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Detailed Measurements of Indoor Radon Levels in Five Residential Premises and the Effect of Ventilation

Key Words
Indoor radon
Ventilation rate

Abstract

Detailed radon measurements and ventilation testing were carried out in five residential premises in Hong Kong. Continuous radon detectors were located in the bedrooms of each site and corresponding CO_2 decay tests were conducted to estimate the ventilation rate. Four air-conditioning operation modes were used in the measurements. Data obtained from the measurements were used to verify the validity of a simple mass balance model. In this paper, factors including the elevation of the building, geographical composition of the area, diurnal variation of the radon level and influence of the ventilation rate on indoor radon level are also discussed.

Introduction

Modern human life is at risk from many different radioactive sources including X-rays, cosmic rays, gamma rays, radiation from television screens and computer monitors, radon gas. Among these, radon gas (mostly ^{222}Rn) contributes a very large portion [1].

In Hong Kong, the indoor radon guideline set by the Environmental Protection Department [2] is 200 $Bq \cdot m^{-3}$. The annual dose for a person subject to this limit is about 8.76 mSv. The average dose from a diagnostic X-ray is about 0.7 mSv. Hence, exposure to 200 $Bq \cdot m^{-3}$ radon gas gives an annual dose equivalent to about 12 X-ray diagnoses every year. The actual annual dose depends on the exact exposure of the population and is perhaps around 2–3 mSv to the body [1] but this as a calculated health risk is quite important. Based on a territory-wide indoor radon survey conducted by the Hong Kong Environmental Protection Department [3], it was shown that Hong Kong is susceptible to elevated radon levels. This is because over one third of the territory is in granite areas and granite has high radium content. This stone is also widely used as a building material. In their report, which was based on measurements conducted from December 1992 to August 1993, the average radon concentrations were 86 $Bq \cdot m^{-3}$ for residential premises and 98 $Bq \cdot m^{-3}$ for all premises. About 5% of the residential and 10% of the non-residential premises had levels beyond the 200 $Bq \cdot m^{-3}$ guideline. Another test conducted in newly constructed residential premises in 1994/95 gave similar results [4]. The data triggered concern for radon research in Hong Kong.

A long-term programme is being carried out by the Indoor Environmental Research Group of the Hong Kong Polytechnic University to understand the various factors influencing the indoor radon level, as well as looking for practical ways for the mitigation of radon pollution. Particular attention is paid to the fact the most of the buildings in Hong Kong are high rise, with concrete as the main

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Table 1. Description of site

Location	Site 1 on 7th floor	Site 2 on 14th floor	Site 3 on 15th floor	Site 4 on 15th floor	Site 5 on 28th floor
Surface area, m^2	80	40	85	36	40
Volume, m^3	47	17	47	14	17
Finishing material	plastic floor finish, painted walls	wooden floor finish, wallpapered walls	floor in tile finish, walls with plaster and paint	wooden floor finish, painted walls	wooden floor finish, wallpapered walls
Geological composition of area	volcanic rock	granite	unknown	reclamation land	granite

source of building materials. This paper reports results of detailed investigations in five residential units and shows how different air-conditioning modes affect the indoor radon level.

Materials and Methods

The solid-state continuous radon detector, Niton Rad7 (Niton Corporation; Mass., USA), was used in this study. The Rad7 detector pulls samples of air through a fine inlet filter into a chamber, for analysis. The filtered air decays inside the chamber producing detectable alpha-emitting progeny, particularly the polonium isotopes. The solid-state detector converts alpha radiation directly to an electrical signal using the technique of alpha spectrometry which is able to distinguish radon from thoron and signal from noise [5].

The survey was conducted in the winter time (November 1994 to February 1995) and during the experimental period, two radon detectors were located in the bedrooms of five different domestic premises which were located in different regions of Hong Kong with different finishing materials and room sizes. Table 1 summarises the details of each site. One radon detector was used to measure the indoor radon level and one for the outdoor level. Each measurement lasted for 24 h in order to catch the day-time and night-time radon levels. In Hong Kong a window unit air-conditioner is commonly used in apartments. For each bedroom, four combinations of measurement modes were used: i.e. (1) window closed and air-conditioner off; (2) window closed and air-conditioner at high-fan with air-conditioning off, (3) window closed and air-conditioner at high-fan with air-conditioning on, and (4) window open and air-conditioner off. The outdoor radon level was measured simultaneously during these tests.

In addition to the radon level measurements, the ventilation rates at each of the premises was also measured using the tracer gas technique with CO_2. CO_2 was released in each site up to a level of 1,800 ppm. The investigators were then evacuated from the site and the CO_2 was allowed to decay through fresh air exchange. Both indoor and outdoor CO_2 levels were monitored using Telaire CO_2 monitors. Both day-time and night-time ventilation rates were estimated. The day-time ventilation rate was measured in the afternoon. Apart from the period that the ventilation tests were conducted, the dwellings were inhabited while the radon measurement took place.

Results

Results of the radon measurements and the ventilation rates are shown in table 2 and table 3 respectively. From table 2 it can be seen that the ventilation rates were the highest in case 4, when the windows of the bedroom were open and the air-conditioners were turned off. In this case, the fresh air exchange depended on natural ventilation. The ventilation rate in this situation depends a lot on the meteorological conditions and the building envelope design (external construction of building) and can vary quite significantly. In our measurements it was found that the ventilation rate during the natural ventilation mode varied from 4.8 to 16.8 h^{-1}. The lowest ventilation rate occurred with case 1, when all the windows were closed and the air conditioners were switched off. The ventilation rate varied from 0.57 to 4.6 h^{-1}. The fresh air exchange was due to infiltration from outside and the infiltration rate depended on the tightness of the building and also on the outside meteorological conditions. No consistent difference was found between case 3, when the air-conditioners were turned on and running on high fan with air-conditioning and case 2 the same without air-conditioning.

It was found that a low indoor radon level corresponded to a high ventilation rate. This observation is reasonable since the outdoor air has a lower radon content. The outdoor radon level is also shown in table 2 and it depends on both the geographical composition of the area, the elevation of the premise and also the meteorological conditions, wind speed, etc. Sites 2, 3 and 4 were on roughly at the same elevation and their corresponding mean outdoor levels were 23 $Bq \cdot m^{-3}$, 12 $Bq \cdot m^{-3}$ and 16 $Bq \cdot m^{-3}$. Site 2 was located in an area of heavy granite content and the outdoor level here was the highest. Site 5 was also located on a granite area but due to the much higher elevation (28th floor), the outdoor radon level was only 9 $Bq \cdot m^{-3}$.

Table 2. Summary of ventilation rate (ACH, h^{-1} and mean indoor radon level ($Bq \cdot m^{-3}$)

Location	Site 1 on 7th floor		Site 2 on 14th floor		Site 3 on 15th floor		Site 4 on 16th floor		Site 5 on 28th floor	
	radon level	ACH	radon level	ACH	radon level	ACH	radon level	ACH	radon level	ACH
Window closed and air-conditioner off	16.9	4.6	198.4	0.57	36.0	2.2	48.9	2.2	166.3	0.57
Window closed, air-conditioner on high fan and AC off	21.4	5.4	99.4	0.65	20.3	2.2	37.1	2.0	121.0	0.9
Window closed, air-conditioner on high fan and AC on	15.1	5.3	78.0	1.34	38.0	2.2	29.4	4.3	45.7	3.1
Window open and air-conditioner off	13.0	6.4	52.8	15.1	10.3	4.8	18.7	16.8	33.9	12.8
Outdoor radon level	13.1	–	23.1	–	12.0	–	15.9	–	8.9	–

AC = Air-conditioning.

Table 3. Summary of night-time and day-time radon concentration

Location	Radon level, $Bq \cdot m^{-3}$									
	site 1 on 7th floor		site 2 on 14th floor		site 3 on 15th floor		site 4 on 16th floor		site 5 on 28th floor	
	night[1]	day[2]	night	day	night	day	night	day	night	day
Window Closed and air-conditioner off	18 26 6	16 20 5	181 255 19	216 300 111	46 80 15	24 67 3	61 105 25	37 59 11	171 278 76	162 259 70
Window closed, air-conditioner on high fan and AC off	21 42 11	22 32 8	93 115 68	106 124 65	20 50 4	21 36 7	37 71 9	38 86 8	127 161 91	115 151 49
Window closed, air conditioner on high fan and AC on	18 34 5	13 26 0	64 70 19	77 92 18	46 77 25	30 62 12	31 51 5	28 45 12	49 84 29	43 70 17
Window open and air-conditioner off	14 37 5	12 28 3	43 97 48	63 101 48	11 22 1	10 22 1	20 40 0	18 37 0	34 55 12	34 71 11
Outdoor radon level	14 28 5	13 25 3	23 45 6	23 49 0	13 28 0	11 18 6	15 32 9	16 28 6	9 25 0	9 18 3

The 3 numbers in each cell, reading from top to bottom, are the average radon concentration ($Bq \cdot m^{-3}$), maximum radon concentration ($Bq \cdot m^{-3}$) and minimum radon concentration ($Bq \cdot m^{-3}$) respectively.

1 Mean night-time (18.00–06.00 h) radon concentration ($Bq \cdot m^{-3}$).

2 Mean day-time (06.00–18.00) radon concentration ($Bq \cdot m^{-3}$).

The radon levels shown in table 2 were mean values over a 24-hour measurement period. A detailed investigation of the night-time and day-time components is shown in table 3. From table 3, it was observed that the highest radon level in the premises occurred more often at night time (18.00–06.00 h) and the lowest radon level often occurred during the day time (06.00–18.00 h). This might be due to the more frequent opening and closing of doors during the day. Another possibility was a slightly higher outdoor radon level observed at night. This may be due to

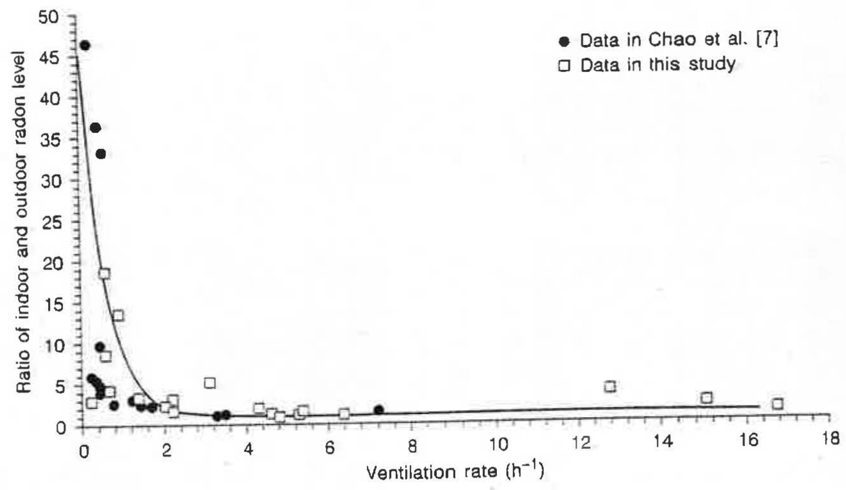

Fig. 1. Influence of ventilation rate on the ratio of indoor radon to outdoor radon levels.

the phenomenon that temperature gradient is periodically positive and negative with a positive period during the night and early morning hours, when a stable atmospheric layer known as an inversion layer is formed [6]. At night time, there is less upward diffusion of air and a higher outdoor radon level. The indoor radon level therefore increases correspondingly.

Simple mass balance analysis can be conducted and the following equation can be found:

$$V\frac{dC}{dt} = r_e A - \lambda C V - q\,(C - C_o), \tag{1}$$

where

C = indoor radon concentration ($Bq \cdot m^{-3}$)
C_o = outdoor radon concentration
q = ventilation rate ($m^3 \cdot s^{-1}$)
r_e = radon emanation rate from wall, ceiling or floor ($Bq \cdot m^{-2} \cdot s^{-1}$)
λ = ^{222}Rn radon decay constant ($0.0000021 \cdot s^{-1}$)
A = surface area of the room that emits radon (m^2)
V = effective volume of the room (m^3)
t = time (s)

Solving equation (1) using the initial condition that at $t = 0$, $C = C_i$, which is the initial radon concentration in the room gives the following equation:

$$C(t) = C_i e^{-\left(\frac{\lambda + q}{V}\right)t} + \left(1 - e^{-\left(\frac{\lambda + q}{V}\right)t}\right) \left(\frac{r_e \frac{A}{V} + \frac{q}{V} C_o}{\lambda + \frac{q}{V}} \right) \tag{2}$$

At steady state when $t \to \infty$, equation (2) can be reduced to:

$$C = \frac{r_e \frac{A}{V} + \frac{q}{V} C_o}{\lambda + \frac{q}{V}} \tag{3}$$

Under normal circumstances, the air exchange rate is much larger than the decay constant and equation (3) can be further simplified to the following:

$$C = \frac{r_e A}{q} + C_o . \tag{4}$$

From equation (4), it can be seen that the indoor radon level at steady state is affected by the radon emanation rate from radon emitting surfaces, the ventilation rate and also the outdoor radon level. The difference between the indoor and outdoor radon levels ($C - C_o$) is inversely proportional to the ventilation rate q ($m^3 \cdot s^{-1}$). This point can be validated from the result shown in tables 2 and 3 (also refer to figure 1 discussed in the next two paragraphs).

If all relevant factors in equation (4) can be found, the indoor radon concentration can be estimated. However, information on radon emanation rate is not conclusive at this stage, and this parameter remains unknown in the analysis. In order to further validate the applicability of equation (4), data in our measurement were used. In our experiments, four modes of ventilation were studied and the measured indoor radon concentration in case (2) (window closed, air conditioner at high fan and air conditioning mode off) was used in equation (4) to evaluate the emanation rate r_e. This radon emanation rate was then used in the other three cases to evaluate the indoor radon level using equation (4). The calculated radon concentration and measured radon concentration showed a correlation of y = 0.748x + 2.745 with an R^2 of 0.80, which indicated that equation (4) could be used to obtain a fairly accurate prediction of the indoor radon level.

From equation (4), due to the small variation of outdoor radon concentration, the ratio of indoor to outdoor radon levels can be shown to be inversely proportional to the ventilation rate if the variations in the radon emanation rate are small. In order to verify this point, data from this study together with experimental data from another study also conducted by this research group were used [7] and the result is shown in figure 1. From the figure it was found that as the ventilation went beyond about 3 h^{-1}, the ratio of indoor and outdoor radon levels came close to unity. This further confirms the validity of model in equation (4), and it also suggests that there is a critical ventilation rate approach for radon mitigation.

Discussion

The experimental data obtained in this study were used to verify the validity of equation (4) in predicting the level of radon indoors. The result was confirmed by the good correlation and also by the result shown in figure 1. Another separate piece of research is being carried out to develop a comprehensive database of the radon emanation rate of commonly used building materials in Hong Kong, part of which has already been published [8]. Knowing the emanation rate of each building material enables better use of the model.

Ventilation has been found to be an important factor in reducing radon levels in the indoor environment. The study described here correlated the ratio of the indoor radon level and the outdoor radon level with the ventilation rate, and a critical ventilation rate when the ratio is smallest was observed. It has been found that such a critical ventilation rate exists for each of the premises beyond which the indoor radon level is the same as the outdoor radon level. This observation agrees with experimental results found by other researchers [9]. Information on this aspect of radon mitigation should be further developed since it can be used to develop design guidelines for engineers and architects in the building services industry. The critical ventilation rate clearly depends on building envelope design but whether building materials play an important part or not still needs further investigation. It may be found that an exact value, as such, for the ventilation rate does not exist, but it is probable that a working range can be developed for use in HVAC design. Calculation of an optimum ventilation rate also involves other consideration like energy consumption in buildings. A balance between good indoor air quality and energy efficient building will definitely require further discussion.

Only five premises have been studied in this paper and the amount of data gathered is not sufficient to draw definite conclusions on how the indoor radon level depends on parameters such as the size of apartments, their construction, height above ground, and the surrounding geology. Further work on these aspects to back up the survey described here is important.

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