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Evaluation of correlation between PM2.5 and radon-progeny equilibrium factor in radon chamber

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Abstract The dosage of environmental radon progeny is typically estimated according to the environmental radon exposure and the recommended radon-progeny equilibrium factor, F. To investigate the relationship between PM2.5 and the radon-progeny equilibrium factor, cigarettes are used to simulate the haze–fog in a multi-functional radon chamber to achieve a stable radon concentration environment. A radon detector and a portable laser aerosol spectrometer are used to obtain the values for C_{mean} PM2.5, C_{Rn}, and C_{p}. The results show that the mean values of F conform with the typical value recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation and are within the reasonable range of 0.1–0.9. In this study, a positive correlation is observed between the F values and PM2.5 concentrations.

Keywords PM2.5 · Radon chamber · Equilibrium factor · Linear regression

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1 Introduction

In recent years, the issue of haze–fog in the middle-eastern region of China has become increasingly serious. According to analysis of the relationship between the air visibility and the aerosol levels in China, this phenomenon is mainly due to the significant increase in anthropogenic atmospheric aerosols [1–3]. Haze–fog is a general expression for the excess amounts of various suspended particulates in the atmosphere. Among these, PM2.5 (< 2.5 μm in diameter) is considered as the main factor of haze–fog. High concentrations of fine particles in the air can result in the accumulation of hazardous substances, such as heavy metals, acid, alkali, salt, amine, and phenol [4, 5]. These substances affect the respiratory tract and cardiovascular system in humans, inducing or aggravating chronic asthma, heart disease, diabetes [6–8]. Moreover, when ^{222}Rn decays, the new progenies are all heavy-metal radioisotopes [9, 10]. Most of the radon products, such as ^{218}Po, ^{214}Po, ^{214}Pb, and ^{214}Bi, rapidly attach to the surrounding PM2.5 [11, 12]. The size of the attachment depends on the number of available particles in the air. In addition to the radioactive decay, the physical behavior of the attached part is the same as that of stabilizing atmospheric particles [13–15]. Therefore, the concentration and behavior of fine particulate matter in air can affect the fraction of radon progenies attached to aerosols and may affect the equilibrium factor (F).

The dosage of environmental radon progeny is estimated according to the environmental radon exposure and the recommended radon-progeny equilibrium factor. F is defined as the ratio of the equilibrium equivalent radon concentration ($\mathrm{EEC_{Rn}}$) to the radionuclide concentration of radionuclides in the air. It is a very important parameter for estimating radon and its progenies exposure for humans. In 2000, the evaluation report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) suggested an indoor standard value of *F* [16]. At present, many studies focus on the aerosol conditions, gas exchange rate, humidity, and other factors or on theoretical research regarding the influence of these factors on indoor radon progeny. The effects of the aerosol, wind speed, temperature, and humidity on the radon, combined radon progeny, and equilibrium factor have not been studied in a stable radon concentration environment (such as a radon chamber) [17, 18].

To investigate the relationship between PM2.5 and the *F* value, we first focus on an experiment involving solid particles produced by burning cigarettes to examine the role of the radon progeny in the multi-functional ecological radon chamber. Then, a radon detector is used to monitor the radon and its progeny concentration in the chamber. Finally, the *F* value is calculated according to the radon and its progeny concentration.

2 Experimental

The radon chamber is a metering device in a radon laboratory. It can be used to perform experiments at a certain radon concentration under a controlled temperature and humidity, as well as for radon instrument calibration. The multi-functional radon chamber is a medium-sized radon chamber developed by the East China University of Technology, whose structure is shown in Fig. 1.

The volume of the radon cabinet is 4.13 m^3. The glass cabinet around the chamber is equipped with eight sampling holes. A PM2.5 aerosol generator can be connected to two of these holes to ensure the full combustion of the cigarette after air circulation. The monitoring system for the PM2.5 concentration and the radon and its progeny comprises a portable laser aerosol spectrometer and a radon detector. These devices are placed on the working stage in the radon chamber before the experiment. Control software allows remote control of the radon detector instruments as well as the dynamic stabilization of the radon concentration in the radon chambers.

In the experiment, the radon concentration is maintained at approximately 1000 Bq/m^3. For setting the temperature/humidity simulation value, the Nanchang area is used as an example. Over a recent 10-year period (2008–2017), the average temperature/humidity was 28.04 °C/77.51% in summer and 7.91 °C/83.04% in winter [19]. However, the winter temperature and humidity simulation value exceed the range of the multi-functional radon chamber. To obtain the simulation effect at a low temperature and contrast with the higher temperature, 15.50 °C/50.00% is selected as an alternative value for the multi-functional radon chamber temperature and humidity stability experimental results. According to the PM2.5 detection network of new air-quality standards, a set of five levels of experiments are conducted at two different temperature/humidity settings: the excellent level (0–35 μg/m^3), good level (35–75 μg/m^3), mild pollution level (75–115 μg/m^3), moderate pollution level (115–150 μg/m^3), and heavy pollution level (150–250 μg/m^3). The experiment lasted for 24 h at each grade.

2.1 Generation of PM2.5 aerosol

The semiautomatic cigarette smoke emitter (PM2.5 generator) consists of a 1000-mL heat-resistant glass sealed container, a pump, a fixed clip, a silicone tube, and two sampling holes with quick coupling, as shown in Fig. 2. The pump connects the heat-resistant glass sealed container to the radon chamber cabinet through the silicone tube, and the cigarette to burn is affixed to the container using a clip. Thus, smoke generated in the container can be injected into

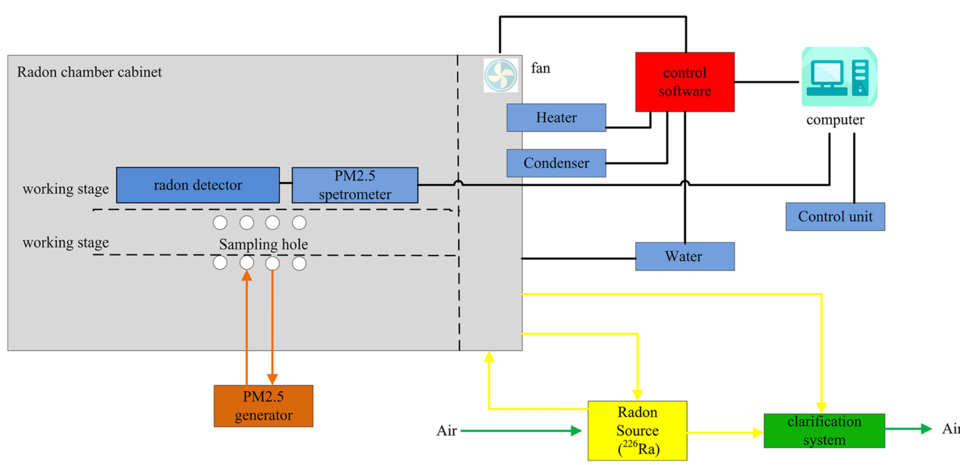


Fig. 1 (Color online) Structure of the multi-functional radon chamber

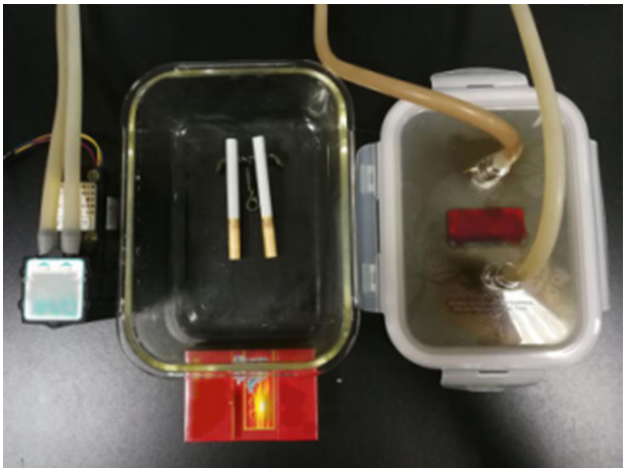


Fig. 2 (Color online) Semiautomatic cigarette smoke emitter

the radon chamber cabinet. The cigarette can be lit or extinguished by opening the lid of the heat-resistant glass sealed container.

2.2 Measurement of PM2.5 concentration

The PM2.5 concentration is measured using a portable laser aerosol spectrometer (GRIMM GmbH, Germany). The device uses 31 size channels, allowing particles to be detected in a very broad size range of 0.25–32 μm. The value of the sampling flow is 1.2 L/min, whereas the minimum value of the mass concentration is 0.1 μg/m^3. After the measurement begins, results are obtained continuously every 6 s. During the experiment, real-time data are depicted on a personal computer and can be controlled remotely via Bluetooth.

2.3 Measurement of radon and its progeny

The radon concentration (C_{Rn}) and the potential alpha energy concentration (C_p) are measured using a radon detector (SARAD GmbH, Germany) in the fast measurement mode. The sampling flow is 1.5 L/min, with a 10-min measurement cycle. The C_{Rn} uncertainty is 5.7%, and the C_p uncertainty is 5.0%. The fast measurement mode calibration constant is 0.0032 cpm/Bq/m^3, which equals 312.5 Bq/(m^3·cpm). In this study, only the number of ^{218}Po atoms is recorded, and the response time is 15 min. In measuring the radon progeny, the response time is 120 min owing to the collection of radon-progeny particles in the steady state.

2.4 Calculation method for C_p and F

The F value characterizes the nonequilibrium between the short-lived progeny mixture in the air and its mother nuclide, which is expressed according to the alpha potential:

$$F = 1.81 \times 10^8 C_p / C_{Rn}, \tag{1}$$

where 1.81 × 10^8 is called the conversion factor; C_p represents the radon-progeny potential concentration, J/m^3 (1 MeV = 1.6 × 10^{-13} J); and C_{Rn} represents the radon concentration, Bq/m^3.

3 Results and discussion

The temperature/humidity value in the radon chamber is controlled before the experiment. After the temperature/humidity value is stable, we can start the experiment. The change in the temperature/humidity value in the radon chamber is shown in Fig. 3.

3.1 C_{mean} PM2.5, C_{Rn}, C_p (15.50 °C/50.00%)

Figure 4 shows the measurement results for C_{mean} PM2.5, C_{Rn}, and C_p when the temperature/humidity is stabilized at 15.50 °C/50.00%. The average radon concentration for the whole experiment is 1042.0 Bq/m^3. As shown in Fig. 4, the result is close to the theoretical radon concentration of 1000 Bq/m^3. The average PM2.5 concentrations at the five levels are 20.4, 56.8, 94.1, 129.5, and 191.8 μg/m^3. This shows that the PM2.5 concentrations comply with the new air-quality standard.

To study the effect of the wind speed on the radon-progeny equilibrium factor F, the rotation frequency of the built-in fan in the HD-6 multi-functional radon chamber is increased from 30 to 35 Hz under PM2.5 with a mild pollution level (as shown in Fig. 4b). During this period, the average PM2.5 concentration is 94.1 ± 10.8 μg/m^3.

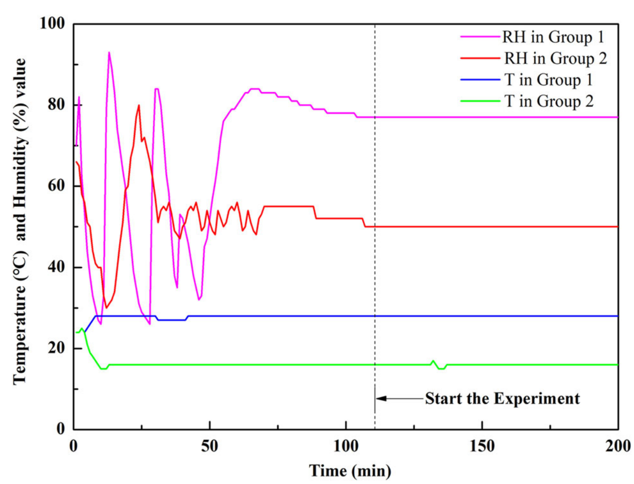
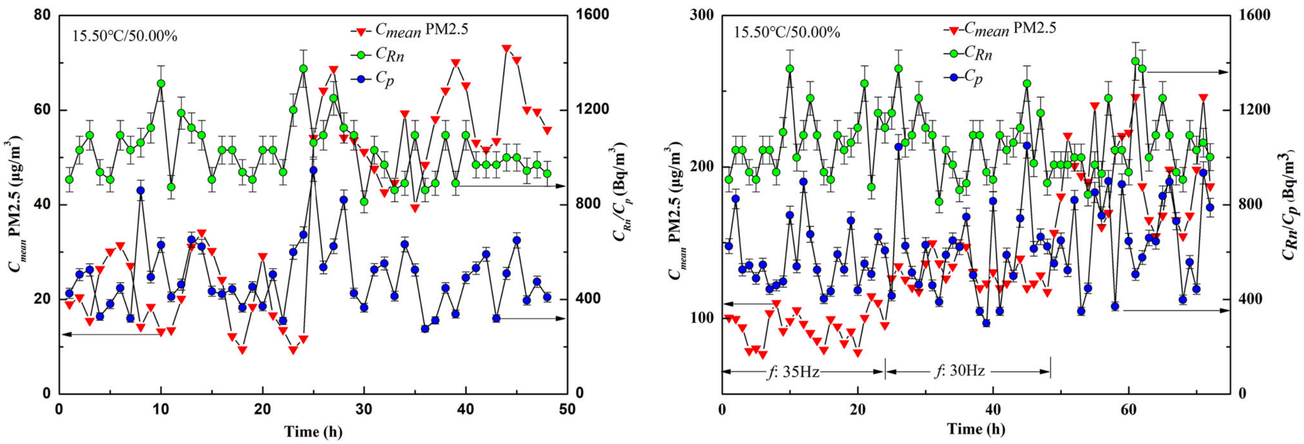


Fig. 3 (Color online) Stability of the temperature/humidity in the radon chamber



(a) (b)

Fig. 4 (Color online) C_{mean} PM2.5, C_{Rn}, C_{p} (15.50 °C/50.00%); **a** PM2.5 level is excellent or good (0–75 μg/m^3); **b** PM2.5 level indicates pollution (75–250 μg/m^3)

3.2 C_{mean} PM2.5, C_{Rn}, C_{p} (28.04 °C/77.51%)

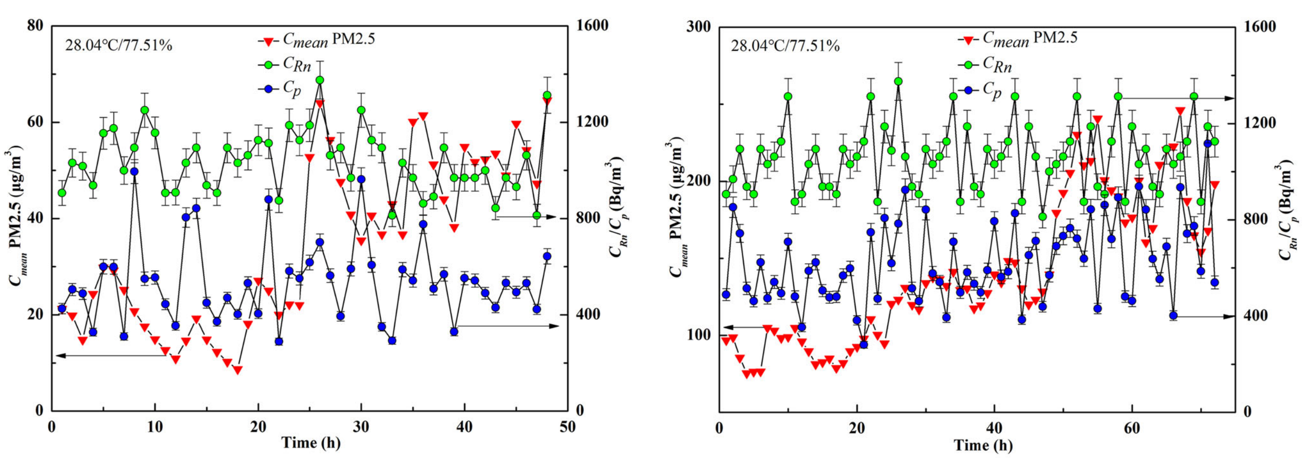
Figure 5 shows the time-dependent C_{mean} PM2.5, C_{Rn}, and C_{p} when the temperature/humidity is stable at 28.04 °C/77.51%. The average PM2.5 concentrations at the five levels are 19.0, 49.8, 91.6, 130.3, and 196.2 μg/m^3. The average radon concentration for the whole experiment is 1,048.0 Bq/m^3, which is within a reasonable range. The activity of the gas increases owing to the temperature rise. Therefore, the fluctuation of the radon concentration increases.

In this study, approximately 2 min of data is not measured, because the PTFE filter is replaced during the experiment. Relative to the whole experiment, 2 min is an extremely short period, and the impact of this omission on the experimental results can be ignored.

3.3 Discussion regarding radon-progeny equilibrium factor

According to the equation $F = 1.81 \times 10^8\ C_{\mathrm{p}}/C_{\mathrm{Rn}}$, the F values are shown in Table 1. The average F value is 0.54 ± 0.15 ($n = 120$) when the temperature/humidity is stable at 15.50 °C/50.00%, calculated using values of 0.48 ± 0.12 (0–75 μg/m^3, $n = 48$) and 0.58 ± 0.16 (75–250 μg/m^3, $n = 72$), respectively. The results conform with the indoor F standard value recommended by UNSCEAR, which is related to the low temperature and low humidity. C_{mean} for PM2.5 is 98.5 μg/m^3 during the entire monitoring period.

In Fig. 5a, b, the average F value is 0.56 ± 0.14 ($n = 120$) when the temperature/humidity is stable at 28.04 °C/77.51%, calculated using values of 0.52 ± 0.14 (0–75 μg/m^3, $n = 48$) and 0.59 ± 0.16 (75–250 μg/m^3,



(a) (b)

Fig. 5 (Color online) C_{mean} PM2.5, C_{Rn}, C_{p} (28.04 °C/77.51%); **a** PM2.5 level is excellent or good (0–75 μg/m^3); **b** PM2.5 level indicates pollution (75–250 μg/m^3)

Table 1 C_{mean} PM2.5, C_{Rn}, C_p, and radon equilibrium factors (F)

Temperature and humidity	PM2.5 level	C_{mean} PM2.5 (μg/m^3) X ± SD	C_{Rn} (Bq/m^3) X ± SD	C_p (Bq/m^3) X ± SD	n	F X ± SD
15.50 °C/50.00%	Excellent	20.4 ± 7.6	1048.7 ± 126.9	485.4 ± 129.3	24	0.46 ± 0.10
	Good	56.8 ± 8.9	994.5 ± 101.5	505.1 ± 154.0	24	0.50 ± 0.13
	Mild pollution	94.1 ± 10.8	1057.8 ± 127.0	574.4 ± 125.3	24	0.54 ± 0.10
	Moderate pollution	129.5 ± 9.4	1061.0 ± 138.3	593.8 ± 189.0	24	0.56 ± 0.17
	Heavy pollution	191.8 ± 28.7	1048.0 ± 138.2	655.5 ± 179.9	24	0.63 ± 0.17
28.04 °C/77.51%	Excellent	19.0 ± 5.9	1046.6 ± 104.1	530.6 ± 181.5	24	0.50 ± 0.15
	Good	49.8 ± 8.7	1027.2 ± 145.1	542.9 ± 141.8	24	0.52 ± 0.12
	Mild pollution	91.6 ± 10.0	1033.9 ± 122.3	553.2 ± 138.1	24	0.54 ± 0.12
	Moderate pollution	130.3 ± 8.9	1061.0 ± 141.9	608.4 ± 142.2	24	0.57 ± 0.10
	Heavy pollution	196.2 ± 24.7	1071.6 ± 135.2	708.3 ± 174.9	24	0.66 ± 0.15

n = 72), respectively. Notably, the F value is not only higher than the indoor standard value (UNSCEAR 2000) but also higher than the value at the same PM2.5 level (mild pollution) when the temperature/humidity is stable at 28.04 °C/77.51%. This indicates that the environmental damage caused by fine-particle pollution is more serious at a high temperature.

The rotation frequency of the built-in fan in the multi-functional radon chamber is increased from 30 to 35 Hz under mild pollution at a temperature/humidity of 15.50 °C/50.00%. During this time, the average F value is 0.54 ± 0.10, whereas the temperature/humidity remains stable at 28.04 °C/77.51%. It is proven that the enhanced wind speed has a reduced effect on F.

3.4 Correlation analysis of data

In the air, the radon progeny combined with the condensation of nuclei is called the combined radon progeny. The radon progeny existing in the form of individual particles (ion or atom) is called the cluster radon progeny [20, 21]. f_p is defined as the ratio of the cluster radon-progeny potential value ($C_{p,u}$) to the total potential value ($C_{p,\ total}$):

$$f_p = C_{p,u}/C_{p,total}. \tag{2}$$

The concentration of PM2.5 is gradually increased in the experiment, and f_p is affected by changes in the cluster radon progeny. There is a relationship between C_p and C_{mean} PM2.5, as well as between F and C_{mean} PM2.5. Linear regression is a statistical analysis method that employs regression analysis together with mathematical statistics to determine the quantitative relationship between two or more interdependent variables. Thus, the relationship between C_p and C_{mean} PM2.5 or between F and C_{mean} PM2.5 can be calculated using linear regression.

As shown in Table 1, five levels of PM2.5 average data (n = 10) under two different temperature/humidity values are analyzed using linear regression. In Fig. 6a, the results indicate that there is a positive correlation between F and

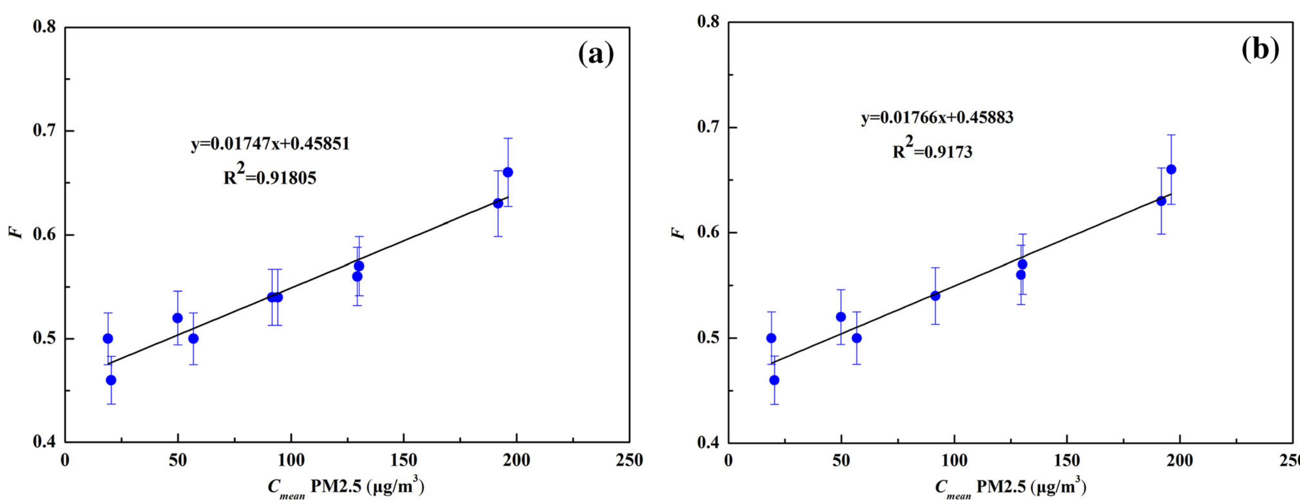


Fig. 6 (Color online) Correlation between F and C_{mean} PM2.5; **a** n = 10; **b** n = 9

Table 2 Correlation factors for C_p–C_{mean} PM2.5 and F–C_{mean} PM2.5

Temperature and humidity	PM2.5 level	R^2		
		n	C_p–C_{mean} PM2.5	F–C_{mean} PM2.5
15.50 °C/50.00%	Excellent and good	48	− 0.01996	0.02997
	Pollution	72	0.04313	0.06239
28.04 °C/77.51%	Excellent and good	48	− 0.00959	0.00176
	Pollution	72	0.11885	0.10757

C_{mean} PM2.5 (R^2 = 0.91805). Even if a set of data is discarded because of the impact of the enhanced wind speed (n = 9), a positive correlation between F and C_{mean} PM2.5 (R^2 = 0.9173) is observed, as shown in Fig. 6b.

The classification method shown in Figs. 4 and 5 can also be analyzed with linear regression. It is also not difficult to show that the correlation between F and C_{mean} PM2.5 is stronger than that between C_p and C_{mean} PM2.5. The resulting R^2 values for C_p–C_{mean} PM2.5 and F–C_{mean} PM2.5 are shown in Table 2.

The correlation factor R^2 for F–C_{mean} PM2.5 ranges from 0.00176 to 0.10757. However, only one group of C_p–C_{mean} PM2.5 values has a correlation factor R^2 of > 0.1. When the PM2.5 level is excellent or good, the correlation factor R^2 of C_p–C_{mean} PM2.5 is negative.

4 Conclusion

In this study, the radon-progeny equilibrium factor F is 0.56 ± 0.14 (28.04 °C/77.51%, n = 120) and 0.54 ± 0.15 (15.50 °C/50.00%, n = 120). The F value conforms with the indoor standard value recommended by UNSCEAR. The growth rate of F increases with the PM2.5 level. From moderate pollution to heavy pollution, the growth rate of F is significantly higher than the previous growth rate, but F remains within the reasonable range of 0.1–0.9. There is a positive correlation between the radon-progeny equilibrium factor F and the concentration of PM2.5 (R^2 = 0.91805), and these two parameters are closely related. The study of the radon-progeny equilibrium factor F is significant and can provide an important reference for environmental protection and radiation protection.

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