Study on Radon Concentration inside Building Materials by Experiment and Simulation using Gamma-ray Spectrometry: Influence of the Moisture and Porosity

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1. Introduction

Various estimation methods have been developed for radon exhalation from building materials and soils. Recently, a new method using only gamma detectors has been proposed by A. Awhida.[1] In a previous study by Seyoung Yu[2], the gamma peaks of radon progenies in building materials was analyzed using NaI(Tl) detectors. The study evaluated the gamma-ray spectrum of radon-emitting samples, assuming closed and open surface conditions, using Monte Carlo simulation (MCNP6.2). The relative ratios of open-closed measurements for radon progeny by energy was compared as in Figures 1 and 2.

In this paper, to evaluate the radon depth profile in the building material, the radon diffusion model with various moisture contents and porosities within the sample is studied. Monte Carlo simulation results of the ratios of gamma peaks from radon progenies are presented for various values of moisture and porosity.

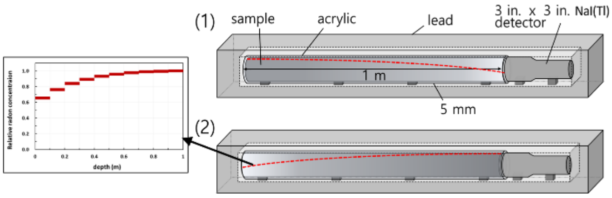

Fig. 1. Building material and NaI(Tl) detector layout used in MCNP (1) measurement on an open surface (2) measurement on a closed surface

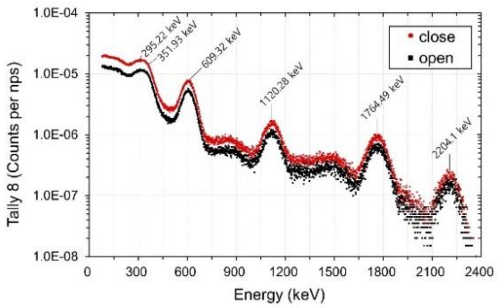

Fig. 2. Simulated gamma peaks of radon progenies (comparison between open/closed surface measurements)

2. Materials and Methods

2.1 Radon Diffusion model

Radon (^{222}Rn), produced from the decay of ^{226}Ra, can diffuse through the air within the sample. The radon diffusion equation in the sample is expressed as follows:

$$(1)\ D_e \frac{\partial^2 C_e(x)}{\partial x^2} - \lambda C_e(x) + \lambda C_{max} = 0$$

$$(2)\ D_e = D_{a0} p \exp\left(-6mp - 6m^{14p}\right)$$

$$(3)\ \epsilon = f_0\{1 + a[1 - \exp(-bm)]\}[1 + c(T - 298)]$$

$$(4)\ L = \sqrt{\frac{De}{\lambda}}$$

Where D_e is the effective diffusion coefficient, ϵ is the emanation coefficient, λ is the decay constant of ^{222}Rn, L is the radon diffusion length, m is the moisture content in the sample, and p is the porosity of the sample. Additionally, the parameters f_0, a, b and c are emanation parameters related to grain size of the sample.[3]

The general solution of Eq. (1) with boundary conditions ($C_e(0) = 0, \partial C_e(H)/\partial x = 0$) is as follows:

$$(5)\ C_{ne} = C_{Ra}(1 - \epsilon)$$

$$(6)\ C_e(x) = C_{Ra}\epsilon\left(\tanh\left(\frac{H}{L}\right)\sinh\left(\frac{x}{L}\right) - \cosh\left(\frac{x}{L}\right) + 1\right)$$

$$(7)\ C_{tot} = C_{ne} + C_e(x) = C_{Ra}\left(1 + \varepsilon\tanh\left(\frac{H}{L}\right)\sinh\left(\frac{x}{L}\right) - \varepsilon\cosh\left(\frac{x}{L}\right)\right)$$

Where H is the height of the sample. Radon exists in both the particle (C_{ne}) and the air within the sample (C_e). Therefore, the total radon concentration in the sample (C_{tot}) is sum of C_{ne} and C_e.[1]

Due to ϵ and D_e are functions of moisture and porosity, the radon depth profile was evaluated based on radon diffusion model with varying moisture content and porosity within the sample, as shown in Figure 3.

2.2 Monte Carlo Simulation

In MCNP6.2[4] Monte Carlo simulation, two NaI(Tl) gamma spectra were taken: one with the detector on the open surface and the other with the detector on closed surface.

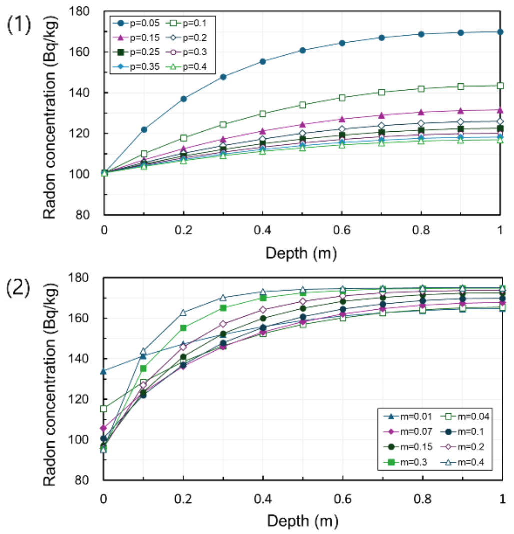

Fig. 3. The radon depth profiles based on the radon diffusion model: (1) with various values of porosity (moisture m = 0.1), (2) with various values of moisture content (porosity p = 0.05)

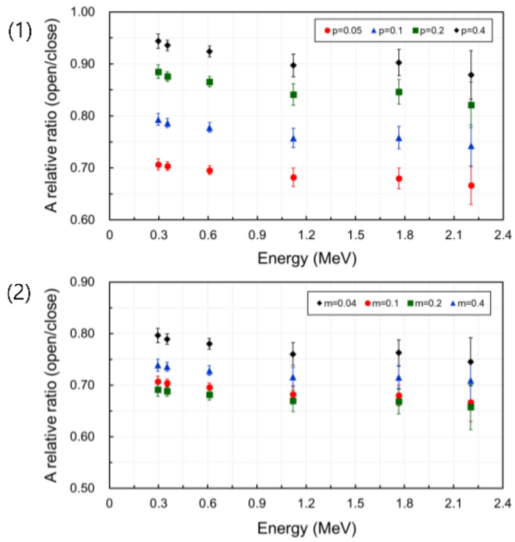

Fig. 4. Open/closed peak ratios of radon progenies by energy: (1) with various values of porosity, (2) with various values of moisture content

The measurement system is made of a cement sample (1 m × Φ 0.07 m), an acrylic cylinder (5 mm thick, only one side open), and a 3 x 3 inch NaI(Tl) detector whose resolution data are taken from Maeng's study[5]. All of the system is surrounded by lead shield as shown in Figure 1.

We assumed equilibrium between radon and its progenies in the sample, the source nuclides of interest are ^{214}Pb (with γ-ray energies of 295.22, 351.93 keV) and ^{214}Bi (with 609.32, 1120.28, 1764.49, 2204.1 keV). The radon concentration for each case was calculated by dividing the sample into 10 regions based on the radon diffusion model, and the relative radon concentration was input in the MCNP. For spectral results F8 tally was used.

3. Results and Discussions

Monte Carlo simulation results of the relative ratios of open-closed measurements from radon progenies were evaluated for various values of moisture and porosity as in Figure 4. From the results, one can tell as porosity increases the relative peak ratio increases. In addition, the theoretical values derived from the radon diffusion model and Monte Carlo simulation result were compared in Figure 5.

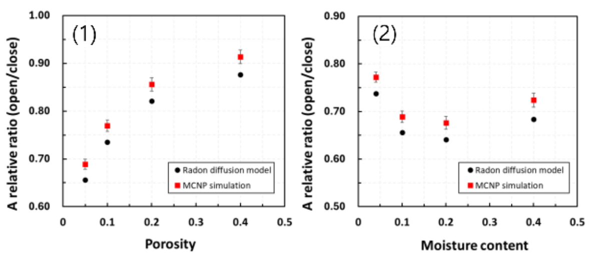

Fig. 5. Comparison between theoretical values derived from the radon diffusion model and results from MCNP simulations: (1) with varying porosity, (2) with varying moisture content

For instance, at a moisture value of 0.1 and porosity is 0.2, the average ratio of open-closed gamma peaks is 0.856 ± 0.014, differing about 4.3 % from the radon diffusion model. Similarly, with a porosity of 0.05 and moisture of 0.4, the average ratio is 0.684 ± 0.010, differing about 5.9 % from the radon diffusion model.

4. Conclusions

In this study, the depth profile was evaluated from the radon diffusion model with varying moisture contents and porosities. Additionally, Monte Carlo simulation results for the gamma peak ratio of radon progenies were calculated and confirmed a difference of 4 ~ 6 % from the diffusion model. This will provide valuable data for evaluating radon concentration inside building materials with various moisture content and porosity.

In the future, we will focus on the reliability of simulations by conducting experiments and continue to invent a new methodology of finding radon concentration and surface exhalation rate of building material by external gamma spectrometry.

REFERENCES

[1] A.Awhida. et al., Novel method of measurement of radon exhalation from building materials, Journal of Environmental Radioactivity, Vol. 164, p. 337-343, 2016.
[2] 유세영 외, 감마선 분광분석 측정과 전산모사를 이용한 라돈 농도 평가에 관한 사전 연구, 2023 대한방사선방어학회 추계학술대회 논문요약집, p. 500-501, 2023.
[3] Griffiths,A.D. et al., A map of radon flux at the Australian land surface, Atmos. Chem. Phys., 10, 8969–8982, 2010.
[4] C. J. Werner. et al., MCNP User's Manual Code Version 6.2, Los Alamos National Laboratory, LA-UR-17-29981, 2017.
[5] S.Maeng. et al., Detection efficiency evaluation for low energy of a NaI(Tl) scintillation detector, Radiation Physics and Chemistry, Vol. 199, 110325, 2022.