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Mass throughput rate calculation for X-ray facilities

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Abstract In this work, the mass throughput rate in a radiation processing center, equipped with an X-ray facility, is calculated by means of a curve against the thickness of the material, along with the variation of dose uniformity. Therefore, depending on the desired dose value, the best thickness and the mass throughput rate can be calculated. The calculation results for the 5 and 10 MeV X-ray bremsstrahlung for polyethylene and wood as the irradiation products, have been obtained by using a Monte-Carlo computer code. In addition, the experimental results at the same geometry and materials were compared with those calculated.

Key words bremsstrahlung • dose uniformity • radiation processing • dynamic mode • mass throughput rate • conversion efficiency • X-ray target • Rhodotron

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Introduction

X-ray processing of products and materials is complementary to electron beam processing and is an alternative to the use of gamma rays from radioactive isotopes. The penetrating quality of high energy X-rays permits the treatment of thick objects, large packages and pellet loads of inhomogeneous products, whereas the limited range of energetic electrons favors the treatment of thin materials and small, low-density packages. However, the X-rays' throughput rate is significantly lower as compared to the electrons' throughput rate, with a higher unit cost.

An attractive feature of an electron accelerator facility with X-ray conversion equipment is the capability to treat products with either electrons or X-rays, as one desires. Whether bremsstrahlung is a practical source for industrial radiation processing is ultimately a question of the cost per unit of product treated with a specified dose. This, in turn, depends on the efficiency of conversion of electrical power to photons and the efficiency of absorption of photon energy in processed material within a prescribed maximum to minimum dose ratio [1, 2, 4, 5]. In the previous paper a user program for EGS4 computer code was introduced to calculate the dose distribution in materials for stationary irradiation case [7]. In this paper, the user code was modified to estimate the depth-dose relationship, dose uniformity ratio and the mass throughput rate for dynamic case in which the materials move under the radiation field.

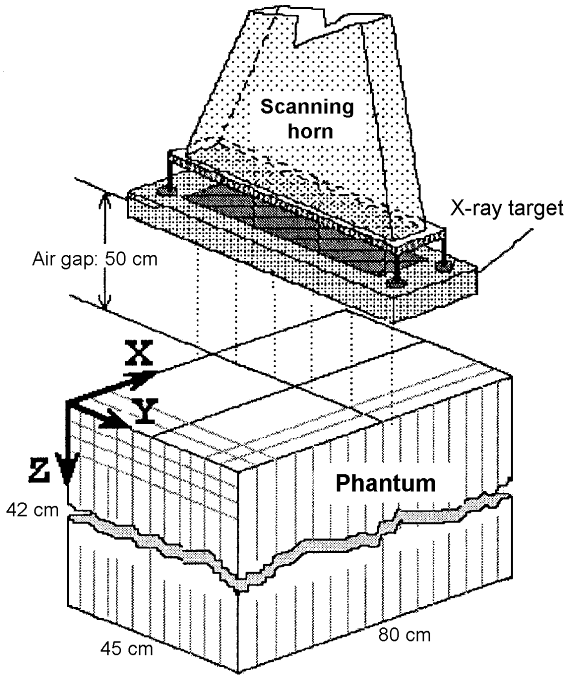

Fig. 1. Defined geometry for the code.

Experimental

The experimental parts of this work are performed with a scanned beam from a high-energy electron accelerator, Rhodotron TT200 type. The system is provided with 5 and 10 MeV electron energies with the maximum available beam current of 8 mA, and a scan width of 100 cm, at a scan frequency of 100 Hz. The accelerator is also equipped with two converter targets. Each target consists of three layers which are: tantalum sheet (main part as the X-ray converter), water channel (as the cooling system) and stainless steel sheet. These layer thicknesses are: 1.2 mm, 1.5 mm, 2 mm and 1.75 mm, 2 mm, 4 mm, for the 5 and 10 MeV electron energies, respectively. The cooling channel also serves to stop the electrons that are transmitted through the converter plate.

The scheme of the irradiation system is shown in Fig. 1. The scanning horn height is 258 cm and the lengths of both converters are 120 cm. The electron beam spot widths, on the converter surface were measured as 1.5 cm and 2.5 cm for 5 and 10 MeV electron beam, respectively. In both cases the beam spot length was 100 cm. The dosimetric methods used were as in previous publication [6]. A 50 cm air gap and a thick phantom that represents the irradiated product follow the converter. The phantoms were polyethylene and wood, which consisted of several plates with various thickness, with a 0.97 g/cm^3 and 0.5 g/cm^3 bulk density, respectively. CTA and FWT-60 film dosimeters were used in the measurements, and an UV spectrophotometer, SPECTRONIC GENESYS made in USA, is commonly used as the readout system for the dosimeters. The alanine dosimeter pellets delivered by Bruker-Company were used to calibrate the film dosimeters. The alanine dosimeter responses were measured using the BRUKER EMS-104 EPR system.

Monte-Carlo calculation

The electron/photon Monte-Carlo EGS4 computer code was used to calculate the desired parameters [3]. The EGS4 user code for stationary case simulation was introduced and published before. In the present work, the user code was modified to estimate the dynamic depth-dose relationship which is the case that the material is moving under the radiation field. In addition, mass throughput rate and dose uniformity ratio as a function of product thickness can be calculated as well. The method is that the curve areas of dose distribution along the conveyor direction for various layers of material are calculated. Then, the integrated values for each layer were assumed as the dose value at the same depth (Fig. 2). Therefore, the dose values in the depth z are calculated as

$$\text{(1)} \qquad \dot{D}(z) = \frac{1}{P \cdot T} \sum_{n} D_i(z) \cdot \Delta l \quad [\text{kGy} \cdot \text{m/kW} \cdot \text{h}]$$

where: the P is the beam power, kW; T is the irradiation time, h; Δl is the length interval along the conveyor direction, m; $D_i(z)$ is the dose values in each point along the conveyor direction at the same depth, kGy. The mass throughput rate here were defined as the amount of known products which pass the radiation field, in the unit power and conveyor speed, which absorb the amount of radiation energy. To calculate the mass throughput rate, the following relations were used:

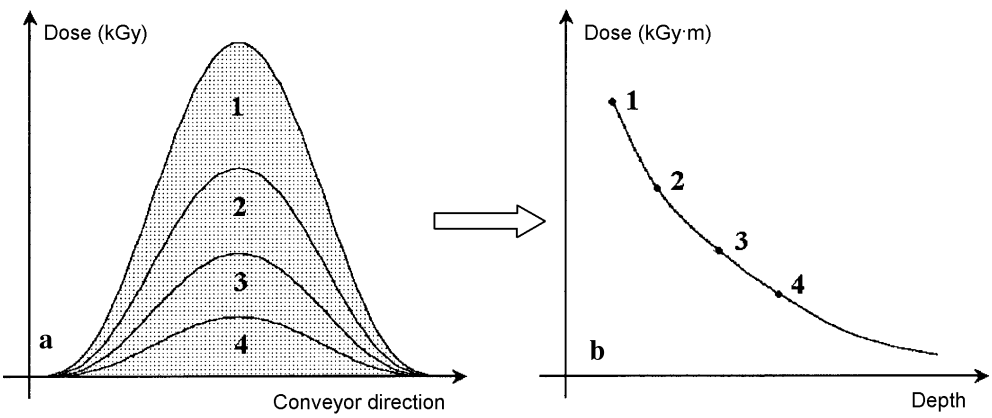

Fig. 2. a – Dose distribution in layers of material in stationary case and the curve areas; b – dynamic depth-dose curve.

(2) $$MT_{SS} = \dot{D}(t)\cdot\rho\cdot t\cdot L \quad [\mathrm{kGy\cdot m/kW\cdot h}]$$

(3) $$MT_{DS} = \dot{D}\left(\frac{t}{2}\right)\cdot\rho\cdot t\cdot L \quad [\mathrm{kGy\cdot m/kW\cdot h}]$$

where: MT_{SS} is the mass throughput rate in single-side irradiation case; MT_{DS} is the mass throughput rate in double-side irradiation case; t is the product thickness, m; ρ is the product density, Kg/m^3 and L is the scanning length, m. The dose uniformity ratios for single-side and double-side irradiation cases are calculated by

(4) $$f_{SS} = \frac{D_{\max}}{D_{\min}} \cong \frac{\dot{D}(z=0)}{\dot{D}(z=t)}$$

(5) $$f_{DS} = \frac{D_{\max}}{D_{\min}} \cong \frac{\dot{D}(z=0)+\dot{D}(t)}{2\dot{D}\left(z=\frac{t}{2}\right)}$$

where: f_{SS} is the dose uniformity ratio for single-side irradiation and f_{DS} is the dose uniformity ratio for double-side irradiation.

Measurements

In order to evaluate the calculated results, a few measurements were considered to provide the dynamic depth-dose relationship. In order to obtain the mass throughput rate curve, the mentioned formulas were used, considering the measured values as the primary data. Large volume of foodstuff materials was simulated by stacking sheets of wood or polyethylene as the irradiation phantom. The sheets sizes were 45 cm by 80 cm, and 0.5, 1 or 2 cm thick. Dosimeter strips in the cross form were spaced in depth, in order to obtain the dose distributions within the absorbing materials in two conveyor and scanning direction. Stationary exposures of the thick stacks, centered under the scanning horn or X-ray target were made [7].

On the other hand, sensitivity of CTA dosimeter changes with dose rate range of bremsstrahlung X-ray ($10^4 – 10^5$ Gy/h). Therefore, the alanine dosimeters were irradiated along with CTA under 10 MeV X-ray simultaneously, to calibrate the CTA dosimeter responses. The mentioned dosimeters were placed in a Risø made polystyrene phantom and irradiated under a few dose values. The alanine dosimeters were read out using an EPR system, and the dose values were obtained using the calibration curve prepared by irradiated alanine dosimeters submitted by the Bruker. Thus, the resulted dose values were assigned to the CTA film dosimeters and the calibration curve was drawn consequently.

Results and discussion

Depth-dose curves in stationary and dynamic mode for 5 and 10 MeV X-ray are shown in Figs. 3 and 4, respectively*. The experimental and calculated results are in good agreement except for the region below the 5 cm product thickness. This is due to the fact that in the defined geometry for EGS4 code, the height of unit cells in the z direction (depth) was not defined as short enough to calculate the same results as experimental one. In fact, in order to calculate the precise results for this region the interval should be consider shorter and, in turn, it will need a longer computer run time to calculate the dose values with an acceptable uncertainty. On the other hand, due to the high penetration of high energy X-ray in material the low depth was not expected. Figures 5, 6 and 7 show the obtained mass throughput

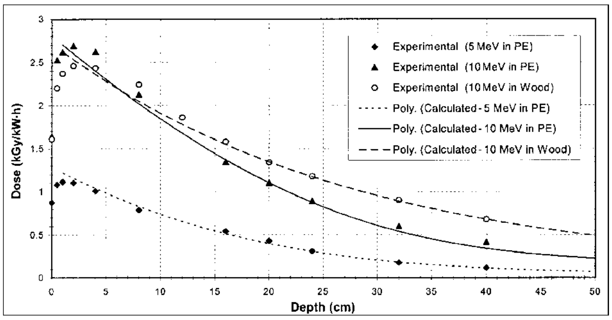

Fig. 3. Stationary mode depth-dose curve in polyethylene and wood phantoms for 5 and 10 MeV e/X-ray.

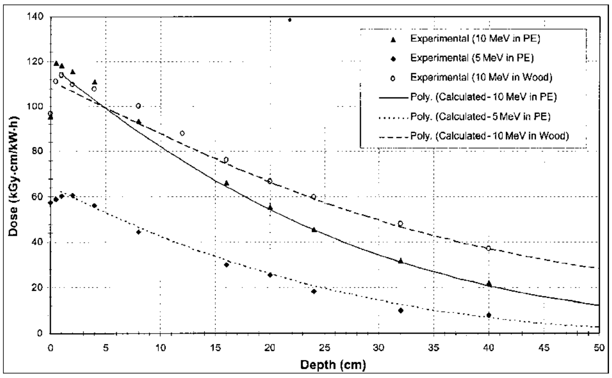

Fig. 4. Dynamic mode depth-dose curve in polyethylene and wood phantoms for 5 and 10 MeV e/X-ray.

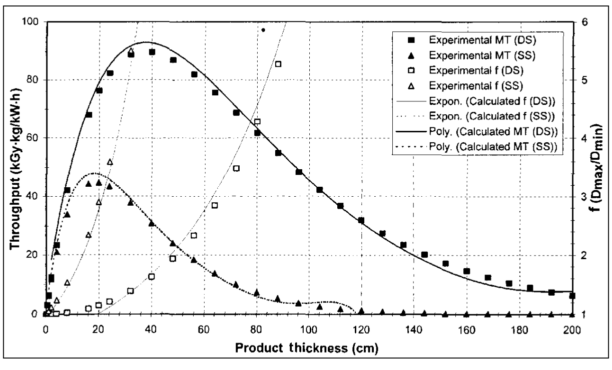

Fig. 5. Throughput and dose uniformity ratio for 5 MeV e/X-ray in polyethylene phantom.

* All of the calculated results were shown by using the fitted polynomial or exponential curves.

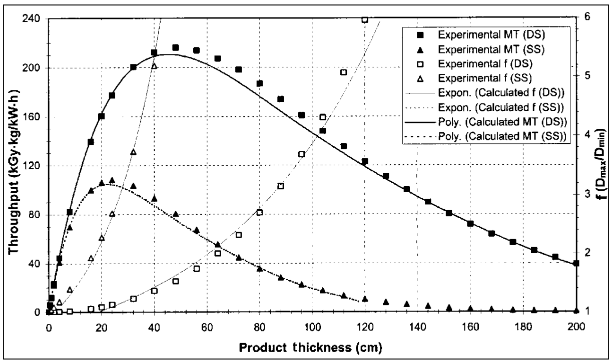

Fig. 6. Throughput and dose uniformity ratio for 10 MeV e/X-ray in polyethylene phantom.

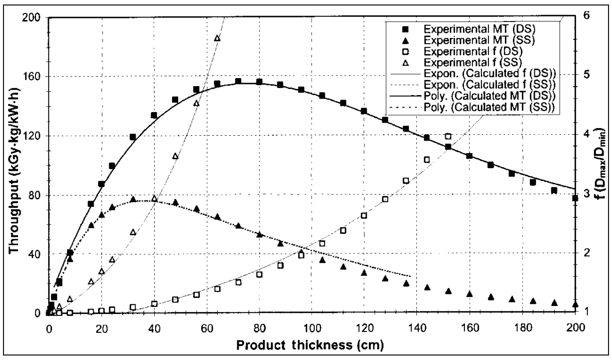

Fig. 7. Throughput and dose uniformity ratio for 10 MeV e/X-ray in wood phantom.

rate and the dose uniformity ratio for single- and double-side irradiation for the 5 and 10 MeV X-ray in polyethylene and wood phantoms as the irradiated product. In these figures, the calculated and measured results were compared and shown good agreement, as well. In both cases the extreme differences between the dose uniformity ratio for single- and double-side irradiation case were obtained. Thus, double-side irradiation could be recommended because of the lower dose uniformity ratio.

Conclusion

The modified user code can be useful to get a fast and good estimation for dynamic depth-dose relationship and especially the mass throughput rate for any new materials. This method is also very useful to choose the efficient beam parameters, conveyor speed, considering the dose uniformity ratio in each chosen value for mass throughput rate. On the other hand, by estimation the mass throughput rate, we can evaluate the product irradiation unit cost in a radiation processing plant.

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