Radiation Physics and Chemistry (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Dose mapping inside a gamma irradiator measured with doped silica fibre dosimetry and Monte Carlo simulation

F. Moradi[a], M.U. Khandaker[a,*], G.A. Mahdiraji[b,c], N.M. Ung[d], D.A. Bradley[e,f]

[a] Department of Physics, University of Malaya, Kuala Lumpur, Malaysia
[b] School of Engineering, Taylor's University, 47500 Subang Jaya, Selangor, Malaysia
[c] Flexilicate Sdn. Bhd., University of Malaya, 50603 Kuala Lumpur, Malaysia
[d] Clinical Oncology Unit, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia
[e] Department of Physics, University of Surrey, Guildford, Surrey, UK
[f] Sunway University, Institute for Health Care Development, 46150 Petaling Jaya, Malaysia

ARTICLE INFO

Keywords:
Silica fibre
Thermoluminescent dosimeter
Gammacell 220
Monte Carlo

ABSTRACT

In recent years doped silica fibre thermoluminescent dosimeters (TLD) have been demonstrated to have considerable potential for irradiation applications, benefitting from the available sensitivity, spatial resolution and dynamic dose range, with primary focus being on the needs of medical dosimetry. Present study concerns the dose distribution inside a cylindrically shaped gamma-ray irradiator cavity, with irradiator facilities such as the familiar ^{60}Co versions being popularly used in industrial applications. Quality assurance of the radiation dose distribution inside the irradiation cell of such a device is of central importance in respect of the delivered dose to the irradiated material. Silica fibre TLD dose-rates obtained within a Gammacell-220 irradiator cavity show the existence of non-negligible dose distribution heterogeneity, by up to 20% and 26% in the radial and axial directions respectively, Monte Carlo simulations and available literature providing some support for present findings. In practice, it is evident that there is need to consider making corrections to nominal dose-rates in order to avoid the potential for under-dosing.

1. Introduction

In recent years the capabilities of Ge-doped silica fibre thermoluminescence dosimeters (TLDs) have been widely studied, the results of such investigations demonstrating the excellent dosimetric performance of such media, including the high spatial resolution (Issa et al., 2013), wide dynamic dose range over which linear response is obtained (Bradley et al., 2012), low fading (Noor et al., 2012), favourable response when compared to commercial phosphor-based TLDs (Mahdiraji et al., 2015) and water resistance. Over the past decade, use of these newly developed dosimeters in practical dosimetry has been demonstrated in such areas as kilovoltage X-ray therapy (Issa et al., 2011), brachytherapy (Issa et al., 2012), external MV radiotherapy (Noor et al., 2014), interface dosimetry (Abdul Rahman et al., 2012), small field dosimetry (Jafari et al., 2014) and Intensity-modulated radiation therapy (IMRT) dosimetry (Noor et al., 2010). A practical TL dosimetry system can provide relative or absolute doses, calibration and appropriate corrections being required.

Industrial gamma irradiation facilities, with different source arrangements and geometry, have at their definitive core the irradiation cavity, often more simply referred to as the sample chamber, the resulting dose distribution changing point by point, depending on source geometry, carrier system and shielding structure. Using Monte Carlo codes and/or dosimetry systems, several earlier studies showed dose distributions for a number of irradiator types, illustrated for instance in the work of Oliveira and Salgado (2001) and Sohrabpour et al. (2002), with dose mapping reported for the respective particular irradiation facilities, UTR and IR-136. The Monte Carlo code MCNP was used in both cited studies, the results of simulation in the latter case being benchmarked against a polymethylmethacrylate (PMMA)-based dosimetry system. The Gammacell-220 (GC-220) system, a facility which is based on an arrangement of ^{60}Co γ-ray sources and is one of a number of such devices, has been widely used in various fields of radiation research, including in medicine, biology, agriculture, and investigation of radiation effects on different materials. The particular system incorporates within it a cylindrically-shaped sample chamber that is 20.6 cm long and 15.2 cm in diameter. For the purposes of irradiation, it may often be the case, allowing for fact that materials of different dimensions can be located within the sample chamber, that the distribution of dose-rate inside the chamber will

* Corresponding author.
E-mail address: mu_khandaker@um.edu.my (M.U. Khandaker).

http://dx.doi.org/10.1016/j.radphyschem.2017.01.032
Received 30 September 2016; Received in revised form 24 January 2017; Accepted 27 January 2017

need to be closely defined. Indeed, other than in particular applications in which accuracy of dose deposition is non-critical, nominal dose-rates calculated by the exponential decay law alone will not provide sufficient accuracy, as for instance in blood irradiators and in investigations of dosimetric capability of various media, with need for a close mapping of dose-rate at each point within the cavity. As an example, correction factors need to consider the effect of scattered radiation in examining the energy dependence of a dosimeter, with demand for knowledge of the energy spectrum of photons inside the irradiator.

Only a very limited number of studies are to be found in the literature that concern investigation of the dose distribution inside the GC-220 sample chamber (see for instance, Raisali and Sohrabpour, 1992; Hefne, 2000). The first of these studies reported use of the EGS4 Monte Carlo simulation code combined with comparison measurements made using Fricke (ferrous to ferric ion) dosimeters, while the second utilized only the Monte Carlo MCNP code to obtain dose-rates in a number of regions of interest inside the chamber. Present work aims to evaluate the ability of micrometer diameter doped silica fibre TLDs for the first time to obtain dose distribution inside the chamber and investigate reliability of measured doses by dosimetry system using dose distribution calculated by MCNP simulation.

2. Materials and methods

2.1. Optical fibre TL (thermoluminescence) dosimetry

The fibre samples used in this study were selected from standard single mode 125 (± 1) µm outer diameter Ge-doped fibre with doped core diameter of 8.5 (± 0.07) µm. The sample preparation procedure for dosimetry and the relevant TL characteristics have been reported earlier (Mahdiraji et al., 2015). The TLDs were prepared in 5 mm lengths and were annealed at 400 °C for 1 h in a preheated furnace. After annealing and gradual cooling down to ambient temperature (to prevent thermal shock), the samples were ready for dosimetry.

The 5 mm fibre sample were of approximate mass 0.132 (± 0.01) mg, as reported by Mahdiraji et al. (2015), but this estimation has been obtained by considering the average mass of 10–20 pieces of fibre, and precise measurement of mass for each fibre sample was not possible with available electronic scales (precision 10^{-5} g). Since the variations in fibres length (and mass) can be the cause of uncertainty in the reading of samples irradiated with the same dose, a screening process was followed. A total of 100 pieces of fibre (each 5 mm length) arranged in 5 groups (20 samples in each group) were irradiated to a sample dose of 1 Gy and then measured by a TLD reader. Samples with readings in the range of ± 1.5% were selected for the dose mapping experiment.

The selected samples were placed on small pieces of sticky (*post-it note*) paper and positioned at predefined points on the plane passing through the centre of the cylindrical sample chamber of the GC-220. To provide for this, very low density Styrofoam (used so as to not affect the existing dose distribution), was applied in fixing to it a transparent plastic sheet that actually retained the fibre samples, with the fibres positioned at 1 cm intervals (Fig. 1). Delivered dose in both the radial and axial directions on this plane was measured by the fibre TLDs. The coordinate axes are also shown in Fig. 1. The various media to be irradiated are typically positioned on the bottom surface of the Gammacell sample chamber. Therefore, the dose distribution on this surface is also needed. Fig. 2 shows the fibres arranged on the bottom surface to obtain dose-rate ratios on this plane. Using this arrangement, for each distance from the centre point on the bottom plane, 6 samples were irradiated in equal positions. 4 samples were also used at the centre point and the average of their readings was used to calculate dose rate ratios relative to the central point.

The dosimeter samples were arranged as described and the exposure time was adjusted to obtain 20 Gy nominal dose at the central point of the irradiator. The nominal dose-rate calculated by

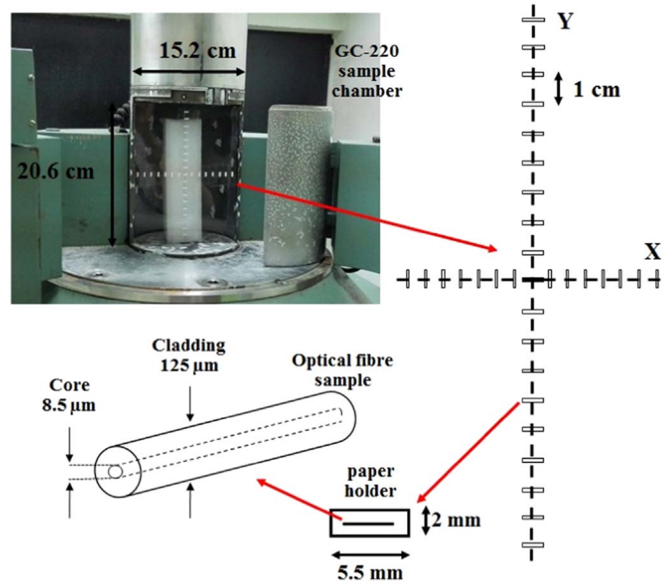

Fig. 1. Arrangement of fibre dosimeters on the vertical and horizontal axes passing through the central plane of the sample chamber.

means of the decay law at the time of experiment was 2.15 Gy/min. An Harshaw 3500 TLD reader was used for readout. In regard to the readout cycle, the samples were subjected to a pre-readout temperature of 50 °C to remove low temperature fading effects, the samples then being readout using a heating rate of 25 °C/s to reach a maximum temperature of 400 °C, producing a total readout time of 20 s.

2.2. Monte Carlo simulation

The MCNP (Monte Carlo N Particle) code (LANL, 2000), a popular 3-D simulation tool for radiation dose calculations, has been used herein to calculate dose distribution inside a Gammacell-220 irradiator because of its variety of possibilities for geometry creation, source description and output definition. Details of the geometry formed from the various components of the Gammacell-220 was derived from the information available in the instruction manual (Atomic Energy Canada, 1968). In particular the Gammacell-220 consists of 48 cylindrical ^{60}Co source elements, each of 1 cm diameter and 20.3 cm length, encapsulated in stainless steel and held in a rack, producing a cylindrical shell geometry of 10.45 cm radius as a result of the radioactive sources arrangement. The steel layer is not the only attenuating layer placed between the gamma sources and the media to be irradiated, with an additional 4 mm thick aluminum layer adding to the cylindrical sample chamber, also affecting the spectrum of particles reaching the chamber volume. The entire facility/cell is well shielded by lead and an access tube also includes lead-filled steel cylinders in the upper and lower drawers, providing acceptable radiation protection for the user in moving the sample chamber upward and downward. Fig. 3 shows the GC-220 irradiator together with the geometry modeled by MCNP code.

The material specifications, including atomic weights and mass densities, were entered into the MCNP input file. The predominant ^{60}Co gamma ray lines (1.1732 and 1.3325 MeV), which are emitted isotropically and with identical probability, complete the description of the rod-shaped sources. Two series of models were used to obtain the desired parameters. The first allowed calculation of the photon energy spectrum for the entire sample chamber volume and subsequently for a spherical cell of 2 cm radius at the centre of the sample chamber. Photon counting was performed using tally f4 and 20 keV energy intervals over the range 0–1340 keV, covering the total expected