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Behaviours and influence factors of radon progeny in three typical dwellings

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Abstract

To investigate the behaviours and influence factors of radon progeny in rural dwellings in China, site measurements of radon equilibrium factor, unattached fraction and some important indoor environmental factors, such as aerosol concentration, aerosol size distribution and ventilation rate, were carried out in three typical types of dwellings, and a theoretical study was also performed synchronously. Good consistency between the results of site measurements and the theoretical calculation on equilibrium factor F and unattached fraction f_p was achieved. Lower equilibrium factor and higher unattached fraction in mud or cave houses were found compared to those in brick houses, and it was suggested by the theoretical study that the smaller aerosol size distribution in mud or cave houses might be the main reason for what was observed. The dose conversion factor in the mud houses and the cave houses may be higher than that in brick houses.

1. Introduction

Radon is considered to be one of the most significant sources of indoor pollutants. Inhalation of indoor radon and its progeny contributes more than half of the effective dose to human beings of total contributions from all natural radiation sources [1]. Furthermore, radon progeny contributes the greatest portion of radon exposure compared to radon gas itself. It is necessary and important to investigate and understand the behaviours and influence factors of indoor radon progeny for the evaluation of radon exposure.

It was suggested by a large scale survey carried out recently that the indoor level of radon concentrations in cities in China has risen greatly during the last 30 years, and a lot of research has been carried out on urban dwellings [2–4]. In contrast, knowledge on the behaviours of radon and its progeny in rural dwellings is limited. Considering the large population in the countryside, and the difference in building materials and construction between cities and country areas, it is interesting and meaningful to do such a study on radon and its progeny in detail in typical rural dwellings.

For a better understanding on the behaviours of radon progeny in rural dwellings, in this paper, as a pilot study, some key factors related to radon exposure evaluation, such as radon equilibrium equivalent concentration (EEC), equilibrium factor (F) and unattached fraction (f_p), were measured.

EEC is defined as the equivalent concentration of the decay products in equilibrium with the parent gas that yields the same potential alpha energy per unit volume as the existing mixture [5]:

$$\mathrm{EEC}(^{222}\mathrm{Rn}) = 0.105C(^{218}\mathrm{Po}) + 0.516C(^{214}\mathrm{Pb}) + 0.379C(^{214}\mathrm{Bi}), \qquad (1)$$

where $C(^{218}\mathrm{Po})$, $C(^{214}\mathrm{Pb})$ and $C(^{214}\mathrm{Bi})$ are concentrations of each progeny in Bq m^{-3}. F is the ratio of EEC to concentration of radon gas:

$$F = 0.105(f_1^{\mathrm{u}} + f_1^{\mathrm{a}}) + 0.516(f_2^{\mathrm{u}} + f_2^{\mathrm{a}}) + 0.379(f_3^{\mathrm{u}} + f_3^{\mathrm{a}}), \qquad (2)$$

where f_i^{u} and f_i^{a} are ratios of activity concentrations of the ith unattached and attached radon progeny to the radon concentration, respectively ($i = 1, 2, 3$ for ^{218}Po, ^{214}Pb, ^{214}Bi, respectively; u for unattached and a for attached). f_p is defined as the fraction of alpha potential energy of the unattached progeny to that of all radon progeny:

$$f_p = \frac{3.60f_1^{\mathrm{u}} + 17.8f_2^{\mathrm{u}} + 13.1f_3^{\mathrm{u}}}{3.60(f_1^{\mathrm{u}} + f_1^{\mathrm{a}}) + 17.8(f_2^{\mathrm{u}} + f_2^{\mathrm{a}}) + 13.1(f_3^{\mathrm{u}} + f_3^{\mathrm{a}})}. \qquad (3)$$

On the other hand, indoor environmental factors, such as aerosol particle concentrations, aerosol size distributions and room ventilation rates, were also measured synchronously, and their influence on radon progeny behaviours were discussed by analysing the radon progeny room model.

2. Site measurements and results

2.1. Study sites

To verify our theoretical prediction, site measurements were carried out in some typical houses which were classified according to their building materials. They were brick houses (red brick or cyan brick), mud houses (sun-dried mud brick) and a cave house. In this study, two brick houses and three mud houses in the suburban area of Beijing and a cave house located in Shanxi province were chosen. They were all one storey with three or four rooms and unoccupied during the measurements. Bedrooms with sizes of 40–60 m^3 were chosen because they are geometrically similar and less disturbed by artificial activities.

2.2. Methods and results

For indoor radon and its progeny measurements, the methods can be introduced as follows: radon gas concentration was measured by RAD-7 monitor (Durridge Company, USA); radon progeny was measured by BWLM monitor (Tracerlab Company, Germany); the unattached fraction was measured by EQF3120 monitor (SARAD Company, Germany). The instruments, which were all compared and calibrated by the National Institute of Metrology, were placed close to each other in the centre of the rooms and measured continuously for more than 12 h. The sampling cycles of radon and radon progeny were 1 h. The results are shown in table 1.

It is indicated in table 1 that radon concentration in the cave house was much higher than that of the other two types of houses; on the other hand, the F values for both mud houses and

Table 1. Results of radon and its progeny in different types of houses (Bq m^{-3}). (Note: the measurements were based on active sampling and the sampling cycles were 1 h.)

	Radon concentration	EEC	F	f_p
Brick house	32.8 ± 33.3	17.97 ± 1.80	0.55 ± 0.56	0.03 ± 0.01
Mud house	9.72 ± 15.23	2.77 ± 0.52	0.28 ± 0.45	0.10 ± 0.02
Cave house	62.1 ± 30.1	21.26 ± 4.81	0.34 ± 0.18	0.11 ± 0.05

Table 2. Results of related indoor environmental factors in three types of houses.

		Aerosol size distribution		
	Aerosol conc. (cm^{-3})	CMD (nm)	GSD	Ventilation rate (h^{-1})
Brick house	$9\,154 \pm 414$	119	2.48	0.56 ± 0.14
Mud house	$37\,179 \pm 2056$	30.3	2.34	1.56 ± 0.50
Cave house	$17\,853 \pm 3192$	36.2	2.29	0.54 ± 0.16

cave houses were much lower than that for brick houses, and f_p values for the first two types of houses were much higher than that for brick houses.

For a better understanding of radon progeny behaviour and its influence factors, related indoor environmental factors were also measured at the same time. The methods of this section can be introduced as follows: aerosol concentrations were measured continuously by a TSI condensation particle counter (TSI model 3007, TSI Company, USA); aerosol particle size distributions were measured by a self-developed screen diffusion battery (SDB) and TSI condensation particle counter (TSI model 3007); room ventilation rates were measured by adopting a model 1370 CO_2 tester according to the Chinese Standard [6]. Aerosol size distributions are often lognormal distributions, characterized by count median diameter (CMD) and geometric standard deviation (GSD).

Results of related indoor environmental factors are shown in table 2.

It is shown in table 2 that the aerosol concentration in brick houses was much smaller than that in the other two types of houses; however, the aerosol diameter was much larger than that of other houses. It is also noticed here that mud houses had the highest room ventilation rates, the highest aerosol concentration and the smallest aerosol size distribution. Aerosol size distributions and aerosol concentrations indicated that, in both mud and cave houses aerosol particles were merely in nucleation mode, in which particles were smaller and derived from nucleation processes, while in brick houses accumulative mode, in which larger particles were formed by coagulation, was dominant.

To discuss and explain the site measurement results above, a theoretical model study of indoor radon progeny is carried out in section 3.

3. Theoretical model of indoor radon progeny

Behaviours of radon progeny in a room are described by parametric differential equations, primarily given by Jacobi [7], taking into account radioactive decay, removal by ventilation, deposition and transition from one form to another. Parameters of the Jacobi model are decay constant λ_i, ventilation rate λ_v, attachment rate λ_a and deposition constants of unattached and attached progeny, λ_d^u and λ_d^a, respectively, in s^{-1} (or h^{-1}). Jacobi's equations are written as

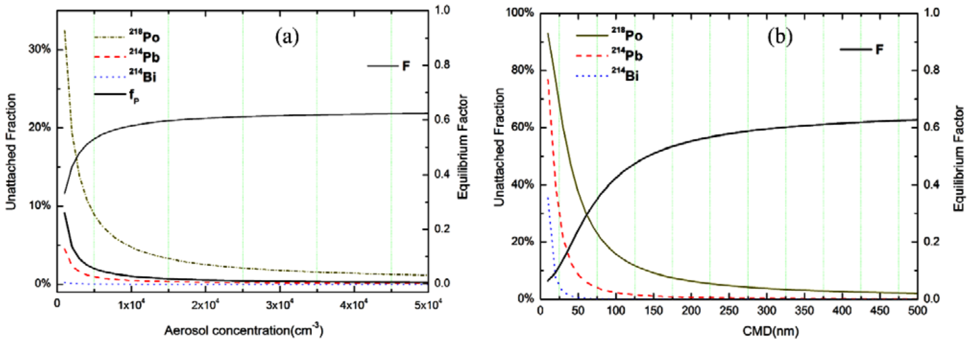

Figure 1. The correlation between F, f_p and aerosol concentration (a) and aerosol size distributions (b). The curves of ^{218}Po, ^{214}Pb and ^{214}Bi are concentration-fractions of each unattached progeny. CMD of aerosol is 250 nm and the ventilation rate is 1.5 h^{-1} for (a), while the aerosol concentration is 10 000 cm^{-3} and the ventilation rate is 1.5 h^{-1} for (b). GSD values of both are assumed to be unity.

(This figure is in colour only in the electronic version)

follows:

$$f_i^\mathrm{u} = \frac{\lambda_i(f_{i-1}^\mathrm{u} + p_{i-1} f_{i-1}^\mathrm{a})}{\lambda_i + \lambda_\mathrm{v} + \lambda_\mathrm{d}^\mathrm{u} + \lambda_\mathrm{a}} \tag{4}$$

$$f_i^\mathrm{a} = \frac{\lambda_\mathrm{a} f_i^\mathrm{u} + \lambda_i(1 - p_{i-1}) f_{i-1}^\mathrm{a}}{\lambda_i + \lambda_\mathrm{v} + \lambda_\mathrm{d}^\mathrm{a}}, \tag{5}$$

where f_i^u and f_i^a are ratios of activity concentrations of the ith unattached and attached radon progeny to radon concentration, respectively ($i = 1, 2, 3$ for ^{218}Po, ^{214}Pb, ^{214}Bi, respectively; u for unattached and a for attached). p_{i-1} is the recoil factor defined as the average probability of detachment of the recoil nuclei after radioactive decay. Among them λ_a in the equations is a function of aerosol size distribution and aerosol concentration, and is calculated by the equation of Porstendorfer *et al* [8]. Therefore, given the values of ventilation rate, aerosol size distribution and aerosol concentration, F and f_p are obtained by solving equations (2)–(5).

To analyse the influence of indoor environmental factors on the behaviours of radon progeny theoretically, the above model was used, and the following parameters were adopted: $\lambda_\mathrm{v} = 0.55$ h^{-1} [9], $\lambda_\mathrm{d}^\mathrm{u} = 20$ h^{-1} [9], $\lambda_\mathrm{d}^\mathrm{a} = 0.2$ h^{-1} [9], for ^{214}Pb, $p_1 = 0.87$, $p_2 = p_3 = 0$ [10]. The correlation between indoor equilibrium factor (F), unattached fraction (f_p), aerosol concentrations and aerosol size distributions is shown in figure 1.

It is suggested by the theoretical study results, as figure 1 shows, that there is no close correlation between equilibrium factor, unattached fraction and aerosol concentration in normal environmental conditions in a room, i.e. aerosol concentration had a limited effect on equilibrium factor and unattached fraction. However, aerosol size distribution affects the above two factors a lot—an increasing aerosol particle diameter leads to a drop in unattached fraction, and an increase in equilibrium factor.

4. Comparison and discussion

To verify the consistency of site measurements and theoretical model analysis, equilibrium factor F and unattached fraction f_p were calculated by equations (2)–(5) for the three types of dwellings, adopting the data in table 2. Theoretical and measured results are shown in table 3.

Table 3. Comparison between calculated results and measured results.

	F		f_p	
	Calculated results	Measured results	Calculated results	Measured results
Brick house	0.493	0.55 ± 0.56	0.023	0.03 ± 0.01
Mud house	0.250	0.28 ± 0.45	0.094	0.10 ± 0.02
Cave house	0.297	0.34 ± 0.18	0.106	0.11 ± 0.05

It is noticed in table 2 that EEC in brick houses was consistent with 16.41 ± 9.02 Bq m^{-3} in rural Beijing, reported by Zhang *et al* [3], and F in brick houses was consistent with 0.55, an average level of a nation-wide survey reported by Shang *et al* [2], while F in the other two types of houses was extraordinarily low.

A good consistency between theoretical and experimental results was achieved for both unattached fraction f_p and equilibrium factor F. It was shown that the theoretical model could describe the behaviours of indoor radon progeny well, and the site measurement results were reasonable, though F and f_p values of mud houses and cave houses were extraordinary. According to our theoretical prediction, the lower F and higher f_p of mud houses and cave houses could be attributed to the smaller size distribution of the aerosol.

5. Conclusion

To investigate behaviours and influence factors of radon progeny in rural dwellings in China, site measurements on radon equilibrium factor, unattached fraction and some important indoor environmental factors, such as aerosol concentration, aerosol size distribution and ventilation rate, were carried out in three typical types of dwellings, and theoretical study was also performed synchronously. Good consistency between site measurements and the theoretical calculation on equilibrium factor F and unattached fraction f_p was achieved. Lower equilibrium factor and higher unattached fraction in mud or cave houses were found compared to brick houses, and it was suggested by the theoretical study that the smaller aerosol size distribution in mud or cave houses might be the main reason.

It was suggested by ICRP that dose coefficients would be given for different reference conditions of domestic and occupational exposure, taking into account factors including inhaled aerosol characteristics and disequilibrium between radon and its progeny [11]. In general, smaller aerosol size distribution leads to higher dose conversion factor [12]. Therefore, dose conversion factor in mud houses and cave houses may be higher due to their aerosol characteristics. Future work is needed to verify the difference in dose conversion factors in these types of houses.

Acknowledgments

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