Radiation Physics and Chemistry 104 (2014) 328–331

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Characterization of the new free-air primary standard for low-energy X-rays at CMI

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HIGHLIGHTS

- A new primary standard for low-energy X-ray beam constructed at CMI.
- Correction factors calculated by MCNPX simulations.
- The chamber performance tested by an informal comparison with BEV (Austria).
- The chamber considered ready for key comparison and standardization of X-ray beams.

ARTICLE INFO

Article history:
Received 24 June 2013
Accepted 1 March 2014
Available online 12 March 2014

Keywords:
Free-air chamber
FAC corrections
X-rays
Air kerma
Monte Carlo simulation
Radiation transport

ABSTRACT

In 2011 a decision was made by Czech Metrology Institute to build a free-air ionization chamber (FAC) intended to be used as a primary standard of air kerma rate for low-energy X-rays (photon energy below 50 keV, including mammography X-ray qualities) in order to replace the currently used secondary ionization chamber and to decrease the uncertainty of air kerma reference value. In the period 2011–2012, the FAC has been designed, manufactured and put into operation. Its performance was tested using a calibrated secondary chamber and then by an informal comparison with a national primary standard of BEV (Austria). Physical characteristics of the FAC are described and individual correction factors are discussed focusing on computational methods utilized in their estimation. Summary of the correction factors with the uncertainty budget is presented.

1. Introduction

Czech Metrology Institute provides the traceability for measurement instruments in radiodiagnostic qualities of X-rays by means of Czech national standard of exposure and air kerma No. ECM 440-5/11-049. This national standard has been built as a secondary standard, i.e. it is based on a set of secondary cavity ionizing chambers covering all basic photon energy regions, which are traceable to primary standards abroad. Such primary standards for the realization of radiological quantities for low and medium-energy X-rays are widely realized utilizing free-air ionization chambers (FACs).

In 2011 CMI's management made a decision to build a primary standard in the form of a FAC for low-energy X-rays. During 2011 a physical design of the FAC, solutions of important design nodes and drawings were created. The FAC was then manufactured and equipped with connectors, wires and a voltage divider. During the FAC construction precise dimension measurements using a coordinate measuring machine were performed and models of the FAC were created in the radiation transport Monte Carlo code MCNPX^{TM} (Pelowitz et al., 2011) and in the finite element analysis software QuickField^{TM} (Tera Analysis Ltd., Denmark). In 2012 simulations and experiments were performed in order to verify the expected FAC parameters and stability of measurements, and to determine the correction factor values. Finally the chamber performance was verified by comparison to a primary standard in a primary laboratory abroad.

2. Materials and methods

2.1. Free-air ionization chamber

The FAC is built in the usual way as a parallel-plane ionization chamber. A beam of X-rays enters a shielded metal box through an aperture (circular entrance opening in a diaphragm which is a high atomic number metal plate at the FAC front wall), then it travels between two parallel-plane electrodes and leaves the box through

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http://dx.doi.org/10.1016/j.radphyschem.2014.03.001
0969-806X/

an opening on the opposite side without touching the structure of the FAC. An electric field exists between these electrodes; its homogeneity is maintained by a set of guarding rings connected to have equidistantly divided polarizing potential. Electric charge released by photon interactions in the air inside the FAC is then collected by a collecting electrode and measured as ionization current (Attix, 1986; Burns and Büermann, 2009).

The value of air kerma rate, $\dot{K}_{air}$, at the aperture can be determined from measured value of ionization current I according to

$$\dot{K}_{air} = \frac{W_{air}}{e}\frac{I}{Ad\rho}\frac{\prod_i k_i}{(1-g_{air})} \quad (1)$$

The variables in Eq. (1) represent the mean energy per charge required to create an ion pair in air, W_{air}/e; air density, ρ_{air}; aperture area, A; collecting electrode length, d; mean correction for energy given to radiated photons, $(1-g)$; and correction factors k_i introduced to correct for the limitations of the FAC measured current. A comprehensive description of free-air ionization chambers is provided by Burns and Büermann (2009).

Design of the CMI's FAC was inspired by FACs already used in other primary laboratories in the world. Therefore some of CMI's FAC dimensions are almost identical to those of other FACs, especially the low-energy BIPM chamber as described by Kessler et al. (2010) and Burns et al. (2011). Fig. 1 presents a photograph of the FAC.

Table 1 summarizes a comparison of main dimensions of CMI's FAC with the selection of similar FACs for low-energy X-rays operated by other primary laboratories in the world.

Basic dimensions of CMI's FAC ensure that it can be used for photons of the energy up to approximately 50 keV. Calibration coefficient values, $N_{K,air} = (W_{air}/e)/(Ad\rho)$, for individual aperture diameters were calculated using values presented in Table 1 and the resulting values for all three aperture diameters are 3.6313×10^7, 2.3965×10^7 and 1.5955×10^7 Gy/C (for 101.325 kPa and 20 °C).

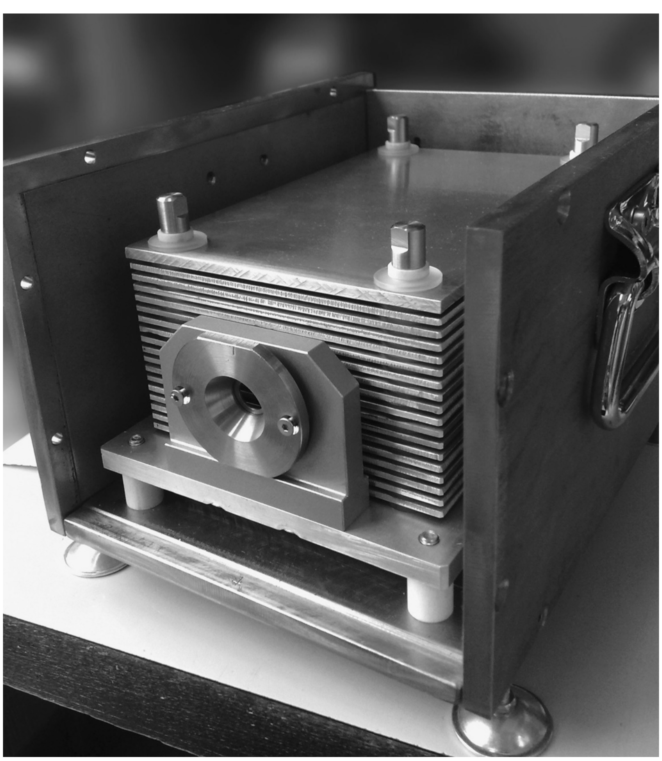

Fig. 1. A photograph of the FAC including a steel shielding box. The diaphragm holder and guarding rings are also visible.

2.2. Correction factors

Correction factors introduced in Eq. (1) correct the value of the ionization current which is influenced by the FAC construction, X-ray quality, conditions for charged particles equilibrium, air physical properties, etc. Unless a reference is given to a literature where the appropriate correction factor is discussed, a detailed description of each correction factor is presented by Burns and Büermann (2009).

The following correction factors were determined experimentally:

- k_{tp}—correction for air temperature and pressure;
- k_{pol}— correction for electric field polarity;
- k_{sat}—correction for lack of saturation, i.e. to ion recombination and diffusion before the ion reaches a collecting electrode.

The following correction factors were determined by means of Monte Carlo simulation using the MCNPX™ code:

- k_{att} —correction for primary photon attenuation in the air layer between the aperture and the collecting electrode. Primary photons are such photons which enter the FAC through an aperture and do not interact either with FAC material or with air inside FAC.
- k_{sc}—correction for scattered photons, i.e. to collected charge resulting from interactions of secondary photons. Secondary photons are such photons which enter the FAC through an aperture and interact with FAC material or with the air inside the FAC except for a collecting volume.
- k_{fl}—correction for collected charge resulting from fluorescence photons produced by photon interactions with argon in the air.
- k_e—correction for electron loss, i.e. loss of charge caused by electrons leaving the collecting volume laterally.
- k_{dtr}—correction for collected charge resulting from photons transmitted through a diaphragm (Kurosawa and Takata, 2005).
- k_{dsc}—correction for collected charge resulting from photons scattered on a diaphragm (Kurosawa and Takata, 2005).
- k_{tr}—correction for wall transmission, i.e. to collected charge resulting from photons transmitted through FAC front wall.

The following correction factors were determined using the calculations done in the software QuickField™:

- k_d—correction for electric field distortion.

The following correction factor was determined from tabulated data:

- k_h—correction for air humidity (CCEMRI, 1985);
- k_{ii}—correction for excess charge of a secondary electron collected on the collecting electrode.

2.3. Monte Carlo simulations

The Monte Carlo code MCNPX™ in version v2.7e (Pelowitz et al.) was used for the determination of several correction factors. The detailed FAC Monte Carlo model consisted of chamber shielding, tungsten diaphragm, diaphragm holder, guarding rings, parallel-plane electrodes and a collecting electrode (Fig. 2).

A point photon source was located 82.5 cm away from the aperture corresponding to the distance of 50 cm from a reference point used at CMI. Vertex angle of the conical beam was 4.2° resulting in approximately 6 cm beam diameter at the FAC front wall. Spectral fluence distributions of source photons were taken