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THE INFLUENCE OF ENVIRONMENTAL FACTORS ON THE DEPOSITION VELOCITY OF THORON PROGENY

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Passive measuring devices are comprehensively employed in thoron progeny surveys, while the deposition velocity of thoron progeny is the most critical parameter, which varies in different environments. In this study, to analyse the influence of environmental factors on thoron progeny deposition velocity, an improved model was proposed on the basis of Lai's aerosol deposition model and the Jacobi's model, and a series of measurements were carried out to verify the model. According to the calculations, deposition velocity decreases with increasing aerosol diameter and also aerosol concentration, while increases with increasing ventilation rate. In typical indoor environments, a typical value of 1.26×10^{-5}m s^{-1} is recommended, with a range between 7.6×10^{-7} and 3.2×10^{-4} m s^{-1}.

INTRODUCTION

Thoron (^{220}Rn) is a radioactive gas originating from thorium (^{232}Th) with a half-life of 55.6 s. As an isotope of radon (^{222}Rn), thoron has been neglected for a long period and often considered an interfering factor in the measurement of radon, because of its low concentration(1). Recent surveys reveal that high concentrations of thoron exist in some places, and the dose caused by thoron and its progeny may be underestimated(2–4). Exposure to thoron and its possible health effects have gained increasing attention in recent years, as indicated in a recent report of the United Nations Scientific Committee on the Effects of Atomic Radiation(5). Thoron progeny contributes most of the doses, so it is important to measure the concentration of thoron progeny precisely.

Traditional methods for measuring the concentration of thoron progeny can be divided into active measurement methods and passive measurement methods(6). While active methods generally measure thoron progeny concentrations shortly using pumps, most passive methods which give more representative results of thoron progeny level measure the concentration of integrated thoron progeny for a long time without pumps. There is an increasing need to improve the accuracy of passive measurements for thoron progeny(7).

In the 1990s, a device for passive measurements based on the deposition of thoron progeny was developed by Zhuo and Iida(8), mainly composed of a solid-state nuclear track detector with an aluminium film covered on it. Mishra *et al*. designed a deposition-based direct thoron progeny sensor (DTPS), using an absorber-mounted LR-115-type nuclear track detector(9–12). These methods were highly discriminative of radon progeny because the covering aluminium film opened a narrow window only for ^{212}Po, a decay product of thoron which emits alpha particle of 8.78 MeV during decay. Because of their small sizes, low costs and power-free features, this kind of device has been comprehensively employed in thoron surveys(3, 13, 14).

The deposition velocity of thoron progeny (V_d) is the key parameter of the method, defined as the deposition rate (number of deposited particles per unit time divides particle concentration) per unit area, and is dimensionally identical to velocity. Zhuo and Iida derived a deposition velocity of $(5.3\pm1.1)\times10^{-5}$m s^{-1} from a field survey of 13 rooms(8), in which concentrations of thoron progeny and track densities were simultaneously measured(5). This value was adopted in thoron surveys(3, 13, 14). However, the deposition velocity is influenced by several environmental factors, such as aerosol and ventilation rate. Mishra *et al*. theoretically predicted the value of deposition velocity and carried out a large number of experiments to determine the sensitivity factor of DTPS. According to their studies, the experimental result of V_d for vertical surfaces is $(1.53\pm0.11)\times10^{-5}$m s^{-1}(9, 10). Their theoretical results revealed that V_d depends on aerosol concentration and ventilation rate and they suggested that different sensitivity factors should be considered for extreme environments(11). However, influence of ventilation rate on friction velocity, which is a parameter in the deposition model, is not taken into account in their models.

Stevanovic *et al*. (15)established the correlation between friction velocity and ventilation rate on the basis of a model describing the vertical profile of wind speed in an urban environment to calculate the deposition rate of unattached and attached radon progeny in rooms, and studied the relationship of the parameters in Jacobi's model[16]. By fitting experimental data, Hussein *et al*. provided another correlation between friction velocity and ventilation rate, which is adopted in this paper.

To precisely estimate the variance of the deposition velocity of thoron progeny in different environments and the influence of environmental factors, and then to effectively improve the accuracy of the method, a model for the deposition of thoron progeny is introduced in this paper, which is based on Jacobi's model[17] and Lai's deposition model[18], taking into account the functional relation between ventilation rate and friction velocity.

MODEL

In indoor environments, thoron decays into ^{216}Po in the air, forming unattached progeny. Then the ^{216}Po decays into a series of thoron progeny. A portion of airborne thoron progeny attaches to aerosol particles after generated in the air, forming attached progeny. Let V_i and f_{pi} denote the deposition velocity and the unattached fraction of thoron progeny i (index i=2, 3 refers to ^{212}Pb and ^{212}Bi respectively), and V_d^u and V_d^a denote the deposition velocity of unattached and attached thoron progeny, respectively. Then the deposition velocity of progeny i is[12]

$$V_i = V_d^u f_{pi} + V_d^a (1 - f_{pi}) \tag{1}$$

Therefore, the theoretical deposition velocity of thoron progeny V_d^{the} can be defined as[11]:

$$V_d^{the} = \frac{0.91 V_2 C(^{212}\mathrm{Pb}) + 0.09 V_3 C(^{212}\mathrm{Bi})}{0.91 C(^{212}\mathrm{Pb}) + 0.09 C(^{212}\mathrm{Bi})} \tag{2}$$

where $C(^{212}$Pb) and $C(^{212}$Bi) are the activity concentrations. The activity concentration and unattached fraction of each thoron progeny could be calculated by the equation for attachment rate given by Porstendorfer and Reineking[19] and the Jacobi's model[17]. According to the Jacobi's model, the attachment rate, as well as the unattached fraction, depends on the aerosol diameter, concentration of aerosol and ventilation rate, assuming fixed quantities for V_d^u and V_d^a (2×10^{-2} and 2×10^{-4} m s^{-1}, respectively)[17]. However, V_d^u and V_d^a themselves are also functions of aerosol and ventilation rate, so a deposition model is necessary to characterise these functional relations.

Deposition models generally assume a boundary layer in which the aerosol concentration and turbulent intensity decrease from the bulk region to the surface and there is a homogeneous distribution of aerosol concentration in the bulk region[18]. Aerosol particles are transferred to the surface through Brownian diffusion and turbulent diffusion. For vertical surfaces, gravitational sedimentation is not considered. The particle flux J is characterised by a modified Fick's law:

$$J = -(D + \varepsilon_p)\frac{\partial C}{\partial y} \tag{3}$$

where y is the distance to the surface; D is the Brownian diffusion coefficient and ε_p is the eddy diffusivity, a function of y. Lai and Nazaroff derived a sectional function of ε_p and y from direct numerical simulation data and proposed their three-layer model, in which the deposition velocity is determined by[18]:

$$v_d = \frac{u^*}{\int_{r^+}^{30} \nu/D + \varepsilon_p(y^+)\,\mathrm{d}y^+} \tag{4}$$

In the equation, y^+ and r^+ are non-dimensional distance and particle diameter, respectively: $y^+ = yu^*/\nu$, $r^+ = ru^*/\nu$. In the equations, ν is the kinetic viscosity and u^* is the friction velocity, a parameter that characterises the indoor turbulent intensity and is affected by ventilation rate. This relation is determined by Hussein *et al.*[20] by fitting experimental results:

$$u^* = 2.05\lambda_v + 1.04 \tag{5}$$

where λ_v is the ventilation rate. With Equations (4) and (5), V_d^u and V_d^a can be obtained if the aerosol diameter and the ventilation rate are known. Then the theoretical deposition velocity of thoron progeny V_d^{the} can be obtained by Equation (2).

EXPERIMENT

To verify the model, a passive integrating device for thoron progeny (PIDTP) is designed, as shown in Figure 1. In Figure 1a, A1, A2, B1, B2 and C are symmetrical parts composed of conductive plastics. There are two cavities on each surface of C to place the 1×1 cm CR-39 detectors. Each of B1 and B2 has a circular vacancy in the centre, where the aluminium film with a thickness of 9.96 mg cm^{-2} is covered to discriminate radon progeny as absorbers. While not in use, A1 and A2 need to be twisted on B1 and B2 in order to protect the aluminium and protect the CR-39 detectors from exposure. While in use, A1 and A2 are twisted off while B1 and B2 are twisted on C, and the aluminium films are covered right on the surface of the CR-39 detectors. Then the device is vertically hung in the room with the aluminium films exposed in the air, as shown in Figure 1b. Thoron progeny could deposit onto the aluminium film and be recorded by CR-39 detectors.

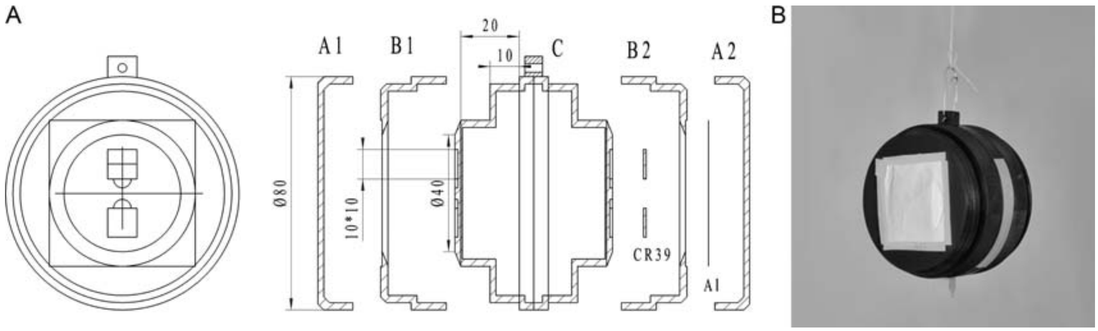

Figure 1. Diagram and photograph of the PIDTP.

Calibration experiments were done and the detection efficiency η for ^{212}Po was found to be 0.024.

A house and two basements in Peking University were selected for the experiments. Thoron source using lantern mantles (^{232}Th: 131 ± 4 kBq kg^{-1}; ^{238}U: 61 ± 20 Bq kg^{-1}; no ^{226}Ra found)[21] were placed to increase the thoron concentration in the house. Experiments were carried out in the house with the windows closed or slightly opened. Several PIDTPs were hung and the environmental factors were measured. Indoor aerosol concentrations (N) were measured by WCPC Model 3781 (TSI company, USA); distributions of aerosol diameter [count median diameter (CMD) and geometric standard deviation (GSD)] were measured by a screen diffusion battery[22]; ventilation rates (λ_v) were measured by a method recommended by National Standard (GB-T 18204.19-2000) of China; and the equilibrium-equivalent concentrations of thoron (EEC_{Tn}) were measured by BWLM Monitor (Tracerlab company, Germany).

Accumulation time (T) and the track density of CR-39 (D_t) were also recorded. Then the experimental deposition velocity of thoron progeny can be obtained:

$$V_d^{exp} = \frac{D_t}{\eta \eta_b X T} \tag{6}$$

where η is the efficiency, η_b the branching ratio of ^{212}Bi and $X = EEC_{Tn} \times 6.03 \times 10^4$ s is the number density of thoron progeny.

RESULTS AND DISCUSSION

To analyse the influence of aerosol diameter, aerosol concentration and ventilation rate, the variances of V_d versus single factor were simulated on the basis of the model. Typical ranges of environmental factors are shown in Table 1. Among them, data on CMD and aerosol concentration (N) are derived from field measurements in China, and data on ventilation rate are derived from a survey of dwellings in Beijing[23]. In the calculation, the geometry of the room is assumed as $3\times4\times5$ m, and the GSD is assumed as 2.0.

Table 1. Typical environmental parameters.

Parameter	CMD (nm)	N (cm^{-3})	λ_v (h^{-1})
Typical value	147	15 700	0.53
Range	57–405	6600–31 200	0.25–2.0

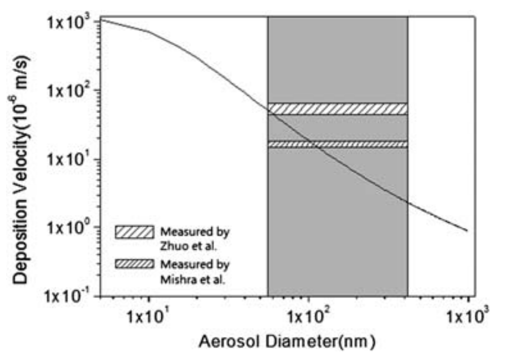

Figure 2. Deposition velocity of thoron progeny at different aerosol diameters.

The influence of aerosol diameter, aerosol concentration and ventilation rate on the deposition velocity of thoron progeny are shown in Figures 2–4, respectively. Two experimental values, which are derived from many indoor measurements, are compared with theoretical ones in the figures. Since the detailed environmental parameters of their measurements are not clear, it is assumed that the parameters are within the ranges as given in Table 1, i.e. the two values may be located within the densely and the sparsely striped areas, respectively. The shadowed areas stand for the ranges listed in Table 1. The densely striped areas stand for the range of deposition velocity measured by Mishra *et al.* while the sparsely striped areas stand for the range given by Zhuo and Iida.

It is shown in Figure 2 that V_d decreases with increasing aerosol diameter. According to the model, aerosol diameter influences V_d directly through the Brownian diffusion coefficient of attached progeny and through the unattached fraction as well. It is reasonable that V_d decreases because both the Brownian diffusion coefficient and the unattached fraction of attached progeny decrease with increasing aerosol diameter.

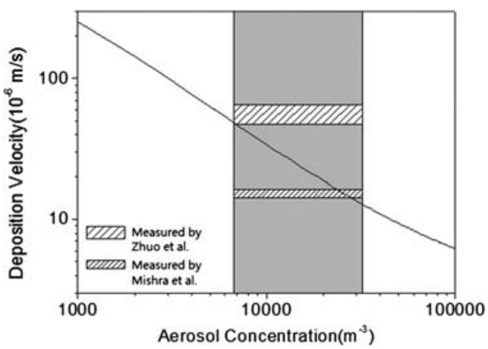

Figure 3. Deposition velocity of thoron progeny at different aerosol concentrations.

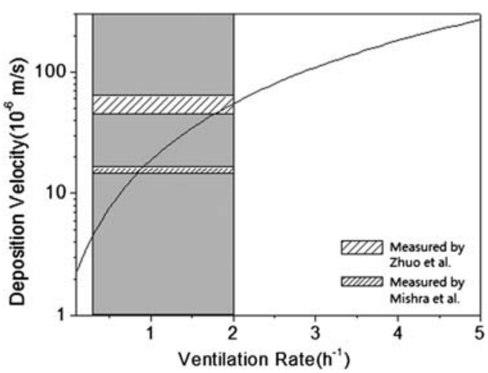

Figure 4. Deposition velocity of thoron progeny at different ventilation rates.

According to the model, aerosol concentration influences V_d through the unattached fraction. A decreasing tendency is shown in Figure 3 because the increase in aerosol concentration would shrink the unattached fraction of thoron progeny, which has a greater deposition velocity.

According to the model, ventilation rate influences V_d directly through turbulent intensity and through the unattached fraction. It is shown in Figure 4 that the deposition velocity increases with the increase in ventilation rate, because of the increasing of turbulent intensity of indoor air and the increase in unattached fraction.

Obviously, the values given by Mishra and Zhuo are generally covered in the ranges. Despite the discrepancy of the two values that might be due to the difference in aerosol and ventilation rates, both the values are in a reasonable range.

According to calculations with the parameters given in Table 1, the typical value of V_d is 1.26×10^{-5}m s^{-1}, with a range between 7.6×10^{-7} and 3.2×10^{-4} m s^{-1}. It is found from the results that the deposition velocity of thoron progeny could vary in a large range in different environments, so care should be taken to adopt one particular value for all thoron surveys in different environments.

To assure the accuracy of the calculations, some calculated results are compared with experimental ones. Using the environmental parameters measured by the aforementioned methods, the theoretical values of V_d in the four environments are calculated. The experimental value V_d^{exp} and the theoretical value V_d^{the} in the four different environments, as well as environmental parameters, are shown in Table 2. Accumulating times for the house with lantern mantles are 8 d and 11 d, for closed windows and opened windows, respectively; 114 d and 94 d for basement 1 and basement 2, respectively.

The theoretical results are approximately consistent with experimental results in acceptable ranges, suggesting that the calculated results discussed in this article are convincible. Compared with the house with closed windows, the house with opened

Table 2. Comparisons of experimental and theoretical values of deposition velocity.

	House (closed)	House (opened)	Basement 1	Basement 2
λ_v (h^{-1})	0.34	1.17	0.56	0.27
CMD (nm)	120 ± 62	126 ± 56	52.3 ± 22.3	56.5 ± 14.9
GSD	4.3 ± 1.6	6.4 ± 1.7	3.1 ± 2.1	3.3 ± 0.4
N (cm^{-3})	$15\,800\pm5900$	$20\,700\pm4000$	$11\,600\pm4\,900$	2420 ± 120
EEC_{Tn} (Bq m^{-3})	227	95	0.97	2.4
V_d^{the} (m s^{-1})	4.17×10^{-5}	1.58×10^{-4}	1.37×10^{-4}	1.38×10^{-4}
V_d^{exp} (m s^{-1})	$(3.12\pm1.21)\times10^{-5}$	$(1.30\pm0.50)\times10^{-4}$	$(1.26\pm0.46)\times10^{-4}$	$(1.22\pm0.63)\times10^{-4}$

windows has a remarkable higher ventilation rate, similar aerosol concentration and similar aerosol diameter, so the different ventilation rate is responsible for its higher deposition velocity. The deposition velocity in basement 2 is very close to that in basement 1, probably because the effects of a lower ventilation rate and a lower aerosol concentration of basement 2 counteract each other.

CONCLUSION

To improve the accuracy of passive measurements for thoron progeny, the influence of environmental factors on the deposition velocity of thoron progeny is studied. The typical value of V_d is 1.26×10^{-5}m s^{-1}, with a range between 7.6×10^{-7} and 3.2×10^{-4} m s^{-1}. According to the calculations, deposition velocity varies in a large range and is sensitively influenced by aerosol diameter, aerosol concentration and ventilation rate, demonstrating that deposition velocity is environment-dependent. However, for practical applications, the influence may be relevant in extreme conditions. In extreme conditions, care should be taken to choose one measured value in different environments in thoron surveys; otherwise, the deviation would be unacceptable. In real environments, with sufficient aerosols and not too large ventilation rates, the deposition velocity may vary in a limited range. This may be reasonable, considering the non-availability of alternative passive techniques for passive integrating measurements in indoor environments. It is also suggested that more site measurements of V_d in different environments should be done in the future.

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REFERENCES

1. Steinhausler, F. *Environmental ^{220}Rn: a review.* Environ. Int. **22**(Suppl. 1), 1111–1123 (1996).
2. Doi, M. and Kobayashi, S. *Characterization of Japanese wooden houses with enhanced radon and thoron concentrations.* Health Phys. **66**, 274–282 (1994).
3. Shang, B., Chen, B., Gao, Y., Wang, Y., Cui, H. and Li, Z. *Thoron levels in traditional Chinese residential dwellings.* Radiat. Environ. Biophys. **44**(3), 193–199 (2008).
4. Chen, J., Moir, D., Sorimachi, A. and Tokonami, S. *Characteristics of thoron and thoron progeny in Canadian homes.* Radiat. Environ. Biophys. **50**, 85–89 (2011).
5. The United Nations Scientific Committee on the Effects of Atomic Radiation (2009) *Volume II, Annex E: sources-to-effects assessment for radon in homes and workplaces.* UNSCEAR 2006 Report, United Nations.
6. Bi, L., Shang, B., Zhu, L., Cui, H. and Zhang, Q. *Comparison of several methods for thoron progeny measurement*. At. Energy Sci. Technol. **43**(5) 461–465 (2009) (in Chinese).
7. McLaughlin, J. *An overview of thoron and its progeny in the indoor environment*. Radiat. Prot. Dosim. **141**(4), 316–321 (2010).
8. Zhuo, W. and Iida, T. *Estimations of thoron progeny concentrations in dwellings with their deposition rate measurements.* J. Health Phys. **35**(3), 365–370 (2000).
9. Mishra, R. and Mayya, Y. S. *Study of a deposition-based direct thoron progeny sensor (DTPS) technique for estimating equilibrium equivalent thoron concentration (EETC) in indoor environment*. Radiat. Meas. **43**, 1408–1416 (2008).
10. Mishra, R., Mayya, Y. S. and Kushwaha, H. S. *Measurement of ^{220}Rn/^{222}Rn progeny deposition velocities on surfaces and their comparison with theoretical models.* J. Aerosol Sci. **40**, 1–15 (2009).
11. Mishra, R., Prajith, R., Sapra, B. K. and Mayya, Y. S. *Response of direct thoron progeny sensors (DTPS) to various aerosol concentrations and ventilation rates.* Nucl. Instrum. Methods Phys. Res. Sect. B **268**, 671–675 (2010).
12. Mishra, R., Prajith, R., Sapra, B. K. and Mayya, Y. S. *An integrated approach for the assessment of the thoron progeny exposures using direct thoron progeny sensors.* Radiat. Prot. Dosim. **141**(4) 363–366 (2010).
13. Tokonami, S. *et al*. *Radon and thoron exposures for cave residents in Shanxi and Shaanxi provinces.* Radiat. Res. **162**(4), 390–396 (2004).
14. Ramola, R. C. *et al*. *Preliminary indoor thoron measurements in high radiation background area of southeastern coastal Orissa, India.* Radiat. Prot. Dosim. **141**(4), 379–382 (2010).
15. Stevanovic, N., Markovic, V. M. and Nikezic, D. *Deposition rates of unattached and attached radon progeny in room with turbulent airflow and ventilation.* J. Environ. Radioact. **100**, 585–589 (2009).
16. Stevanovic, N., Markovic, V. M. and Nikezic, D. *Relationship between deposition and attachment rates in Jacobi Room model*. J. Environ. Radioact. **101**, 349–352 (2010).
17. Jacobi, W. *Activity and potential-energy of 222radon and 220radon-daughters in different air atmospheres.* Health Phys. **22**, 441 (1971).
18. Lai, A. C. K. and Nazaroff, W. W. *Modeling indoor particle deposition from turbulent flow onto smooth surfaces.* J. Aerosol. Sci. **31**(4), 463–476 (2000).
19. Porstendorfer, J. and Reineking, A. *Indoor behaviour and characteristics of radon progeny.* Radiat. Prot. Dosim. **45** 303–311 (1992).
20. Hussein, T., Hruska, A., Dohanyosova, P., Dzumbova, L., Hemerka, J., Kulmala, M. and Smolik, J. *Deposition rates on smooth surfaces and coagulation of aerosol particles inside a test chamber.* Atmos. Environ. **43**(4), 905 (2009).
21. Zhang, L., Wu, J., Guo, Q. and Zhuo, W. *Measurement of thoron gas in the environment using a LSC.* J. Radiol. Prot. **30**, 597–605 (2010).
22. Yamada, Y., Tokonami, S., Fukutsu, K. and Shimo, M. *Improvement of the SDB/CNC aerosol sizing system for fast measurement at field*. Radiat. Prot. Dosim. **88**, 329–334 (2000).
23. Ren, T. *et al*. *Measurement and Assessment of Environmental Radiation*. Atomic Energy Press, p. 201 (2005) (in Chinese).