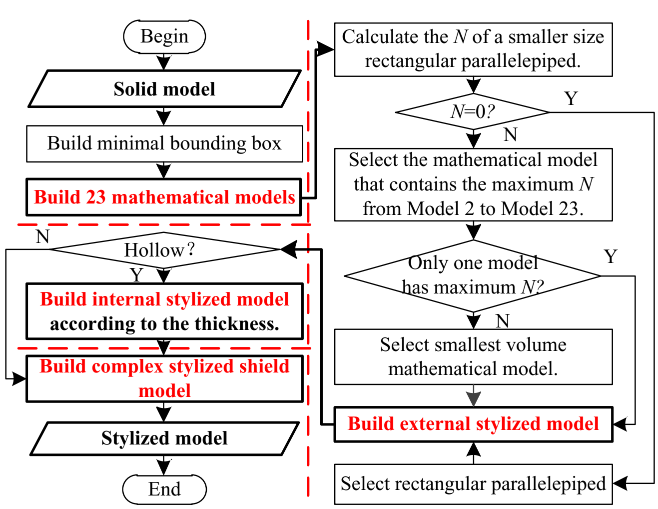


Fig. 8. The procedure for build complex stylized model.

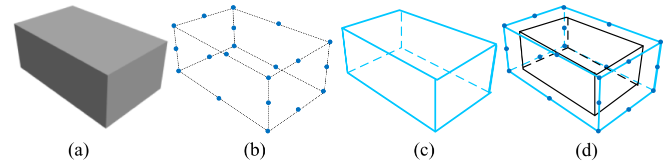


Fig. 9. Select stylized model for a box. (a) Solid model. (b) The solid model is described with 20 vertices. (c) The minimum bounding box of solid model. (d) Build a rectangular parallelepiped mathematical model which little smaller than bounding box. Since N = 0, the bounding box is used as external stylized model directly.

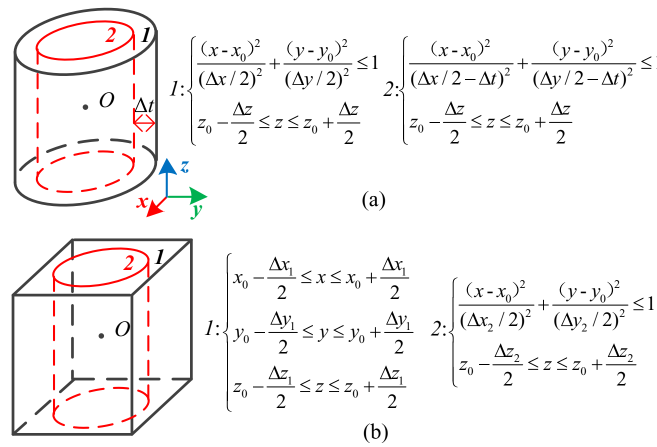


Fig. 10. The formula of external stylized model 1 and internal stylized model 2. (a) Hollow model with a uniform shell thickness △t. (b) Hollow model with uneven shell thickness.

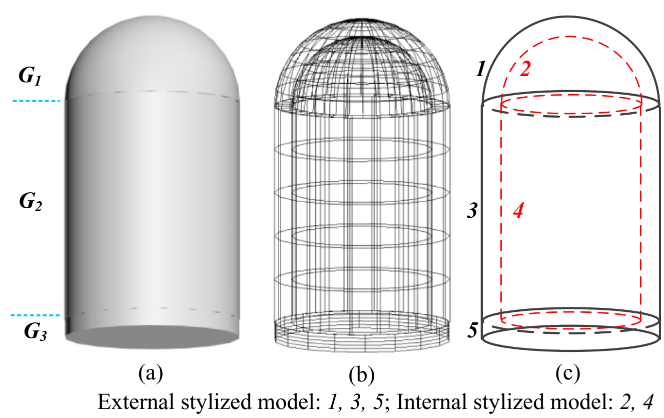


Fig. 11. Build complex stylized model. (a) Pressure vessel solid model G1∪G2∪G3. (b) The pressure vessel is described by curved mesh. (c) Complex stylized model.

the radiation at the detecting point can be obtained by the summation of the contributions from individual differential sources.

Divide radiation source volume to several point kernels is an important process for PK method. Since the source model has been converted to stylized model, the source division can be simplified as the split of stylized model. In this method, there are two ways to split a stylized model. As shown in Fig. 13, when the model is standard shape, the program divides the volume mesh according to the θ, Φ, $\triangle x$, $\triangle y$ and $\triangle z$. After the mesh division, the stylized model is split up in several smaller geometries with equal volume. When the model is non-standard shape, the minimum bounding box of the source model is voxelized as voxels (see Fig. 14(b)), and the voxel whose coordinates satisfy the formula of the stylized

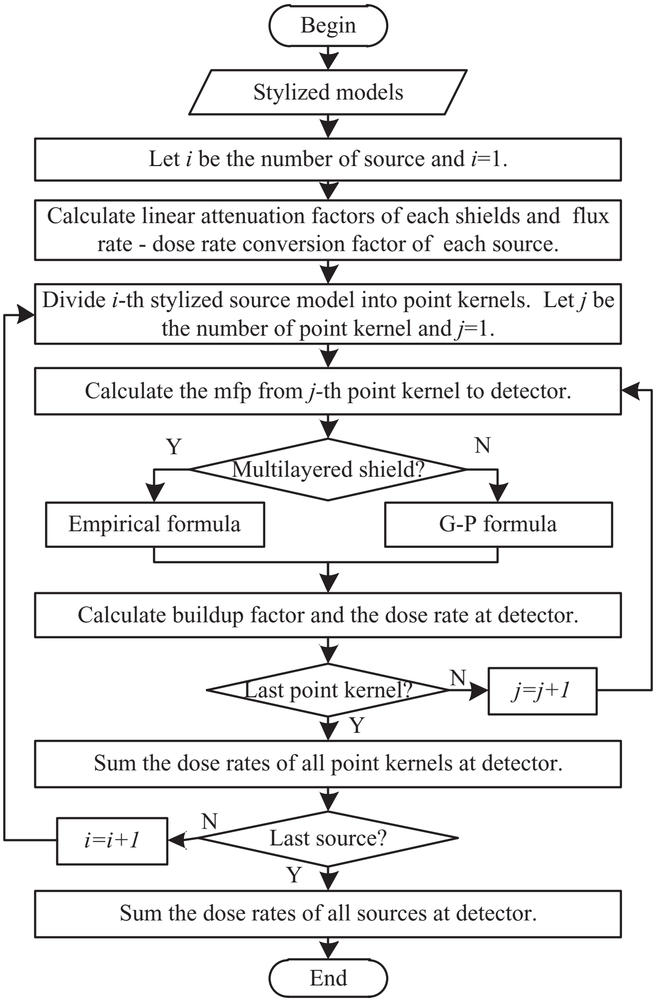


Fig. 12. The procedures of PK method used for stylized models.

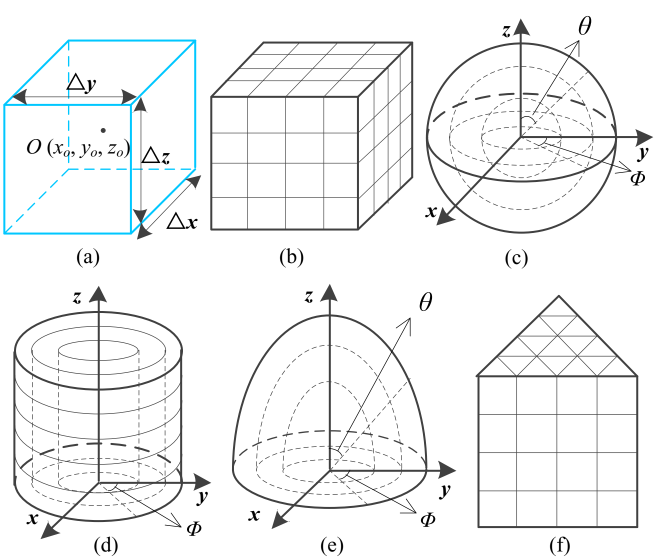


Fig. 13. Source options with geometry parameters. (a) The minimum bounding box. (b) Rectangular parallelepiped source, divisions along the △x, △y and △z coordinates. (c) Sphere source, divisions along the θ, Φ, △x, △y and △z coordinates. (d) Cylindrical source, divisions along the Φ, △x, △y and △z coordinates. (e) Semi-sphere source, divisions along the θ, Φ, △x, △y and △z coordinates. (f) Right-angled triangular column source, divisions along the △x, △y and △z coordinates.

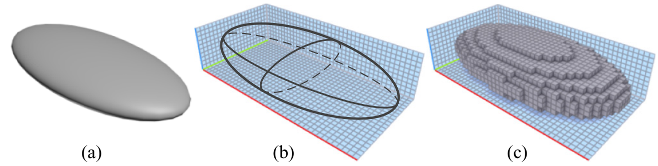


Fig. 14. Divide an ellipsoid source to point kernels. (a) Elliptical solid model. (b) Voxelize the minimum bounding box of stylized model. (c) Build the voxel model based on the formula of stylized model.

model is the point kernels of the source (see Fig. 14(c)).

After the source division, the strength $s(E)$ of a point kernel with photon energy E is defined as

$$s(E) = \frac{S(E)}{N} \tag{1}$$

where $S(E)$ is the source density of the source body, and N is the point kernel number of the source body. The core of the PK method is a simple formula for calculating the dose rate from a point isotropic source to the detector with photon energy E in a homogeneous infinite medium,

$$D(r,E) = C(E)s(E)B(E,t(E))\frac{\exp(-t(E))}{4\pi r^2} \tag{2}$$

where $C(E)$ is photon flux-to-dose rate conversion factor obtained from the 1977 ANSI/ANS [10] and the ICRP-21 [11], $B\ (E,\ t)$ is the buildup factor. For single-layer shielding, $B\ (E,\ t)$ can be obtained from the ANSI/ANS-6.4.3 [12,13] and the Geometric Progression (G-P) formula [14]; for multi-layer shielding, it can be obtained from empirical formula proposed by Ref. [15]. r is the distance between the point kernel and the detector, $t(E)$ is the optical thickness from the source to the detector in mfp

$$t(E) = \sum_{i=1}^{n} \mu_i(E) d_i \tag{3}$$

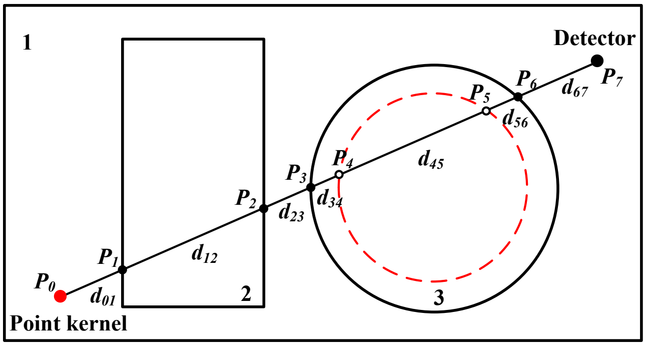
where i is index of the space region, n is the number of regions, μ_i is the linear attenuation coefficient for i-th region, and d_i is the section of the line between the detector and the point kernel in the i-th region. Calculate the section d_i is the key to calculate the mfp. In this paper, an example of calculating mfp between point kernel and the detector is given in Fig. 15. At first, calculate the intersections between shield models and tracing ray. For hollow model, the intersections between gamma ray and internal stylized model are also need to calculate. Then calculate the section of different space region according to adjacent intersections. Finally the mfp are obtained by integration of equation (3).

In the PK method, the point-source kernels are assumed to be independent. So the total dose rate at detecting point can be obtained by integration of equation (2) over the source volume V and summation over the energies E of radiation spectrum

$$D = \int_0^{E_{max}} dE \iiint D(r,E)dV \tag{4}$$

3. Experiments and results

In this paper, a dose equivalent rate assessment code named as SPK has been developed based on the stylization algorithm. The SPK is implemented in C ++. In this section, a series of related experiments were designed to verify the accuracy of the SPK. The



$$t(E) = \mu_1(E)(d_{01} + d_{23} + d_{45} + d_{67}) + \mu_2(E)d_{12} + \mu_3(E)(d_{34} + d_{56})$$

Fig. 15. Calculate the mfp between point kernel and detector. The area 1 is an empty room filled with air; area 2 is a non-empty shield body; area 3 is a hollow shield body. Calculate the intersections between stylized models and tracing ray and get the distance between adjacent intersections. The t(E) between P0 and P7 is calculated according to the linear attenuation factor μi and the section di of i-th region.

first set of experiments was run to test the feasibility of stylization algorithm. The second set of experiments was run to verify the dose rate accuracy of the SPK compared with the MCNP code in three basis cases. All experiments were tested on a Core i5 3.33 GHz processor and 3.49 GB of RAM Windows operation system.

3.1. Basic geometries modeling experiments

In actual modeling, the complex models of nuclear environment are composed of a series of basic geometries. In order to verify the validity and accuracy of the stylization algorithm, six kinds of basic geometries were used to test the geometric modeling capability of SPK. The six geometries are parallelepiped, right-angled triangular column, elliptical cylinder, tube, ellipsoid and hemispherical shell. These six geometries contain the convex surface, concave surface, flat surface and their combination. The six basic models with specific dimensions and the stylized models are shown in Fig. 16. The comparison results of the volume between original model and stylized model were shown in Table 1. For all geometries, the relative deviations are 0%.

3.2. Gamma ray shielding calculation experiments

The SPK is a PK code for gamma-ray shielding calculation in complex radiation environment. In order to test the accuracy and validity of SPK in radiation field gamma ray shielding calculation, three sets of experiments were designed in this section. The volumetric sources used in experiments are supposed to be immaterial. There is no self-absorption. The performance of SPK have compared with MCNP in three basis cases: unshielded case, single-layer shielding case and multilayered shield case. The method used in this work disregards the effects of radiation backscattering.

Table 1
Compare the volume between original model and stylized model.

Basic geometries	Stylized model	Model volume (cm^3)		Deviation (%)	Time (ms)
		Original	Stylized		
Parallelepiped	1	1000000	1000000	0	73
Elliptical cylinder	3	471238.89	471238.89	0	105
Ellipsoid	2	188495.56	188495.56	0	115
Triangular column	16	500000	500000	0	99
Tube	3	120637.16	120637.16	0	107
Hemisphere shell	6	57939.35	57939.35	0	126

3.2.1. Unshielded case

In the unshielded case, three basic geometric sources positioned at the origin of coordinates aligned with the axis were tested separately in an empty room filled with air. The basic geometries are parallelepiped, cylinder and sphere used in modeling experiment. In both geometries the energy was assumed to be 1.5 MeV and the activity was 4.86×10^9 Bq. The source was distributed in the air. The results obtained with SPK are compared in Table 2 with MCNP. There is a general agreement between the presented code and MCNP: relative deviations are lower than 8.1% in all the simple geometries.

3.2.2. Single-layer shielding case

To further assess the performance of SPK, a cylindrical source with radius of 50 cm and height of 60 cm was positioned at the origin of coordinates aligned with the axis in an empty room filled with air. The energy of the source was 1.5 MeV and the activity was 4.86×10^9 Bq. The source was distributed in the air. Four typical shielding materials were selected in the experiment. 0.2 cm and 2 cm thick shielding layer were considered in the materials. As shown in Fig. 17, the slab shield was placed in the x-axes 50 cm away from the cylindrical source, and the detectors were in the x-axis 150, 250, 350 cm away from the origin respectively.

The results obtained with SPK are compared in Table 3 with those obtained for the same geometries with MCNP. For thin layer, the maximum relative deviation of SPK to the result of MCNP is

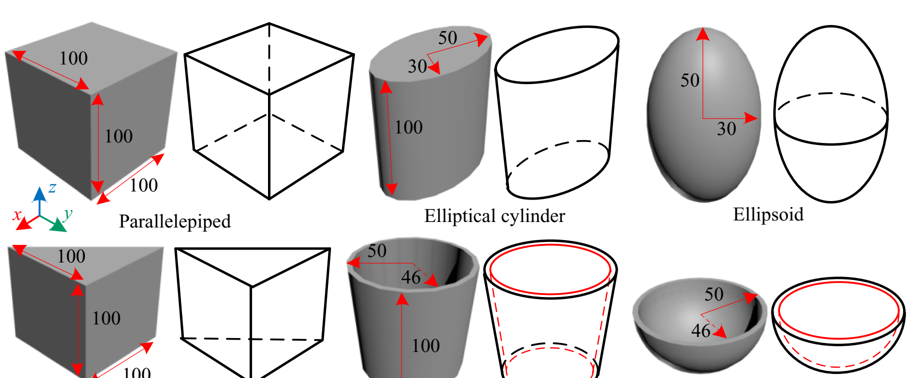


Fig. 16. Six basic geometries used in experiments. The left models are original model, and the right models are stylized model. The dimensions of each model are in centimeter.

Table 2
Comparison of SPK with MCNP in unshielded case.

Calculated positions (x,y,z) [cm]	Parallelepiped			Cylinder			Sphere		
	SPK (mSv/h)	MCNP5 (mSv/h)	Deviation (%)	SPK (mSv/h)	MCNP5 (mSv/h)	Deviation (%)	SPK (mSv/h)	MCNP5 (mSv/h)	Deviation (%)
(100,0,0)	1.0619	0.9942	6.81	1.0587	0.9795	8.09	1.0763	1.0006	7.57
(150,0,0)	0.4628	0.4334	6.80	0.4606	0.4277	7.71	0.4622	0.4307	7.31
(200,0,0)	0.2576	0.2409	6.93	0.2567	0.2387	7.55	0.2570	0.2396	7.27
(250,0,0)	0.1639	0.1531	7.04	0.1635	0.1521	7.48	0.1636	0.1524	7.36

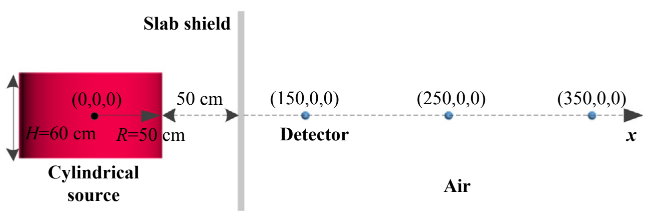


Fig. 17. The irradiation setup for single-layer slab shielding.

7.6%; for thick layer, the relative deviations are lower than 10.8%. Again, results of the different codes acceptably match together.

3.2.3. Multilayered shield case

In the multilayered shield case, a cylindrical source with radius of 20 cm and height of 50 cm was positioned at the origin of coordinates aligned with the axis in an empty room filled with air. The energy of the source was 1.5 MeV and 0.8 MeV, and the corresponding activity was 4.86×10^9 Bq and 5.14×10^9 Bq. The source was distributed in the air. As shown in Fig. 18, four slab layers which filled with different materials with equal thickness were adjacent and the layer 1 was positioned at 20 cm from the cylindrical source at *x* axis. Both 0.2 cm and 2 cm thick shielding layers were tested separately in the experiment. The detectors were in the x-axis 60 cm away from the origin respectively. The comparison of SPK with MCNP in multilayered shield case is shown in Table 4. For thin layers, the relative deviations of SPK from MCNP are all less than 10.6%, while the maximum relative deviation for thick layers is 16.81%. The results show acceptable correlation with the results of the SPK and MCNP.

4. Discussion

The PK code SPK has been developed for the simulation of complex geometries and the calculation of gamma-ray distribution. The aim of the geometrical simulation was to convert complex solid model from their complex geometric representation into the combination of several simple geometries that approximates it. In the basic geometries modeling experiments, the volume relative deviations of all geometries are 0%, which shows the good shape adaptability of SPK. Meanwhile, it should be pointed out that the time in the design of the geometry description was dramatically reduced by using stylization algorithm. More important is that this allows performing simulations on much more complicated radiation environment and to have a more realistic description of them.

In the dose rate calculation experiments, the perfect agreement of results between SPK and MCNP in three basis cases proves shows that the SPK can calculate dose rate correctly under complex shielding situations. So the PK method implemented by SPK code an efficient instrument for dose rate calculations. However, it was observed that the thicker the shield, the greater the error. The

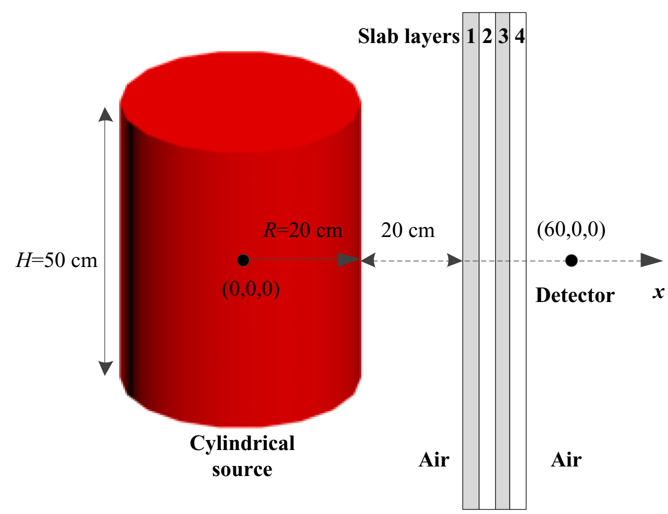


Fig. 18. The irradiation setup for benchmarking in multilayered shield.

Table 3
Comparison of SPK with MCNP in single-layer shielding case.

Material	Calculated positions (x,y,z) [cm]	Thin layer (0.2 cm thick)			Thick layer (2 cm thick)		
		SPK (mSv/h)	MCNP (mSv/h)	Deviation (%)	SPK (mSv/h)	MCNP (mSv/h)	Deviation (%)
Aluminum (2.7 g/cm^3)	(150,0,0)	0.4659	0.4338	7.39	0.4323	0.3905	10.72
	(250,0,0)	0.1632	0.1517	7.55	0.1516	0.1368	10.77
	(350,0,0)	0.0825	0.0767	7.57	0.0767	0.0693	10.60
Water (1 g/cm^3)	(150,0,0)	0.4684	0.4367	7.24	0.4569	0.4180	9.31
	(250,0,0)	0.1641	0.1527	7.43	0.1601	0.1460	9.66
	(350,0,0)	0.0830	0.0772	7.50	0.0810	0.0738	9.78
Lead (11.34 g/cm^3)	(150,0,0)	0.4354	0.4113	5.87	0.2080	0.1934	7.57
	(250,0,0)	0.1524	0.1444	5.49	0.0747	0.0696	7.31
	(350,0,0)	0.0770	0.0730	5.45	0.0386	0.0359	7.62
Concrete (2.56 g/cm^3)	(150,0,0)	0.4659	0.4339	7.38	0.4324	0.3910	10.59
	(250,0,0)	0.1632	0.1517	7.52	0.1516	0.1371	10.60
	(350,0,0)	0.0825	0.0767	7.54	0.0767	0.0694	10.45

Table 4
Comparison of SPK with MCNP in multilayered shield case.

Material				Thin layer (0.2 cm thick)			Thick layer (2 cm thick)		
Layer 1	Layer 2	Layer 3	Layer 4	SPK (mSv/h)	MCNP (mSv/h)	Deviation (%)	SPK (mSv/h)	MCNP (mSv/h)	Deviation (%)
Aluminum	Air	Air	Air	4.6461	4.2532	9.24	4.3223	3.7774	14.42
Aluminum	Water	Air	Air	4.5579	4.2305	7.74	4.1245	3.5594	15.88
Aluminum	Water	Lead	Air	4.1969	3.8287	9.62	1.2725	1.0971	15.99
Aluminum	Water	Lead	Concrete	4.1770	3.7778	10.57	1.1003	0.9420	16.81

errors were caused by the buildup factor used by the program. At the same time, all calculations presented in this work were carried out less than 130 ms in stylized simulation process and less than 0.5 s in PK calculation process. The computing speed of SPK code is considerably higher than those of MCNP, which make the SPK a realizable code for dynamic dose calculation.

5. Conclusions

In this paper, a fast gamma-ray dose rate shielding assessment method based on stylized model reconstruction has been developed for complex geometries. This method uses the geometric modeling capabilities of 3dsMax software to construct the 3D geometrical solid with material and radiometric attributes. In this way, the designers can implement 3D geometries visually and inspect the models from different viewpoints, at different scales and the time in the design of the geometry description was dramatically reduced. The solid models are automatically converted into stylized models based on 3D stylized model reconstruction of solid mesh. In PK calculation, the stylized source models are divided into point kernels and the mfp are calculated by the intersections between shield stylized models and tracing ray.

The proposed method has been tested in two cases: first, testing geometric modeling capability and second, comparing against commercial software MCNP codes in different radiation environment. The geometric modeling results were verified by simulating basic geometries, which include convex surface, a concave surface, flat surface and their combination. The simulation results show that the stylization algorithm can simulate original model accurately. In the dose calculation process, the dose calculation results show good correlations between SPK and MCNP, which proves the flexibility and accuracy of the SPK. It should be pointed out that the SPK generates result faster and needs less computation time in dose rate shielding calculation compared with most existing software. This code is suitable for the calculation of higher time requirement. Consequently, our next research work will focus on the dynamic dose calculation based on the stylized model reconstruction.

Acknowledgements

This research work was funded by Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Decommissioning of Nuclear Facilities and Radioactive Waste Management Research, Project supported by the Natural Science Foundation of Heilongjiang Province, China (Grant No. A2016002), the technical support project for Suzhou Nuclear Power Research Institute (SNPI) (No. 029-GN-B-2018-C45-P.0.99-00003), the Foundation of Science and Technology on Reactor System Design Technology Laboratory (HT-KFKT-14-2017003) and the project of Research Institute of Nuclear Power Operation (No. RIN180149-SCCG).

References

[1] J.F.E. Briesmeister, MCNP - A General Monte Carlo N-Particle Transport Code, 2010.
[2] A. Ferrari, P.R. Sala, A. Fasso, J. Ranft, FLUKA: A Multi-Particle Transport Code, 2005. CERN 2005-10/SLAC-R-773 preprint.
[3] D.T. Ingersoll, User's Manual for PUTZ: a Point-Kernel Photon Shielding Code, Oak Ridge National Lab., 1986.
[4] R.E. Malefant, QAD: A Series of Point Kernel General Purpose Shielding Programs, LA-3572, 1967.
[5] K.V. Subbaiah, R. Sarangapani, S. Baskar, GUI2QAD - a Graphical User Interface for Qad-Cgpic Program, Radiation Protection & Environment, 2001.
[6] K.V. Subbaiah, L. Thilagam, R. Sarangapani, D.K. Mohapatra, An inverse calculation technique for optimization of gamma ray shielding designs, Ann. Nucl. Energy 57 (2013) (2013) 246–255.
[7] T.M. Caracena, J.G.M. Gonçalves, P. Peerani, E.V.l Vida, A variable point kernel dosimetry method for virtual reality simulation applications in nuclear safeguards and security, IEEE Trans. Nucl. Sci. 60 (5) (2013) 3862–3871.
[8] O. Vela, E.D. Burgos, J.M. Perez, Dose rate assessment in complex geometries, IEEE Trans. Nucl. Sci. 53 (1) (2006) 304–311.
[9] L.Q. Yang, Y.K. Liu, M.J. Peng, M.K. Li, A gamma-ray dose rate assessment method for arbitrary shape geometries based on voxelization algorithm, Radiat. Phys. Chem. 158 (2019) (2019) 122–130.
[10] ANS-6.1.1 Working Group, M.E. Battat, American National Standard Neutron and Gamma-Ray Flux-To-Dose Rate Factors, ANSI/ANS-6.1.1-1977 (N666), American Nuclear Society, LaGrange Park, Illinois, 1977.
[11] ICRP Committee 3 Task Group, P. Grande, M.C. O'Riordan, Data for Protection against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15, ICRP-21, International Commission on Radiological Protection, Pergamon Press, 1971.
[12] ANSI/ANS-6.4.3., Gamma Ray Attenuation Coefficient and Buildup Factors for Engineering Materials, American Nuclear Society, La Grange Park in Illinois, 1991.
[13] L.A. Durani (Ed.), reportUpdate to ANSI/ANS-6.4.3-1991 for Low-Z and Compound Materials and Review of Particle Transport Theory: A Master Thesis Dissertation, Nevada University, 2009.
[14] Y. Harima, An approximation of gamma ray buildup factor by modified geometric progression, Nucl. Sci. Eng. 83 (1983) 299–309.
[15] U.T. Lin, S.H. Jiang, A dedicated empirical formula for γ-ray buildup factors for a point isotropic source in stratified shields, Radiat. Phys. Chem. 48 (4) (1996) 389–401.