Calculation for Graphite Cavity Ion Chamber Response to Cs-137 Gamma Ray using EGSnrc Monte Carlo Code

Pongphanot Rindhatayathon and Apichart Siriwitpreecha*

Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Bangkok,Thailand
*Corresponding author: E-mail: asp.kmutnb@gmail.com

Abstract

The calculation of the ionization chamber response is one factor in establishing a primary standard of air kerma in Thailand. The EGSnrc Monte Carlo code was used for calculation a cylindrical model of the ionization chamber. The chamber was computed the response by applying the Cs-137 spectrum incident on the chamber flat surface. The physical constants simulation comprises the stopping power ratio between graphite and air, the ratio of mass-energy absorption between air and graphite, the fraction of electron energy lost by bremsstrahlung production in air. The constants were calculated by a radiation key data recommendation following ICRU report 37 and ICRU report 90. Besides, Wall scattering and attenuation correction and axial non-uniformity were also calculated. The results based on ICRU report 37 are 1.0100(11), 0.9992(6), and 0.0012(2) for the stopping power, the ratio mass-energy absorption, and electron energy loss, respectively. However, the stopping power ratio following ICRU 90 is decreased by 0.78%. For the correction factor, wall scattering is 0.9623 (1), wall attenuation is 1.0671 (1), and 0.9998 (5) for axial non-uniformity. The calculation results were compared with the PENELOPE code and EGS5 code. The comparison between this work and the others do not possess a significant difference. Therefore, the result is acceptable to use for the graphite cavity ion chamber.

Keywords: *Monte Carlo, cavity chamber, EGSnrc, Cs-137*

1. Introduction

The graphite cavity ionization chamber has been used as a primary standard instrument for Air Kerma of gamma-ray. The primary standard for gamma-ray has established since 1973 by the International Bureau of Weights and Measures (BIPM) using the graphite plane-parallel plate ion chamber. The suggestion quantity of measurement is the exposure of Co-60 that means all charged particles liberated from the air when the gamma-ray passes through the medium. Furthermore, the physical constants and correction factors were recommended for calculating the quantity and corrected the result to ideal. The necessary physical constants are average energy spent by an electron of charge, e, to produce an ion pair in dry air, the ratio of the mean mass energy-absorption coefficient of air and graphite energy, and the ratio of the mean stopping power of graphite and air. The correction factors, namely wall scattering and attenuation, radius, and axial non-uniformity of the beam over the chamber, were applied for adjustment of the result to an ideal. Those were introduced by Boutillon and Niatel (1973).

Monte Carlo method has widely accepted for calculation in the field of radiation. In practically, The method is used for approximating a complicated experiment, such as axial non-uniformity, scattering and attenuation of a chamber wall, and calculating the constants for specific each ion chamber. (Rogers & Treurniet, 1999). The accuracy of the calculation is more than 0.1% (Rogers & Treurniet, 1999; Yi, Hah, & Yeom, 2006) that enough to approach the real measurement result. The EGSnrc is one popular code of Monte Carlo calculation developed by the Research Council of Canada. The code is an open-source that they have a researcher community to developed and maintain. Since the code has many libraries that suit each problem, for example, patient radiation dose when CT scan or phenomena of a chamber; thus, users can select a library suitable for their own problem.

Office of Atoms for Peace Thailand cooperate with Korea Research Institute of Standard and Science has installed the primary standard for Cs-137 gamma rays since 2017. The primary standard is a cylindrical graphite cavity chamber that has 19 mm diameter and length. The calculation of physical constants and correction factors is the first step for establishing standard cause it is necessary to evaluate Cs-137 irradiation, which uses for radiation safety in hospitals and factories.

This research presents the Monte Carlo calculation results for physical constants and correction factors by EGSnrc code. The recommendation key data for radiation fields of the International Committee of Radiation and Unit (ICRU) reports 37 and 90 are applied to calculate the mass stopping power ratio and the mass-energy absorption of graphite and air. Moreover, the fraction of electron energy lost by bremsstrahlung production in the air with wall attenuation and scattering correction and axial non-uniformity is also calculated and demonstrated in this paper.

2. Objectives

1. To propose Monte Carlo for calculation physical constants and correction factors for OAP's graphite cavity chamber and comparing the calculation result with another work.
2. To supporting to establish the primary gamma-ray standard in Thailand.

3. Materials and Methods

The ionization chamber has measured volume *V*, and the air kerma rate $\dot{K}$ can be determined as (Kessler, Burns, Li, & Wang, 2015; Kessler *et al.*, 2015)

$$\dot{K} = \frac{I}{\rho_{air} V} \frac{1}{1-\bar{g}_{air}} \frac{W}{e} \left(\frac{\mu_{en}}{\rho}\right)_{a,c} \bar{S}_{c,a} \prod_i k_i \,. \tag{1}$$

where *I* is the ionization current, W/e is the average energy sperate by an electron of charge *e* to produce an ion pair in dry air that was applied following the recommendation from the Consultant Committee for Ionizing Radiation; $\bar{g}_{air}$ is the mean fraction of electron energy lost through radiative processes in the air, $(\mu_{en}/\rho)_{a,c}$ is the ratio of the mean mass energy-absorption of air and graphite, $\bar{S}_{c,a}$ is the ratio of the mean stopping powers of graphite and air, and $\prod k_i$ is the product of the correction factors applied to the standard.

The Monte Carlo calculation was computed by the EGSnrc code, and the libraries are as follows (Kawrakow, Mainegra-Hing, Roger, Tessier, & Walters, 2020).

1. SPRRZnrc is a library for calculating the stopping power ratio base on Spencer-Attix model is expressed by
2.

$$\bar{S}_{c,a} = \frac{\int_{\Delta}^{T_{\max}} \psi_T \left\{ \left(L(\mathrm{T},\Delta)/\rho\right)_c dT + \left(S_{col}(\Delta)/\rho\right)_c \Delta \right\}}{\int_{\Delta}^{T_{\max}} \psi_T \left\{ \left(L(\mathrm{T},\Delta)/\rho\right)_a dT + \left(S_{col}(\Delta)/\rho\right)_a \Delta \right\}} \,. \tag{2}$$

Where $S_{col}(\Delta)/\rho$ is unrestricted mass collision stopping power; $L(\mathrm{T},\Delta)/\rho$ is the restricted stopping power and Δ is kinetic energy. The stopping power would be express as a ratio of graphite c and air a.

3. '*g*' code is a library for calculating $(\mu_{en}/\rho)_{a,c}$ and $\bar{g}_{air}$. This code must be in a separate calculation for each of the material interested. In this case, the calculation was done for air and graphite by the Cs-137 gamma-ray spectrum. The mass-energy absorption is integrating all energy fluence as

$$\frac{\bar{\mu}_{en}}{\rho} = \frac{\int \psi_E (\bar{\mu}_{en}/\rho) dE}{\int \psi_E dE}. \quad (3)$$

For $\bar{g}_{air}$ expressed as

$$\bar{g}_{air} = \frac{\int \psi_T (g_{air}) dT}{\int \psi_E dT}. \quad (4)$$

Where ψ_E is energy fluence of photons and ψ_T is an energy fluence of primary electrons of initial kinetic energy *T*.

4. CAVRZnrc is a library for calculating wall scattering and attenuation correction factors k_{wall} and axial non-uniformity correction factor k_{an}. The k_{wall} compensates photon energy when interacting with the chamber wall. The interaction consists of attenuation photon energy when passing through the wall and scattering with electron or atomic nuclei, the correction for the wall can be expressed by

5.

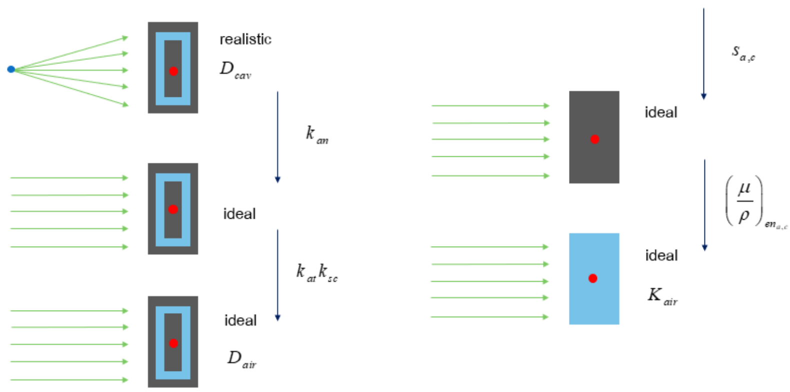
$$k_{wall} = k_{sc} k_{att} = \frac{D_{noatt,noscatter}}{D_{noscatter}} \frac{D_{noscatter}}{D_{real}}. \quad (5)$$

The calculation for axial non-uniformity was taken to account for changing realistic as a point source to an ideal that is a parallel source. Thus, the correction would be shown as

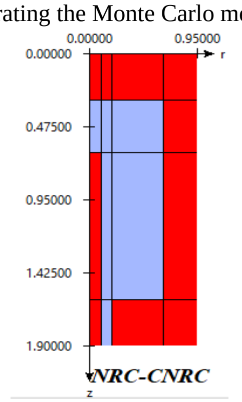
$$k_{an} = \frac{D^{parallel}_{noscatter,noatt}}{D^{point}_{noscatter,noatt}}. \quad (6)$$

where *D* is the energy deposited is as follows for each condition, where a subscript shows the condition of photons interaction, and superscript represents the characteristic.

The method of the Monte Carlo calculation is shown in Figure 1.



a) Demonstrating the Monte Carlo method for calculation



b) Model for wall correction factor and axial non-uniformity calculation

Figure 1 The method of the Monte Carlo calculation.

Figure 1 shows a step of the calculation procedure. In the first step, we calculated the axial non-uniformity correction factor to transform a point source into a parallel source. Then, the correction factor for wall scattering and attenuation was applied for compensating photon energy losses from the chamber wall. After that, the air inside the cavity was converted to whole graphite by the stopping power ratio between graphite and air and changed it as air by mass-energy transfer between air and graphite. The red point in figure 1 is an interesting point that responds to the Cs-137 gamma-ray. For $\overline{g}_{air}$ is compensates electron energy loss when they pass through the air inside the cavity (D. T. Burns, 2006).

The calculation was set ECUT (Electron energy cut) equal to 10 keV (Szymko, Michalik, Knyziak, & Wójtowicz, 2019). The graphite density is 1.700 g/cm^3 for a recommendation of ICRU reports 37 and 2.265 g/cm^3 for ICRU reports 90 (D. Burns & Kessler, 2018; Szymko et al., 2019). All coefficients were computed by the EGSnrc code and applied the Cs-137 gamma-ray spectrum into the code that shows in Figure 2. The results are compared with other codes (PENELOPE and reference article) to prove their equivalence. Furthermore, the wall and axial non-uniformity correction factors are also calculated and compare the result with the other. All calculations were computed 10^8-10^9 histories with Xenon 2.2 GHz 24 cores and spent around 2-3 hours each condition.

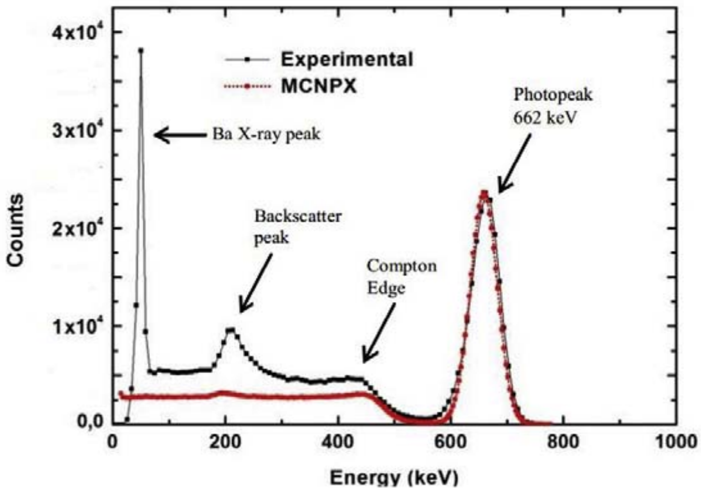


Figure 2 Cs-137 gamma-ray spectrum using in the calculation for physical constants and correction factors (Mouhti, Elanique, Messous, Belhorma, & Benahmed, 2018)

4. Results and Discussion

Table 1 shows the Monte Carlo results for the constants. They consist of the mass stopping power ratio between graphite and air, the ratio of mass-energy absorption of air and graphite, and mean fraction of electron energy lost through radiative processes in the air that configuration the codebase on ICRU report 37. The calculation results are compared with the PENELOPE code.

Table 1 The calculation results and compare with the PENELOPE code.

	This work	PENELOPE	difference
$\bar{S}_{c,a}$	1.0100 (11)	1.0099 (11)	0.01%
$\bar{\mu}_{en}/\rho$	0.9992 (6)	0.9992 (6)	0.00%
$\bar{g}_{air}$	0.0012 (2)	0.0012	0.00%

*(Kessler et al, 2010)

The international committee of unit and radiation has announced a new key data in ICRU reports 90 for the radiation field since 2016. They strongly recommend a new current of graphite is 81 eV with 3.8% the relative uncertainty. (D. Burns & Kessler, 2018, Szymko et al., 2019). The density of graphite also recommends to 2.265 g/cm^3. (only case of physical constants). Thus, the graphite properties are changed and mainly affect to the stopping power constant. New physical constants are calculated, as shown in Table 2, and compared with other works that also used EGSnrc and BIPM values.

A total difference in the calculation based on ICRU reports 37 and ICRU reports 90 is approximately 0.81%. The main difference is that the stopping power ration decreased by 0.78% while others are increased by 0.04%.

Table 2 The calculation results base on ICRU 90 and compare with other papers are accepted.

	This work	BIPM (D. Burns & Kessler, 2018)	GUM (Szymko et al, 2019)	% Diff with ICRU report 37
$\bar{S}_{c,a}$	1.0020 (36)	1.0023 (12)	1.0023 (8)	-0.78%
$\bar{\mu}_{en}/\rho$	0.9992 (6)	0.9992 (6)	0.9994 (3)	+0.02%
$\bar{g}_{air}$	0.0012 (2)	0.0012	0.0014 (2)	+0.02%

The correction factors for the cavity chamber are calculated using the model in Figure 1b. The calculation details are 1.825 g/cm^3 graphite density and 1.725 cm^3 cavity volume. Dry air at 293.15 K and 1013.25 hPa was set for the air inside the cavity. Table 3 shows the results with uncertainty inside a bracket and compares them with the EGS5 code and PENELOPE code.

Table 3 The correction factor for the wall scattering and attenuation and axial non-uniformity.

	This work	PENELOPE	EGS5
k_{sc}	0.9623 (1)	0.9552 (1)	-
k_{att}	1.0671 (1)	1.0742 (3)	k_{wall} = 1.0269 (3)
k_{an}	0.9998 (5)	1.0000 (5)	0.9999 (5)

In the case of the EGS5 code, due to the limitation of calculation, which does not separate for scattering and attenuation, the result only composited both phenomena and express it as the wall correction factor follow equation (5).

5. Conclusion

The results provide physical constants of 1.0100(11) for the mass stopping power ratio between graphite and air, 0.9992(6) for the mass-energy absorption air and graphite, and 0.0012(2) following ICRU reports 37. However, the calculation based on ICRU reports 90 is decreased by around 0.81%. The significant change is that the stopping power ratio is decreased by around 0.78% while the others are increased by 0.04%. For correction factors are 0.9623(1) and 1.0671(1) for photons scattering and attenuation at the wall, respectively and the axial non-uniformity shows the ratio between a parallel and a point source for this chamber is 0.9998(5). All calculations are compared with the PENELOPE code, EGS5 code, and reference article is no significant difference. Therefore, the calculation has proven confidence and could be applied to OAP's graphite cavity ion chamber that using for the Cs-137 gamma-ray.

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