

## Study on the Method for Simultaneous Regulation of $^{222}\text{Rn}/^{220}\text{Rn}$ Progeny Activity Concentration in a $^{220}\text{Rn}$ Chamber

**Authors:** Ao, Mr. Tao, Xiao, Ya-Song, Xu, Ms. Jing-Yi, Pei, Ms. Jing-Yue, Liu, Mr. YuFan, Feng, Jia-Lu, Wang, Miss Kexin, Lv, Mrs. Lidan, He, Prof. Zhengzhong, Lv, Mrs. Lidan

**Date:** 2025-04-28T12:34:07+00:00

### Abstract

The activity concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny is the critical parameter for precise estimation of internal radiation dose to lung tissues. To investigate the behavior of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny and to improve the calibration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration monitors, a  $^{220}\text{Rn}$  chamber that could generate stable and adjustable activity concentrations of both  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$  progeny was established. This study developed a theoretical model for  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations in the  $^{220}\text{Rn}$  chamber and established a simultaneous regulation method for these concentrations. Based on a tunable carrier aerosol generation system, comprehensive tests were conducted to evaluate the stability and spatial uniformity of aerosol concentrations,  $^{222}\text{Rn}/^{220}\text{Rn}$  gas concentrations, and progeny activity concentrations within the chamber. The results show that the  $^{220}\text{Rn}$  chamber can realize the stable regulation of aerosol particle number concentration in the range of 101 particles/cm<sup>3</sup>-105 particles/cm<sup>3</sup>, and realize the activity concentration range of  $^{222}\text{Rn}$  progeny ( $^{218}\text{Po}$ ,  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ) in the range of 268 Bq/m<sup>3</sup>-12351 Bq/m<sup>3</sup>, 18 Bq/m<sup>3</sup>-5573 Bq/m<sup>3</sup>, 8 Bq/m<sup>3</sup>-3868 Bq/m<sup>3</sup>, and the activity concentrations of  $^{220}\text{Rn}$  progeny ( $^{212}\text{Pb}$ ,  $^{212}\text{Bi}$ ) range from 53 Bq/m<sup>3</sup>-1217 Bq/m<sup>3</sup>, 10 Bq/m<sup>3</sup>-794 Bq/m<sup>3</sup>. Except for the poor stability of activity concentration of  $^{214}\text{Bi}$  and  $^{212}\text{Bi}$  at low aerosol concentration, the stability of activity concentration of all other subsomes is better than 10% in other cases. And the results demonstrate that the spatial uniformity of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations is better than 10% throughout the chamber, ensuring homogeneous distribution of progeny species. In conclusion, the simultaneous regulation method for  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny concentrations developed in this study provides a reliable platform for instrument calibration and performance verification.

## Full Text

# Study on the Method of Simultaneous Regulation of $^{222}\text{Rn}/^{220}\text{Rn}$ Progeny Activity Concentration in a $^{220}\text{Rn}$ Chamber

Tao Ao<sup>1</sup>, Ya-Song Xiao<sup>1</sup>, Jing-Yi Xu<sup>1</sup>, Jing-Yue Pei<sup>1</sup>, Yu-Fan Liu<sup>1</sup>, Jia-Lu Feng<sup>1</sup>, Ke-Xin Wang<sup>1</sup>, Li-Dan Lv<sup>1,†</sup>, and Zheng-Zhong He<sup>1</sup>

<sup>1</sup>School of Nuclear Science and Technology, Hunan Provincial Key Laboratory of Radon, University of South China, Hengyang, Hunan Province, 421001, China

The activity concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny is a critical parameter for precise estimation of internal radiation dose to lung tissues. To investigate the behavior of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny and to improve the calibration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration monitors, a  $^{220}\text{Rn}$  chamber that could generate stable and adjustable activity concentrations of both  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$  progeny was established. This study developed a theoretical model for  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations in the  $^{220}\text{Rn}$  chamber and established a simultaneous regulation method for these concentrations. Based on a tunable carrier aerosol generation system, comprehensive tests were conducted to evaluate the stability and spatial uniformity of aerosol concentrations,  $^{222}\text{Rn}/^{220}\text{Rn}$  gas concentrations, and progeny activity concentrations within the chamber.

The results show that the  $^{220}\text{Rn}$  chamber can achieve stable regulation of aerosol particle number concentration in the range of  $10^1$ – $10^5$  particles/cm<sup>3</sup>, and realize the activity concentration range of  $^{222}\text{Rn}$  progeny ( $^{218}\text{Po}$ ,  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ) as 268–12,351 Bq/m<sup>3</sup>, 18–5,573 Bq/m<sup>3</sup>, and 8–3,868 Bq/m<sup>3</sup>, respectively, and the activity concentrations of  $^{220}\text{Rn}$  progeny ( $^{212}\text{Pb}$ ,  $^{212}\text{Bi}$ ) in the range of 53–1,217 Bq/m<sup>3</sup> and 10–794 Bq/m<sup>3</sup>. Except for the poor stability of activity concentration of  $^{214}\text{Bi}$  and  $^{212}\text{Bi}$  at low aerosol concentration, the stability of activity concentration of all other species is better than 10% in other cases. The results demonstrate that the spatial uniformity of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations is better than 10% throughout the chamber, ensuring homogeneous distribution of progeny species.

In conclusion, the simultaneous regulation method for  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny concentrations developed in this study provides a reliable platform for instrument calibration and performance verification.

**Keywords:**  $^{220}\text{Rn}$  progeny;  $^{222}\text{Rn}$  progeny; activity concentration; simultaneous regulation

*These authors contributed equally to this work.*

## INTRODUCTION

Radon ( $^{222}\text{Rn}$ ), thoron ( $^{220}\text{Rn}$ ), and their decay progeny constitute significant sources of ionizing radiation. During radioactive decay, these nuclides emit  $\alpha$  or  $\beta$  particles. When these particles traverse cellular structures, they interact with biological tissues in the lungs, potentially causing DNA damage and increasing cancer risks. According to the report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR),  $^{222}\text{Rn}$  is the second largest contributor to lung cancer [1, 2]. When inhaled by the human body,  $^{222}\text{Rn}$ ,  $^{220}\text{Rn}$ , and their radioactive progeny attach to aerosol particles that deposit in distinct regions of the respiratory tract according to particle size distribution, thereby creating internal radiation exposure. The activity concentrations of  $^{222}\text{Rn}$ ,  $^{220}\text{Rn}$ , and their decay products constitute critical parameters for internal radiation dose assessment, and therefore,  $^{222}\text{Rn}$ ,  $^{220}\text{Rn}$ , and their progeny activity concentrations in a typical environment need to be determined. To ensure the measurement reliability and accuracy of instruments and meet their calibration requirements, it is essential to establish a  $^{220}\text{Rn}$  chamber that can stably regulate various activity concentrations of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny.

The  $^{222}\text{Rn}/^{220}\text{Rn}$  chamber serves as an important part of the  $^{222}\text{Rn}/^{220}\text{Rn}$  metrology system and can provide a reference for testing and calibrating  $^{222}\text{Rn}/^{220}\text{Rn}$  detectors. Extensive research on  $^{222}\text{Rn}/^{220}\text{Rn}$  has been conducted both domestically and internationally [3–7], and the variation of  $^{222}\text{Rn}/^{220}\text{Rn}$  concentration and their progeny concentration is mainly studied by modulating the aerosol particle number concentration, air exchange rate, and  $^{222}\text{Rn}/^{220}\text{Rn}$  production rate. At present, a number of countries have established  $^{222}\text{Rn}$  or  $^{220}\text{Rn}$  chambers to study the behavioral characteristics of  $^{222}\text{Rn}/^{220}\text{Rn}$  and their progeny. Canada was the first to build  $^{220}\text{Rn}$  chambers in 1984 [8], followed by the German PTB in 1999 to establish a national radon and its progeny activity concentration standards, with an internal volume of 21.035  $\text{m}^3$  and external dimensions yielding a total volume of 26.28  $\text{m}^3$  for the radon calibration chamber [9, 10]. The University of South China also conducted earlier research on  $^{222}\text{Rn}/^{220}\text{Rn}$  and established a small  $^{220}\text{Rn}$  accumulation tank in 2002 to achieve uniform distribution of  $^{220}\text{Rn}$  as well as a stable concentration level by charging the source and recirculating the airflow loop [11]. Later, in 2003, the German PTB built a set of simple  $^{220}\text{Rn}$  chambers with a volume of 0.1  $\text{m}^3$  in order to study the relationship between aerosol concentration and the share of unbound states of  $^{220}\text{Rn}$  progeny [12]. The Korea Research Institute of Standards and Science established a 50.05  $\text{m}^3$  radon calibration room in 2004 to study the behavioral characteristics of radon decay products, which can achieve stable regulation of temperature and humidity [13]. In 2005, Japan established a  $^{220}\text{Rn}$  chamber with a volume of 150 L based on NIR spectroscopy, and the  $^{220}\text{Rn}$  concentration can be adjusted in the range of 0.9–45  $\text{kBq}/\text{m}^3$ , which can realize stable  $^{220}\text{Rn}$  progeny [14, 15]. It also established a simple  $^{220}\text{Rn}$  chamber with a volume of 1  $\text{m}^3$  in 2005, which can stabilize the radon concentration from about 200  $\text{Bq}/\text{m}^3$  to about

10 kBq/m<sup>3</sup> by using the accumulation of a solid source of <sup>226</sup>Ra supplied by the Pylon company [16].

In order to meet the needs of the development of national standards for radon and its progeny in China, the National Institute of Metrology developed a set of radon chambers with a volume of about 20 m<sup>3</sup> in 2015 to realize the stable regulation of radon progeny concentration and equilibrium factor in a wide range [17]. In 2017, Poland, in order to solve the problem of radon hazards during underground mining, established a radon chamber with a volume of 17 m<sup>3</sup> and capable of remotely adjusting the temperature and humidity range, which can achieve stable regulation of indoor radon concentration [18]. In 2018, Hirosaki University, Japan, established an exposure chamber with a volume of 0.00676 m<sup>3</sup> for calibration of radioactive gas monitoring instruments, which can be adjusted to maintain the concentration level of <sup>222</sup>Rn at 0.2–10 kBq/m<sup>3</sup> and <sup>220</sup>Rn at 3.5–29 kBq/m<sup>3</sup> [19]. In 2021, Jian Lin from the University of South China, in order to study the behavioral characteristics of unattached fraction <sup>220</sup>Rn progeny, established <sup>220</sup>Rn chambers that can stably regulate the share of different unattached fractions of <sup>220</sup>Rn progeny [20]. In the following year, Lidan Lv from the University of South China constructed a thorium chamber capable of realizing <sup>220</sup>Rn regulation in the range of 3.2–37 kBq/m<sup>3</sup> in order to investigate the response of diffusion-type detectors to the concentration of <sup>220</sup>Rn under different wind speeds. The stability and uniformity of the <sup>220</sup>Rn concentration in the chamber were within 5% [21]. At present, these <sup>222</sup>Rn chambers and <sup>220</sup>Rn chambers mainly regulate the concentrations of <sup>222</sup>Rn, <sup>220</sup>Rn, and their progeny individually by controlling environmental factors such as aerosol concentration, temperature, and humidity, and a few <sup>222</sup>Rn chambers and <sup>220</sup>Rn chambers also regulate the share of unattached fraction of the <sup>222</sup>Rn progeny and <sup>220</sup>Rn progeny. However, most studies only examined <sup>222</sup>Rn or <sup>220</sup>Rn alone and did not combine the two. Moreover, the simultaneous presence of <sup>222</sup>Rn/<sup>220</sup>Rn both cross-interfered with the measuring instrument [29], with the presence of <sup>220</sup>Rn interfering most significantly with the measurement of <sup>222</sup>Rn in the low-energy region [22].

Based on the behavioral characteristics of <sup>222</sup>Rn/<sup>220</sup>Rn progeny aerosols, this study establishes a control scheme and theoretical model for the simultaneous regulation of indoor <sup>222</sup>Rn and <sup>220</sup>Rn progeny activity concentrations. Through performance testing, the feasibility of the control scheme was confirmed to meet the calibration requirements of instruments measuring characteristic parameters of <sup>222</sup>Rn/<sup>220</sup>Rn and their progeny. Furthermore, it can provide an experimental setting to evaluate the cross-talk signal between <sup>222</sup>Rn and <sup>220</sup>Rn, leading to a more accurate estimation of the individual dose due to <sup>222</sup>Rn, <sup>220</sup>Rn, and their progeny.

## II. MATERIALS AND METHODS

### A. Setting up Experimental Environment

**1. Setting up  $^{220}\text{Rn}$  Injection Chamber Environment** This experiment mainly relies on the  $^{220}\text{Rn}$  chamber of the University of South China. Figure 1 [Figure 1: see original paper] shows the structural layout of the  $^{220}\text{Rn}$  jet gas chamber, which is mainly composed of the calibration chamber and progeny source chamber. The calibration chamber is a rectangular solid with a volume of 1539 L; the progeny source chamber is mainly composed of a cylinder in the middle (Diameter: 600 mm, Length: 1200 mm) and a round table at both ends (the diameter of the lower base is 60 cm and the diameter of the upper base is 25 cm), with a volume of 443 L. The calibration chamber contains a fan-type  $^{220}\text{Rn}$  source with an activity of 3000 Bq, and the progeny source chamber contains a solid flow-gas  $^{222}\text{Rn}$  source and a solid flow-gas  $^{220}\text{Rn}$  source made by the Radon Laboratory at the University of South China, with a flow-gas  $^{222}\text{Rn}$  source activity of 6700 Bq and a flow-gas  $^{220}\text{Rn}$  source activity of 32000 Bq [23]. This streaming gas  $^{220}\text{Rn}$  source has been measured over 5 years of periodic testing and the injection coefficient has stabilized at  $96.5\% \pm 3\%$  with a measurement uncertainty of less than 2.5%.

Driven by micro vacuum pump A (Lab LP02-D12, Kamoer, Inc., China), the gas flowed through the  $^{222}\text{Rn}$  source,  $^{220}\text{Rn}$  source, and then into the progeny source chamber. Given the short half-life of 55.6 s for  $^{220}\text{Rn}$ , the  $^{220}\text{Rn}$  decays into its progeny within the progeny chamber prior to entering the calibration chamber, thereby significantly reducing the equilibration time. The progeny chamber is connected to the calibration chamber via a source-charging circuit that requires continuous operation to maintain stable  $^{222}\text{Rn}/^{220}\text{Rn}$  concentrations.

The measurement of  $^{222}\text{Rn}/^{220}\text{Rn}$  and their progeny activity concentrations is primarily conducted in the calibration chamber. A set of analog sampling loop was connected externally to the calibration chamber. The gas inside was continuously drawn by a micro vacuum pump (Lab LP02-D12, Kamoer, Inc., China), filtered through a high-efficiency filter (filtration efficiency greater than 99%), and then injected back into the progeny source chamber. The analog sampling loop simulates the loss of progeny due to sampling and avoids fluctuations in progeny activity concentration caused by sampling. Two fans were installed to ensure homogeneous aerosol distribution throughout the calibration chamber by maintaining airflow. The aerosol regulation system was positioned at the extreme left end of the progeny source chamber. An exhaust port was installed in the calibration chamber to connect with the external environment, maintaining pressure balance in the  $^{220}\text{Rn}$  chamber. A thermohygrometer (Model 608-H2, Testo AG, Germany) was installed in the calibration chamber to observe temperature and humidity changes during the experiment through a glass window.

**2. Setting up Aerosol Environment** The aerosol source used in this study was solid particulate matter produced by the combustion of smokeless sandal-

wood, which has the advantage of continuous aerosol production over a long period of time. A scanning mobility particle sizer (SMPS, Model 3190, TSI Inc., USA) was used to measure the particle size of the aerosol source, which had a median diameter of about 150 nm. This source demonstrates superior performance in sustained aerosol generation over prolonged durations. In order to continuously feed a stable aerosol into the  $^{220}\text{Rn}$  chamber, an aerosol dilution device was built in this study, as shown in Figure 2 [Figure 2: see original paper]. The aerosol dilution device mainly consists of an aerosol dilution chamber (with a volume of 128 L), a sandalwood combustion hood, two constant flow vacuum pumps with adjustable flow rates, and a filter. After lighting the sandalwood, driven by micro vacuum pump D (Lab LP02-D12, Kamoer, Inc., China), the solid particles generated by the sandalwood combustion enter the aerosol dilution chamber through three-way valve switch K1, and air enters the aerosol dilution chamber through three-way valve switch K2. The aerosol enters the progeny source chamber driven by vacuum pump D. The analog sampling loop is composed of a micro vacuum pump C (Lab LP02-D12, Kamoer, Inc., China) and a filter. By regulating the flow rate of micro vacuum pump C, the aerosol concentration within the dilution chamber can be controlled. In this study, aerosol concentration measurements were performed using a portable particle counter (Model 3007, TSI Inc., USA), which operates as a condensation nucleus counter (CPC). It is worth noting that the sandalwood needs to be replaced every 4 hours.

## B. Measurement of the Activity Concentration of $^{222}\text{Rn}/^{220}\text{Rn}$ and Its Progeny

**$^{222}\text{Rn}/^{220}\text{Rn}$  Concentration Measurement** A RAD7 (RAD7, DUR-RIDGE Inc., USA) was used as the instrument for continuous measurement of  $^{222}\text{Rn}/^{220}\text{Rn}$  concentrations in the  $^{220}\text{Rn}$  chamber. The detector sensitivity was 0.4 cpm/(pCi · L) in conventional measurement mode. The RAD7 was initially connected to a large drying tube to establish a closed-loop circulation system. When the displayed humidity decreased below 10%, the large drying tube was replaced with a small one while maintaining airtight connections at all joints. This measurement procedure was repeated until the humidity stabilized below 10%. Corrections to the measurements are required as the flow rate, drying tube volume, and pipe volume can affect the measurements [24]. Firstly, a decay correction is applied to the  $^{220}\text{Rn}$  source activity:

$$C_{Tn} = C_{Tn0} \cdot e^{-\lambda V}$$

The activity  $C_{Tn0}$  of  $^{220}\text{Rn}$  is 1600 Bq/m<sup>3</sup>; the decay constant  $\lambda$  of  $^{220}\text{Rn}$  is 0.0125 s<sup>-1</sup>; the total volume  $V$  of the pipe and the small drying tube is 0.045 L; and the sampling flow rate  $v$  is 0.74 L/min. Based on the average indications of  $C_{Tn}$  and RAD7 obtained from the above equation, the correction factor can be calculated:

$$K = \frac{\text{RAD7 average number of indications}}{C_{Tn}}$$

The correction factor  $K = 1.79$  was obtained in this study.

**<sup>222</sup>Rn/<sup>220</sup>Rn Progeny Activity Concentration Measurement** In this study, <sup>222</sup>Rn/<sup>220</sup>Rn progeny were sampled using a hybrid cellulose filter membrane (AAWP02500, 0.8 m MCE Membrane, Ireland). The <sup>222</sup>Rn progeny was measured at the end of sampling in time periods (2–12 min and 12–30 min) and the <sup>220</sup>Rn progeny was measured in time periods (2–43 min and 43–120 min) using an Ortec Alpha ensemble spectrometer (Ortec Plus, Ortec Inc., USA) [25]. The detector detection efficiency was calibrated using a <sup>241</sup>Am standard surface source with a relative standard uncertainty of 2%. The sample flow rate was calibrated using a soap film flow meter (Model Gilibrator2, Sensidyne Inc., USA) with a relative standard uncertainty of 1%.

## C. Theoretical Model

**1. Theoretical Model for Calculating Aerosol Concentrations in the <sup>220</sup>Rn Injection Chamber** It is assumed that: (1) the aerosol input flow rate and input concentration remain constant; and (2) the self-loss coefficient due to aerosol attachment, condensation, and deposition in the <sup>220</sup>Rn chamber is constant. The change in aerosol concentration with time can be expressed:

$$\frac{dC_i}{dt} = C_{in}Q_{in} - (\lambda + v_i)C_i$$

When equilibrium is reached, the aerosol concentration in the aerosol dilution chamber can be obtained:

$$C_1 = \frac{C_{in}Q_{in}}{V_1(\lambda + v_1)}$$

The aerosol concentration in the progeny source chamber can be obtained in the same way:

$$C_2 = \frac{C_{in}Q_{in}}{V_2(\lambda + v_2)}$$

And the aerosol concentration within the calibration chamber:

$$C_3 = \frac{C_{in}Q_{in}}{V_3(\lambda + v_3)}$$

$C_1$  denotes the aerosol concentration in the dilution chamber, particles/cm<sup>3</sup>;  $C_{in}$  is the concentration of aerosol before entering the aerosol dilution chamber, i.e., the concentration of aerosol in the sandalwood hood, particles/cm<sup>3</sup>;  $Q_{in}$  is the flow rate of 2 L/min inputted into the dilution chamber;  $V_1$ ,  $V_2$ , and  $V_3$  are the volumes of the aerosol dilution chamber, progeny source chamber, and calibration chamber, m<sup>3</sup>;  $v_1$ ,  $v_2$ , and  $v_3$  are the air exchange rates, h<sup>-1</sup>, for the aerosol dilution chamber, progeny source chamber, and calibration chamber, respectively.  $\lambda$  is the natural attenuation rate of aerosol concentration in static condition, 0.0029 h<sup>-1</sup>.

**2. Theoretical Calculation Model for <sup>222</sup>Rn/<sup>220</sup>Rn Progeny Activity Concentration** Given the short half-life of <sup>220</sup>Rn (55.6 seconds), <sup>220</sup>Rn in the progeny source chamber completely decays before reaching the calibration chamber. Consequently, all <sup>220</sup>Rn present in the chamber originates exclusively from the solid-flow <sup>220</sup>Rn source. Based on the decay of <sup>220</sup>Rn concentration due to the generation, decay, and gas exchange of the solid flow gas type <sup>220</sup>Rn source, the following equation is obtained:

$$\frac{dC_{Tn1}}{dt} = \frac{AR_a \varepsilon \delta \lambda_{Tn}}{V_2} - \lambda_{Tn} C_{Tn1} - \frac{C_{Tn1} Q_2}{V_2}$$

Where,  $C_{Tn}$  is the <sup>220</sup>Rn concentration in the progeny source chamber, Bq/m<sup>3</sup>;  $A_{Ra}$  is the solid stream gas <sup>220</sup>Rn source activity, Bq;  $\lambda_{Tn}$  is the decay constant of <sup>220</sup>Rn;  $\varepsilon$  is the <sup>220</sup>Rn source jet coefficient.  $Q_2$  is the progeny source chamber gas exchange flow rate.  $\delta$  represents the fraction of <sup>220</sup>Rn emitted by the source that enters the progeny source chamber, which is related to the <sup>220</sup>Rn jet flow through the pipe. It is related to the volume  $V_T$  of the <sup>220</sup>Rn jet flow through the duct, and the air exchange rate  $v_2$  of the substrate source box:

$$\delta = e^{-\frac{v_T}{Q_2}}$$

Then the <sup>220</sup>Rn concentration in the progeny source chamber at stabilization is:

$$C_{Tn1} = \frac{A_{Ra} \varepsilon \delta \lambda_{Tn}}{\lambda_{Tn} V_2 + Q_2}$$

Similarly, the concentration of <sup>220</sup>Rn in the calibration chamber at the stabilization time is as follows (the fan-type <sup>220</sup>Rn source can be considered as 100%):

$$C_{Tn} = \frac{A_{Ra} \varepsilon \lambda_{Tn}}{\lambda_{Tn} V_3 + Q_3}$$

$Q_3$  is the air exchange flow rate of the calibration chamber.

The growth of unattached  $^{220}\text{Rn}$  progeny in the calibration chamber originates from the decay of their precursor unattached states, while the attenuation results from radioactive decay, aerosol binding, air exchange, and attachment to the wall; the growth of the attached  $^{220}\text{Rn}$  progeny comes from the decay of the attached state of the previous progeny, the binding of the unattached progeny to the aerosol, and the compensation of the progeny source chamber. Thus the variation in the activity concentration of  $^{220}\text{Rn}$  progeny in the unattached and attached states satisfies:

$$\frac{dC_f^j}{dt} = \lambda_j C_f^{j-1} - (\lambda_j + X + v + q_f) C_f^j$$

$$\frac{dC_a^j}{dt} = X C_f^j + \lambda_j C_a^{j-1} - (\lambda_j + v + q_a) C_a^j$$

$C_f^j$  and  $C_a^j$  represent the activity concentration of the  $j$ th unattached and attached progeny, respectively,  $\text{Bq}/\text{m}^3$ ;  $\lambda_j$  is the decay constant of the  $j$ th progeny,  $\text{h}^{-1}$ ;  $C_f^{j-1}$  and  $C_a^{j-1}$  represent the activity concentration of the  $(j-1)$ th unattached and attached progeny, respectively,  $\text{Bq}/\text{m}^3$ ;  $q_f$  and  $q_a$  represent the attachment rate of the unattached and attached progeny, respectively,  $\text{h}^{-1}$ ;  $N_{in}$  is the activity per unit of bound progeny of the  $j$ th progeny source chamber,  $\text{Bq}/\text{h}$ ;  $X$  is the binding rate of the unattached progeny to the aerosol,  $\text{h}^{-1}$ :

$$X = \beta \cdot N$$

Where  $\beta$  is the adsorption coefficient,  $\text{Bq}/\text{h}$ , which usually takes the value of 0.0085;  $N$  is the aerosol concentration,  $\text{particles}/\text{cm}^3$ .

The  $^{220}\text{Rn}$  progeny in the progeny source chamber was transported to the  $^{220}\text{Rn}$  chamber under the drive of the pump, and the activity concentration of the unattached state  $^{216}\text{Po}$  in the calibration chamber was nearly equal to that of the  $^{220}\text{Rn}$  concentration because the  $^{216}\text{Po}$  (ThA) half-life was only 0.15 s, and the deposition of  $^{216}\text{Po}$  and the loss of air exchange could be neglected. The vast majority of the unattached  $^{220}\text{Rn}$  progeny will adhere to the pipe wall when passing through a pipe of 1.8 cm diameter within a length of 60 cm, resulting in an increase in the loss of unattached  $^{220}\text{Rn}$  progeny.

The activity concentration of the attached states  $^{212}\text{Pb}(\text{ThB})$  and  $^{212}\text{Bi}(\text{ThC})$  in the calibration chamber and the activity concentration of the unattached and attached states  $^{212}\text{Pb}(\text{ThB})$  and  $^{212}\text{Bi}(\text{ThC})$  are calculated as follows:

$$C_{ThB}^f = \frac{\lambda_1 + X + v_3 + q_f}{X} \times C_{Tn}$$

$$C_{ThB}^a = \frac{X \cdot C_f^{ThB} + \lambda_1 + v_3 + q_a}{R_{aB}}$$

$$C_{ThB}^a = \frac{X \lambda_1 C_{Tn}}{(\lambda_1 + v_2 + q_a)(\lambda_1 + X + v_2 + q_f)} \times \frac{V_2}{R_{aB}}$$

$$C_{ThC}^f = \frac{\lambda_2 C_f^{ThB}}{\lambda_2 + X + v_3 + q_f}$$

$$C_{ThC}^a = X \cdot C_f^{ThB} + \lambda_2 C_a^{ThB} + \lambda_2 + v_3 + q_a + \lambda_2 C_a^{ThC}$$

$$C_{ThC}^a = \frac{\lambda_2 + v_2 + q_a}{N_{in}}$$

For the  $^{222}\text{Rn}$  concentration and  $^{222}\text{Rn}$  progeny activity concentration, the derivation process is similar to that for the  $^{220}\text{Rn}$  concentration and  $^{220}\text{Rn}$  progeny activity concentration.

It is worth noting that for  $^{214}\text{Pb}$  in the unattached state, the source also includes the item that recoil causes the  $^{214}\text{Pb}$  in the attached state to detach from the aerosol particles to revert back to the unattached state, and thus it can be obtained that the change in  $^{222}\text{Rn}$  progeny concentration in the unattached and attached states satisfies the following equation:

$$\frac{dC_f^j}{dt} = \lambda_j C_f^{j-1} + \lambda_j C_a^{j-1} - (\lambda_j + X + v + q_f) C_f^j$$

$$\frac{dC_a^j}{dt} = X C_f^j + \lambda_j C_a^j (1 - R_{j-1}) - (\lambda_j + v + q_f) C_a^j$$

where  $R$  is the recoil coefficient. The activity concentrations of the attached states  $^{218}\text{Po}$  (RaA),  $^{214}\text{Po}$  (RaB),  $^{214}\text{Bi}$  (RaC) in the calibration chamber as well as the activity concentrations of the unattached and attached states  $^{218}\text{Po}$  (RaA),  $^{214}\text{Po}$  (RaB),  $^{214}\text{Bi}$  (RaC) can be obtained by calculating the formulas below:

$$C_{RaA}^f = \frac{\lambda_1 + X + v_3 + q_f}{X} \times C_{Rn}$$

$$C_{RaA}^a = \frac{X \cdot C_f^{RaA} + \lambda_1 + v_3 + q_a}{R_a}$$

$$C_{RaA}^a = \frac{X\lambda_1 C_{Rn}}{(\lambda_1 + v_2 + q_a)(\lambda_1 + X + v_2 + q_f)} \times \frac{V_2}{R_a}$$

$$C_{RaB}^f = \frac{R_1 C_a^f + \lambda_2 C_f^{RaA}}{\lambda_2 + X + v_3 + q_f}$$

$$C_{RaB}^a = X \cdot C_f^{RaA} + \lambda_2(1 - R_1)C_a^{RaA} + \lambda_2 + v_3 + q_a$$

$$C_{RaB}^a = \frac{\lambda_2 + v_2 + q_a}{N_{in}}$$

$$C_{RaC}^f = \frac{\lambda_3 C_f^{RaB}}{\lambda_3 + X + v_3 + q_f}$$

$$C_{RaC}^a = X \cdot C_f^{RaC} + \lambda_3 C_a^{RaB} + \lambda_3 + v_3 + q_a$$

$$C_{RaC}^a = \frac{\lambda_3 + v_2 + q_a}{N_{in}}$$

The formula for calculating EEC given by the definition of equilibrium equivalent radon concentration (EEC) is as follows:

$$EEC = 0.105C_a^{RaA} + 0.516C_a^{RaB} + 0.379C_a^{RaC}$$

$$EEC = 0.105C_f^{RaA} + 0.516C_f^{RaB} + 0.379C_f^{RaC}$$

Calculation of the binding rate  $X$ , the concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny of the aerosol using the theoretical equations requires the values of the parameters  $v_2$ ,  $v_3$ ,  $\delta$ ,  $q_f$ ,  $q_a$ ,  $\varepsilon$ , and the values used in this study are shown in Table 1 [26–28].

### III. RESULTS AND DISCUSSIONS

#### A. Stability of Aerosol Concentration

Without connecting to the  $^{222}\text{Rn}/^{220}\text{Rn}$  source, the aerosol conditioning system was directly linked to the calibration chamber (with valves K1 and K2 open). Sandalwood was burned inside the sandalwood hood while pump D maintained a flow rate of 2 L/min. The aerosol concentration in the calibration chamber stabilized after 3 h, after which measurements were taken at 30 min intervals. This study primarily adjusted the aerosol concentration by controlling the three-way

valve switching and regulating the flow rate of pump C. The aerosol concentration of pump C was also varied in the study. At different pump C flow rates, the aerosol concentration in the calibration chamber varied as follows: when K2 was turned on and the pump C flow rate was adjusted to 10 L/min, the aerosol concentration was  $545 \pm 25$  particles/cm<sup>3</sup> (Figure 3 Figure 3: see original paper), with an RSD of 4.7%. With K2 closed and pump C flow rate set at 9 L/min, the aerosol concentration increased to  $2070 \pm 81$  particles/cm<sup>3</sup> (Figure 3(b)), exhibiting an RSD of 4.0%. Maintaining K2 in the closed position while reducing the pump C flow rate to 4 L/min resulted in a further concentration increase to  $5236 \pm 125$  particles/cm<sup>3</sup> (Figure 3(c)), with an RSD of 5.0%. Ultimately, at the minimal pump C flow rate of 2 L/min, the aerosol concentration increased to  $9365 \pm 186$  particles/cm<sup>3</sup> (Figure 3(d)), demonstrating an RSD of 2.1%.

During the experiment, the temperature was  $12.2 \pm 3$  °C and the humidity was  $57 \pm 4\%$ . Overall, the relative standard deviations (RSDs) of the four aerosol concentrations were less than 10%, and the aerosol concentrations in the calibration chamber were relatively stable. The stabilization of aerosol concentration in the calibration chamber mainly depends on key parameters such as the coagulation rate, wall attachment rate, and deposition rate, and the aerosol concentration decreases continuously due to the presence of wall attachment, deposition, and air exchange rate. Higher airflow rates enhance aerosol particle coagulation and wall deposition. The combined effects of Brownian diffusion and gravitational sedimentation govern aerosol particle deposition. Consequently, increased airflow intensifies both particle diffusion and sedimentation processes [29, 30].

## B. Stability and Homogeneity of the Activity Concentration of <sup>222</sup>Rn/<sup>220</sup>Rn and Their Progeny

The <sup>222</sup>Rn/<sup>220</sup>Rn concentration in the calibration chamber over time for three different combinations of <sup>222</sup>Rn and <sup>220</sup>Rn sources with different activities is shown in Figure 4 [Figure 4: see original paper]. The charge source loop (pump A flow rate of 2 L/min) and the analog sampling loop (pump B flow rate of 10 L/min) were opened, the fan source was placed into the calibration chamber, the fan source was turned on, and the <sup>222</sup>Rn/<sup>220</sup>Rn reached equilibrium in the calibration chamber after about 3 days. After that, the aerosol dilution chamber was connected to the progeny source chamber, and the pump C flow rate and pump D flow rate were adjusted to 2 L/min, and the aerosol concentration inside the calibration chamber was stabilized at about 10,000 particles/cm<sup>3</sup> after about 3 h. RAD7 and 3007 were used for continuous monitoring of the calibration chamber.

Figure 4(a) shows the stability of the <sup>222</sup>Rn/<sup>220</sup>Rn concentrations with 32,000 Bq of <sup>220</sup>Rn source, 6700 Bq of <sup>222</sup>Rn source, and the fan source turned on, at which time the <sup>222</sup>Rn concentration was  $1557 \pm 47$  Bq/m<sup>3</sup> and the <sup>220</sup>Rn concentration was  $17149 \pm 387$  Bq/m<sup>3</sup>. Replacing the 3702 kBq source of <sup>222</sup>Rn

with a 6700 Bq source of  $^{222}\text{Rn}$ , with the valves of the source open 1/3, Figure 4(b) shows the stability of the  $^{222}\text{Rn}/^{220}\text{Rn}$  concentration with 32,000 Bq of  $^{220}\text{Rn}$ , the 3702 kBq source of  $^{222}\text{Rn}$ , and the fan source open, at which time the concentration of  $^{222}\text{Rn}$  is  $14388 \pm 332 \text{ Bq/m}^3$ , the  $^{220}\text{Rn}$  concentration is  $17455 \pm 498 \text{ Bq/m}^3$ . With the valve of the 3702 kBq source of  $^{222}\text{Rn}$  open 2/3 of the way, the 32,000 Bq source of  $^{220}\text{Rn}$  left connected, and the fan source turned off, Figure 4(c) shows the stability of the  $^{222}\text{Rn}/^{220}\text{Rn}$  concentrations with the 32,000 Bq source of  $^{220}\text{Rn}$ , the 3702 kBq source of  $^{222}\text{Rn}$ , and the fan source turned off, at which time the  $^{222}\text{Rn}$  concentration was  $21154 \pm 256 \text{ Bq/m}^3$  and the  $^{220}\text{Rn}$  concentration is  $884 \pm 57 \text{ Bq/m}^3$ . The  $^{222}\text{Rn}/^{220}\text{Rn}$  concentrations in the calibration chamber are more stable in these three cases, the RSD is less than 10%, and the stability of  $^{222}\text{Rn}$  concentration is higher than that of  $^{220}\text{Rn}$  concentration, because the half-life of  $^{220}\text{Rn}$  is short, and the  $^{220}\text{Rn}$  jet gas is easily perturbed by the airflow in the calibration chamber. It was demonstrated that this regulation scheme ensured the stabilization of  $^{222}\text{Rn}/^{220}\text{Rn}$  concentration in the calibration chamber after source replacement.

In order to study the stability and homogeneity of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration under different aerosol concentrations, 32,000 Bq of  $^{220}\text{Rn}$  source and 6700 Bq of  $^{222}\text{Rn}$  source were connected to the progeny source chamber, the charge source loop and the analog sampling loop flow rates remained unchanged without connecting to the aerosol regulating system, and  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration inside the calibration chamber was sampled and measured. The aerosol concentration in the calibration chamber at this time was  $92 \pm 10 \text{ particles/cm}^3$ , the  $^{222}\text{Rn}$  concentration was  $1565 \pm 47 \text{ Bq/m}^3$ , and the  $^{220}\text{Rn}$  concentration was  $17145 \pm 339 \text{ Bq/m}^3$ . The aerosol conditioning system was connected to the progeny source chamber (K1 and K2 on), pump C flow rate was adjusted to 9 L/min and pump D flow rate was adjusted to 2 L/min to raise the aerosol concentration in the calibration chamber to  $2188 \pm 129 \text{ particles/cm}^3$ . After turning off K2 and adjusting the pump C flow rate to 4 L/min, the aerosol concentration in the calibration chamber increased to  $5537 \pm 250 \text{ particles/cm}^3$ . Eventually, the aerosol concentration was further elevated to  $10259 \pm 671 \text{ particles/cm}^3$  by adjusting the pump C flow rate to 2 L/min only. Under these conditions, Figure 5 [Figure 5: see original paper] demonstrates the stability of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations in the calibration chamber across four test scenarios. Notably, while the RSD of RaC and ThC activity concentrations exceeded 10% at aerosol levels of  $92 \pm 10 \text{ particles/cm}^3$ , all progeny maintained RSD values below 10% at other tested aerosol concentrations. These results fully comply with the 10% requirement specified in the IEC 61577-2 standard [31]. The results show that the regulation scheme can achieve stable regulation of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration in different aerosol environments. The  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration increases as the aerosol concentration increases, as shown in Figure 6 [Figure 6: see original paper]. Furthermore, the stability of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations demonstrates a positive dependence on aerosol concentration levels. The mechanism primarily originates from enhanced progeny-aerosol binding

rate in high-concentration aerosol environments, which concurrently suppresses progeny deposition rate and wall attachment rate. This ultimately leads to an overall elevated activity concentration of the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny, and the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration at high levels of aerosol concentration is less affected by statistical rise and fall errors.

In this study,  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny were sampled at different locations to test the uniformity of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny distribution in the calibration chamber. The sampling depths were 30 cm and 60 cm, and the sampling position was uniformly in the center of the calibration chamber, at which time the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration is shown in Figure 7 [Figure 7: see original paper]. The sampling depth was uniformly 60 cm, and the two sampling positions were 40 cm to the left and 40 cm to the right of the center of the calibration chamber, at which time the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration was shown in Figure 8 [Figure 8: see original paper]. Overall, the RSD of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration is less than 10% for different locations sampled. It is shown that the proposed regulation method can ensure the uniform distribution of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny concentration under multiple airflow circuits as well as fans. Owing to the constraints of limited sampling ports and available samplers, uniformity tests were currently conducted using only two samplers simultaneously. Subsequent implementation of additional sampling ports in the  $^{220}\text{Rn}$  chamber will enable multi-point measurements, thereby enhancing the reliability of experimental data.

### C. Regulatory Range of $^{222}\text{Rn}/^{220}\text{Rn}$ Progeny Activity Concentrations

The aerosol serves as a carrier for the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny aerosol, and the aerosol concentration in the  $^{220}\text{Rn}$  chamber is a direct influence on the concentration of the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny, provided that the concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  remains constant. The aerosol was regulated following the procedure described in Section III B. During the experiment, the calibration chamber maintained the  $^{222}\text{Rn}$  concentration of  $1570 \pm 48 \text{ Bq/m}^3$  and the  $^{220}\text{Rn}$  concentration of  $17248 \pm 478 \text{ Bq/m}^3$ , along with the temperature of  $12.2 \pm 3 \text{ }^\circ\text{C}$  and the relative humidity of  $57 \pm 4\%$ . When the aerosol concentration grew from  $92 \pm 10 \text{ particles/cm}^3$  to  $10529 \pm 671 \text{ particles/cm}^3$ ,  $^{218}\text{Po}$  activity concentration grew from  $268 \text{ Bq/m}^3$  to  $935 \text{ Bq/m}^3$ ;  $^{214}\text{Pb}$  activity concentration grew from  $18 \text{ Bq/m}^3$  to  $413 \text{ Bq/m}^3$ ;  $^{214}\text{Bi}$  activity concentration grew from  $8 \text{ Bq/m}^3$  to  $322 \text{ Bq/m}^3$ ; EEC activity concentration grew from  $42 \text{ Bq/m}^3$  to  $431 \text{ Bq/m}^3$ ;  $^{212}\text{Pb}$  activity concentration grew from  $53 \text{ Bq/m}^3$  to  $1116 \text{ Bq/m}^3$ ; and  $^{212}\text{Bi}$  activity concentration grew from  $10 \text{ Bq/m}^3$  to  $785 \text{ Bq/m}^3$ . The relationships of  $^{222}\text{Rn}$  progeny activity concentration, equilibrium equivalent radon concentration, and  $^{220}\text{Rn}$  progeny activity concentration with aerosol variation are given in Figure 9 [Figure 9: see original paper] and Figure 10 [Figure 10: see original paper], respectively. The range of equilibrium factor for  $^{222}\text{Rn}$  is 0.032–0.340, and the range of equilibrium factor for  $^{220}\text{Rn}$  is 0.0064–0.413 obtained by calculation.

High levels of equilibrium factors can be stabilized by increasing the aerosol concentration or increasing the concentration of the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny, and vice versa for low levels of equilibrium factors, as has been similarly reported in the literature [32–36]. The results show that the activity concentrations of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny all increase with the aerosol concentration, but the higher the aerosol concentration, the slower the growth of progeny activity concentration. At very low aerosol concentration ( $92 \pm 10$  particles/cm<sup>3</sup>), the activity concentrations of  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  are very low, much lower than that of  $^{218}\text{Po}$ . This is because most of the progeny at this time are in the unattached state, and the rate of attachment of the unattached  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  to the wall is much higher than the rate of their production. The RSD between the theoretical and experimental values of the activity concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny is less than 20%, which may be due to the following reasons: the air exchange rate is not constant in the real situation, the change of environmental factors will lead to a change in the rate of progeny attachment to the wall and the rate of deposition, and due to the use of a fan source in the calibration chamber as well as the use of two small fans to maintain the flow of the airflow, they will exacerbate the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny attachment, the theoretical case underestimates the attachment rate of walled  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny.

In addition to regulating the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration by regulating the aerosol concentration, the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration can also be regulated by replacing the  $^{222}\text{Rn}/^{220}\text{Rn}$  source in the manner shown in Section III B. Figure 11 [Figure 11: see original paper] shows the  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations for three different combinations of  $^{222}\text{Rn}/^{220}\text{Rn}$  sources with different activities under conditions of constant aerosol concentration. Due to the short half-life of the  $^{222}\text{Rn}$  progeny and the long half-life of the  $^{220}\text{Rn}$  progeny, and the  $^{220}\text{Rn}$  progeny concentration is more affected by the gas exchange and cannot accumulate to a high level, therefore, when the  $^{222}\text{Rn}$  concentration is much less than the  $^{220}\text{Rn}$  concentration, the activity concentrations of  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$  progeny are similar, and when the  $^{222}\text{Rn}$  concentration is similar to the  $^{220}\text{Rn}$  concentration, the  $^{222}\text{Rn}$  progeny activity concentration will be higher than the activity concentration of  $^{220}\text{Rn}$  progeny.

In summary, the range of progeny activity concentrations of  $^{222}\text{Rn}/^{220}\text{Rn}$  can be obtained as follows: the activity concentration of RaA is regulated in the range of 268–12,351 Bq/m<sup>3</sup>; the activity concentration of RaB is regulated in the range of 18–5,573 Bq/m<sup>3</sup>; the activity concentration of RaC is regulated in the range of 8–3,868 Bq/m<sup>3</sup>; the activity concentration of ThB is regulated in the range of 53–1,217 Bq/m<sup>3</sup>; the activity concentration of ThC is regulated in the range of 10–794 Bq/m<sup>3</sup>.

## IV. CONCLUSIONS

In this study, a  $^{220}\text{Rn}$  chamber that can stabilize and simultaneously regulate different  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentrations was constructed. By ana-

lyzing the behavioral mechanisms of aerosol particles and  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny in the  $^{220}\text{Rn}$  chamber, a theoretical model and regulatory scheme for the simultaneous regulation of the activity concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny in the  $^{220}\text{Rn}$  chamber was established.

The experimental results show that the aerosol concentration in the calibration chamber and the activity concentration of  $^{222}\text{Rn}/^{220}\text{Rn}$  and its progeny can be stabilized for a long period of time under the operation of each chamber and circuit, and a uniform distribution of aerosol particles and  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny within the calibration chamber is achieved. The practical regulation guided by the theoretical model is proved to be feasible through experiments. This study provides an experimental setup to evaluate the cross-interference between  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ , establishing a basis for the calibration of  $^{222}\text{Rn}/^{220}\text{Rn}$  progeny activity concentration monitors.

## REFERENCES

- [1] M. Charles, UNSCEAR report 2000: sources and effects of ionizing radiation. *J. Radiol. Prot.* 21(1), 83-86 (2001). <https://doi.org/10.1088/0952-4746/21/1/609>
- [2] W.J. Bair (INVITED). The ICRP Human Respiratory Tract Model for Radiological Protection. *J. Radiat. Prot. Dosim.* 60(4), 307-310 (1995). <https://doi.org/10.1093/oxfordjournals.rpd.a082732>
- [3] K. Mitev, P. Cassette, D. Pressyanov, et al. Methods for the experimental study of radon and thoron progeny aerosols. *J. J. Aerosol. Sci.* 22, S801-S804 (1991). [https://doi.org/10.1016/S0021-8502\(05\)80221-6](https://doi.org/10.1016/S0021-8502(05)80221-6)
- [4] T. Hattori, K. Ishida. A continuous monitor for radon progeny and its unattached fraction. *J. Radiat. Prot. Dosim.* 55(2), 113-122 (1994). <https://doi.org/10.1093/oxfordjournals.rpd.a082383>
- [5] S.K. Belkina, T.E. Zalmanzon, Y.V. Kuznetsov, et al. Special aerosol sources for certification and test of aerosol radiometers. *J. J. Aerosol. Sci.* 22, S801-S804 (1991). [https://doi.org/10.1016/S0021-8502\(05\)80221-6](https://doi.org/10.1016/S0021-8502(05)80221-6)
- [6] Z. He, D.T. Xiao, L.D. Lv et al. Controlling  $^{212}\text{Bi}$  to  $^{212}\text{Pb}$  activity concentration ratio in thoron chambers. *J. J. Environ. Radioactiv.* 178, 77-83 (2017). <https://doi.org/10.1016/j.jenvrad.2017.07.011>
- [7] L.F. He, Y.H. Xu, F.D. T, et al. An Analysis on Influence Factors of Radon Concentration Measurement in the Standard Radon Chamber. *J. Nucl. Electron. Detect. Technol.* 33 (10), 1199-1202 (2013). <https://doi.org/10.3969/j.issn.0258-0934.2013.10.019>
- [8] J. Bigu, R. Kaldenbach. Theory, operation and performance of a time-integrating, continuous, radon (thoron) daughter working level monitor. *J. Radiat. Prot. Dosim.* 9(1), 19-26 (1984). <https://doi.org/10.1093/oxfordjournals.rpd.a083066>

- [9] A. Paul, A. Honig, S. Röttger, et al. Measurement of radon and radon progenies at the German radon reference chamber. *J. Appl. Radiat. Isotopes.* 52(3), 369-375 (2000). [https://doi.org/10.1016/S0969-8043\(99\)00180-3](https://doi.org/10.1016/S0969-8043(99)00180-3)
- [10] A. Paul, S. Röttger, A. Honig, et al. Measurement of short-lived radon progenies by simultaneous  $\alpha$ -spectrometry at the German radon reference chamber. *J. Nucl. Instrum. Meth. A.* 434(2-3), 303-312 (1999). [https://doi.org/10.1016/S0168-9002\(99\)00526-4](https://doi.org/10.1016/S0168-9002(99)00526-4)
- [11] D.T. Xiao, Z.Q. Pan, Q. Ling, et al. A Sim (220)Rn Chamber for the Calibration of Passive and Integrated (220)Rn Dosimeter. *J. Atom. Energy. Sci. Technol.* 36(1), 89-89 (2002). <https://doi.org/10.7538/yzk.2002.36.01.0089>
- [12] E. Gargioni, A. Honig, A. Röttger. Development of a calibration facility for measurements of thoron activity concentration. *J. Nucl. Instrum. Meth. A.* 506(1-2), 166-172 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01359-7](https://doi.org/10.1016/S0168-9002(03)01359-7)
- [13] J.M. Lee, K.H. Ahn, H.S. Chai, et al. Development of radon calibration chamber at KRISS. *J. Appl. Radiat. Isotopes.* 61(2-3), 237-241 (2004). <https://doi.org/10.1016/j.apradiso.2004.03.052>
- [14] Y. Kobayashi, S. Tokonami, H. Takahashi, et al. Practicality of the thoron calibration chamber system at NIRS, Japan. *International Congress Series.* Elsevier. February 2005. Volume 1276, 281-282. <https://doi.org/10.1016/j.ics.2004.09.052>
- [15] A. Sorimachi, S. Tokonami, H. Takahashi, et al. Performance of NIRS thoron chamber system. Paper presented at the natural radiation environment: 8th International Symposium (NRE VIII), 07-12 October 2007. <https://doi.org/10.1063/1.2991209>
- [16] F. Campi, M. Caresana, M. Ferrarini, et al. Radon data from different laboratories: an Italian intercomparison. Paper presented at Proceedings of the First International Meeting on Applied Physics (APHYS-2003), Badajoz, Spain, 13-18 October 2003. <https://doi.org/10.1016/B978-008044648-6.50021-0>
- [17] J.C. Liang, P.H. Zheng, Z.J. Yang, et al. Development of calibration facility for radon and its progenies at NIM (China). *J. Radiat. Prot. Dosim.* 167(1-3), 82-86 (2015). <https://doi.org/10.1093/rpd/ncv222>
- [18] K. Skubacz, S. Chałupnik, P. Urban, et al. Radon chamber in the central mining institute—the calibration facility for radon and radon progeny monitors. *J. Radiat. Prot. Dosim.* 177(1-2), 164-167 (2017). <https://doi.org/10.1093/rpd/ncx177>
- [19] C. Pornnumpa, Y. Oyama, K. Iwaoka, et al. Development of radon and thoron exposure systems at Hirosaki University. *J. Radiat. Environ. Med.* 7(1), 13-20 (2018). <https://doi.org/10.51083/radiatenvironmed.7.113>
- [20] J. Lin, D.T. Xiao, Z. He, et al. Regulation and control methods for the

- unattached fraction of  $^{220}\text{Rn}$  progeny in a  $^{220}\text{Rn}$  progeny chamber. *J. J. Environ. Radioactiv.* 235, 106653 (2021). <https://doi.org/10.1016/j.jenvrad.2021.106653>
- [21] L.D. Lv, Z. He, D.T. Xiao, et al. Development of a thoron chamber for calibration of thoron monitors under natural wind speed conditions. *J. Meas. Sci. Technol.* 33(5), 055001 (2022). <https://doi.org/10.1088/1361-6501/ac4c0b>
- [22] T. Turtiainen, K. Mitev, R. Dehqanzada, et al. Testing of thoron cross-interference of continuous radon measuring instruments. *J. J. Eur. Radon. Assoc.* 3 (2022). <https://doi.org/10.35815/radon.v3.7694>
- [23] S. Qiu. Calibration of a  $^{220}\text{Rn}$  flow-through source. *J. Radiat. Environ. Bioph.* 45, 215-220 (2006). <https://doi.org/10.1007/s00411-006-0059-y>
- [24] Y.R. Ma, L. Zhang, Q.J. Guo. Study on Accurate Measurement of  $^{220}\text{Rn}$  Activity Concentration by Using RAD7 Radon Monitor. *J. Atom. Energy. Sci. Technol.* 46(11), 1397-1401 (2012). <https://doi.org/10.7538/yzk.2012.46.11.1397>
- [25] X. Kang, D.T. Xiao, J.L. Li. Optimization of alpha energy spectrum method for measuring radon and thoron daughters in air. *J. Nucl. Tech.* 31(12), 925-930 (2008). <https://doi.org/10.3321/j.issn:0253-3219.2008.12.010>
- [26] C. Huang, Z. He, D.T. Xiao, QIU Shoukang, SHAN Jian. Simulation Research of Radon Progeny Parameter Control Method in Small Radon Chamber. *J. Atom. Energy. Sci. Technol.* 52(3), 570-576 (2018). <https://doi.org/10.7538/yzk.2017.youxian.0287>
- [27] Z. He, D.T. Xiao, L.D. Lv, et al. Stable control of thoron progeny concentration in a thoron chamber for calibration of active sampling monitors. *J. Radiat. Meas.* 102, 27-33 (2017). <https://doi.org/10.1016/j.radmeas.2017.02.013>
- [28] D.T. Xiao, J.L. Zhou, S. Qiu. A study of  $^{220}\text{Rn}$  and its progeny meter scale and experimental setup. Paper presented at Radiation protection subvolume. Progress report on nuclear science and technology in China (Volume II), 11-14 October 2011.
- [29] D.B. Jaynes, A.S. Rogowski. Applicability of Fick's law to gas diffusion. *J. Soil Sci. Soc. Am. J.* 47(3), 425-430 (1983). <https://doi.org/10.2136/sssaj1983.03615995004700030007x>
- [30] J. Porstendörfer. Properties and behaviour of radon and thoron and their decay products in the air. *J. J. Aerosol. Sci.* 25(2), 219-263 (1994). [https://doi.org/10.1016/0021-8502\(94\)90077-9](https://doi.org/10.1016/0021-8502(94)90077-9)
- [31] J. Radiation protection instrumentation - Radon and radon decay product measuring instruments - part 2: Specific requirements for  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$  measuring instruments, IEC 61577-2 standard, (2014).
- [32] A. Röttger, A. Honig, D. Arnold. The German thoron progeny chamber—concept and application. *J. Appl. Radiat. Isotopes.* 67(5), 839-842 (2009). <https://doi.org/10.1016/j.apradiso.2009.01.043>

- [33] P. Singh, K. Saini, R. Mishra et al. Attached, unattached fraction of progeny concentrations and equilibrium factor for dose assessments from  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ . *J. Radiat. Environ. Bioph.* 55: 401-410 (2016). <https://doi.org/10.1007/s00411-016-0656-3>
- [34] J. Chen, D. Moir, A. Sorimachi, et al. Determination of thoron equilibrium factor from simultaneous long-term thoron and its progeny measurements. *J. Radiat. Prot. Dosim.* 149(2): 155-158 (2012). <https://doi.org/10.1093/rpd/ncr228>
- [35] S.K. Belkina, Y.E. Zalmanzon, Y.V. Kuznetsov et al. Special aerosol sources for certification and test of aerosol radiometers. *J. J. Aerosol. Sci.* 22, S801-S804 (1991). [https://doi.org/10.1016/S0021-8502\(05\)80221-6](https://doi.org/10.1016/S0021-8502(05)80221-6)
- [36] M.D. Hoover, G.J. Newton. Performance testing of continuous alpha-emitting radionuclides air monitors. *J. Radiat. Prot. Dosim.* 79(1-4), (1998). <https://doi.org/10.1093/oxfordjournals.rpd.a032460>

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv — Machine translation. Verify with original.*