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Photon-scattering, electron-loss and shadow-effect correction factors calculation for cylindrical free-air chamber

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ABSTRACT

A cylindrical free-air ionization chamber is used as the medium X-ray air kerma primary standard at the Institute of Nuclear Energy Research (INER, Taiwan). Photon-scattering, electron-loss and shadow-effect correction factors are taken into account for the measurement of air kerma by the cylindrical free-air ionization chamber. The photon-scattering correction factor is used to deduct the ionizations caused by scattered photons. The electron-loss correction factor compensates for the loss of electrons striking the electrode shell without fully depositing their energies to charges in the air. The shadow-effect correction factor compensates for the loss of electrons striking the collecting rod inside the chamber. The photon scattering and electron loss correction factors previously used at INER were based on a least-squares fit with experimental data published in the NBS Handbook 64. The shadow-effect correction factor was not considered.

In this study, photon-scattering, electron-loss and shadow-effect correction factors for each mono-energetic photon were calculated by a Monte Carlo code, EGS5. Then, the mono-energetic correction factors were substituted into the ISO 4037 radiation qualities spectrum, and the energy weighted correction factors were calculated. Comparing the calculated correction factors with the previous correction factors, the maximum differences were 0.51% and 1.22% for IN-250 and IN-300 radiation qualities, respectively.

In a report detailing an international comparison of air kerma standards for the ISO 4037 narrow spectrum series (EUROMET.RI(I)-S3), which was conducted from 2004 to 2005, the ratio of differences and expanded uncertainties (Di/Ui) for INER's IN-250 and IN-300 radiation qualities were 0.9 and 1.8, respectively. If the correction factors obtained in this study are substituted, the differences can be reduced, and the (Di/Ui) ratios become 0.36 and 0.6 for IN-250 and IN-300, respectively.

1. Introduction

A self-made cylindrical free-air chamber (FAC) (Attix, 1986), as shown in Fig. 1, is used as the medium energy X-ray air kerma primary standard at the Institute of Nuclear Energy Research (INER, Taiwan). The outermost layer of the FAC is a shield composed of lead and iron to block the scattered radiation from exiting. The X-ray beam passes along the FAC axis through holes in the FAC ends. The aperture diameter is 1 cm. The distance between the defined plane of the FAC and the X-ray tube focus spot is 150 cm. Two 0.00143-cm-thick graphite sheets are placed at the entrance and exit of the FAC cavity to achieve charged particle equilibrium. The chamber shell is a 30-cm-diameter cylindrical aluminum tube and is operated at high voltage (e.g., ± 3500 V). The collecting rod is made of aluminum and is located between the X-ray beam and the chamber shell. The pistons can be moved forward and back to obtain different collection volumes.

A schematic view of air kerma measurement of the cylindrical FAC is shown in Fig. 2. The volume inside the pistons is the collecting region of the chamber; therefore, moving the pistons can adjust the length of the collection chamber. First, the measurement is performed with the chamber fully open (chamber length L_1), and the collection charge is Q_1. Then, the measurement is performed with the chamber half open (chamber length L_2), and the collection charge is Q_2. Since L_2 is about half the length of L_1, the charge Q_2 is also about half of Q_1. Because the electric field distribution in the part of the cavity that is close to the pistons (the shadowed region in Fig. 2) is uneven, the charge collection would be incomplete. The collection charge measured with the chamber half open can be subtracted from the charge measured with the chamber fully open when doing calculations of air kerma. Thus, the collection charge close to the piston can be subtracted, leaving only the charge within the central portion of the chamber where the electric field is more uniform. The air kerma calculation equation is as follows:

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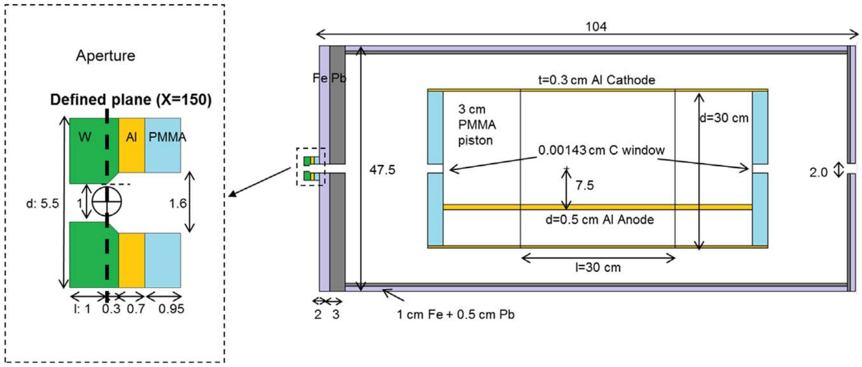

Fig. 1. Geometry of a cylindrical free-air chamber.

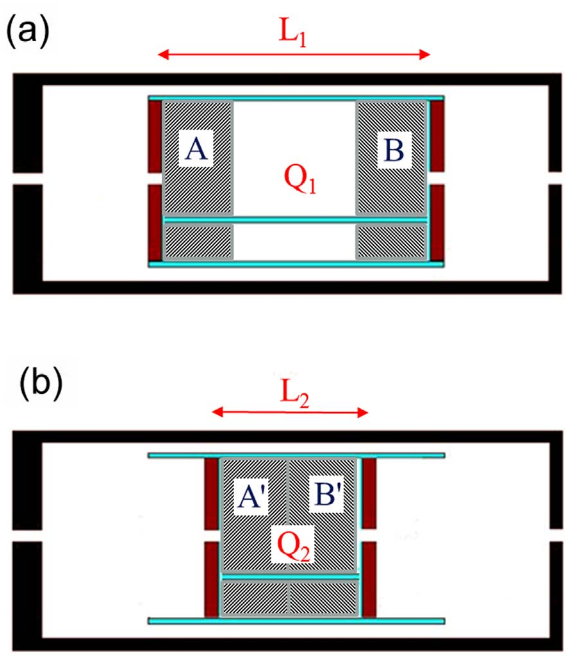

Fig. 2. Schematic diagram of air kerma measurement with a cylindrical FAC (a) fully open and (b) half open. The ionization charges from volume A' and B' are almost the same as those from volume A and B except for slight attenuation changes. Therefore, (Q_1–Q_2) can eliminate the charges from the edges.

$$K_{air} = \frac{Q_1 - Q_2}{\rho A(L_1 - L_2)} \times \frac{W/e}{1-g} \times k_{T,P} \times k_h \times \prod k_i$$

where ρ is the air density at the reference condition, A is the aperture area, W/e is the average energy imparted to the air per ion pair created, g is the bremsstrahlung correction value, $k_{T,P}$ is the temperature and pressure correction, k_h is the humidity correction, and $\prod k_i$ is the product of the FAC correction factors. The latter includes air attenuation (k_a), window attenuation (k_w), ion recombination (k_i), photon-scattering (k_{sc}), electron-loss (k_{el}) and shadow-effect (k_{sh}) correction factors, where the k_{sc} is used to deduct ionizations caused by scattered photons. k_{el} is used to compensate for the loss of electrons striking the electrode shell without fully depositing their energies to the charges in the air. k_{sh} compensates for the loss of electrons striking the collecting rod inside the chamber. The values of k_{sc} and k_{el} previously used at INER were based on the least-squares fit (Lee et al., 2005) to experimental data published in the NBS Handbook 64 (Wyckoff and Attix, 1969). k_{sh} was not previously taken into account. In this study, k_{sc}, k_{el} and k_{sh} are evaluated using Monte Carlo simulations.

The advantages of a cylindrical FAC are as follows:

(a) The effect of field distortion at the ends of the chamber can be deducted by subtracting measurements taken at different chamber lengths.
(b) In a parallel-plate FAC, the collectors must be aligned and maintained at ground potential; otherwise, electric field distortion will occur, resulting in a change in the collection volume. The cylindrical FAC does not have these problems.
(c) Since the length of the collection volume can be precisely measured, the mass of air can be defined more accurately, and the uncertainty of collection length can be reduced.

2. Material and methods

When air kerma was measured using a cylindrical free-air chamber, it was measured in two different cavity lengths. However, to simplify the simulation geometry, the calculations only considered energy deposition in the middle cylindrical volume. Fig. 3 shows the simulation arrangement, where A is the air within the scoring region, B is the chamber shell and C is the collecting rod. k_{sc}, k_{el} and k_{sh} for each mono-energetic photon were calculated by the following equations (Kurosawa et al., 2005),

$$k_{sc} = \frac{E_{ap}}{E_{ap} + E_{as}}$$

$$k_{el} = \frac{E_{ap} + E_{bp}}{E_{ap}}$$

$$k_{sh} = \frac{E_{ap} + E_{bp} + E_{cp}}{E_{ap} + E_{bp}}$$

where E_{ap}, E_{bp} and E_{cp} are the energy deposition caused by primary photons in region A, B and C, respectively, and E_{as} is the energy deposition caused by scattered photons in region A. (E_{ap}+E_{as}) represents the actual result measured in the FAC, but because the definition of air kerma does not include the energy deposition caused by scattered radiation, E_{as} must be deducted. Therefore, the photon scatter correction factor is defined as E_{ap} divided by (E_{ap}+E_{as}). The electron loss correction compensates for the underestimation of measurement that

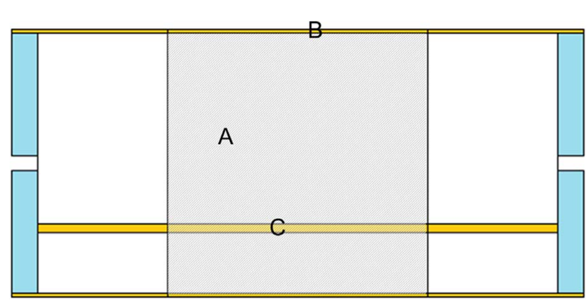

Fig. 3. Cylindrical FAC geometry for calculations (A: air within the scoring region; B: chamber shell; C: collecting rod).